Scientific session on Energy saving and Green energy

Chairman: Erik Dahlquist, Mälardalen University

1. Investigations on CO2 absorption using amine solvents in hollow fiber membrane contactors by experiments. Yuexia Lv1, Xinhai Yu1*, Shan-tung Tu1, J. Yan2, E. Dahlquist2, School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai, 200237, China; 2. Dept. IST, Mälardalen University, Västerås, Sweden

2. Intensification of transesterification for synthesis of biodiesel using microchannel reactors. Zhenzhong Wen1, Xinhai Yu1*, Shan-tung Tu1, J. Yan2, E. Dahlquist2 1. School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai, 200237, China; 2. Dept. IST, Mälardalen University, Västerås

3. Continuous bioethanol production by fermentation. Bernt Lie, Juan I. Videla. Telemark University College, Porsgrunn, Norway

4. Optimization and Economic Analysis of Marnoch Thermal Energy Conversion System, C.C. Chukwu1, G.F Naterer2, M.A. Rosen3, E. Dahlquist4 I.A Marnoch5 1,2,3,4 University of Ontario Institute of Technology, Oshawa. Ontario, Canada, 4 Malardalen University, Vasteras Sweden, 5 Marnoch Thermal Power Inc. Toronto, Ontario, Canada,

5. Analysis of the coal based polygeneration system of hybrid type Guoqiang Zhang1,2, Lin GAO1, Hongguang JIN1,* 1 Institute of Engineering Thermophysics, Chinese Academy of Sciences

6. Power transformer parameters identification using extended kalman filter Kourosh Mousavi Takami. TDI researcher and phd student in Malardalen University , Jafar Mahmoudi, Erik Dahlquist, Malardalen University

7. An advanced energy saving method for Aluminium - iron - copper bonding using explosive welding. Mohammad Tabatabaee. TDI institute, Teheran, Iran and Mälardalen University
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EXPERIMENTAL INVESTIGATION ON CO₂ ABSORPTION USING ABSORBENT IN HOLLOW FIBER MEMBRANE CONTACTOR

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ABSTRACT

Carbon dioxide absorption from nitrogen and carbon dioxide mixture has been investigated by experiments using deionized water and low concentration amine solvents including methyl diethanolamine (MDEA) and monoethanolamine (MEA) in polypropylene (PP) hollow fiber membrane. A relatively low solvent concentration of 0.05 mol/l MEA and MDEA was used in the experiment. The dependency of CO₂ removal efficiency and mass transfer rate on operating parameters were studied which include the mixed gas flow rate, the volume concentration of CO₂ at the feed gas inlet, liquid flow rate as well as concentration of absorbents using lower absorbent concentration. It has been found that the CO₂ removal efficiency increases with the increase of the liquid flow rate and solvent concentration, while the CO₂ mass transfer rate increases with the increase of liquid flow rate, CO₂ volume fraction in the feed gas, solvent concentration and gas flow rate. It has been concluded that the absorbent concentration should be compromised between absorption efficiency and the membrane wetting to ensure a stable and efficient removal of CO₂ with a long life of the hollow fiber membrane. It was observed by the experiments that a long operation period may lead to partial membrane wetting even when using relatively low solvent concentrations, resulting in a significant decrease of membrane absorption performance, which might be a main drawback for industrial applications with the studied membranes and solvents.

Keywords: Carbon dioxide; Hollow fiber membrane absorption; Amine solvents; Gas separation
1. INTRODUCTION

The CO\textsubscript{2} emissions are mainly contributed by power generation and transport sectors. CO\textsubscript{2} capture and storage (CCS) has been recognized as one of the approaches for mitigating greenhouse gases. Current CO\textsubscript{2} capture systems includes post-combustion capture, oxy-fuel combustion capture and pre-combustion capture, which make it possible to capture CO\textsubscript{2} from large, centralized sources like power plants and large industries (IPCC, 2005). CO\textsubscript{2} capture from flue gases produced by fossil fuels combustion is referred to as post-combustion capture, which is corresponding to the most widely applicable option in terms of industrial sectors and is compatible to a retrofit strategy.

At present, a wide variety of technological options have been used to capture CO\textsubscript{2} from flue gas of power plants, such as chemical and physical absorption, solid adsorption, cryogenic distillation, and membrane techniques (Mandal et al., 2006; Moon et al., 2006; Andrea Corti et al., 2004). This paper is focused on the membrane techniques for the CO\textsubscript{2} capture. Membrane gas absorption technology is a hybrid technology that combines membrane separation technology and chemical absorption technology with advantages of both membrane contactor and solvent absorption processes. The principle of a membrane contactor is schematically shown in Fig. 1. Instead of depending on the membrane selectivity, the liquid flowing in a hollow fiber contactor provides the selectivity and the unselective membrane only acting as the physical barrier between the liquid and gas phases. CO\textsubscript{2} is absorbed in the membrane contactor when the gas stream contacts with the liquid phase flowing on the opposite side of the membrane. Gabelman and Hwang (1999) studied the advantages and disadvantages of a membrane contractor in details. Compared to conventional absorption devices such as packed towers or bubble columns, the membrane contactor has advantages (Falk-Pedersen et al., 2000), such as

- the gas and fluid phase can be manipulated independently avoiding the problems such as flooding, foaming, channeling and entrainment which are commonly encountered in conventional absorption devices;
- compact structure, high specific surface area and less voluminous is less energy-consuming;
- the modularity of membrane modules makes the design simple and easy to be scaled up linearly with predictable performances.

Even though the mass-transfer coefficient of the membrane contactor is inferior to the conventional devices for the flow of gas and liquid are normally laminar where the turbulent flow is power-consumption, the membrane gas absorption due to its large interfacial area, is still considered as one promising alternative to conventional and potential large scale application technology for CO\textsubscript{2} recovery and removal (Li et al., 2005).
Fig. 1. Schematic drawing of CO₂ absorption in a hollow fiber membrane contactor.

Zhang and Cussler (1985) were the pioneers who proposed the idea of CO₂ absorption by sodium hydroxide in a hollow fiber membrane contactor. In recent years, hollow fiber membrane technology has been extensively studied. Various liquid absorbents including pure water and aqueous solutions of NaOH, KOH, monoethanolamine (MEA), diethanolamine (DEA), 2-Amino-2-methyl-1-propanol (AMP), N-methyldiethanolamine (MDEA), CORAL and the potassium salt of glycine and taurine were used as absorption liquids in polyethylene (PE) or polypropylene (PP) or polytetrafluoroethylene (Teflon) microporous hydrophobic hollow fiber membrane contactors, in which the MDEA and MEA aqueous solutions in PP hollow fiber membrane contactor are the most widely used for CO₂ absorption (Kumar et al., 2002; Kim et al., 2000; Mandal et al., 2001). Compared with other fibers, PP fibers are less expensive and commercially available in a wider size range. Wang et al. (2004) performed a theoretical simulation to study CO₂ absorption using three typical alkanolamine solutions of AMP, DEA and MDEA in a hollow fiber membrane contactor. The effects of operating parameters, membrane configuration, module structures and different solvents on absorption flux and removal efficiency were investigated. Lu et al., (2007) studied the effects of activators 2-Amino-2-methyl-1-propanol (AMP) and piperazine (PZ) on mass-transfer enhancement using MDEA alkanolamine solutions in a hollow fiber contactor and concluded that the mass transfer fluxes of the activated MDEA solutions are significantly higher than that of MDEA solution and effects of operation conditions on mass-transfer enhancement are limited. Theoretical simulations and corresponding experiments were carried out to describe the CO₂ absorption by distilled water and aqueous diethanolamine (DEA) solutions for better understanding of CO₂ absorption in a hollow fiber membrane contactor (Zhang et al., 2006). A theoretical model was developed based on CO₂ absorption simulation by water and DEA under the wetted and the non-wetted operation modes to study the influence of membrane wetting on CO₂ capture in microporous hollow fiber membrane contactors (Zhang et al., 2007). Matsumiya et al. (2005) developed a novel facilitated transport membrane system where the feed gas and aqueous diethanolamine solutions were supplied to the lumen side of the hollow fiber ultrafiltration membrane module with an upward
flow. In addition, they evaluated the energy consumption and compared with conventional separation processes. Liu et al. (2005) examined the mass transfer performances using coiled hollow fiber membrane modules. Their results showed that coiled hollow fiber modules can remarkably enhance the mass transfer compared with conventional straight module. Most researches were limited to atmospheric pressure applications using aqueous absorption solvents, so CO₂ absorption in propylene carbonate at elevated pressure using hollow fiber membrane contactor was investigated by Dindore et al. (2004). The results showed that the decrease in the binary gas phase diffusivity and hence the membrane mass transfer coefficient due to gas pressures increase does not have a significant impact on the overall mass transfer coefficient.

As mentioned above, a variety of experiments and simulations have been carried out to study the membrane absorption performance using different kind of solvents in the hollow fiber membrane contactor. The solvent concentration used by most researches was varied from 1mol/l to 3mol/l. However, it was reported that the surface tension of most absorbent solutions significantly decreases with increasing solution concentration (Vázquez et al., 1997; Rinker et al., 1994), which resulted in PP membrane wetting according to the Laplace-Young equation (Franken et al., 1987), thus reducing the membrane performance. According to Laplace-Young equation, lower solvent concentration can reduce membrane wetting and prolong the membrane service life.

In this paper, the effects of operating parameters on membrane absorption performance using solutions of relative low concentration were investigated in the pilot-scale hollow fiber membrane module. The wetting phenomenon of PP membrane, which is often neglected in reported studies, was also observed in prolonged operation. In addition, the optimal operating parameters were obtained for the specified membrane module.

2. EXPERIMENTAL

The experiments were performed to obtain the operating parameters effect on the absorption using deionized water and MEA and MDEA aqueous solutions of low concentration as the absorbent in a PP hollow fiber membrane contactor.

Table 1. Specifications of the hollow fiber membrane module

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Module outer diameter (mm)</td>
<td>50</td>
</tr>
<tr>
<td>Module inner diameter (mm)</td>
<td>42</td>
</tr>
<tr>
<td>Module length (mm)</td>
<td>360</td>
</tr>
<tr>
<td>Fiber inner diameter (μm)</td>
<td>380</td>
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<tr>
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<td>500</td>
</tr>
<tr>
<td>Fiber length (mm)</td>
<td>300</td>
</tr>
<tr>
<td>Number of fibers</td>
<td>3200</td>
</tr>
<tr>
<td>Fiber porosity</td>
<td>0.65</td>
</tr>
<tr>
<td>Pore size (μm)</td>
<td>0.16</td>
</tr>
<tr>
<td>Contact area (m²)</td>
<td>1.5</td>
</tr>
</tbody>
</table>

A sketch of CO₂ absorption in hollow membrane contactor is shown in Fig. 2. And the photo of experimental setup is shown in Fig. 3. The HDMF-100-1 type microporous polypropylene hollow fiber membrane module (Tianjin Blue Cross Membrane Technology Co., Ltd.) was used as the contactor in this study. The characteristics of the membrane module are listed in Table 1. A gas mixture containing CO₂, N₂ with various volume ratios was selected as the feed gas. Deionized water, aqueous solutions of Monoethanolamine (MEA), methyldiethanolamine (MDEA) were chosen as absorption liquids. The 99.5% grade MEA and MDEA (Shanghai Bangcheng Chemical Co., Ltd.) were dissolved in deionized water to make aqueous solutions of 0.05mol/l-0.25mol/l. The gas phase and liquid phase flowed countercurrent through the module (the gas passed through the shell side, and the absorbent flowed countercurrent through the lumen side of the hollow fibers).

In the experiment, the feed gas was introduced into the system from compressed gas cylinders and the flow rate was adjusted by Mass Flow Controller (Sevenstar Electronics Co., Ltd. MFC D07) which can precisely control the gas flow rate. Then the gas was introduced into the static mixer where the mixtures can be mixed uniformly. Pressure gauges at the inlet and outlet of the membrane module measure the gas pressures, and outlet gas flow rate was measured by a mass flow meter (Sevenstar Electronics Co., Ltd.). The inlet and outlet gas compositions were analyzed on-line by a 9790 III gas chromatograph (FuLi Analytical Instrument Co., Ltd.) using a thermal conductivity detector (TCD). A stainless steel peristaltic pump (Tian Li Liquid Industrial Equipment Factory) was used to pump the liquid into the lumen side of the hollow fibers from solvent container, and the flow rate of liquid was controlled by a rotational flow meter. The
concentrations of the inlet and outlet absorption liquids were measured by a chemical titrimetric method.

Fig.2. Sketch of experimental system.

Fig.3. Experimental setup.
Before each run of an experiment, the system was operated for 15 min by deionized water to eliminate the influence of the former experiment. All data were collected at steady state, after at least 20 min of operating time. Steady state will be indicated by a constant CO$_2$ concentration in the outlet gas stream. Under the same operating conditions, five samples of the gas and absorbent samples were taken and the average value was calculated. All experiments were carried out at atmospheric pressure (0.1MPa) and at room temperatures.

3. RESULTS AND DISCUSSION

Removal efficiency ($\eta$) and mass transfer rate of CO$_2$ ($J_{CO_2}$) were used to describe the separation properties of hollow fiber membrane module using low concentration absorbents, which can be calculated by Eq.(1) and Eq.(2) (Kumar et al., 2002; Yeon et al., 2005):

$$\eta = \frac{Q_{in} \times C_{in} - Q_{out} \times C_{out}}{Q_{in} \times C_{in}}$$

(1)

$$J_{CO_2} = \frac{(Q_{in} \times C_{in} - Q_{out} \times C_{out}) \times 273.15}{0.0224 \times T_g \times S}$$

(2)

Where $\eta$ denotes the CO$_2$ removal efficiency, %; $J_{CO_2}$ is the CO$_2$ mass transfer rate, mol/ (m$^2$·h); $Q_{in}$ and $Q_{out}$ represent the inlet and outlet gas flow rate respectively, m$^3$/h; $C_{in}$ and $C_{out}$ are the CO$_2$ volumetric fraction in the gas inlet and outlet respectively, %; $T_g$ is the gas temperature, K; $S$ represents the gas-liquid mass transfer area and herein equals to the effective membrane area, m$^2$.

3.1. Effect of liquid flow rate on CO$_2$ removal efficiency and CO$_2$ mass transfer rate

In Fig. 4 and Fig. 5, the CO$_2$ removal efficiency and mass transfer rate are plotted against liquid flow rate using 0.05 mol/l MEA, 0.05 mol/l MDEA and deionized water as the absorbent respectively. The CO$_2$ volume fraction in feed gas is 40 % and the gas flow rate is 150 ml/min. As shown in Fig. 4 and Fig. 5, the liquid flow rate has an important influence on both CO$_2$ removal efficiency and CO$_2$ mass transfer rate. As the liquid flow rate increases, CO$_2$ removal efficiency and CO$_2$ mass transfer rate increase. Even though physical absorption using deionized
water, the CO₂ removal efficiency could reach 60.3% as the liquid flow rate is 68 ml/min. With the increase of liquid flow rate, the liquid disturbance is enhanced, which results in a higher speed of CO₂ diffusing into the liquid. The consumed absorbents at the membrane boundary layer could diffuse into the liquid phase at a higher speed due to the increase of liquid flow rate. Therefore, the gas-liquid interface could be maintained at a higher solvent concentration, which increases the CO₂ removal efficiency. In addition, as the increase of liquid flow rate, the thicknesses of gaseous and liquid-phase boundary layers decrease, leading to enhancement of the mass transfer rate. However, CO₂ removal efficiency and mass transfer rate increase slowly at higher liquid flow rate due to the limited boundary layer thickness, which are also shown in the Fig. 4 and Fig. 5.

Fig. 4. Influence of liquid flow rate on CO₂ removal efficiency.

Fig. 5. Influence of liquid flow rate on CO₂ mass transfer rate.
3.2. Effect of CO₂ volume fraction in feed gas on CO₂ removal efficiency and mass transfer rate

The influence of inlet CO₂ volume fraction at the inlet of feed gas on the removal efficiency and mass transfer rate is shown in Fig. 6 and Fig. 7, respectively. Deionized water, 0.05 mol/l MEA and 0.05 mol/L MDEA were used as the absorbent. The gas flow rate is 150 ml/min and the liquid flow rate is 17 ml/min. The CO₂ volume fraction in the feed gas varied from 10 % to 40%. Fig. 6 demonstrates that the CO₂ removal efficiency decreases with the increase of CO₂ volume fraction in the feed gas. As the CO₂ is absorbed in the liquid through physical absorption or chemical absorption, more liquid is consumed with higher CO₂ concentration at the liquid membrane. The liquid will be insufficient relative to higher CO₂ concentration at a constant liquid flow rate, which results in a decrease of CO₂ removal efficiency.

Fig. 7 shows that the increase of CO₂ volume fraction could effectively enhance the mass transfer rate. With the increase of CO₂ volume fraction, the CO₂ concentration gradient at the liquid-gas boundary layer increases. That is, the CO₂ driving force of mass transfer in the gas is enhanced, which leads to the increase of CO₂ diffusion mass transfer rate. Therefore, more CO₂ is absorbed in the liquid by permeating the membrane module.

Fig. 6. Influence of CO₂ volume fraction at the feed gas inlet on the CO₂ removal efficiency.
Fig. 7. Influence of CO₂ volume fraction at the feed gas inlet on CO₂ mass transfer rate.

3.3. Effect of solvent concentration on CO₂ removal efficiency and mass transfer rate

The influences of the absorbent concentration on the CO₂ removal efficiency and mass transfer rate are plotted in Fig. 8 and Fig. 9. Deionized water, MEA and MDEA with the liquid concentration varying from 0.05 mol/l to 0.25 mol/l were used as the absorbent. The gas flow rate is 150 ml/min with 40 vol.% CO₂ in the feed gas and the liquid flow rate is 17 ml/min. As shown in Figs. 8 and 9, the CO₂ removal efficiency and mass transfer rate obviously increase with the increase of the concentration of MEA and MDEA. With the increase of absorbent concentration, the effective component absorbing CO₂ in the liquid boundary layer increases, resulting in higher CO₂ transfer rate into the liquid. As CO₂ enters the liquid and reacts with the corresponding solvent, the CO₂ concentration decreases in liquid-gas boundary layer. It enhances the CO₂ solubility rate and increases the CO₂ removal efficiency. The CO₂ removal efficiency can be as high as 95 % with the MEA concentration of 0.25 mol/l.

As shown in Fig. 8, the CO₂ removal efficiency of MEA and MDEA is much higher than that of deionized water under the same operating conditions. This might be caused by more CO₂ consumed in the presence of MEA and MDEA by the chemical reaction. In addition, Fig. 8 also indicates that the CO₂ removal efficiency of MEA is higher than that of MDEA especially at high absorbent concentration due to the higher rate of MEA reacting with CO₂.

As discussed above, a higher removal efficiency and mass transfer rate can be effectively achieved by increasing the solvent concentration. However, with the increase of concentration of the solvent, the PP membrane is more likely to be wetted and its performance is deteriorated. It can be explained by that the surface tension of aqueous MEA and MDEA solution decreases with the increase of the amine concentration according to the Laplace-Young equation. The membrane is successfully operated for about 60 h without being wetted by using MEA and MDEA at the concentration of 0.05 mol/l. Therefore, the absorbent concentration should be...
compromised between removal efficiency and the wetting to ensure a stable and efficient absorption of CO₂ over a long life of the hollow fiber membrane. Many researches on improving non-wettability have shown promising results. Studies have shown that the performance of polyethylene (PE) membranes could be greatly improved by a hydrophobic treatment to its surface using fluorocarbonic materials (Nishikawa et al., 1995). The wetting problem can also be achieved by coating the membrane with a very thin permeable layer (Kreulen et al., 1993). However, a hollow fiber membrane with non-wettability is still required to be further investigated and developed.

Fig. 8. Influence of solvent concentration on CO₂ removal efficiency.

Fig. 9. Influence of solvent concentration on the mass transfer of CO₂.
3.4. Effect of gas flow rate on CO₂ removal efficiency and CO₂ mass transfer rate

Effect of gas flow rate on the CO₂ removal efficiency and mass transfer rate are shown in Figs. 10 and 11. Deionized water, 0.05 mol/l MEA and 0.05 mol/l MDEA were used as the absorbent. The gas flow rate was varied from 75 ml/min to 200 ml/min with 40 vol. % CO₂ in the feed gas and the liquid flow rate is 17 ml/min. It is clearly shown in Fig.11 that there is a difference in the effects of gas flow rate on CO₂ mass transfer rate of MEA, MDEA aqueous solutions and deionized water due to some uncontrolled factors. With the decrease of gas retention time, the CO₂ concentration at the gas-liquid interface increases, resulting in an increase of the mass transfer rate for MEA and MDEA aqueous solutions. Although increase of gas flow rate can reduce the thickness of gas boundary layer and enhance the gas mass transfer, which is favorable for the CO₂ removal. However, it simultaneously decreases the residence time of gas in the membrane contactor, which is unfavorable for the CO₂ removal. The combined effects result in the tendency as shown in Fig. 10 and Fig. 11. It indicates that the residence time plays an important role in the removal of CO₂.

![Graph showing CO₂ removal efficiency vs gas flow rate](image)

Fig. 10. Influence of gas flow rate on CO₂ removal efficiency.
Fig. 11. Influence of gas flow rate on CO₂ mass transfer rate.

4. CONCLUSIONS

Experiments have been carried out to investigate the effect of operating parameters on the efficiency of carbon dioxide removal using deionized water and low concentration MDEA and MEA in polypropylene hollow fiber membrane. It has been found that the CO₂ removal efficiency increases with the increase of the liquid flow rate and solvent concentration, while the CO₂ mass transfer rate increases with the increase of liquid flow rate, CO₂ volume fraction in the feed gas, solvent concentration and gas flow rate. It is concluded that the absorbent concentration should be compromised between absorption efficiency and the membrane wetting to ensure a stable and efficient removal of CO₂ with a long life of the hollow fiber membrane. It has also been observed by the experiments that a longer operation period render partial membrane wetting even using relative lower solvent concentration, resulting in significant decrease of membrane absorption performance. It is indicated that the decrease of residence time plays more important role in the removal of CO₂ than the intensification of the gas mass transfer.

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REFERENCES


2. INTENSIFICATION OF TRANSESTERIFICATION FOR SYNTHESIS OF BIODIESEL USING A MICROCHANNEL REACTOR

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ABSTRACT

In this paper, transesterification of soybean oil with methanol in the presence of concentrated sodium hydroxide as a catalyst has been experimentally investigated in a zigzag micro-channel reactor. The operating parameters have been optimized which include molar ratio of oil to methanol, catalyst quantity, volumetric rate, and reaction temperature. Compared with the contact time for complete conversion from several minutes to several hours in conventional reactors, the corresponding contact time is significantly reduced to 28 seconds at the conditions of oil-to-methanol molar ratio of 1:9 and temperature of 56°C with catalyst of 1.2% (weight-based). Intensification of the mixing of the immiscible reactants in transesterification reaction by the zigzag micro-channel is the most influence factor, which is characterized by optical method. It is shown that chaotic intensification mixing in micro-scale is an effective way to improve the efficiency of the biodiesel synthesis process.

Keywords: Biodiesel; Micro-channel reactor; Mixing; Transesterification

INTRODUCTION

Biodiesel is a renewable fuel that can be produced from vegetable oils, animal fats, grease, or waste frying oil. Due to the increased price of the petroleum and the environmental concern
including both local pollution from the vehicle exhausts and global climate changes, biodiesel is becoming more attractive biofuel of high interests. (Marchetti et al, 2007). In addition, biodiesel is an alternative of non-toxic and biodegradable fuel, and essentially free of sulfur and aromatics (Karmee et al., 2005). Biodiesel has been produced by transesterification of triglyceride to methyl esters using homogeneous basic catalysts (Vicente et al, 2004), such as sodium or potassium hydroxides, carbonates or alkoxides, as represented by the following equation (Marchetti et al, 2007):

\[
\begin{align*}
\text{CH}_2\text{-OOC-R}_1 & \quad \text{R1-COO-R'} & \quad \text{CH}_2\text{-OH} \\
\quad | & \quad \text{Catalyst} & \quad | \\
\text{CH}_2\text{-OOC-R}_2 & \quad + 3\text{R'OH} & \quad \text{R2-COO-R'} & \quad \text{CH}=\text{OH} \\
\quad | & & \quad | \\
\end{align*}
\]

Most of biodiesel production are batch processes, which need more reagents and are generally of lower efficiency. Recently, new production technologies have been studied including e.g., ultrasonic irradiation (Stavarache et al. 2007), supercritical transesterification (van Kasteren et al., 2007) and fixed-bed reactors using heterogeneous catalysts (Xie et al., 2006). Micro-channel reactors have high volume/surface ratio, short diffusion distance, fast and efficient heat dissipation and mass transfer (Kobayashi et al., 2006). Those features have been used in organic synthesis (Mason et al., 2007). In this paper, a zigzag micro-channel reactor has been developed and applied in the transesterification process. Process performance has been evaluated on intensification of mass transportation by the chaotic mixing. Based on experimental results, a highly efficient and compact reactor is proposed for biodiesel production in a mini-fuel processing plant.

**EXPERIMENTAL**

**Objectives of the experiment**

The objectives of the experiments are investigating various parameters influencing biodiesel production and mixing performance between immiscible reagents. Parameters in micro-channel reactions such as catalyst rates, temperatures, methanol/oil ratios, residence time were discussed. The catalyst rates varied as 0.55, 0.67, 0.88, 1, 1.2, 1.5, 2% (by wt. of oil). The temperatures were varied as 40, 45, 50, 56, 62, 70, 75°C. The molar ratios (methanol/oil) were varied as 4:1,
5:1, 6:1, 9:1, 10.5:1, 17:1. The residence times were varied as 14, 18, 28, 32, 39 seconds. Mixing performance influenced by different residence times, batch to micro-channel under the same condition were discussed. Before testing mixing performance, methyl violet was premixed in methanol so as to be observed in optical microscope conveniently.

**Experimental set-up**

The sketch of the experimental setup is presented in the Fig. 1. Two syringe pumps (Harvard Apparatus, USA) were used to inject the fluids of different flow rates. The soybean oil and methanol aggregated through a T shape three-way junction (the outlet diameter of 200 μm). The outlet of the junction is linked with the inlet of the zigzag micro-channel reactor. The reactor is immersed in a water bath, to ensure the accuracy of reaction temperature. The outlet of the micro-channel reactor is connected with a collection flask placed in an ice-water vessel in order to terminate the transesterification reaction quickly. Sodium hydroxide was dissolved in methanol as the catalyst by electro-stirring before experiments. The biodiesel samples were analyzed by using a gas chromatograph (FULI9790) with a capillary column for identification and quantification. Methyl Undecanoate (Fluka) was used as the internal standard solvent.

Fig.1. Schematic drawing of the continuous transesterification of soybean oil in a micro-channel reactor.

**Micro-channel reactor fabrication**

The micro-channel reactor was made of stainless steel of 316L (Fig.2). Three types of patterned sheets were prepared to construct the reactor: cover sheet, medium sheet and bottom sheet. The cover sheet has two holes, which act as the flow paths, The medium sheet, shown in
Fig. 3, has one zigzag micro-channel. The dimension of micro-channel is 200μm (W) X 300μm (D) X 1.07 m (L). The thickness of the bottom sheet is 0.5 mm without holes. Surfaces of all sheets in three types were polished to a roughness of 2μm followed by cleaning in acetone prior to diffusion bonding. The dimensions of the micro-channel reactor are about 72 mm × 72 mm × 4 mm, respectively. The effective volume of the micro-channel reactor is 0.125 cm³, including the micro-channels and the inlet and outlet zones.

Fig. 2. Photo of the micro-channel reactor.        Fig. 3. Schematic drawing of the micro-channel sheet.

Characterization

Characterization of the experimental set up is conducted by applying the method of optical measurement. Determining droplet size distribution requires a few minutes, coalescence of methanol droplets emerge immediately as the sample removed from collection vessel. Therefore, a stabilizing agent or surfactant needed to be added to the dispersion to slow the coalescence phenomenon (Wu et al, 2007).

Decaglycerol monooleate ester as a surfactant was dissolved in methanol before mixing to avoid coalescence phenomenon, which is adverse for measurement. The experiment on mixing was carried out in the micro-channel reactor and the three-necked batch reactor without the catalyst of sodium hydroxide. The size of the droplets of the emulsion was identified using an optical microscope (Sharpscope SF-1 Industrial Microscope, Nanjing, China) with supporting software (VIS ver 2.90 professional-Digital Imaging and Measured System) that allows 950X enlargement and has a color camera, which sends a signal to a personal computer. The software was used to measure the diameters of methanol droplets directly on a monitor by a three-point
measurement technique. As the diameter distribution is dependent on the population (Lemenand et al., 2003), a large number of samples (600) for the measurement were measured to ensure the accuracy of the results.

Since the measurements of droplet diameter are based on sampling a large number of experiments (Lemenand et al. 2003), it is importantly to determine the number of droplets of the samples so that the diameter distribution is independent of the population. The empirical method used here entails concerning errors between two distributions, the error is evaluated by a normalized standard deviation, defined by

\[
SD_n = \frac{\sum_i (f_i - f'_i)^2}{N_c}
\]

(1)

Where \( f_i \) and \( f'_i \) are the droplet frequencies of the same class diameter and \( N_c \) is the class number. For this case, the normalized standard deviation between two successive distributions is as a function of number of droplets, this minimal number of 600 is needed for droplet diameter measurement so as to assure the reproducibility.

RESULTS AND DISCUSSION

Comparison between the micro-channel reactor and impeller batch reactor

Fig. 4 shows the difference in the soybean oil conversion between the impeller batch-reactor under the conditions: temperature of 56 °C, methanol/oil molar ratio of 9:1, catalyst amount of 1.2% (weight fractions of the oil supplied). The experimental results show the time scale for stirring in the impeller batch reactor compared to the contact time for the micro-channel reactor. It can be seen from the Fig. 4 that the conversion of soybean oil in micro-channel reactor is higher even if the time for the micro-channel reactor is only one tenth the corresponding value for the batch reactor. In the absence of the catalyst, the mixing experiments were carried out in the same conditions. Two photos of the emulsions formed in the mixing experiments are presented in Fig. 5. It is indicated that the diameter of the droplets in the emulsion by the micro-channel reactor is smaller than that by the batch reactor with an agitator. Several big droplets can be seen in the emulsion by the batch reactor whereas the droplets by the micro-channel reactor are of approximately the same size. The distribution and mean droplet size were calculated by 600 droplet samples. The results are shown in Fig. 6. The mean droplet size for micro-channel is 4.21μm, smaller than that of 4.92μm for the batch reactor. As immiscible fluids mix using a batch stirrer, convection is induced, resulting in a turbulence and chaotic mixing. In a mixture of two immiscible liquids, there is a critical agitator speed, \( N_C \), at which a separated immiscible layer disappears (Shinji, 1975). \( N_c \) can be calculated by the empirical equation:
\[ N_c = KD^{2/3} \left( \frac{\mu_c}{\rho_c} \right)^{1/9} \left( \frac{\rho_d - \rho_c}{\rho_c} \right)^{0.26} \]  

(2)

Fig.4. Comparison between the zigzag micro-channel reactor and batch impeller.

In which \( K \) is a proportionality coefficient, \( \rho_c \) and \( \rho_d \) are the densities of the continuous and dispersed phase, respectively, \( \rho_c \) is the viscosity of the continuous phase, and \( D \) is the vessel diameter. As for the mixing of methanol and soybean oil, the following parameter values are used to estimated this speed (Wu et al., 2007), \( K \) was taken as 750 for the agitation in center of the vessel, \( \rho_c \) is 920 kg/m\(^3\), \( \rho_d \) is 791 kg/m\(^3\), \( \mu_c \) is 0.05 Pa s, and \( D \) is 17 cm. The minimum critical agitator speed is 493 rpm, which means the agitator speed of 600 rpm in the experiment is acceptable. The shear forces that cause the convection are obviously dampened away from the stirrer and most of the bottom flask and axis of the impeller. Therefore, longer time is needed for mixing to avoid the disadvantages of convective dead zones (Alvarez et al., 2002). In addition, the dampened shear force also results in the broad distribution of droplet size as shown in Fig. 6, which in accordance with a unsteady-state of the emulsion by an agitator. Taking advantage of the recirculation phenomenon, the mixing efficiency of zigzag micro-channels could be significantly improved compared to straight micro-channels (Virginie et al., 2002). These recirculations induce a transversal component of velocity, which improves the mixing process. Therefore, the smaller and size and narrow distribution of droplet can be effectively achieved in the zigzag micro-channel as shown in Fig. 5 and Fig. 6.
Banks and coworkers (Banks et al., 2003) derived rate expressions for a liquid-liquid interfacial reaction system for copper extraction from an aqueous solution into an organic phase. If mixing in both the dispersed and continuous phase is good, then the bulk concentrations of each phase will be near to that of the interfaces and the change in concentration with time is

\[
- \frac{d[B]}{dt} = \frac{k4\pi r^3}{V} N[B]
\]

(3)
Where $V$ is the volume of the dispersed phase, $r$ is the droplet radius and $N$ is the total number of particles. The effective rate constant for the process should correspond to the surface rate constant by

$$K_{\text{eff}(r)} = \frac{k4\pi^2}{V}N = \frac{kN}{V}S_{\text{droplet average}}$$

(4)

As the mean droplet size for the impeller agitation is 1.17 times larger than that for the micro-channel reactor, the effective rate constant for the micro-channel reactor could be as much as 1.4 times higher than that of the conventional agitation system. Therefore, the zigzag micro-channel might improve the efficiency of the transesterification effectively by reductions in the mean droplet size.

**Performance of the micro-channel**

The effect of catalyst amount on the performance of the micro-channel is shown in Fig. 7. The catalyst rate was varied in the range of 0.55 -2%. These percentages were weight fractions of the oil supplied for this reaction. It can be seen that the conversion rate was increased first with the increase of catalyst rate from 0.55% to 1.2%. But, with further increase in the catalyst rate, the conversion rate was decreased, which might be due to the formation of soap (Meka et al., 2007).

In the presence of homogeneous catalyst, the reaction mixture constitutes of a two-phase system. One is methanol-catalyst, and another is oil. In general, the rate of the transesterification reaction can be accelerated with the increase of the reaction temperature. As shown in Fig. 8, the conversion increased with reaction temperature to nearly 97.3% at 56 °C and then decreased with the further increase of temperature above 56 °C. A large number of bubbles were observed at the outlet of the micro-channel reactor as the temperature was increased to 65 °C. This might be caused by the vaporization of methanol at temperatures around 56°C and higher. The bubbles reduce the interface of oil and methanol. On the other hand, the flow rate of the mixture was accelerated in the existence of the bubbles. The combination of both phenomena presents unfavorable impacts on the conversion of soybean oil. Based on this, the appropriate reaction temperature shall be considered to be around 56 °C.
Fig. 7. Influence of catalyst amount on the conversion.
Reaction conditions: methanol/oil molar ratio 6:1, residence time 18 seconds and temperature 63 °C.

Fig. 8. Influence of reaction temperature on the conversion.
Reaction conditions: methanol/oil molar ratio 6:1, catalyst amount 1.2%, at the residence time 28 seconds.

Stoichiometrically, the methanolysis of soybean oil requires three moles of methanol for each mole of oil. However, in practice, the methanol/oil molar ratio should be higher than that of stoichiometric ratio in order to drive the reaction towards completion and produce more methyl esters as product. As shown in Fig. 9, when the methanol loading amount was increased from 4 to 6, the conversion was increased considerably. The maximum conversion was very close to
12:1. However, with further increase in the molar ratio there was only little improvement in the conversion. Therefore, we could conclude that to elevate the conversion an excess methanol feed was effective to a certain extent.

The effect of the residence time on the conversion of soybean oil is illustrated in Fig. 10. The conversion was increased with the increase of the reaction time from 14 to 28 seconds, and thereafter remained nearly constant as a representative of a nearly equilibrium conversion. The effect of the residence time on the mean droplet size is shown in Fig.11 (a). It can be seen that the mean droplet size increases with the increase of the residence time from 14 s to 31 seconds and decreases thereafter. As shown in Fig.11 (b), an increase of the residence time has little influence on the distribution of the droplet size. On the one hand, the increase of residence time is favorable for the mixing of the immiscible flows and the conversion of soybean oil due to the increase of contact time. On the other hand, the secondary flow in the zigzag microchannel is weakened by the decrease of the flow rate, which is unfavorable for the mixing and formation of small droplet (Virginie et al., 2002). Thus, the suitable reaction time for the synthesis of biodiesel shall be considered to be around 28 seconds.

![Graph](image)

**Fig.9.** Influence of methanol/oil molar ratio on the conversion.
Reaction conditions: catalyst amount 1.2%, residence time 28 seconds and temperature 56 °C.
Fig. 10. Influence of residence time on the conversion.
Reaction conditions: Methanol/oil molar ratio 9:1, catalyst amount 1.2% and temperature 56 °C.

Fig. 11. Differential droplet distribution and mean droplet diameter of various residence times.
(a) Mean droplet size of different residence times. (b) Distribution of droplet size for different residence time.

CONCLUSIONS

Experimental studies for the improvement of biodiesel by using micro-channel reactor were conducted. A zigzag micro-channel reactor was developed by electric spark and diffusion bonding for the transesterification of soybean oil with methanol in the presence of concentrated sodium hydroxide as a catalyst. Compared with the contact time for complete conversion from
several minutes to several hours in conventional reactors, the corresponding contact time by the micro-channel reactor is reduced sharply to 28 seconds at the following conditions: oil/methanol molar ratio of 1:9, temperature of 56 °C, catalyst amount 1.2% (wt, %). This might be resulted from the intensification of the mixing of the immiscible reactants in transesterification reaction by the zigzag micro-channel, which is characterized by a microscope method. It is shown that intensification of the chaotic mixing on the micro-scale is a desirable way to promote the efficiency of biodiesel synthesis process.

Even though the total throughput of biodiesel by the zigzag micro-channel reactor is small, the important effect of intensification by the micro-channel is crucial to the high efficiency for the production of biodiesel. Further work will include, for example, designing new type micro-mixers to enlarge the total volume of biodiesel production, and studying new solid catalysts so as to avert strenuous after-treatment process.

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Abstract

Alcoholic fermentation is an important biochemical process which has been known for some 5000 years, e.g. in beer production. The process is relevant for producing bioethanol fuel, thus avoiding the introduction of fossil carbon dioxide into the atmosphere. The aim of this paper is to give a simple introduction to the fermentation process and to dynamic models of such systems in order to familiarize control engineers with the topic. Based on equations for a fermentation reactor in the literature, a rational model description is given, with parameter values and operating conditions. The model description includes extensions of the literature model. In this paper, several alternative reaction rates are discussed, and a more general model of oxygen uptake is introduced, e.g. by including the effect of the substrate.

The various models are compared by simulation, and a simple analysis of controllability is suggested to illustrate possible use of the model. The presented model is complete in the sense that all necessary information is given to implement the model in a simulation tool. Several applications of the model are discussed, and various model developments are indicated.
4. Thermal Optimization and Economic Analysis of a Marnoch Heat Engine

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Abstract

The Marnoch Thermal Energy Conversion (MTEC) device is a novel heat engine that recovers heat to produce electricity, using lower temperature differences than normally utilized in conventional heat recovery systems. A laboratory-scale proof-of-concept device has been built and tested at the University of Ontario Institute of Technology, Canada. It produces electricity by using heat exchangers and a piston assembly at temperatures and gauge pressures as low as 65°C and 1.03 MPa (150 psi), respectively. A performance assessment and thermodynamic optimization of the MTEC system are reported in this article. A thermodynamic model and control system developed for improved operation of the system are described. Results are provided of a numerical optimization of key design variables with appropriate constraints, and an economic analysis for different configurations is presented which demonstrates the practical viability of the system.

Keywords: Heat Engine, Optimization, Economic Analysis, Conservation, Efficiency

Nomenclature

\[ A \quad - \text{Area (ft}^2\text{)} \]
\[ c \quad - \text{Specific heat capacity (Btu/lb °F)} \]
\[ D \quad - \text{Inner diameter (ft)} \]
\[ d \quad - \text{Thickness (ft)} \]
\( F \) - Friction factor
\( f \) - Fouling factor
\( h \) - Thermal conductivity (Btu/hr ft \(^{\circ}\)F)
\( I \) - Irreversibility (Btu)
\( K \) - Number of variables
\( L \) - Length (ft)
\( m \) - Mass flow rate (gpm)
\( P \) - Pressure (psi)
\( Q \) - Heat (Btu)
\( \dot{Q} \) - Heat transfer rate (Btu/hr)
\( T \) - Temperature (\(^{\circ}\)F)
\( U \) - Internal energy (Btu)
\( U' \) - Overall heat transfer coefficient (Btu/hr ft\(^{2}\) \(^{\circ}\)F)
\( v \) - Mean velocity of fluid (ft/s)

Greek
\( \rho \) - Density (lb/ft\(^{3}\))

Subscripts
0 - Environment
1 - Tube
2 - Shell
gas - Air
v - Volumetric
b - Boundary

1 Introduction
Although fossil fuels will continue to remain prominent in the world energy mix for many years, renewable energy sources are almost certain to become increasingly important to reduce greenhouse emissions. Correspondingly, alternative technologies that facilitate the use of renewable energy sources are expected to be increasingly developed.

The paper examines a promising alternative energy technology, the Marnoch Thermal Energy Conversion (MTEC) system, which can operate using renewable energy as well as other sources of thermal energy. The MTEC device is intended to produce electricity from a small temperature difference, as little as 15°C. Operation over such small temperature differences allows for a highly flexible energy generation system, which can operate using a variety of heat sources and cooling reservoirs. Potential sources include waste heat from industrial facilities and co-generation applications, including those with steam cycle-based power generation. Solar thermal systems can also be used to provide heat in commercial applications of this device. Jeong et al. [1] have outlined the methods with which systems like the one considered here can be applied in waste heat recovery.

The MTEC device is a heat engine that consists of four cylindrical tanks, each fitted with helical copper tube coil heat exchangers. Each tank is connected to both a hot source and cold sink, via tubes and valves that allow a controlled mass flow at any step of the process. Initially, all tanks are kept at a constant pressure and mass. One-half of the Marnoch cycle is driven by heat supplied to the tanks, which drives pistons external to the tanks. The other half of the cycle connects to a colder tank, facilitating thermal expansion in the hot tank and thermal contraction in the cold tank, via a piston assembly.

The MTEC system utilizes an innovative sequence of steps that together achieve a desired electrical output. The operation of the MTEC device involves three steps: 1) conversion of internal energy to a pressure difference between two pressure vessels; 2) conversion of flow work into mechanical energy by means of a specialized piston assembly; and 3) conversion of mechanical energy to electrical energy by means of a generator.

The amount of electricity generated from a MTEC system strongly depends on the size and design of the heat exchangers, the pressure difference and the overall temperature difference. The working fluids for this device are water and dry air. The cylinders are arranged such that at any given time there is at least a pair each of a hot source and cold sink. A photograph of the MTEC system and the arrangements of the heat exchangers are shown in Figs.1 and 2, respectively.
2 Thermodynamic Model of the MTEC System

Modeling of the MTEC device and control system has been reported by Armstrong et al. [2]. The first step of the device operation consists of developing a pressure difference between two pressure vessels, through a temperature difference. When device operation commences, these vessels have the same initial condition. Heat exchangers placed within the vessels transfer heat from an external source to their interiors.

A general configuration of the heat exchanger and pressure vessel is illustrated in Fig. 3. Depending on whether individual tanks are used for heating or cooling, a thermal energy source or sink is connected accordingly.
By increasing or decreasing the temperature within the pressure vessel, the pressure increases or decreases for each case, respectively. Once a pressure difference has been generated between a pair of vessels, a specialized piston assembly is actuated to convert the pressure difference to mechanical energy. The piston assembly consists of two chambers separated by a piston. The piston moves back and forth, thereby converting the energy in the transferred mass to boundary work. As the first chamber’s volume increases, the second chamber’s volume decreases. A valve system is configured so that the chamber with less volume is connected to the vessel with a higher pressure, while the lower pressure vessel is connected to the chamber with the larger volume, as shown in Fig. 4.

The pressure difference between the two chambers results in a net force on the piston, moving it to the right in Fig. 4. Once the piston has reached the end of the cylinder (the right side in Fig. 4), a valve system is activated, which causes chamber 2 to be connected to the high-pressure vessel and chamber 1 to the low-pressure vessel. This yields a net mass flow from the high-pressure vessel to the low-pressure vessel, as the gas in the chamber with decreasing volume is transferred to the low-pressure vessel. The second half of the piston’s movement, which returns the piston to its starting position, is shown in Fig. 5. The cycle continues as long as there is a pressure difference sufficient to move the piston.
Through the operations of the piston, the internal energy of the working fluid piston is directly converted to mechanical energy which, via a flywheel connected to a generator, is converted to electrical energy.

Two thermodynamic models of the system are developed to predict the system performance. These models are intended to simulate the conversion of internal energy to flow work and mechanical energy of piston movement.

Performing an energy balance for the heat exchanger,

$$Q = U_2 - U_1 = m \cdot c_v \Delta T$$

(1)

Here $U$ is the internal energy, $m$ is the mass of air transferred, $c_v$ is the volumetric specific heat capacity and $\Delta T$ is the temperature difference. Alternatively, the heat transfer rate can in a given time interval can be expressed as

$$\int_{t_1}^{t_2} \dot{Q}(t) dt = mc_v \Delta T$$

(2)

By substituting the known boundary values at the initial condition, the following temperature expression can be derived:

$$T_{gas}(t) = \frac{1}{mc_v} \int_{t_1}^{t_2} \dot{Q}(t) dt + T_{gas}(0)$$

(3)

The heat transfer rate $\dot{Q}$ can be expressed as follows:

$$\dot{Q} = U' A \Delta T$$

(4)
where the overall heat transfer coefficient \( U' \) is determined by means of a generalized thermal resistance network, i.e.

\[
U' = \frac{1}{\frac{1}{h_c} + \frac{1}{h_{water}} + f_{water} + f_{gas} + \frac{1}{h_{cond,cyl}}} \tag{5}
\]

Combining the above equations, an expression for \( T_2 \) with respect to time is obtained:

\[
T_{gas}(t) = U' \frac{A^c t}{m c_v} \int_{t_i}^{t} (T_{water} - T_{gas}(t)) dt + T_i(0)
\]

This function is integrated numerically. The model is applicable to both the heat exchanger that supplies heat to the tank, as well as the heat exchanger that rejects heat from the tank. The value of \( Q \) is negative for the side that is rejecting heat. In this manner, the instantaneous gas temperature and pressure within the pressure vessel may be determined. This model assumes a closed system, with no mass entering or leaving the pressure vessel.

The model is further extended to predict the power output and number of strokes, based on the initial conditions within the pressure vessels. This model is based on the principle of conservation of mass and Bernoulli’s equation. For a fixed time interval, it is assumed that each side of the system is at constant temperature and no frictional losses occur during pressure transfer. By utilizing the Bernoulli equation (3), it can be shown that
Using this equation, it is possible to determine the mass flow rate from each tank into the
cylinder.

Based on the mass flow rates, numerical integration leads to the predicted change of mass
with time in each tank as follows:

\[
m_1(t) = m_1(0) - \int_{t_i}^{t_f} \frac{dm_1}{dt} dt
\]

(9)

Rearranging (9) gives

\[
m_2(t) = m_2(0) + \int_{t_i}^{t_f} \frac{dm_2}{dt} dt
\]

(10)

These equations are based on the pistons and pressure vessels being configured as shown in Fig.
6. Based on the mass in each of the piston chambers, the pressures at points 3 and 4 are
calculated as a function of time. With this information, the boundary work produced by the
system during a given power stroke is determined as follows:

\[
W_b = \int_1^2 p_3 dV - \int_1^2 p_4 dV
\]

(11)

These calculations are repeated for several strokes, until the difference between p_1 and p_2
becomes negligible. The resulting boundary work terms of all strokes are added to obtain a total
value, and the result is divided by the time required for the strokes to occur to determine the average power output of the system.

Figure 6: Sequence of steps in the piston motion

3 Results and Optimization

Using the heat transfer model presented in the previous section, results are generated for a variety of heat source and sink temperatures. In this section, results are presented for initial pressures of 200 psi and 2000 psi, and simulations over 60 seconds using 0.1 second time intervals. The conditions are intended to replicate actual working conditions of the prototype at UOIT, as well as planned future extensions to higher pressure units. In modeling the MTEC device, heat transfer within the pressure vessels and pressure changes in the piston-cylinder device are included.

The characteristics of the system at a given initial pressure and varying heat and source temperatures are presented in Figs. 7-10 for a pair of heated and cooled cylinders over a period of 60 seconds. The source temperature ranges from 113°F to 194°F, and the sink temperature from 4°F to 50°F. The pressures at varying source temperatures are shown in Figs. 7-10.
The pressure model presented earlier is used to predict the power output of the device. Results are obtained on a per-stroke basis and simulations are performed for two initial pressures, varying the working temperature conditions. Results are presented in Figs. 11 and 12.
that depict the performance of the heat exchangers in terms of energy output after 60 seconds with initial cylinder pressures of 200 psi and 2000 psi, respectively.

Irreversibilities in the system are also assessed. The irreversibilities in the system follow closely those outlined by Cornelissen and Hirs [3]. The total irreversibility of the system is the sum of thermal and frictional irreversibilities:

\[ I = I^{\Delta T} + I^{\Delta p} \]  

The thermal component of the irreversibility is given by

\[ I^{\Delta T} = T_0 \left[ m_1 c_p \ln \frac{T_{1out}}{T_{1in}} + m_2 c_p \ln \frac{T_{2out}}{T_{2in}} \right] \]  

and the frictional component by

\[ I^{\Delta p} = \left[ \frac{m_1}{\rho_1} (p_{1in} - p_{1out}) + \frac{m_2}{\rho_2} (p_{2in} - p_{2out}) \right] \]  

Note that

\[ mc_p (T_{1out} - T_{1in}) = hA\Delta T \]  

and
\[ T_{2\text{out}} = T_{1\text{in}} + \Delta T, \quad T_{2\text{in}} = T_{1\text{out}} + \Delta T \]  

Substituting eqs. (15) and (16) into (13) yields

\[
I_t \Delta T = I_0 \left[ m_1 c_p \ln \left( \frac{T_{1\text{out}}}{T_{1\text{in}}} \right) + m_2 c_p \ln \left( \frac{T_{1\text{out}} + m_2 c_p (T_{1\text{out}} - T_{1\text{in}})}{h_i A_i} \right) \right] 
\]

(17)

where \( A_i = \pi D_i L_i \) and \( h_i \) is obtained according to Kern [4].

For the frictional component,

\[
I_t \Delta p = m_1 v_1 \Delta p_1 + m_2 v_2 \Delta p_2 
\]

(18)

where \( \Delta p_1 \) and \( \Delta p_2 \) are expressible as

\[
\Delta p_1 = p_{1\text{in}} - p_{1\text{out}} = 2 f_1 \rho \nu_1^2 \frac{L}{D_1} 
\]

(19)

\[
\Delta p_2 = p_{2\text{in}} - p_{2\text{out}} = 2 f_2 \rho \nu_2^2 \frac{L(D_2 + (D_1 + 2d_i))}{(D_2^2 - (D_i + 2d_i)^2)} 
\]

(20)

The mean velocity of the gas in the cylinder is assumed zero and the mean velocity of the water in the tube can be written as

\[
\nu_2 = \frac{4m}{\rho \pi \left[ D_2^2 - (D_i + 2d_i)^2 \right]} 
\]

(21)

\[
I_t \Delta p = \frac{32 f_2 m_2^3 L_2 (D_2 + (D_1 + 2d_i))}{\pi^2 \rho_2^2 \left( D_2^2 - (D_i + 2d_i)^2 \right)^2} 
\]

(22)

where the friction factor along the tubes \( f_2 \) is obtained from the friction law of Blasius [5], given by

\[
f_2 = 0.0791 \left( \frac{\mu_2}{\rho \nu_2 D_2} \right)^{0.25} 
\]

(23)

The bounded constraints for the size of the heat exchangers and the flow rate are set to minimize the pressure drops. Having expressed \( L_1 \) and \( D_1 \) in terms of \( L_2 \) and \( D_2 \) respectively, the constraints are
Design Expert, a design of experiment (DOE) software package is used here, specifically for its optimization capability in predicting the optimal variable combination for the MTEC device. The Responsive Surface Method (RSM) is used, where experimental and predicted values are combined to determine the optimal process design. Three optimization variables: length of the tube ($L$), Diameter of the tube ($D$) and mass flow rate in the tube ($m$), labeled A, B and C respectively are considered. Weights are also assigned to these variables since our problem is multi-objective. Constraints are set in terms of limits and target and are given in Table 1. These limits are based on the results from the models in appendix 1. Neglecting the gas side of tanks, the pressure drop in the tube is minimized so as to reduce the irreversibility due to frictional components. Different transformations are tried to find the best curve fit for this variables. For $k$ number of variables, the logarithmic transformation gives the best curve fit and is related to the pressure drop according to equation (27).

$$\Delta p' = \log_{10}(\Delta P + k)$$  \hspace{1cm} (27) 

<table>
<thead>
<tr>
<th>Name</th>
<th>Lower limit</th>
<th>Upper limit</th>
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<td>55.62</td>
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</tbody>
</table>

Table 1: Constraints and weighting factors used for the optimization problem

The objective is to find the combination of the three variables that achieves a pressure drop of 5 psi or less within the constraints given in Table 1. The solution of the optimization after ten runs using Design Expert is shown in Table 2. The plots of the relationships when
different variables are combined are shown in Figs. 13 and 14. The desirability is an indication of how good our result is compared to the target, with a desirability of 1 being the best. The prediction indicates a desirability when 2 or 3 variables are combined in a run. The color code indicates the trend from low to high with red being the highest. The individual and combined desirability of the variables are shown in Figs. 15 and 16.

<table>
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<th>L (in)</th>
<th>D (in)</th>
<th>m (gpm)</th>
<th>ΔP (psi)</th>
<th>Desirability</th>
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</thead>
<tbody>
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<td>20000</td>
<td>4.54819</td>
<td>0.91</td>
</tr>
<tr>
<td>2</td>
<td>1104.14</td>
<td>0.12</td>
<td>20000</td>
<td>4.55929</td>
<td>0.912</td>
</tr>
<tr>
<td>3</td>
<td>1105.83</td>
<td>0.12</td>
<td>20000</td>
<td>4.56799</td>
<td>0.912</td>
</tr>
<tr>
<td>4</td>
<td>1102.49</td>
<td>0.12</td>
<td>20000</td>
<td>4.57008</td>
<td>0.91</td>
</tr>
<tr>
<td>5</td>
<td>1100.5</td>
<td>0.12</td>
<td>19999.9</td>
<td>4.58302</td>
<td>0.92</td>
</tr>
<tr>
<td>6</td>
<td>1103.06</td>
<td>0.12</td>
<td>20000</td>
<td>4.58653</td>
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</tr>
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<td>7</td>
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<td>20000</td>
<td>4.58813</td>
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<tr>
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<td>20000</td>
<td>4.59386</td>
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<tr>
<td>9</td>
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<td>20000</td>
<td>4.60855</td>
<td>0.922</td>
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<tr>
<td>10</td>
<td>1096.5</td>
<td>0.12</td>
<td>20000</td>
<td>4.60897</td>
<td>0.922</td>
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</tbody>
</table>

Table 2: Results of the optimization after 10 runs
Figure 13: Combination of flow rate and tube diameter

Figure 14: Combination of flow rate and tube length
Figure 15: Desirability of individual and combined variables

Figure 16: Desirability of individual and combined variables with constraints
4 Economic Analysis of MTEC Device

The economic viability of the MTEC device is examined based on the amount of electricity that can be effectively harnessed from the device and the cost of producing this energy, given a certain configuration. The relationship between cost and anticipated revenue is examined, and a payback analysis is carried out to help determine the project viability.

The model provided in Appendix 1 with a configuration of 8 tanks of 432 US gallons each is used. The initial pressure of air in the tanks is 5000 psi and the heat transfer rate is 556 kW/h. The Carnot efficiency for this configuration is 23% and the system efficiency for mechanical components is assumed to be 50%. The projected output and annual revenue for continuous operation using steady solar heat source and waste heat source assuming that electricity is sold at $110 per MWh are given in Table 3.

<table>
<thead>
<tr>
<th>Tank configuration/hour (3456 gallon)</th>
<th>257.245 kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 hours solar source</td>
<td>2572.454 kWh</td>
</tr>
<tr>
<td>10 hours peak solar and 14 hours low intensity at 50% efficiency</td>
<td>4373.27 kWh</td>
</tr>
<tr>
<td>24 hrs steady output</td>
<td>6173.89 kWh</td>
</tr>
<tr>
<td>Annual revenue using direct solar heating only</td>
<td>$103,284</td>
</tr>
<tr>
<td>Annual revenue using steady waste heat source</td>
<td>$247,881</td>
</tr>
<tr>
<td>Annual revenue using waste heat + solar sources</td>
<td>$175,582</td>
</tr>
</tbody>
</table>

Table 3: Projected output and annual income for a given configuration using 8 cylinders

Using the cost tables for the components in Appendix 2 and assuming 2% and 3%, for solar and waste heat maintenance costs, respectively, the payback periods are determined and shown in Table 4. The revenue discount rate charts are shown in Figs. 17 and 18.
Table 4 shows that the MTEC device will pay back the capital investment in less than 3 years if the source of heat is derived from waste heat of a process industry and in 9 years if solar panels are deployed for the of heat. When both heat sources are efficiently combined, the payback period on the investment would be 4 years. Figs. 17 and 18 show the profitability of the project with various interest rates based on yearly returns. Fig. 17 shows that the MTEC device is profitable even beyond a 20% interest rate on borrowed capital. This is a case where the heat source is obtained from waste heat. Fig. 18 is profitable up to a 10% interest rate. This occurs when the heat is from a solar source. These calculations do not consider subsidies from the government which would make the system more profitable.

5 Conclusions
The novel MTEC technology is demonstrated to be a promising system, both technically and economically. Using waste heat from nuclear plants or other sources, the system can continuously generate electricity and pay back the initial capital investment in a few years. By not using fossil fuels, this device is capable of reducing the greenhouse gas emissions associated with conventional fossil fuel energy systems. Much work is ongoing to improve the transmission system and scale up the system. Future thermal optimization processes are expected to include the gas side of the heat exchangers. Physical measurements will also be done to validate the results obtained.

References


Appendix 1: Data used in calculations for heat exchangers

<table>
<thead>
<tr>
<th><strong>Tank and Coil Data</strong></th>
<th></th>
<th></th>
<th><strong>Water Flow Data</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank inner diameter</td>
<td>in</td>
<td>23.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tank total length</td>
<td>in</td>
<td>230</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume</td>
<td>US gal.</td>
<td>431.83</td>
<td>Properties</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Density</td>
<td>lb/ft³</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>62.4</td>
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</tr>
<tr>
<td>Operating pressure</td>
<td>psig</td>
<td>5000</td>
<td></td>
<td></td>
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<tr>
<td>Design pressure</td>
<td>psig</td>
<td>3500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating pressure</td>
<td>atm</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Number of coils</td>
<td></td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil tube outer diameter</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Coil tube thickness</td>
<td>in</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Tube inner diameter</td>
<td>in</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Number of turns in coil</td>
<td></td>
<td>32</td>
<td></td>
<td></td>
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<tr>
<td>Pitch</td>
<td>in</td>
<td>6</td>
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<td></td>
</tr>
<tr>
<td>Coil outer diameter</td>
<td>in</td>
<td>22</td>
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<td></td>
</tr>
<tr>
<td>Coil length</td>
<td>in</td>
<td>192.00</td>
<td></td>
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</tr>
<tr>
<td>Tube length</td>
<td>ft</td>
<td>921.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tube volume</td>
<td>US gal.</td>
<td>84.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percent of total coil to tank volume</td>
<td>%</td>
<td>19.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total surface area of coil</td>
<td>ft²</td>
<td>361.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tank inside area of coil</td>
<td>ft²</td>
<td>117.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat Balance Data</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total surface area of coil</td>
<td>ft²</td>
<td>361.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tank inside area of coil</td>
<td>ft²</td>
<td>117.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water temperature change</td>
<td>°F</td>
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<td></td>
</tr>
<tr>
<td>Volume of gas in tank</td>
<td>ft³</td>
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<td></td>
</tr>
<tr>
<td><strong>Mass of gas</strong></td>
<td><strong>lb</strong></td>
<td>1253.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
<td>--------</td>
<td>---------</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Rate of temperature change</strong></td>
<td>°F/min</td>
<td>104.77</td>
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<tr>
<td><strong>Heat Transfer Data</strong></td>
<td><strong>Rate of pressure change</strong></td>
<td>psi/min</td>
<td>1059.59</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Required pressure change</strong></td>
<td>psi</td>
<td>100.00</td>
<td></td>
</tr>
<tr>
<td><strong>Gas thermal conductivity</strong></td>
<td>Btu/hr ft °F</td>
<td>0.016</td>
<td><strong>Calculated time</strong></td>
<td>min</td>
</tr>
<tr>
<td><strong>Molecular weight of gas</strong></td>
<td></td>
<td>29</td>
<td><strong>Calculated time</strong></td>
<td>sec</td>
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<tr>
<td><strong>Specific heat capacity of gas</strong></td>
<td>Btu/lb °F</td>
<td>0.24</td>
<td><strong>Gas temperature change</strong></td>
<td>°F</td>
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<tr>
<td><strong>Assumed water temperature</strong></td>
<td>°F</td>
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<td></td>
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<tr>
<td><strong>Assumed gas temperature</strong></td>
<td>°F</td>
<td>42.80</td>
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</tr>
<tr>
<td><strong>Gas viscosity</strong></td>
<td>ft² s⁻¹</td>
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<td></td>
</tr>
<tr>
<td><strong>Approximate water heat transfer coefficient</strong></td>
<td>Btu/hr ft² °F</td>
<td>500</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Gas density</strong></td>
<td>lb/ft³</td>
<td>26.9957</td>
<td></td>
<td></td>
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<tr>
<td><strong>Water fouling factor</strong></td>
<td>h ft² F/Btu</td>
<td>0.001</td>
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<tr>
<td><strong>Gas fouling factor</strong></td>
<td>h ft² F/Btu</td>
<td>0.001</td>
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<td><strong>Wall thermal conductivity</strong></td>
<td>Btu/hr ft °F</td>
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<tr>
<td><strong>Wall resistance</strong></td>
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<td><strong>Coefficient of thermal expansion</strong></td>
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<td><strong>Kern k_f factor</strong></td>
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<tr>
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<td><strong>Heat transfer rate Q</strong></td>
<td>Btu/h</td>
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### Gas heat transfer coefficient calculated

<table>
<thead>
<tr>
<th>Btu/hr ft² °F</th>
<th>40.16</th>
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### Appendix 2: Material costing for the MTEC device

<table>
<thead>
<tr>
<th>No.</th>
<th>Items</th>
<th>Estimated cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Solar panels for 1 acre (1600 at $300 each)</td>
<td>480,000</td>
</tr>
<tr>
<td>2</td>
<td>Pressure vessels (8 x 432 gallons at $30,000 each)</td>
<td>240,000</td>
</tr>
<tr>
<td>3</td>
<td>Generator and transformer</td>
<td>80,000</td>
</tr>
<tr>
<td>4</td>
<td>Grid connection/interconnection</td>
<td>180,000</td>
</tr>
<tr>
<td>5</td>
<td>Foundation/construction work</td>
<td>30,000</td>
</tr>
<tr>
<td>6</td>
<td>Piston assemblies</td>
<td>8,500</td>
</tr>
<tr>
<td>7</td>
<td>Controls</td>
<td>25,000</td>
</tr>
<tr>
<td></td>
<td><strong>Total capital cost</strong></td>
<td><strong>1,043,500</strong></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>No.</th>
<th>Items</th>
<th>Estimated cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2 shell and tube type heat exchangers</td>
<td>100,000</td>
</tr>
<tr>
<td>2</td>
<td>Pressure vessels (8 x 432 gallons at $30,000 each)</td>
<td>240,000</td>
</tr>
<tr>
<td>3</td>
<td>Generator and transformer</td>
<td>80,000</td>
</tr>
<tr>
<td>4</td>
<td>Grid connection/interconnection</td>
<td>180,000</td>
</tr>
<tr>
<td>5</td>
<td>Foundation/construction work</td>
<td>30,000</td>
</tr>
<tr>
<td>6</td>
<td>Piston assemblies</td>
<td>8,500</td>
</tr>
<tr>
<td>7</td>
<td>Controls</td>
<td>25,000</td>
</tr>
<tr>
<td></td>
<td><strong>Total capital cost</strong></td>
<td><strong>663,500</strong></td>
</tr>
</tbody>
</table>
5. ANALYSIS OF THE COAL BASED HYBRID TYPE POLYGENERATION SYSTEM

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ABSTRACT

A Polygeneration system with production of both chemicals and power is a promising option for fossil fuel utilization. The configuration of a polygeneration system has a significant effect on its performance, energy and component utilization character, and flexibility of production capacity ratio. The polygeneration system of hybrid type, which bears the configuration characters of both parallel and sequential polygeneration systems, is proposed and its performance feature is investigated. The relation between the main parameters and performance are described by analytical equations. For this system, the main parameters affecting the energy utilization level are the ratio of the exergy consumed in the chemical subsystem to that consumed in the power subsystem, and the exergy efficiency of the chemical subsystem. The parameters effect on the system is described qualitatively and quantitatively. Through system simulation the energy utilization level and effective component conversion character of the system are analyzed. It is identified that the hybrid polygeneration system has a wide range of energy saving rate, from 2% to 14%, covering the energy saving range of parallel and sequential type. Compared with the parallel and sequential type, the hybrid polygeneration system has more freedom on performance distribution with better performance, that is to say it has an excellent performance at each designed production capacity ratio.

Key words: hybrid polygeneration system, configuration character, performance analysis, flexibility of production distribution

1. INTRODUCTION

Coal is the main energy resource and will last for a long time in China. But coal is a dirty energy resource with low quality, resulting in many environmental problems. High efficiency and clean utilization of coal is attracting more and more attention. Coal gasification technology is a promising option for clean coal technology [1-3]. The present chemical production energy systems show their disadvantages in energy integration for pursuing high production rate and the power energy systems suffer much exergy destruction in the combustion process. The polygeneration system can deal with these negative impacts borne in the individual energy systems by integrating the power generation system and chemical production system, and the environmental problem can also be mitigated [4]. Some polygeneration systems have been studied mainly from the aspect of chemicals production [5-7]. The main reason for the high efficiency of the polygeneration system is system integration under the principle of cascading utilization of chemical and physical energy [8,9]. The configuration of a polygeneration system has a significant impact on the degree of system
integration. In the parallel polygeneration system, the captive power plant is replaced by a combined cycle with high efficiency and the heat is integrated between the chemical subsystem and power subsystem [10]. The energy saving effect of a parallel polygeneration system is less significant than that of a sequential one [11]. In the sequential polygeneration system, the component adjusting unit is canceled and partial recycle of the unreacted syngas is applied, which result in reasonable component conversion and chemical energy conversion. But there is a strong constraint on the production capacity ratio for the small range of recycle ratio for the proper component conversion rate. This may have strong impact on the design of a sequential polygeneration system.

To avoid the disadvantages of the sequential and parallel polygeneration system, in this paper a novel polygeneration system of hybrid type is proposed. The configuration characters and performance is analyzed and the internal relation between its configuration character and its performance is discussed.

2. THE CONFIGURATION CHARACTERS OF THE HYBRID POLYGENERATION SYSTEM

Description of the reference system

As shown in Fig. 1 (a), the individual coal gas based power system (IGCC) is based on a TEXACO O2-blown and slurry-feed gasifier with O2 provided by an air separation unit (ASU). The hot coal gas from the gasifier firstly is cooled in a waste heat boiler (WHB), and then flows to a fines removal and low temperature purification unit. The cleaned coal gas fuels the following power generation subsystem including gas turbine (GT), heat recovery steam generator (HRSG) and steam turbine (ST).

The methanol production (MP) system is shown in Fig. 1 (b). The coal is gasified in the gasifier similar to that used in IGCC, and to fit the methanol synthesis reaction the pressure of the gasifier is increased to 6.8MPa. The hot gas from the gasifier is quenched from about 1619K to 513K. After the quenching process, about 56% of the gas from the quenching unit is divided to the shift unit to adjust the CO/H2 ratio via the water-gas shift reaction. The rest of the stream bypasses the shift unit and mixes with the shifted gas. After cooled down in a heat recovery unit where the low pressure steam and medium pressure hot water are produced, the mixed gas flows into the purification unit where impurities like sulfur compounds, carbon dioxide and etc. are absorbed by MDEA (methyl dimethyl aether). From the purification process, the clean syngas is sent to the methanol synthesis (MS) unit equipped with Lurgi technology. The temperature of the synthesis process is kept at about 523K by controlling the evaporation temperature of the cooling water. After cooled down, the
unreacted gas is compressed and recycled to the synthesis unit and the raw methanol is purified in the flash drum and then the distillation unit. In the distillation unit, there are two columns (L-C and H-C) to remove the light components containing H2, CO, DME, and aldehyde, and the heavy components including ethanol, water and higher alcohols.

**Description of the hybrid polygeneration system**

As shown in figure 2, the flow diagrams of the parallel polygeneration system (a) and sequential polygeneration system (b) are presented. In the parallel polygeneration system, the characters of the individual production systems (IGCC system and methanol production system) are still obvious. The chemical subsystem and power subsystem are rather similar to the individual methanol production system and IGCC power system respectively, except some material and heat interactions between the two subsystems are present. For the sequential polygeneration system, the power subsystem is arranged downstream the chemical subsystem fueled by the unreacted syngas from the chemical subsystem. Thus the chemical process upstream has a constraint and significant effect on the power subsystem. It is necessary to stress that the chemical subsystem is reformed by canceling the shift unit and partially recycling the unreacted syngas. The expander in both 2(a) and

![Diagram of the parallel polygeneration system](image1)

Fig. 2 (a) The flow diagrams of the parallel polygeneration system

![Diagram of the sequential polygeneration system](image2)

Fig. 2 (b) The flow diagrams of the sequential polygeneration system

2 (b) is used to reduce the pressure of the stream for the power subsystem and produce some power.
In figure 3, the flow sheet of the hybrid polygeneration system is presented. Coal is gasified in the gasifier similar to that of the individual chemical methanol production system. The raw syngas is first cooled down in the waste heat boiler, then divided into two streams in the R1 (to stand for it, r1 is defined as the fraction of the stream flow to the chemical subsystem.), one to the chemical subsystem the other to the power subsystem after purified by MDEA. In the purification unit, CO2 is not removed from the stream that will go to the power subsystem, while for the stream will to the chemical subsystem the CO2 is removed. The clean syngas to the chemical subsystem is firstly used to produce methanol, after cooled down in the heat regenerator the raw methanol and the unreacted syngas are separated. Part of the unreacted syngas is divided in the R2 (to stand for it, r2 is defined as the fraction of the unreacted syngas stream flow recycled to the synthesis unit) to the recycle compressor (RC) through which the unreacted syngas is recycled to the synthesis unit. Then the raw methanol is distillated in the distillation unit. The other part of the unreacted syngas is mixed with the off gas from the distillation unit and then goes to the power subsystem. The syngas from the purification unit in the syngas preparation subsystem and the unreacted syngas from the chemical subsystem go the power subsystem to fuel the combined cycle. The power needed in the syngas preparation subsystem and chemical subsystem is provided by the power subsystem, and the heat integration among the three subsystems is carried out by water/steam with proper pressure.

It can be seen that both configuration characters of the parallel and the sequential polygeneration systems can be identified in this novel polygeneration system. Firstly, the chemical subsystem and the power subsystem are arranged in parallel style, which gives the system more freedom on the production distribution. Secondly, in the chemical subsystem the component adjusting unit is canceled and partially recycling unreacted syngas.

3. PERFORMANCE OF THE HYBRID POLYGENERATION SYSTEM

Evaluation criterion and basic simulation assumption

The performance of the hybrid polygeneration system is evaluated by the energy saving rate (ESR), which can be define by

\[
ESR=\frac{(E_{pi}+E_{ci})-E_{pg}}{(E_{pi}+E_{ci})} \quad (1)
\]

Where \(E_{pi}\) and \(E_{ci}\) represent the total energy input to the electricity generation and the
methanol production system, respectively, and $E_{pg}$ represents the energy input to the polygeneration system. It must be sure that the polygeneration system and the individual systems should have the same amount of production when they are compared. Then the ESR stands for the fuel saving rate of the polygeneration system compared with the individual systems with the same production.

The hybrid polygeneration system is simulated by means of Aspen Plus 1.11, in which the mass and energy balances are assured. The pressure drops of all streams flowing throw a heat recover, a combustor, a gas cleaner and other resistance units are set to 5%. For the chemical subsystem, the synthetic pressure and temperature are set to 78bar and 255°C respectively. The simulation is carried out according to the state of art for the present technology, and the main assumptions during the simulation are listed in table 1.

### Energy utilization and component utilization characters

#### 3.1.1 Qualitative evaluation of chemical energy utilization and effective components conversion

From the configuration character analysis, it can be seen that the hybrid polygeneration system has both of the characters of the parallel and sequential polygeneration systems. Thus from the point of view of energy, the hybrid polygeneration system bears the energy utilization and component conversion characters of the other two polygeneration systems. Compared with the parallel polygeneration system, the hybrid polygeneration system cancels the component adjusting. Consequently, there is no need for quenching the raw coal gas from the coal gasifier, and the heat of the raw coal gas can be used to generate high-pressure steam. The low-heat-value of the syngas will not decrease without the exothermic shift unit, which does a great mater to the power subsystem. Partially recycling the unreacted syngas enables the effective components (CO/H$_2$) to be converted sufficiently and properly to methanol, and the rest of the components that are not suitable for methanol synthesis will be burned as fuel in the power subsystem. Thus the chemical energy of effective components realizes their cascading utilization.

Compared with sequential polygeneration system, the hybrid type has a relative excellent performance of the chemical subsystem, but not all of the components from the syngas preparation subsystem go to the chemical subsystem. Thus the first stream division r1 has a negative effect on the performance. However, when the production capacity requires more power production, the hybrid polygeneration system, because of its flexible configuration, can perform better than the sequential one. For the power production requirement, the sequential polygeneration has to break the principle of partial recycling of the unreacted syngas to choose a not sufficient recycling. The chemical subsystem of the hybrid polygeneration system manages the proper utilization of the effective components chemical energy at each of the first split ratio. That is to say for the same production capacity ratio the hybrid polygeneration has a relatively better performance than the sequential type.

#### 3.1.2 Analytical analysis
The hybrid polygeneration system is characterized by the two divisions, and to investigate how the two stream divisions effect on the system performance, the role of the main parameters are extracted and analyzed. The system is composed of three subsystem, syngas preparation subsystem, chemical subsystem and power subsystem. Figure 4 is the summarizing exergy balance sketch, which is detailed in figure 3. In the Figure 4, the $E_f$, $E_M$, and $W$ represent the total exergy input of fuel, exergy output of methanol production, and power output, respectively; the $E_{desS}$, $E_{desC}$, and $E_{desP}$ represent the exergy destructions in syngas preparation subsystem, in chemical production subsystem, and power subsystem, respectively.

Due to the exergy balance we can get:

$$E_f = E_{desS} + E_{desC} + E_{desP} + E_M + W \quad (2)$$

In the hybrid polygeneration system, the exergy ratio of the chemical and power production to the exergy input can be expressed:

$$\frac{E_M}{E_f} = \frac{E_f - E_{desS}}{E_f} \cdot \frac{E_{desC} + E_M}{E_f - E_{desS}} \cdot \frac{E_M}{E_f} \quad (3)$$

$$\frac{W}{E_f} = \frac{E_f - E_{desS}}{E_f} \cdot \frac{E_{desP} + W}{E_f - E_{desS}} \cdot \frac{W}{E_f} \quad (4)$$

Make $\alpha_f = \frac{E_f - E_{desS}}{E_f}$; $\alpha_c = \frac{E_M}{E_{desC} + E_M}$; $\alpha_p = \frac{W}{E_{desP} + W}$

And $\beta_c = \frac{E_{desC} + E_M}{E_f - E_{desS}}$; $\beta_p = \frac{E_{desP} + W}{E_f - E_{desS}}$

Then equation (3) and (4) can be expressed respectively by:

$$\frac{W}{E_f} = \alpha_f \cdot \beta_p \cdot \alpha_p \quad (5)$$

$$\frac{E_M}{E_f} = \alpha_f \cdot \beta_c \cdot \alpha_c \quad (6)$$

In the equation (5) and (6), $\alpha_f$ represents exergy efficiency of the syngas preparation subsystem; $\alpha_c$ represents exergy efficiency of the chemical production subsystem; $\alpha_p$ represents exergy efficiency of the power subsystem; $\beta_c$ represents the proportion of the exergy consumption in chemical subsystem accounting for the exergy output from the syngas preparation subsystem; $\beta_p$ represents the proportion of the exergy consumption in power subsystem accounting for the exergy output from the syngas preparation subsystem. From the equation (2), it’s easy to prove that $\beta_c + \beta_p = 1$.

Based on the equation (5) and (6), the evaluation criterion, energy saving rate expressed by equation (1), then can be expressed by:

$$ESR = \left[ (E_{pi} + E_{ci}) - E_{pg} \right] / (E_{pi} + E_{ci})$$

$$= \left( \frac{W}{\eta_{Ep}} + \frac{E_M}{\eta_{Ec}} \right) - E_f$$

$$= 1 - \frac{1}{(W / E_f) / \eta_{Ep} + (E_M / E_f) / \eta_{Ec}}$$

$$= 1 - \frac{1}{\alpha_f \cdot \alpha_p / \eta_{Ep} + \beta_c \cdot (\alpha_c / \eta_{Ec} - \alpha_p / \eta_{Ep})}$$
= f(\alpha_f, \alpha_c, \alpha_p, \beta_c) \quad (7)

It is clear that the main parameter that affect the performance of the system are \( \alpha_f \) exergy efficiency of the syngas preparation subsystem; \( \alpha_c \) exergy efficiency of the chemical production subsystem; \( \alpha_p \) exergy efficiency of the power subsystem; \( \beta_c \) the proportion of the exergy consumption in chemical subsystem accounting for the exergy output from the syngas preparation subsystem.

**Sensitivity analysis of the hybrid polygeneration system**

From the Analytical analysis above, the main parameters that affect the performance are exergy efficiency of the syngas preparation subsystem \( \alpha_f \), the proportion of the exergy consumption in the chemical subsystem accounting for the exergy output from the syngas preparation subsystem \( \beta_c \), and the exergy efficiencies of chemical and power subsystem \( \alpha_c \) and \( \alpha_p \). For this polygeneration system, the exergy efficiency of the syngas preparation subsystem \( \alpha_f \) is almost a constant, since the two stream divisions have no effect on it. The exergy efficiency of power subsystem \( \alpha_p \) varies in a very small range from about 0.55 to 0.56. Thus the parameters that significantly affect the system’s performance are the proportion of the exergy consumption in the chemical subsystem accounting for the exergy output from the syngas preparation subsystem \( \beta_c \) and the exergy efficiency of the chemical subsystem \( \alpha_c \). The two divisions both decide the value of \( \beta_c \), and the second division decides the exergy efficiencies of the chemical subsystem \( \alpha_c \).

Figure 5 illustrates the simulation results of the proportion variation of the exergy consumption in the chemical subsystem accounting for the exergy output from the syngas preparation subsystem \( \beta_c \) due to the two stream divisions. From figure 5 it can be seen that, the \( \beta_c \) increases with both the increase of the two stream divisions \( r_1 \) and \( r_2 \), and the tendency of the increase due to the second stream division \( r_2 \) seems strengthened. But from the analytical formulae expression, it can be seen that the increase of the \( \beta_c \) benefits the system performance.

Figure 6 illustrates the simulation results of the variation of exergy efficiency of the chemical subsystem \( \alpha_c \) due to the two stream divisions. And it can be seen that, the \( \alpha_c \) decreases with the increase of the second division \( r_2 \), and the tendency of the decrease is more significant than the increase tendency of the \( \beta_c \). The main reason for the decrease of the \( \alpha_c \) is the sharp increase of the
work consumed by the recycle compressor. The decrease of the $\alpha_c$ results in a bad energy utilization level. On the other hand, the value of the first stream division $r_1$ has almost no effect on the exergy efficiency of the chemical subsystem $\alpha_c$. It just decides the $\beta_c$.

Compromising both effects of the proportion of the exergy consumption in chemical subsystem accounting for the exergy output from the syngas preparation subsystem $\beta_c$ and the exergy efficiency of the chemical subsystem $\alpha_c$, the performance simulation result of the system is shown in the figure 7, the performance of the hybrid polygeneration system due to different values of the two stream divisions. The energy saving rate increases as the first stream division $r_1$ increases, which result in the increase of the $\beta_c$. For the second stream division $r_2$, there is an optimal value corresponding to the highest energy saving rate, and the optimal value of the second stream division $r_2$ is between 0.8 and 0.9. The line of the highest energy saving rate along the first stream division $r_1$ represents the polygeneration systems that apply a proper recycling ratio of the unreacted syngas in their chemical subsystem. The line of the lowest energy saving rate along the first stream division $r_1$ represents the polygeneration systems without unreacted syngas recycle. The right line corresponding to the first stream division $r_1 = 1$ represents the sequential polygeneration system, in which all the syngas passes through the chemical subsystem without bypass. The highest point thus is the sequential polygeneration system with proper recycle of the unreacted syngas from the synthesis unit.

**Character of different design working condition**

From the configuration character analysis of the hybrid polygeneration system, it is concluded that compared with the other two polygeneration system, this system deserves a better performance when the power production capacity increases. To quantitatively analyze this character, the performances of the two polygeneration system is compared at different production capacity ratio. In figure 8, we can identify that both the hybrid and the sequential polygeneration system have a better performance than the parallel type at each production capacity ratio. Compared with the sequential polygeneration system, the hybrid polygeneration system is better, and the advantage increases when the power production capacity increases. When the capacity ratio of chemical production to power production increase the critical value about 1.4, the two systems have the same performance for in that case the hybrid polygeneration system have transferred to the sequential type in configuration.

This character of more flexible production capacity production with higher performance
provides a flexible option for the designing of a polygeneration system. It may be the first choice for its flexible production capacity, easier management, and relative higher performance.

4. CONCLUSION

A new type of polygeneration system, a hybrid polygeneration system is proposed. The idea of constructing this system is based on the principle of energy cascading utilization and the combination of the parallel and sequential polygeneration systems. The configuration character of the hybrid polygeneration system is investigated, and its effects on system performance are analyzed. Firstly, the system is evaluated qualitatively from the general principle of cascading utilization of energy. Then the system is analyzed analytically and the main parameters with relation to the system performance are extracted. How the main parameters effect the energy utilization and effective component conversion is detailed. The result is that the hybrid polygeneration system has an energy saving rate of 2% to 14%, and it has a relatively flexible configuration, which may bring forward a convenience on designing a polygeneration system. At each capacity ratio the hybrid polygeneration system performs an excellent efficiency. In all, the hybrid polygeneration system provides an option of high efficiency utilization of fossil fuel, and gives a convenience for selecting a reasonable capacity ratio with better performance.

REFERENCE
ABSTRACT

Power transformer parameters change after many years due to aging, hot spot temperature, short and long term over load, short circuit, isolations degradation an so off line parameter determination by manufacturer. For this reason, on line identification is the best option; it can be followed using load changing that can make the disturbances on voltage, exciting voltage and currents. These disturbances can help to perform the parameter estimation, convergence in value and computations method. Recent advances in computational power has allowed the use of online parameter estimation techniques in varied applications such as reconfigurable or adaptive control, system health monitoring, and fault tolerant control. The combined problem of state and parameter identification leads to a nonlinear filtering problem; furthermore, many systems are characterized by nonlinear models as well as noisy and biased sensor measurements. The Kalman filter (Kalman 1960), which assumes Gaussian distribution for the uncertainties in system dynamics and utilizes the first two moments of the state vector (mean and covariance) in its update rule is an optimal sequential linear estimator ideally suited for recursive implementations Kalman Filter is a commonly used algorithm for recursive parameter identification due to its excellent filtering properties and is based on a first order approximation of the system dynamics. Using Kalman filter estimator, estimated the 230/63 KV, 250 MVA transformer non-dynamic parameters.

A new parameter identification method is proposed in this paper to estimate the parameters of large power transformers. A sudden change of load is imposed to the transformer when it is under load operation respectively in no load condition, while its transients of voltages, currents and temperatures are recorded. For parameter identification and so verification of models authors used MATLAB software for the coding and computation process. Parameters were identified and then measured and so predicted outputs were compared.

Keywords: Estimation. Kalman, parameter, power transformer

INTRODUCTION

Two-winding transformers (TWT) are widely used in power system applications. Determination of its equivalent circuit parameters is useful in performance computations, power system load flow studies, monitoring of rise in winding temperature and health of transformer, design of relays in protection circuit of transformer, etc.

Parameter estimation and System Identification techniques allow the engineer to form a mathematical model of a system using measured data. The power industry has placed great emphasis on system
identification of various equipments since the resulting mathematical models are useful in the system
design and management process, especially for developing elaborate simulation environments and
control systems design.

System identification techniques can roughly be classified in two groups: offline techniques and
online techniques.

Offline system identification techniques tend to depend on iterative methods that exploit the
advantage of having a complete set of data available for processing, whereas online or recursive
system identification techniques must use the data as it becomes available. Recursive system
identification is a valuable tool in the design of adaptive control Laws health monitoring algorithms,
and the design of fault tolerant systems. Increasing availability of onboard computational power
indicates further emergence of applications employing recursive parameter identification algorithms.

Recursive system identification techniques handle loading data as it is measured through onboard
sensors and estimate the required state variables derivatives in real-time. Measured data can contain
considerable amount of noise. Furthermore there might be biases and unobserved states in the system
model which must be estimated; hence filtering techniques are generally employed. Fundamental to
all stochastic filtering methods is a two step Bayesian procedure consisting of prediction, or time
update; and correction, or measurement update. The Kalman filter (Kalman 1960), which assumes
Gaussian distribution for the uncertainties in system dynamics and utilizes the first two moments of
the state vector (mean and covariance) in its update rule is an optimal sequential linear estimator
ideally suited for recursive implementations. However, most power systems involve a nonlinearity of
some form, furthermore the method of parameter estimation through state.

The Kalman filter is a suitable algorithm to use for fault detection in large-scale power transformer.

It will be possible to correlate the parameters of the equivalent circuit to a fault type as shown in Table
1. This approach is currently under investigation. In table 1 some examples of faults that can be
detected on-line through parameter estimation are shown.

Table 1 Correlation of model parameter changes to transformer fault type

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type of fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductances</td>
<td>- Disc deformation</td>
</tr>
<tr>
<td>(primary&amp;secondary)</td>
<td>- Local break down</td>
</tr>
<tr>
<td></td>
<td>- Winding short</td>
</tr>
<tr>
<td>Capacitance</td>
<td>- Disc movement</td>
</tr>
<tr>
<td>(primary&amp;secondary)</td>
<td>- Buckling due to large mechanical forces and moisture ingress</td>
</tr>
<tr>
<td>Resistances</td>
<td>- Shortened or broken disc</td>
</tr>
<tr>
<td>(primary&amp;secondary)</td>
<td>- Partial discharge</td>
</tr>
<tr>
<td>Capacitance between</td>
<td>- Aging of insulation</td>
</tr>
<tr>
<td>(primary&amp;secondary)</td>
<td></td>
</tr>
</tbody>
</table>

Development of the Model:

In this section, we will describe an arrangement by which the state equations of a two-winding
transformer can be implemented in a computer simulation. In this work, currents are chosen as state
variables. The equivalent circuit representation of Figure 1 has a cut set of three inductors. Since
their currents obey Kirchhoff’s current law at the common node, all three inductor currents can not be independent.

V1 is chosen as an input variable, while V2 is an output variable. Core losses are included by approximating them as losses proportional to the square of the flux density in the core, or the square of the internal voltage $e_m$ shown in Figure 1; then an appropriate core loss resistance is connected across $e_m$, in parallel with the magnetizing inductance, $L_m$. The resultant equivalent circuit would then be the same as that derived from steady-state considerations. From Figure 1, current of $L_{ll}$ is represented as $x_1$, $x_2$ for $L_{22}$ and $x_3$ for $L_m$.

**Given Data:**

The following data have been extracted from the nameplate and transformer catalogue:

- $R_1 = 0.002 \, \text{pu}$
- $R_{\text{base}} = (230\text{KV}^2/3*250\text{MVA}) = 70.5 \, \Omega$, $R_1 = 0.002*70.5 = 0.14 \, \Omega$
- $L_1 = 0.08\,\text{pu}$, $L_{\text{base}} = 70.5/(2*3.14*50) = 0.2245 \, \text{H}$, $L_1 = 0.08*0.2245 = 0.018\,\text{H}$
- $L_{1\text{pu}} = L_{2\text{pu}}$, $R_{1\text{pu}} = R_{2\text{pu}}$

**Magnetization resistance and reactance**

Using the resistance and inductance can simulate the core active and reactive losses. When selected, the p.u. values are based on the nominal power $P_n$ and on $V_1$. For example, to specify 0.2% of active and reactive core losses, at nominal voltage, use $R_m = 500 \, \text{p.u.}$ and $L_m = 500 \, \text{p.u.}$ $R_m$ must have a finite value when the inductance of winding 1 is greater than zero.

![Figure 1. Full equivalent circuit of a two-winding transformer (no loaded), 230/63 KV, 250MVA](image)

The general form of the state equations is defined as:

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

(1)

**step1: no load and open circuit in secondary side**

For no load condition, $x_2 = I_2 = 0$, so KVL in primary winding of transformer is equal to:
\[ \frac{dL_1}{dt} = v_1 - x_1 R_1 - (x_1 - x_3) R_{fe} \]
\[ \dot{x}_1 = \frac{1}{L_1} v_1 - \frac{1}{L_1} R_1 x_1 - \frac{R_{fe}}{L_1} x_1 + \frac{R_{fe}}{L_1} x_3 \]
\[ \dot{x}_2 = -\frac{R_{fe}}{L_1} x_1 + \frac{R_{fe}}{L_1} x_3 + \frac{1}{L_1} v_1 \]
\[ i_1 = i_0 + i_m \]
\[ L_m \frac{di_m}{dt} = i_f e R_{fe} \Rightarrow L_m x_3 = (x_1 - x_3) R_{fe} \Rightarrow \dot{x}_3 = \frac{R_{fe}}{L_m} x_1 - \frac{R_{fe}}{L_m} x_3 \]

The state space equation is:
\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\dot{x}_3
\end{bmatrix}
= \begin{bmatrix}
\frac{R_{fe}}{L_1} & R_{fe} & 0 \\
\frac{R_{fe}}{L_1} & R_{fe} & 0 \\
\frac{R_{fe}}{L_m} & \frac{R_{fe}}{L_m} & 0
\end{bmatrix}
\begin{bmatrix}
1 \\
x_1 \\
x_3
\end{bmatrix}
+ \begin{bmatrix}
\frac{1}{L_1} \\
0 \\
0
\end{bmatrix}
v_1
\]
\[
v_2 = (x_1 - x_3) R_{fe}
\]
\[
y = \begin{bmatrix}
R_{fe} & -R_{fe} \\
R_{fe} & -R_{fe}
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_3
\end{bmatrix}
\]
and \([d] = \begin{bmatrix}
\frac{R_{fe}}{L_1} & R_{fe} \\
\frac{R_{fe}}{L_m} & R_{fe}
\end{bmatrix}\]

\[ [d] = [0]. \text{ Of course: } i_0 = (x_1 - x_2) \]

**step2: loaded condition**

In this step an R load has been embedded in secondary terminals. The load energized by the transformer, gives I2 a known value. From the load characteristics, the load resistance is a given value.

\[
(x_1 - x_2) = i_{fe} + x_3
\]
\[
i_{fe} = x_1 - x_2 - x_3
\]

(5)

From the KVL in primary loop and situation I with state variable x, the following equations can be clustered:
\[
L_1 \frac{di_1}{dt} = v_1 - x_1 R_1 - i_0 R_{fe}
\]

(6)
\[ \dot{x}_1 = \left( \frac{R_{fe} + R_1}{L_1} \right)x_1 + \frac{R_{fe}}{L_1} x_2 + \frac{R_{fe}}{L_1} x_3 + \frac{1}{L_1} v_1 \]

\[ L_2 \frac{d}{dt} x_2 = E_1 - x_2 R_2 - x_2 R_{load} \Rightarrow L_2 \dot{x}_2 = (x_1 - x_2 - x_3) R_{fe} - x_2 R_2 - x_2 R_{load} \]

\[ R_{2l} = R_2 + R_{load} \]

\[ \dot{x}_2 = \frac{R_{fe}}{L_2} x_1 - \frac{R_{fe} + R_{2l}}{L_2} x_2 + \frac{R_{fe}}{L_2} x_3 \]

(7)

\[ L_m \frac{d}{dt} \dot{x}_3 = R_{fe} (x_1 - x_2 - x_3) \Rightarrow L_m \dot{x}_3 = R_{fe} x_1 - R_{fe} x_2 - R_{fe} x_3 \]

\[ \dot{x}_3 = \frac{R_{fe}}{L_m} x_1 - \frac{R_{fe}}{L_m} x_2 + \frac{R_{fe}}{L_m} x_3 \]

(8)

\[ v_2 = \dot{x}_2 R_{load} = x_2 R_{load} \]

\[ y = \begin{bmatrix} 0 & R_{load} & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \]

(9)

\[ \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} \left( \frac{R_{fe} + R_1}{L_1} \right) & \frac{R_{fe}}{L_1} & \frac{R_{fe}}{L_1} \\ \frac{R_{fe}}{L_2} & \left( \frac{R_{fe} + R_{2l}}{L_2} \right) & \frac{R_{fe}}{L_2} \\ \frac{R_{fe}}{L_m} & \frac{R_{fe}}{L_m} & \frac{R_{fe}}{L_m} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} v_1 \]

(10)

\[ A = \begin{bmatrix} \frac{R_{fe} + R_1}{L_1} & \frac{R_{fe}}{L_1} & \frac{R_{fe}}{L_1} \\ \frac{R_{fe}}{L_2} & \left( \frac{R_{fe} + R_{2l}}{L_2} \right) & \frac{R_{fe}}{L_2} \\ \frac{R_{fe}}{L_m} & \frac{R_{fe}}{L_m} & \frac{R_{fe}}{L_m} \end{bmatrix} \quad B = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \]

\[ [c] = \begin{bmatrix} 0 & R_{2l} & 0 \end{bmatrix} \quad [\dot{p}] = [0] \]

(11)

**PARAMETER ESTIMATION METHOD**
The Kalman Filter is a linear, discrete time, finite dimensional time-varying system, whose inputs are the system inputs, $u_0, u_1, \ldots, u_{k-1}$, and the system measurements, $y_0, y_1, \ldots, y_k$. The output is the process $\hat{x}(k|k-1)$ or $\hat{x}(k|k)$.

Where; $\hat{x}(k|k-1)$ is the estimate of $x(k)$ given past measurements up to $y_v(k-1)$. $\hat{x}(k|k)$ is the updated estimate based on the last measurement $y_v(k)$.

The time-varying Kalman filter is a generalization of the steady-state filter for time-varying systems or LTI systems with no stationary noise covariance. Given the plant state and measurement equations:

$$
\begin{align*}
x[n+1] &= A x[n] + B u[n] + G o[n] \\
y_v[n] &= C x[n] + v[n]
\end{align*}
$$

The time-varying Kalman filter is given by the recursions.

Measurement update:
\[
\dot{x}[n|n] = \dot{x}[n|n-1] + M[n,y_v[n] - C\hat{x}[n|n-1])
\]
\[
M[n] = P[n|n-1]C^T(R[n|n]+CP[n|n-1]C^T)^{-1}
\]
\[
P[n|n] = (I - M[n]C)P[n|n-1]
\]
(13)

Time update:

\[
\dot{x}[n+1|n] = Ax[n|n] + Bu[n]
\]
\[
P[n+1|n] = AR[n|n]A^T + CQ[n]G^T
\]
(14)

In this simulation, for simplicity we get the white noise in coding then, G=Q=R=1

**SIMULATION RESULTS:**

The presented equations have been coded in Mfile of MATLAB software, using the Kalman estimator method. The Kalman estimator is the optimal solution to the following continuous or discrete estimation problems. The Kalman filter is the filter that obtains the minimum mean-square state error estimate.

The first plot in figure 4 shows the filtered output (solid line). The second plot compares the measurement error (dash-dot) with the estimation error (solid). This plot shows that the noise level has been significantly reduced. This is confirmed by the following error covariance computations.

\[
\text{MeasErr} = y - y_v;
\]
\[
\text{MeasErrCov} = \sum(\text{MeasErr} \times \text{MeasErr})/\text{length(\text{MeasErr})};
\]
\[
\text{EstErr} = y - ye;
\]
\[
\text{EstErrCov} = \sum(\text{EstErr} \times \text{EstErr})/\text{length(\text{EstErr})};
\]

The error covariance before filtering (measurement error) is MeasErrCov.
\[
\text{MeasErrCov} = 1.1138
\]

While the error covariance after filtering (estimation error) is only EstErrCov.
\[
\text{EstErrCov} = 0.2722
\]

This value is smaller than the theoretical value errcov and close to the value obtained for the steady-state design.
Parameter detection can be used to diagnose the health of a transformer and foresee any developing in faults and failures. In online parameter estimation, the parameter is estimated in real time and all of measured input and output will be considered. While the states are monitored, fault detection can be performed by use of identified parameters. The parameters in healthy work of the transformer have a constant value, but in faulty conditions, these parameters change due to internal fault and make a difference between estimated and given parameters. For example, in internal turn to turn fault, due to electrically connection of two or more turn to them (for short circuit, deformation or other faults connect), the resistance and reactance change and deviate from the given value. In on line parameter estimation, estimator can estimate the parameters in real time and can check with given value, and then it can analyze the deviation and send an alarm (for small deviation) or trip for large deviations. Therefore, with comparing the estimated parameters over given parameters, the faults can be detected and identified. It is obvious that the reactance and resistance are proportional with turns; every change in turns can make a change in these parameters. Turns contributed in flux making in transformers and
with an increase or decrease in turns, the flux and all of its related parameters will change. The short circuit or turn to turn faults can make a residual currents or zero sequence values. Some of small turn to turn faults cannot be diagnosed by residual current relay or differential relays so this method is effective and applicable.

The schematically fault detection and data acquisition processes are shown in figure 5.

CONCLUSIONS:
Using the Simulink models in MATLAB software for input and output generation, we have provided virtual data for performing the parameter estimation. The white and Gaussian noise was applied to the model and the IEEE guide line data used for initial conditions. Virtual measured data (from model
running in Simulink) and estimated data had a satisfactory best fit, see table 2. Estimation has been performed using Kalman filter and estimated parameters were close to the given parameters. The variation is for noise and so error rate of iterations.

We have shown that the prediction method can be applied as an on-line method for parameter estimation. With parameter estimation we can do also parameter estimation for use in power flow calculation in power transmission network with high accuracy. The electrical utilities can monitor and detect several different types of internal faults in power transformers, for example turn to turn in winding faults, wax bulk between discs, local break down, insulation aging and others, see table 1.

NOMENCLATURE

Mn  The innovation gain M is chosen to minimize the steady-state covariance of the estimation error given the noise covariances
w  process white noise
v  measurement white noise
u  known inputs
yv  measurements outputs
Q  noise covariance data
R  noise covariance data
y  output
MeasErrCov  The error covariance before filtering (measurement error)
EstErrCov  the error covariance after filtering (estimation error)
X  state variable
P  steady-state error covariance
p.u.  per unit
Rj  winding resistances in secondary and primary, respectively
Lji  winding inductances in secondary and primary, respectively
Rfe  core resistance
Lm  core inductance
Rload  load resistance

Subscripts
fe  core
m  magnetization
11  mutual inductance in primary side of transformer
22  mutual inductance in secondary side of transformer
1  primary
2  secondary
v  measurement
^  estimated value
T  transpose
-1  inverse

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Maria Isabel Ribeiro, ‘‘Kalman and Extended Kalman Filters:Concept, Derivation and Properties’’, *Lectures Notes*, February 2004, Institute for Systems and Robotics Instituto Superior Tecnico, Lisboa Portugal

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**APPENDICES:**

*A part of coding is:*

```matlab
n = length(t);
randn(’seed’,0);Q = 1; R = 1;
w = sqrt(Q)*randn(n,1);
v = sqrt(R)*randn(n,1);
```
sys = ss(A,B,C,0,-1);
y = lsim(sys,u+w); % w = process noise
yv = y + v; % v = measurement noise
P = B*Q*B'; % Initial error covariance
x = zeros(3,1); % Initial condition on the state
ye = zeros(length(t),1);
ycov = zeros(length(t),1);
for i=1:length(t)
    % Measurement update
    Mn = P*C'/(C*P*C'+R);
    x = x + Mn*(yv(i)-C*x); % x[n|n]
    P = (eye(3)-Mn*C)*P; % P[n|n]
    ye(i) = C*x;
    errcov(i) = C*P*C';
    % Time update
    x = A*x + B*u(i); % x[n+1|n]
    P = A*R*A' + C*Q*G'; % P[n+1|n]
end

And:
Mn =
    0.3798
    0.0817
-0.2570
P = [ 0.6124  0.1318  -0.4144
      0.1318  0.7301   0.3890
    -0.4144   0.3890   0.9888 ]
ABSTRACT

Explosive welding occurs when adjacent surfaces of appropriately positioned metals are properly thrust together by energy released from an explosive source. Experimental tests have been performed to explosively welded aluminium to copper, Iron to Iron in flat and non-flat surface in three steps. The tests have been carried out using various stand-off distances and explosive ratios. Various interface geometries have been obtained from these experiments. In this study, all the experiments carried out were simulated using the finite element method. The conventional equations were used to describe the behaviour of explosive. These equations were coded into the COMSOL software. Most aspects of the explosive welding parameters were properly simulated. The flyer plate and collision velocities obtained from the analysis were validated by the pin-measurement experiments. The numerical results showed that very high localized plastic deformation produced at the bond interface.

Keywords: Explosive welding, plate, impact, detonation, velocity, test, FEM

INTRODUCTION

Explosion Welding (EXW) is a solid state process where welding is accomplished by accelerating one of the components at extremely high velocity through the use of chemical explosives. This process is most commonly utilized to clad carbon steel plate with a thin layer of corrosion resistant material (e.g., stainless steel, nickel alloy, titanium, or zirconium).

Unlike other forms of welding such as arc welding, the process for which was developed in the early 1800s, explosion welding was developed rather recently, in the decades after World War II, but its origins go back to World War I. It was observed that pieces of shrapnel that were sticking to armor plating were not only embedding themselves, but they were actually being welded to the metal. Since the extreme heat involved in other forms of welding did not play a role, it was concluded that the explosive forces that the pieces of shrapnel were being subjected to was the cause. These results were later duplicated in laboratory tests, and not long afterwards, the process was patented and put to use.

The fearsome destructive power of explosives can be harnessed to provide a unique joining method, known as Explosive Welding. To form an explosive weld the following conditions need to occur:

• Two surfaces that need to be joined are initially spaced at a small distance (standoff distance).
• An explosive force brings these two surfaces together progressively at a collision front. The collision front's velocity must be lower than the speed of sound in the materials, so that the shock wave
precedes the bond being formed. If not, the shockwave would interfere with the contacted surfaces preventing a bond occurring.

- The interfacial pressure at the collision front must exceed the yield strength of the materials, so that plastic deformation will occur.

A jet of metal is formed just ahead of the collision front, comprising of the two component surfaces, which is finally ejected from the interface. The surfaces and any surface contaminants are removed in the jet. Behind the collision front, the now clean surfaces bond, under extreme pressure, in the solid state. This dynamic welding situation is shown in Fig.1. In cross section, the materials usually bond together in an undulating wave form and the process can weld a parent plate of thickness 0.025mm to over 1m (the maximum flyer plate thickness is one third that of the parent plate). Up to 30m² can be welded in one explosion.

Fig.1. Dynamic situation at the collision front showing the jetting mechanism

In figure 1 Prime component is placed either parallel or at an angle to the base, Explosive is distributed over top surface of prime component, upon detonation, prime component collides with base component to complete welding.
Figure 2: Effect of Velocity on Explosion

Weld Geometry To analyze the process, the hydrodynamic analogy were used by various authors [1,2,3] due to the creation of the high localized pressure and the material fluid like behaviour at the collision zone. The process parameters are the impact velocity, the collision point velocity, the dynamic angle, the stand-off distance, the type of the explosive used and the detonation velocity, density and size and distributions of the explosive mix. Welding windows were proposed to show the weld ability ranges of process parameters i.e. impact velocity (or collision point velocity) versus the dynamic angle for various materials [3,4,5,6]. Nevertheless, the data were obtained by means of large number of experiments performed. However, the process could be simulated using the finite element method and most aspects of the welding process could be obtained. Few attempts have been reported in the literature to simulate the process. Al-Hassani [7] treated the problem as a normal transient loading of plane stress elements of rectangular shape. In this analysis, kinematically equivalent concentrated loads at the nodes represented the uniformly distributed explosive load. Explosive welding process was simulated by Oberg [8] by means of Lagrangian finite difference computer code, but only produced jetting. The explosive welding process was also modelled by Akihisa9. He only produced waves but no jetting. In addition, the author assumed that symmetric or asymmetric shear flow distribution was generated in the flyer and parent plates and the modelling was performed based on this supposition. No attempts have been made in the literature to analyze and test the explosive welding of liquid sources and curvy form surfaces. This matter would be presented in this article.

PROCESS DESCRIPTION

This is a solid state joining process. When an explosive is detonated on the surface of a metal, a high pressure pulse is generated. This pulse propels the metal at a very high rate of speed. If this piece of metal collides at an angle with another piece of metal, welding may occur. For welding to occur, a jetting action is required at the collision interface.

This jet is the product of the surfaces of the two pieces of metals colliding. This cleans the metals and allows to pure metallic surfaces to join under extremely high pressure. The metals do not commingle, they are atomically bonded. Due to this fact, any metal may be welded to any metal (i.e.- copper to steel; titanium to stainless). Typical impact pressures are millions of psi. Fig. 1 shows the explosive welding process.
EXPLOSIVE

The commonly used high explosives are shown in table 1.

Table 1: Detonation velocity for many kinds of material

<table>
<thead>
<tr>
<th>Explosive</th>
<th>Detonation velocity, m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>RDX (Cyclotrimethylene trinitramine, C3H6N6O6)</td>
<td>8100</td>
</tr>
<tr>
<td>PETN (Pentaerythritol tetranitrate, C5H8N12O4)</td>
<td>8190</td>
</tr>
<tr>
<td>TNT (Trinitrotoluene, C7H5N3O6)</td>
<td>6600</td>
</tr>
<tr>
<td>Tetryl (Trinitrophenyl methylinitramine, C7H5O8N5)</td>
<td>7800</td>
</tr>
<tr>
<td>Lead azide (N6Pb)</td>
<td>5010</td>
</tr>
<tr>
<td>Detasheet</td>
<td>7020</td>
</tr>
<tr>
<td>Ammonium nitrate (NH4NO3)</td>
<td>2655</td>
</tr>
</tbody>
</table>

Applications: Joining of pipes and tubes, Major areas of the use of this method are heat exchanger tube sheets and pressure vessels, Tube Plugging, Remote joining in hazardous environments, Joining of dissimilar metals - Aluminium to steel, Titanium alloys to Cr – Ni steel, Cu to stainless steel, Tungsten to Steel, etc., Attaching cooling fins, Other applications are in chemical process vessels, ship building industry, cryogenic industry, etc. and …

Advantages of explosive welding are: Can bond many dissimilar, normally unweldable metals, Minimum fixturing/jigs, Simplicity of the process, extremely large surfaces can be bonded, Wide range of thicknesses can be explosively clad together, No effect on parent properties and Small quantity of explosive used.

Limitations of this method are: The metals must have high enough impact resistance, and ductility, Noise and blast can require operator protection, vacuum chambers, buried in sand/water, The use of explosives in industrial areas will be restricted by the noise and ground vibrations caused by the explosion, The geometries welded must be simple – flat, cylindrical, conical.

THEORETICAL DISCUSSIONS

Experimental tests have been performed to explosively welded aluminium, copper and Iron in three step. In step one; The flyer plate had a thickness of 0,5 mm. The parent plate made of Iron with thickness of 3mm. The tests have been carried out using various stand-off distances and explosive ratios. Various interface geometries have been obtained from these experiments. The explosive material was positioned above the buffer and flyer plate.

In this study, all the experiments were simulated using the finite element method. The conventional equations were used to describe the behaviour of explosive. The explosive properties used were tabulated in Table 2. These equations were coded into the COMSOL software.
A geometrical analysis [11] shows that the plate velocity bisects the angle between the initial plate and the deformed plate orientations. On a per unit of time basis, A goes to B with $V_p$ when point O goes to B with $V_w$, see figure 1. Triangle OAB is isosceles; for triangle OBC one has

$$V_p = 2V_d \sin\left(\frac{\beta}{2}\right)$$

(1)

When $\beta<10$, one can use the approximation $V_p \approx V_d \sin \beta$ and $V_p$ are the most important parameters of explosive welding. The formation of a jet is a necessary prerequisite for explosive welding.

Wittman [12] and Deribas [13] developed an explosive welding window (Fig. 3), in which the collision angle $\beta$ is plotted in the ordinates and the welding velocity, $V_w$; is plotted in the abscissa. They studied jet formation, the critical impact pressure, the maximum impact velocity and wavy–smooth transition velocity. For example, if $V_w$ reaches a supersonic value, there is no jetting. The same happens if the impact pressure is too low. The wavy–smooth transition parameter does not appear in this plot and needs to be studied more closely.

A model capable of predicting the wave geometry would be able to determine the smooth–wavy transition. Deribas [20] developed the first model, based on experimental results. It is a hydrodynamic model, which describes wave formation as being analogous to fluid flow behind an obstacle. Thus, the smooth–wavy boundary corresponds to the laminar-turbulent transition. In fluid mechanics the Reynolds number characterizes this transition. Cowan et al. [15, 16] introduced the following Reynolds number $R_t$ for explosive welding:

$$R_t = \left(\rho_a + \rho_b\right)\frac{V_i^2}{2(H_a + H_b)}$$

(2)

Where $\rho_a$ and $\rho_b$ are the densities of the materials and $H_a$ and $H_b$ are their Vickers hardnesses. This new parameter was an important advance in the domain, but the hydrodynamic analogy contained limitations reported by Jaramillo and Szecket [17]. In the hydrodynamic model, the waves generated behind an obstacle reach a stable configuration after a certain distance while the waves at the weld interface must be created at the collision point. Furthermore, even if the fluid analogy applies to the collision point, what kind of fluid is assumed and what is the response of the regions removed from this area? Nevertheless, Cowan et al. [16] obtained correct results with regard to the smooth–wavy transition. In all of their experiments, Eq. (2) in which $R_t$ is equal to 10.6 describes the transition very well. The limitation is that they studied only one collision angle, $\beta = 12^\circ$. 

<table>
<thead>
<tr>
<th>Plate</th>
<th>Cf (m/s)</th>
<th>H (K g/mm²)</th>
<th>Density (Gr/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HK g/mm²</td>
<td>4900</td>
<td>58</td>
<td>8.9</td>
</tr>
<tr>
<td>Iron 3 mm</td>
<td>6000</td>
<td>80</td>
<td>7.8</td>
</tr>
<tr>
<td>Aluminium 5mm</td>
<td>6400</td>
<td>62</td>
<td>2.7</td>
</tr>
</tbody>
</table>
This relationship is not applicable for a generic collision angle. In order to generalize, it is necessary to obtain a relationship between the Reynolds number and the collision angle. A model was developed by Szecket [17–21] for the three following material couples: Fe–Fe, Cu–Cu, Al–Al and Al-Cu (Al alloy) (Flyer plate thickness: 0.5, 3 and 5 mm).

When all the data for these four different systems are combined, the following general relationship between the Reynolds number and the collision angle is obtained with a correlation factor=0.948:

\[ R_t = K_{EP} = 92.87(±8.92) - 12.87(±2.87)\beta + 0.89(±0.34)\beta^2 - 0.032(±0.12)\beta^3 \]  
\[ (3) \]

Eq. (3) provides a very good approximation of the smooth–wavy transition for the systems studied.

This equation is the first step toward a dynamic plasticity model and implies to redefine \( R_t \) by the elastic–plastic constant \( K_{EP} \).

**WELDABILITY WINDOW**

The advances achieved by Deribas [13], Wittman [12], Cowan [15] and Szecket [18] enable the construction of a plot that Szecket named the “weld ability window”, which includes both a straight and wavy interface domain. This plot is applied to the aluminium alloy used in this investigation. The appropriate equations for the inclined plate configuration used in this investigation are presented next. The establishment of a weld ability window requires the relationship between the initial conditions (the initial angle \( \alpha \) and the characteristics of the explosive) and the collision angle \( \beta \). The geometrical considerations applied to this configuration give the following equations [4]:

\[ V_p = 2\sin\left(\frac{\beta - \alpha}{2}\right)V_d \]  
\[ (4) \]

\[ V_w = \frac{V_p}{2V_d\sin(\beta)} \sqrt{4V_d^2 - V_p^2} \]  
\[ (5) \]
Knowing \(a\); \(V_p\) and \(V_d\); \(\beta\) can be obtained from Eq. (1). \(V_p\) is calculated from the Gurney equation [26, 27] for the specific explosive welding geometry

\[
V_p = \frac{V_p}{\sin(\beta)} \cos\left(\frac{\beta + \alpha}{2}\right)
\]  

(6)

\(R = \frac{C}{M}\) is the mass of explosive for unit mass of flyer plate. \(E\) is the Gurney energy, which is experimentally known for common explosives. The Gurney equation only predicts a terminal velocity; the problem of the flyer plate acceleration is intentionally left out. \(V_w\) and \(V_f\) can be calculated by Eqs. (5) and (6). Known values of \(\alpha\); \(\beta\); \(V_d\); \(V_p\); \(V_f\); \(V_w\) and the properties of the material enable the design of the weldability window. This diagram can be drawn in both the \(V_w\) vs \(\beta\) and \(V_p\) vs. \(\beta\) plane. Eq. (8) gives the lower limit for welding (due to Deribas et al. [14]). In Eq. (8), \(\beta\) is in radians, \(k_1\) is a constant, \(H\) is the Vickers hardness in N/m², and \(\rho\) is the density in kg/m³. The value of \(k_1\) is 0.6 for high-quality

\[
\beta = k_1 \sqrt{\frac{H}{\rho V_w^2}}
\]  

(8)

Pre-cleaning of surfaces, and 1.2 for imperfectly cleaned surfaces. Eq. (9), due to Deribas [13] and Wittman [12], gives the upper limit for welding. \(k_3\) should be evaluated experimentally at a value of \(V_w\); which is equal to half of the compressive wave velocity \(C_f\) (\(V_w=2645\) m/s for pure aluminium); \(t\) is the thickness of the flyer plate:

\[
\sin\left(\frac{\beta}{2}\right) = \frac{K_3}{t^{0.25} V_w^{1.25}}
\]  

(9)

Where:

\[
k_3 = \frac{C_f}{2}, \quad C_f = \sqrt{\frac{K}{\rho}}, \quad K = \frac{E}{3(1-2\nu)}
\]

Eq. (10), due to Szecket [11], gives the smooth–wavy transition zone for the Al alloy. This zone has been built with experimental results. For Al – Cu :

\[
R_t = K_{EP} = 13.87(\pm11.92) - 22.87(\pm5.07)\beta + 2.89(\pm0.14)\beta^2 - 0.012(\pm0.02)\beta^3
\]  

(10)

Correlation factor = 0.926.

Szecket [12] developed a weld ability zone, which contained left and right boundaries. His results for Cu will be merged with data for the aluminium alloy used in this investigation. Specific parameters are: \(\rho=2700\) kg/m³; \(H_v=62\) kg/mm²; \(C_f=6400\) m/s.
The transition zone is given for the aluminium alloy; nevertheless, the parameters corresponding to the lower limit for less perfectly cleaned surfaces ($V_w=3000–5000$ m/s) should enable a welding without waves. These values correspond to the collision angles $\beta$ between $4^\circ$ and $15^\circ$. If PETN and a value of $R=1/3$ are chosen, the range of the initial angle $\alpha$ will be from $4^\circ$ to $10^\circ$. Fig. 3 shows the application of Eqs. (1)–(10) to the $V_w$ vs. $\beta$ space. Two different flyer plate thicknesses $t$ are used: 0.5, 3 and 5 mm. The smooth–wavy interface transition is shown in this plot, and two regimes are clearly seen.

**TEST AND RESULTS**

- **IRON-COPPER**

Flyer plate is copper with 0.5 mm thickness and parent plate with 3 mm thickness is iron.

$aa'$ line: $\beta = 10(V_d - 5.5)$

![Diagram showing the weldability window of the aluminum alloy.](image)

**Table:**

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_d$</td>
<td>5.5</td>
<td>6</td>
<td>6.5</td>
<td>7</td>
<td>7.5</td>
<td>8</td>
<td>8.5</td>
<td>9</td>
<td>9.5</td>
<td>10</td>
</tr>
</tbody>
</table>

$bb'$ line: $(1.2-1.3) \times \text{sound velocity}=1.3 \times 4900=6370$ m/s

$cc'$ line: $\beta=3^\circ$

$dd'$ line: $\beta=31^\circ$

$R_c=10.6 \text{ then } V_{d}=1310$ m/s

$ff'$ line: $V_{p,\text{min}}=180$ m/s and with

$$V_p = 2V_d \sin\left(\frac{\beta}{2}\right)$$

then:
<table>
<thead>
<tr>
<th>β</th>
<th>3</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vd</td>
<td>5.7</td>
<td>3.52</td>
<td>1.72</td>
<td>0.86</td>
<td>0.57</td>
<td>0.44</td>
</tr>
</tbody>
</table>

gg’line: with
\[
\sin\left(\frac{\beta}{2}\right) = \frac{K_3}{l^{0.25}V_w^{1.25}}
\]

<table>
<thead>
<tr>
<th>β</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vd</td>
<td>--</td>
<td>12.25</td>
<td>7</td>
<td>5.1</td>
<td>4.06</td>
<td>3.4</td>
<td>2.95</td>
<td>2.61</td>
</tr>
</tbody>
</table>

- IRON-IRON
Flyer plate is iron with 3 mm thickness and parent plate with 3 mm thickness is iron.

aa’line: \( \beta = 10(V_d - 5.5) \)

bb’ line: \((1.2-1.3)\) sound velocity\(=1.3\times6000=6370 \text{ m/s}\)

cc’ line: \( \beta = 3^\circ \)

dd’ line: \( \beta = 31^\circ \)

\( R_t = 10.6 \) then \( V_d = 1460 \text{ m/s} \)

ff’line=\( V_p(\text{min}) = 271 \text{ m/s} \) and with

\[ V_p = 2V_d \sin\left(\frac{\beta}{2}\right) \]

then:

<table>
<thead>
<tr>
<th>β</th>
<th>3</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vd</td>
<td>5.1</td>
<td>3.18</td>
<td>1.55</td>
<td>0.77</td>
<td>0.51</td>
<td>0.4</td>
</tr>
</tbody>
</table>

gg’line: with
\[
\sin\left(\frac{\beta}{2}\right) = \frac{K_3}{l^{0.25}V_w^{1.25}}
\]

- COPPER- ALUMINIUM
Flyer plate is aluminium with 5 mm thickness and parent plate with 10 mm thickness is copper.

aa’line: \( \beta = 10(V_d - 5.5) \)

bb’ line: \((1.2-1.3)\) sound velocity\(=1.3\times4900=6370 \text{ m/s}\)
cc’ line: $\beta = 3^\circ$

dd’ line: $\beta = 31^\circ$

$R_t = 10.6$ then $V_d = 1466\, \text{m/s}$

ff’line: $V_p(\text{min})= 150\, \text{m/s}$ and with

$$V_p = 2V_d \sin\left(\frac{\beta}{2}\right)$$

then:

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>3</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_d$</td>
<td>3.8</td>
<td>2.34</td>
<td>1.14</td>
<td>0.57</td>
<td>0.38</td>
<td>0.29</td>
</tr>
</tbody>
</table>

gg’line: with

$$\sin\left(\frac{\beta}{2}\right) = \frac{K_3}{t^{0.25}w^{1.25}}$$

SIMULATIONS

The finite difference and finite element communities have used Eulerian methods for over 30 years to analyze problems with explosive loading, but until comparatively recently, they were too computationally demanding and inaccurate to be attractive for solving problems in solid mechanics.

Fig. 4 shows a representative 2D configuration used in Raven. The dimensions are in millimeters, the time is expressed in microseconds, and colors differentiate the materials in this and subsequent figures: the explosive is yellow; the flyer plate is green; the parent plate is blue.

The computational results are presented as time sequences. Fig. 5 shows the simulation with an initial angle of approximately $10^\circ$ at 7, 10, 13, 15 and 20 $\mu$s. Calculations were also run for the other experimental angles. The sequence of Fig. 5a shows that the angle $\beta$ is not constant; rather, it increases with time. Fig. 5b represents a plot of collisions angles, measured from the computed welding sequences as a function of time. These measurements were made for different values of $\alpha$: $4^\circ$, $6^\circ$, $7.8^\circ$, $10^\circ$ and $14^\circ$. This is an important result, and it is consistent with the metallographic characterization of the weld morphology reported in figure 6. It should also be noted that the thickness of the flyer plate is not constant either, contrary to the assumptions made until now.

As the collision angle $\beta$ increases (and this angle increases with time, as shown in Fig. 5) the wavy–smooth boundary is traversed for the three cases.

From that point on the welding interface is smooth. Again, this is in full agreement with the observations made in figure 6. The computations also reveal the effect of $\alpha$: The smaller $\alpha$; the more rapid is the increase of $\beta$ and $V_p$: For $\alpha = 4^\circ$, the interface has a very short smooth–wavy transition part, and the wavelength is not constant. For $\alpha = 8^\circ$, the interface has a large smooth–wavy transition part, and its wavelength should not be constant. Furthermore, the transition zone is reached earlier than for $\alpha = 4^\circ$. For $\alpha = 10^\circ$, the wavy part might be divided in two zones: the first one with decreasing wavelength as in $\alpha = 4^\circ$ and $8^\circ$, the second one with constant wavelength.
The transition region is larger than for 4° but shorter than for 8°. These predictions from the numerical results are confirmed by the experimental observations. Note also, in regard to the wave shapes, that the wavelength depends on the impact velocity \( V_p \) whereas the amplitude depends on the initial angle \( \alpha \): Melting appears when \( V_p \) is constant during a few microseconds (see \( \alpha=10° \)).

![Diagram](image)

**Fig. 4.** 2D section used for the computations (dimensions in mm); yellow: explosive; green flyer plate; light blue: parent plate; red and blue: air. Explosive welding 9.46 degree.

In Fig. 5c (configurations 8°, 10°, 12° with 25 \( \mu s \)), jetting first appears in the 10° configuration, and it is also the configuration for which the jet lasts the longest. One concludes from this that the quality of the welding is better at 10°. The weldability window recommends an initial angle range of 5–10° with PETN and \( R = 1/3 \) All the theories suggest that when jetting occurs, it occurs during the entire welding process. Once again, this is based on a constant collision angle assumption. For Deribas [10], jetting is responsible for the formation of the waves.

Unfortunately, these diagrams do not give information about the microscopic mechanisms.

As one cannot see the jet along the entire welding process, the conclusion could be that it is only made with materials located on the last welded millimeter. However, Fig. 5d shows the 10° configuration with the sacrificial layer. One can observe that this third material is part of the jet. In fact, with the current simulations, one cannot reach a reliable conclusion about the mechanism behind the formation of the waves. However, a relationship between the quantity of ejected matter and the formation of the waves seems reasonable; calculations involving a constant impact angle would help to establish this relationship. Another possibility is that when the melting temperature is reached along the interface, the wavy solid phase welding process ends, and a smooth, liquid phase welding process starts.
for 7.68 degree

for 9.46 Degree
Fig. 5. (a) Numerical simulation of the explosive welding process: material behaviour in function of time. Initial angle $\beta \sim 10^\circ$. It should be noted that the collision angle is not a constant, but increase with weld propagation; (b) impact angle $\beta$ in function of time for different values of initial angle $\alpha$. (c) Jetting at 25 $\mu$s for three different initial configurations ($\alpha \sim 8^\circ$, 10$^\circ$, and 12$^\circ$). Note minute points ahead of collapse region. (d) $\alpha \sim 10^\circ$ configuration with an additional layer of Al (red material) on the flyer plate. One can see that the interlayer material forms the jet.

Figure 6: Metallographic tests, this figures describes on acceptable continuity and analogous welding in joint point.
CONCLUSION

The objective of this study was to establish the conditions for straight, smooth way weld formation in the explosive welding of Aluminium vs. copper and iron and ... The smooth and straight domains defined by Szecket [17] were used to successfully predict the two regimes. Szecket’s [17] results for Al were supplemented by the constitutive response for Cu and yielded a plot applicable to the experimental results containing both wavy and smooth domains. It was possible to calculate the relationship between the terminal velocity $V_p$ and the flyer thickness with the Gurney equation. The agreement between the calculation and the computational simulation proves that the assumption made on the flyer plate acceleration is reasonable. Experimental observations (by optical microscopy) on explosively welded specimens suggested that the $V_p- \beta$ relation was not constant during the welding process since, in all cases, a region of wavy weld was followed by smooth weld. It should be noted that the thickness of the materials influences the welding process and consequently the collision angle $\beta$: For the configuration chosen for the capsules in the Mars Return Mission, the flyer plate thickness is not a constant, and thus, the impact velocity $V_p$ should vary.

Finite element calculations using Raven were conducted in a 2D geometry. The Johnson–Cook constitutive equation was used with experimentally obtained constitutive parameters for Al obtained from quasistatic and dynamic experiments carried out over a broad range of temperatures. From a numerical point of view, the results are particularly convincing. However, it is manageable to reach a higher level of accuracy utilizing a model that would include higher rate sensitivity. Although the individual wave formation could not be monitored because of mesh size limitations, the results demonstrate that the collision angle increases with propagation distance for all initial configurations analyzed. This change in collision angle is directly responsible for the change in interface morphology from wavy to smooth at the welding front.

Furthermore, the correlation between the experiments and the simulations demonstrates that the model is good enough to simulate the process.

The numerical simulation shows the formation of a jet under some initial conditions but does not reproduce the micromechanics of the process. The wave formation occurs on a micrometer scale that cannot be captured by the continuum mechanics computation. Nevertheless, jet formation was observed for 8°, 10°, and 12°.

REFERENCES


8. DESIGN OF HOT WATER USER PROFILES FOR SWEDISH HOUSEHOLDS BASED ON TIME DIARIES

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ABSTRACT

Energy demand from hot tap water usage on individual level has been modelled from data in time use diaries of 179 Swedish households living in detached houses and apartments. Data of activities that involve hot tap water was extracted and converted into energy – time diagrams (user profiles). The report describes the procedure to first convert each type of activity to an amount of hot water and secondly into energy. It was found that the energy use profiles for hot water consumption vary considerably between individual households. The average user profile of all households was compared to models of hot water use in two of the more frequently used simulation tools for solar thermal systems. It is shown that the profiles in the simulation tools are significantly different from the profiles modelled in this study. In a following study it will be investigated how these differences influence an optimal use of solar energy in a solar thermal system.

INTRODUCTION

A solar thermal system should, when functioning optimally, load the hot water storage with as much solar energy from the solar collectors as possible and minimize the use of auxiliary heating. In order to achieve a maximal solar energy usage the heat storage must be designed to keep temperature stratification in the tank. It is also important to charge the tank when the solar collectors are running. This implies the importance of the time for discharging the tank, i.e. when hot water is used in the household. It has to our knowledge not been studied in real cases how different unload strategies influence the solar fraction of the system. Jordan et al however performed system simulations with hot water profiles built on probabilities for different activities and water usage based on studies from Germany and Switzerland. It was shown that the fractional energy savings are reduced by more than three percentage units by introducing a probability based user profile instead of the more simple hot water profiles usually applied in simulation of solar thermal systems. The reason for reduced fractional savings is foremost the much larger number of draw-offs compared to the simplified profiles with only three draw-offs during the day. Furthermore, the main difference to the simplified model is during summer, when the solar energy gain is less with the realistic hot water profile. The importance of taking holidays with no hot water consumption into account is stressed. The probability for different activities to take place on different weekdays, on the other hand, only causes negligible reductions in energy gain. (Jordan et al., 2000) Creating realistic profiles without separating different weekdays, but only weekdays from weekend days, therefore seem reasonable.
Models for predicting domestic hot water use have previously been developed for Swedish conditions as well. For example, Wollerstrand (1997) describes a statistical model based on the empirical work and probabilistic model developed in Holmberg (1987). The models are developed to enable simulation of hot water loads in different types of residential buildings, where the stochastic variables were derived based on measurements. Those models however focus on peak hot water load to enable sizing of components for district heating and do not take the actual hot water consuming activities in a household into account.

In this study we have used data from time use diaries, presenting household activities, to construct profiles for hot water usage on single household level. Such profiles are “true stories” of how the activities follow each other in sequences that makes sense in how a household organises its everyday life. An approach based on probabilities for activities do not contain this dimension of organisation. This dimension is further highly valuable when working out strategies for hot water usage with optimal use of solar energy.

This paper presents the results from construction of hot water profiles for 179 Swedish households living in detached houses and apartments. The time use study on which the hot water profiles are based will first be introduced. The method to convert the data on activities to energy use will then be described and important assumptions presented. The results, in form of the generated hot water profiles for detached houses and apartments as well as profiles used in two simulation tools, are then shown and compared. Finally, the future use of and possibilities with the results are discussed.

**OBJECTIVE OF STUDY**

The aim of this study is to model hot water user profiles based on time use data from Sweden. By translating activities recorded in time diaries to hot water use, average as well as individual hot water profiles can be generated. This means that the profiles will be based on people’s statements about their activities over the day.

**DATA ON HOT WATER USE**

To create hot water profiles the outcome of a Swedish investigation on residents’ use of time has been studied. The pilot study was performed in the autumn 1996 by Statistics Sweden, while the data was coded at Linköping University (Ellegård et al., 2004). The material has previously been used in time geographic studies as well as in a study on residential electricity use (Widén et al., 2008) (Kall et al., 2007).

The time use study includes a total of 464 persons from 179 different households. The households both live in apartments and detached houses and the participants are of varying age. Household members older than 10 years have written so called time diaries during the same days; one weekday and one weekend day, predefined by Statistics Sweden. The persons then fill in all activities they perform during the day. The activities were defined by the persons themselves and are therefore given with different degrees of detail in the material. The number of activities defined in the material is consequently extensive. The time resolution of the data is one minute, but it is seldom used. Five minutes intervals are more frequently used, and therefore the detail of the hot water user pattern is set to 5 minutes resolution.

In the background data family composition, such as number of children older and younger than 10 years, type of living (apartment or detached houses) and occupation among others can be found. The data also tells if the person is at home or not and if the person is alone or in company with one or more family members, or other persons. In this study the activities in which the persons use hot water at home have been extracted. This yields a profile of demanded hot water from the solar heating system, and a load profile representing the household energy use, while inclusion of hot
water use during daytime at work would yield a more extensive picture of a person’s total hot water use. That is however beyond the scope of this study.

**Detached houses**

Out of the total, 271 persons live in detached houses, divided into 92 households. This study mainly focuses on detached houses, since solar heating is most often installed for single family houses. All households were then considered, from one person households to those with up to six persons.

**Apartments**

All households with complete time diaries living in apartments were also considered. A possible difference in hot water use between the two types of living can then be investigated. The time use study comprised a total of 128 persons living in apartments, divided into 64 households. The number of household members varied between one and six persons with a majority of small households.

**MODEL DESIGN**

To enable creation of hot water profiles the time use data had to be converted to energy. This was done in several steps. First, all activities associated with hot water consumption were identified from the list of activities specified in the time diaries. The hot water can either be used *before* or *during* the activity. For example, tapping or taking a bath often means that the bathtub is first filled, and then the person takes the actual bath. Hot water is in fact not used during the activity, but before. In the same way hot water is only assumed to be drawn in the first time interval to do the dishes in the sink, and the same dishwater is used in the other time intervals during the activity.

A certain volume of hot water was then connected to every activity, either as a fixed volume of water per activity or a volume per time unit depending on the type of activity. For those activities requiring large volumes of water, often also extended in time, such as showering or taking a bath, the hot water was defined as a certain volume per five minutes of activity. This means that a certain volume or power was equally added to those five minutes intervals where the activities took place. However, a bath requires a limited volume of water. When this maximum volume is reached the energy use for hot water in the next time step will be zero.

To find the required hot water volumes rules of thumb on average consumption connected to different activities were used in the first place, but when necessary reasonable assumptions were made for example by trying different activities. By programming in the computer based calculation program Matlab profiles could then be generated for every person in the study by adding the hot water used in the different activities performed during the days. Profiles could also be generated for households, groups of people or all participants. To get average consumption patterns the hot water use of all persons living in detached houses and apartments were combined respectively. Finally, the generated profiles were compared to the simplified hot water profiles from two standard solar heating simulation tools, Winsun (Perers et al., 2002) and Polysun (SPF, 2004). The comparison aims at showing the resemblance between the shape of the stylized profiles and those generated by the time use data, since the latter will show when hot water consuming activities are actually taking place. The magnitude of the hot water use will however be analyzed and evaluated in detail in future work focusing on validating the model.

To find exceptions from the average, profiles were also generated for every single household. They were compared to the average profile to find “extreme” hot water behaviour.

The model to design hot water profiles could also be used to separate different activities or tap places. Thereby the hot water demand connected to a certain activity, or the relative distribution of hot water on different activities within a household or a group of people, can be studied in detail.
ASSUMPTIONS

The hot water temperature is assumed to be 55 °C, representing the tank storage temperature. The water is then mixed with cold water of 10 °C at the tap place to reach the desired, usable temperature which differs slightly between different activities.

Statistics on hot water use during different activities are hardly found in literature. The Swedish Energy Agency performs measurements in Swedish households to increase the knowledge about hot water use at different tap places in dwellings (Stengård et al, 2007). That study is however not yet finished and will not separate different activities taking place at the same tap. Therefore values on hot water demand for shower, bath and dishes, used as rules of thumb by Swedish energy companies are applied when generating hot water profiles in this study. The amounts of hot water as well as energy connected to some of the most important hot water consuming activities are presented in Table 1. The volumes in the middle column are the amounts of 55 °C hot water required to reach usable temperatures when mixed with cold water. The amount of energy in the right side column is the increase of heat compared to cold water, here 10 °C.

Most households are assumed to have traditional taps, both in the shower and at the tap places. The flow in a traditional shower tap could be as high as 35 litres per minute, while in a modern tap it is about 12 litres per minute according to armature manufacturers. Water flow in modern taps at washstands is about 5 litres per minute and for kitchen taps about 7 litres per minute.

Table 1. Common hot water activities assuming 55 °C water temperature.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Litres of water</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shower</td>
<td>40 l/5 min</td>
<td>2.1 kWh/5 min</td>
</tr>
<tr>
<td>Bath</td>
<td>100 l</td>
<td>5.2 kWh</td>
</tr>
<tr>
<td>Wash hands/go to toilet</td>
<td>0.7 l</td>
<td>0.04 kWh</td>
</tr>
<tr>
<td>Dishes, by hand, in tub</td>
<td>16 l</td>
<td>0.8 kWh</td>
</tr>
<tr>
<td>Hand wash</td>
<td>0.7 l</td>
<td>0.04 kWh</td>
</tr>
<tr>
<td>Cooking/baking</td>
<td>0.5 l/5 min</td>
<td>0.02 kWh/5 min</td>
</tr>
<tr>
<td>Cleaning, scrubbing</td>
<td>3.3 l/5 min</td>
<td>0.2 kWh/5 min</td>
</tr>
<tr>
<td>Washing clothes by hand</td>
<td>13 l</td>
<td>0.7 kWh</td>
</tr>
</tbody>
</table>

For cooking and baking one hand wash or rinsing household goods was assumed to occur twice every 15 minutes, see Table 1. For washing clothes by hand a temperature of 40 °C was assumed, but also washing up once and rinsing three times.
Washing machines and dish washers have not been considered in this study. At present most of this equipment are fed with cold water and heated with electricity in Swedish households.

RESULTS AND DISCUSSION

To try the hypothesis of the importance of hot water use, simulations were first performed in the solar heating simulation tool Polysun 3.3. The simulations were done for an average new-built house in Stockholm, Sweden, with a combisystem supplying both space heating and hot water. The solar collector system comprises 12 m² ordinary flat plate solar collectors and 1 m³ storage tank. The four different hot water profiles available in Polysun 3.3, which can be found in Fig. 7 below, were introduced in the model. It was found that the profile did affect the solar utilization. The main difference between profiles with morning and evening peaks respectively was in winter, where hot water peaks in the morning increased the solar contribution by up to 14 percent per month due to the decreased need of auxiliary heating to keep the tank temperature during nights. On the contrary, in summer hot water peaks in the evenings were favourable, increasing the solar contribution by up to 3.5 percent or 17 kWh per month.

Hot water use in detached houses

To enable simulations with load profiles based on time use data and compare different user patterns, hot water profiles were modelled. The hot water consuming activities of all 271 persons living in detached houses were combined to one profile; see Fig. 1 for the weekday pattern and Fig. 2 for the weekend pattern. The total hot water use in the weekday is 82 litres or 4.3 kWh per person and day and 86 litres or 4.5 kWh per person and day for the weekend day. Varying figures on average hot water demand in Sweden are given mainly by the energy companies, from 66 to 100 litres per person and day. This, however, indicates that the assumptions made on hot water use for different activities are reasonable.

Fig. 1: The average hot water use over the day (weekday) for all persons in the study living in detached houses.

The main difference between weekdays and weekends is the later morning peak and the broader peaks in the weekend. Furthermore, the morning and evening peaks in the weekend are rather similar, while for weekdays the morning peak is much higher and narrower than the evening peak. Peaks both in the morning and in the evening can however be clearly distinguished for both weekdays and weekends.
Fig. 2: The average hot water use over the day (weekend) for all persons in the study living in detached houses.

Peaks in hot water use for most households fall within the peaks of the average curve in Fig. 1, i.e. in mornings and evenings. Nevertheless, there are households that deviate significantly. In Fig. 3 the hot water use of three families with different “extreme” hot water behaviour are presented. The evenly distributed pattern is for a two person family, the morning peaks for a four person family and the evening peaks for a six person family. The curves represent an average family member. For comparison, the average profile is also shown.

Fig. 3: The weekday hot water use of three families with different “extreme” behaviour, one only using hot water in the morning, one only in the evening and one evenly distributed during daytime. The average use is also shown.

**Hot water use in apartments**

The hot water use of all 128 persons living in apartments was also combined to create an average profile. The hot water use for an average person during a weekday is found in Fig. 4 and for a weekend day in Fig. 5. These profiles resulted in a much higher daily hot water demand compared to the average person in detached houses; see Fig. 1 and Fig. 2. In the apartments a total of 123
litres of hot water per person and day was used during a weekday and 140 litres per person and day for a weekend day. This corresponds to 6.4 kWh per person and day for weekdays and 7.3 kWh per person and day for weekend days. It is considerably higher than the standard values given by the energy companies (66 to 100 litres per person and day), which may indicate that the assumptions on hot water use for the different activities should be corrected. This will however be investigated in detail in future papers.

Fig. 4: The average hot water use over the day (weekday) for all persons in the study living in apartments.

The weekday and weekend profile for apartments differs mainly in the more constant use of hot water during weekdays, with the morning peak being the exception. During weekends there are two well distinguished peaks, while in weekdays only the morning peak is clearly seen.

Fig. 5: The average hot water use over the day (weekend) for all persons in the study living in apartments.
Comparison between detached houses and apartments

The main difference between the hot water profiles generated for detached houses and apartments is the much higher hot water consumption in apartments. Furthermore, the similarities between weekdays and weekends are less for apartments than for detached houses. The morning and evening peaks are not similar in apartments and in weekdays there is no clear evening peak at all. On the other hand, the morning peaks for weekdays are similar for both types of living, although the total hot water use is more or less doubled in apartments compared to detached houses. The higher hot water use in apartments compared to detached houses is also shown in the preliminary results from the measurements performed by the Swedish Energy Agency (Stengård et al, 2007). The common opinion about the reason for higher hot water consumption in apartments is that hot water is usually included in the rent and not individually billed. A qualitative study of effects from introducing volumetric billing in an apartment building in Sweden however shows small, but no substantial, changes in hot water routines (Krantz, 2005). Possible reasons for the minor reduction are discussed, such as the household selection where several participants were already interested in those issues, as well as all households having enough monetary resources to pay for their water use. The participants though consider themselves less wasteful after the introduction of volumetric billing.

Comparison to standard hot water profiles

Rather simple hot water profiles are usually used in solar heating simulations. In the simulation tool Winsun the relative demand profile in Fig. 6 is used. The load is scaled depending on the total hot water demand defined by the program user. All days have the same profile, making no difference between weekdays and weekends.

Comparison between the simplified profile in Winsun and the ones based on time diaries, i.e. Fig. 1 and Fig. 2 for detached houses and Fig. 4 and Fig. 5 for apartments, shows that the peaks appear more or less at the same times for weekdays in detached houses, around 6-7 a.m., 11-12 a.m., 5-6 p.m. and 8-9 p.m., but not for weekdays in apartment, since those have almost no clear peaks. The hot water profile based on time diaries is also much more complex with several smaller peaks and does not coincide very well for the weekend day, neither for detached houses nor for apartments, since the peaks are differently distributed during weekends.

Fig. 6: The hot water demand profile used in the solar collector simulation tool Winsun.

The solar heating simulation tool Polysun enables choice between the four profiles presented in Fig. 7; constant use, morning peaks, evening peaks or daily peaks. The total hot water load is again scaled depending on the chosen daily consumption. Different amounts of hot water can be defined
for different months, but not for separate days. Holiday periods with no hot water demand can also be selected.

Fig. 7: The four different hot water demand profiles (constant use, morning peaks, daytime peaks and evening peaks) that can be chosen in the solar heating simulation program Polysun.

The four profiles in Polysun 3.3 do not coincide with the profiles generated from time use data to as high extent as those from Winsun. The peaks appear too late in the mornings and too early in the evening. The extreme cases are however well represented in Polysun, even though the examples in Fig. 3 are even more extreme with almost no peaks at all at other times and the peaks appearing at different times of the day. The profiles in Polysun also generate a base load of hot water throughout the day, only excluding a few hours during the night.

**Comparison to previous work**

Similar studies focusing on creating realistic hot water user profiles have been performed before, for example by Jordan et al (2000), which was mentioned earlier. The main difference between her work and what is done in this study is the type of background data used. In Jordan et al probabilities for different activities were used to create activity patterns over the day, which means that probable distribution of activities performed by people, distributed over the day and over the week, is shown. This study, on the other hand, starts from peoples own statements about their activities, what people actually consider themselves doing. That means a background data set built on real activities, and activity sequences that are logical to the individual performing them. This therefore yields more realistic profiles of hot water use in households.

Detailed measurements at different tap places in dwellings have seldom been performed. In technical measurements information on individual energy use by different households members are however missed, since only total use at different tap places can be recorded. By generating hot water load profiles based on time diaries the hot water use can be identified to a certain person and feedback can be given to increase the household members’ awareness of energy use at home. Extensive and detailed measurements of hot water load in dwellings would still be a highly advantageous complement to time use studies. Hot water use in eight households is measured in detail by the Swedish Energy Agency (Stengård et al, 2007). This will be extended to include incoming water to another 60 households. To generate reliable and representative data on hot water use at different tap places detailed measurements on a larger number of households would however be desirable.
CONCLUSIONS
Domestic hot water user profiles have been modelled for an average person living in a Swedish detached house based on time diaries from 271 persons in 92 households. Profiles were also generated for an average person living in an apartment based on 128 persons from 64 households. The difference between detached houses and apartments was significant, both regarding total hot water use and the shape of the profiles. During weekdays only a morning peak was clearly distinguished in the apartments, while both a morning and an evening peak is seen for households in detached houses and for weekends in the apartments. It can be concluded that the hot water usage follow considerably different patterns when comparing individual households. How this will finally influence the solar fraction for the same solar heating systems placed in the different households will be the task for our next study. It has been shown here that the hot water profiles used in solar heating simulation tools do not agree with the average hot water profile obtained from the time diaries in this study.

FUTURE WORK
The next step in this study is to validate the model created to convert data from time diaries to energy use. This will be done by introducing time use data from a household where energy supply to the hot water tank has been measured simultaneously. This will yield an idea of how well the model works, but also if the assumptions are within reason. Moreover, by comparing the generated average profiles to average measured data from several Swedish households the model can be further validated. There may however be a certain difference due to the selection of people included in each study. This work will be done and reported in cooperation with a study on electricity use based on the same time use data (Widén et al, 2008).

After validating the model, the hot water profiles will be introduced in solar heating simulations to study how the solar fraction is affected by different profiles. This will yield more realistic dynamics between the solar collector system and the users. The difference between the simplified and the time diary based hot water profiles can then be studied, as well as how different family compositions influence the ability to utilize solar heating.

Solar heating systems are most often installed for single family houses. By investigating profiles based on time diaries from people living in apartments, larger systems for blocks of flats can also be studied. Additionally, the profiles generated from time diaries can be used to study benefits and drawbacks with joint and individual solar heating systems for residential areas. When applying a larger cooperative solar heating system to a residential area the effect of coincident load behaviour is utilized. This means that the hot water load will be more evenly distributed over the day, since different households perform certain hot water consuming activities at different times of the day according to the example presented in Figure 3. This may be beneficial to the solar fraction.

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9. MODELING HOUSEHOLD ELECTRICITY LOAD FROM TIME-USE DATA

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ABSTRACT
Increased knowledge of electricity load patterns in households is needed for many different purposes, a few of which are simulation of distributed electricity production and studies of electricity use in the context of everyday life. This paper describes a modeling approach aimed at obtaining reliable load profiles for household electricity from time-use data. The objective has been to minimize the number of assumptions while still keeping the resulting model output sufficiently accurate. The main material used as input data to the model is a time use survey collected by Statistics Sweden in 1996. The model outputs hourly data on electricity use in eleven appliance/activity categories for one weekday and one weekend day per household. The modeled data covers 169 households and distinguishes between detached houses and apartments. Validation was done against preliminary measurements from the Swedish Energy Agency’s on-going measurement study on household electricity and showed close correspondence between modeled and measured data. Possible uses of the model are identified, as well as benefits of using time-use data instead of, or as a complement to, electricity measurements.

1. INTRODUCTION
Previous studies of energy use in the Swedish residential sector have shown discrepancies between future scenarios and actual energy use (Nässén & Holmberg, 2005). Evidently, development of technical efficiency of household appliances is relatively easy to predict, while activities in households, which govern the use of the technology, are much more complex and unpredictable. There is thus a need for better understanding of the dynamics behind energy use in the residential sector. Moreover, there is an increasing interest in high-resolution statistics on electricity use in households. One example is the current survey by the Swedish Energy Agency (Bennich, 2007).

From a technology point of view, increased knowledge of daily load patterns can contribute to better dimensioning of renewable energy technology in distributed forms (solar power, wind power, micro-CHP, etc.). Since the main idea is to produce electricity close to the load, it is crucial that load and production match each other well. For studies of this, daily load patterns are needed. From the electricity user’s point of view it is important to understand how electricity use is constrained by the
complex patterns of habits and activities in the everyday lives of household members (Green & Ellegård, 2007). For example, which are the opportunities for change in electricity-demanding activities?

This paper reports on work aimed at filling the above needs by a modeling approach. The objective of the study has been to model household electricity use from a detailed data set on the time use for every-day activities in Swedish households. The work is by definition cross-disciplinary, combining the field of modeling and prediction of electricity load with time-geographic studies of household activities. The modeling has been done in a bottom-up manner. Since this modeling approach often is complex and in need of numerous assumptions, thus making the exact modeling procedure nontransparent and hard to reproduce, an important goal has been to use as simple assumptions and modeling techniques as possible, while still keeping the results sufficiently accurate.

There are a number of benefits of using time-use data for modeling electricity load, apart from it yielding detailed data on electricity demand. First, it is possible to express electricity use in terms of the everyday activities in households, which brings electricity use closer to the actual doings of the household members. Second, it adds different dimensions to electricity use. For example it is possible to split energy use between household members, genders and age groups, to study who is performing which electricity-demanding activities. Third, it could be a cost-effective way of estimating electricity use in households. Instead of installing expensive measurement devices, the electricity could be modeled from self-reported activities.

2. ELECTRICITY USE IN THE RESIDENTIAL SECTOR
When considering electricity use in the Swedish residential and service sector, one usually distinguishes between household electricity, direct electric heating and electricity for common purposes. In the official energy statistics of Sweden, electricity for common purposes is electricity used in premises, direct electric heating covers heating in both premises and households, and household electricity is the electricity used for electrical devices (lighting, appliances, etc.) in apartments and detached houses. (Swedish Energy Agency, 2007)

While the use of electric heating peaked in the 1990’s and since then decreased somewhat, reaching 29 TWh in 2006, the use of household electricity, 22,1 TWh in 2006, has increased steadily since the 1970’s. The increase in household electricity is partly due to an increased number of households, partly due to more appliances in each household. (Swedish Energy Agency, 2007)

There have been measurements done on household electricity at appliance level in Sweden (e.g. NUTEK, 1994) but none that reveal detailed daily patterns of use on different appliances. To improve the statistics on household electricity, the Swedish Energy Agency is currently performing a measurement survey of Swedish households, running between 2005 and 2008. The study, which covers 400 households, will show how the electricity use varies during the day and between different appliances. (Bennich, 2007)

3. PREVIOUS LOAD MODELING APPROACHES
The objective of the model presented here is to model electricity with both a high time resolution (hours) and a high ‘spatial’ resolution (single appliances in individual households). Most models do not achieve this; high resolution in time usually implies a low spatial resolution, and vice versa. Examples of models with a high time resolution are load forecast models that predict the power
demand for a cluster of households, typically within a utility’s area of supply (for a review of such models, see Alfares & Nazeeruddin, 2002). What these models have in common is that the model structure can be simplified by application of a low spatial resolution. For example, variations in power demand between large numbers of households can be modeled as noise or implicit variations in time-series. Examples of models with low time resolution and high spatial resolution include econometric models where total annual electricity use is broken down into use per appliance or household activity, e.g. by use of statistics on appliance ownership or sale figures for appliances (Parti & Parti, 1980; Sanchez, et al., 1998; Larsen & Nesbakken, 2004).

Models with both high time resolution and high spatial resolution need large amounts of data. A typical technique for achieving an arbitrary resolution is bottom-up modeling. Starting from the smallest possible units of a system, bottom-up models successively aggregate these to reach higher system levels. The so-called ‘Capasso model’ constructs load curves by adding the power demand of single appliances together. Detailed data on demography, socio-economical status and lifestyle from a variety of sources, including time diaries, are used (Capasso, et al., 1994). It is obvious that this dependency on detailed and specific data narrow the possibilities of applying the model in other contexts. Another bottom-up model, developed at Helsinki University of Technology, uses statistical mean values and general statistical distributions, which lowers the model precision, but also decreases the amount of data needed (Paatero & Lund, 2006).

4. DESCRIPTION OF THE MODEL
As depicted in figure 1, the model presented in the following chapter outputs household electricity demand, as defined above, for all households covered by the time-use data, used as input to the model. The model is dependent on a number of parameters that determine the electricity use of appliances and a daylighting scheme for modeling lighting. Input data, model structure, parameters, implementation and output are all described in detail below.

4.1 Time-use data
The basic material for this study is a pilot time-use survey by Statistics Sweden from 1996 (henceforth called ‘SCB 1996’). Data on the time use for different activities in households were collected by letting each person in every participating household write a diary reporting the timing of activities, defined by the diary-writers themselves, together with information about geographic location or means of transport, and with whom they were (Ellegård & Wihlborg, 2001). Most households wrote diaries for one weekday and one weekend day and all were collected in the autumn.
of 1996, with dates ranging from August to December. Individuals aged between 10 to 97 years took part in the study. The resulting data set is mainly based on 5-minute intervals (although a few households have reported on 1-minute basis) and the activities are organized in a detailed hierarchic activity scheme, defining activities at different levels of abstraction (Ellegård, 1999). An example of the logic behind this scheme is shown in figure 1. The figure shows the different activities involved in cleaning, as a subcategory of “Room care”, which in turn is a subcategory of “Household care”. Cleaning can be subdivided into more detailed activities as shown on the fourth level of detail (“Routine cleaning”, “Airing” and “Thorough cleaning”) and subsequently in even more detailed activities (such as “Sweeping” or “Beat carpets”). Considering energy-demanding activities, “Vacuum cleaning” (marked with bold text in figure 1) is the only activity in need of electricity. The scheme gives an impression of the way in which energy use is embedded in larger activity schemes.

![Activity Code Scheme for Cleaning](image)

**Fig.2.** Activity code scheme for cleaning, a section of the complete scheme used for categorization of activity data. Cleaning is a subcategory to ‘Room care’, which in turn is a subcategory to ‘Household care’. Both of these include various subcategories, apart from those shown here. ‘Household care’ is also one out of seven main categories. Vacuum cleaning, which is the only electricity-demanding activity considered in the modeling, is shown in bold text.

Previous work with the time-use data set has involved the creation of a computer program, developed to visualize the data (Ellegård & Cooper, 2004; Vrotsou, et al., 2007). Figure 3 shows how the cleaning activities defined by the scheme above are distributed among the persons in the data set for weekdays and weekend days. The horizontal axis orders individuals by gender and age, and the occurrence of each person’s activities in time is depicted by vertical lines, with time shown on the vertical axis. From the figure it is easy to see the difference between men and women as well as the difference between weekdays and weekend days.
Fig. 3. Screenshots from the Visual-TimePAcTS program described in Ellegård & Cooper, 2004, showing the occurrence of the cleaning activities defined in figure 2, for weekday (a) and weekend day (b). The horizontal axis orders the individuals by age and gender; men ordered by increasing age to the left, and women ordered by increasing age to the right. The vertical axis shows the time of day. A number of observations are easily made. Women do more cleaning than men, there is more cleaning on weekend days, and cleaning is more concentrated to mid-day on weekend days.

Subsequent time-use surveys were conducted after the 1996 study. One set of data from 2000 and 2001 is currently being imported into the software and it is hoped that the model described here can be applied to this data set to assess differences between 1996 and 2000/2001. Collection of time-use data from diaries has also been carried out in a project in the Swedish Energy Agency’s electricity survey, and these were used for validation of the model in section 5.
4.2 Model structure

Prior to modeling, all activities that were assumed to involve use of electricity were examined. Some activities were then excluded, although electricity use could be assumed, because the occurrence in the material was low (typically in one household) in combination with ambiguities in modeling. None of these activities were assumed to contribute substantially to the total energy use of the households where they appeared. Four different modeling schemes were used, depending on the type of activity and appliance involved:

a) **Power demand not defined by activities.** This applies to the use of cold appliances. This was modeled as a base load in the form of a constant power.

b) **Power demand constant during activity.** This applies to cooking, ironing, cleaning, and use of TV, audio appliances and computer. The power demand is considered constant during the time given for the activity, as shown in figure 3. This is more of a simplification for certain activities than for others, typically for cooking, which covers a variety of different appliances and patterns of usage not captured by the time-use data. It is a simplification for ironing as well, which is thermostat-controlled, but it is the best that can be done without complicating the modeling unnecessarily. Different modeling routines were tested to improve the modeling of cooking, for example making the power demand dependent on the type of meal reported in the “eating” activities subsequent to cooking. However, the simplified approach gave more realistic results both for single households and for the mean load curve. To take into account the possible use of multiple appliances, the company data for each person was used. All persons reporting that they were accompanied by another family member while watching TV or using audio appliances and computer are assumed to use one appliance together, while persons reporting that they were on their own are assumed to use one appliance each. This means that explicit assumptions about the number of appliances in the households are avoided.

c) **Power demand constant after activity.** This applies to dish-washing, washing and drying. The activities used in the model are of the type “Fill washing machine”, so that the actual appliance use can be assumed to begin after the activity has finished. Power is then demanded until a maximum time has elapsed or until the activity starts anew.

![Fig. 3. Modeling scheme for electricity use for activities where electricity is used during the entire course of the activity. Throughout the activity, power of level $P_{\text{max}}$ is demanded.](image-url)
Fig. 4. Modeling scheme electricity use for activities where electricity is used after the entire course of the activity and with a maximum time limit. When the activity is finished, power of level $P_{\text{max}}$ is demanded, until maximum time $t_{\text{max}}$ has elapsed or the activity starts anew.

d) Activities with time-dependent power demand. This applies to lighting and is similar to scheme (b) above, with the difference that the power varies with time. In order to make the modeled load curves exhibit realistic daily and seasonal variations in lighting demand, they were made dependent on the daylighting level. All illuminances above a certain limit value ($L_{\text{max}}$) imply minimum demand of lighting power ($P_{\text{min}}$). For illuminances $L$ between the maximum value and zero, the power demand $P$ is set to vary according to the following formula:

$$P = P_{\text{min}} + (P_{\text{max}} - P_{\text{min}})(1 - L/L_{\text{max}})$$  \quad (1)

This varying power is demanded by each person at home and awake.

4.3 Parameters

The model is dependent on parameters describing the power demand for activities or appliances used during activities. The objective has been to find a “standard appliance set” that gives a realistic mean energy use when applied to all households. Estimates of standard powers and runtime for appliances were obtained through product tests, mainly from the Swedish Consumer Agency, reflecting the range of appliances available at certain times. To the extent possible, the mean lifetime of appliances was taken into account. This method of course gives rough estimates of appliance characteristics, since it is hard to find reliable data on the actual scope of appliances. In the results reported here, the same appliance set has been applied to all households. However, the model is flexible and allows different appliance sets to be defined for each household. The resulting parameters are shown in table 1.

Another important set of parameters, not shown here, is the set of illuminance values used to determine the lighting power scheme. Such data can be obtained as monthly means of hourly values from the online database SatelLight (SatelLight, 2007). In the following simulations SatelLight data for Stockholm were used. The illuminance limit for minimum power demand was set to 500 lux.

Table 1. Parameters used in the model: power demand for activities/appliances and maximum runtime where applicable.

<table>
<thead>
<tr>
<th>Appliance/activity</th>
<th>Power (W)</th>
<th>Maximum runtime (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold appliances</td>
<td>100</td>
<td>–</td>
</tr>
<tr>
<td>Activity</td>
<td>Min (W)</td>
<td>Max (W)</td>
</tr>
<tr>
<td>---------------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>Lighting</td>
<td>80</td>
<td>200</td>
</tr>
<tr>
<td>Cooking</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>Dishwashing</td>
<td>430</td>
<td>160</td>
</tr>
<tr>
<td>Washing</td>
<td>490</td>
<td>130</td>
</tr>
<tr>
<td>Drying</td>
<td>1650</td>
<td>90</td>
</tr>
<tr>
<td>Ironing</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Cleaning</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>TV</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Computer</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Audio</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

### 4.4 Implementation and data preparation

The actual program code for extracting data from the activity database and implementing the model was written partly in Java, partly in Matlab. Before applying the model to the SCB 1996 data, some households were excluded for different reasons. In a few households, there were incomplete data for some persons and in another household two weekend days were reported instead of one weekday and one weekend day. Apartments and detached houses were also separated. The subset finally contained 431 persons in 169 households, with 103 families living in detached houses and 64 in apartments. 2 households’ type of residence was undefined and therefore left out when separating detached houses and apartments.

### 4.5 Output

Although time-use data are recorded on 5-minute intervals, or even 1-minute intervals, one-hour means were chosen as output. This is because the simple assumptions used in the modeling approach are sufficient on an hourly basis, but would be too rough on shorter time intervals. There is obviously a trade-off between model complexity and output resolution, but since hourly intervals are generally needed for applying the model in different simulation programs, this seemed to be a reasonable aim. The general output of the model, when applied to the SCB 1996 data, consists of hourly values of demanded power for the appliances/activities in the eleven categories, shown in table 1, for weekday and weekend day in each household. The lighting demand also varies with each month, which affects the total load curves. Figure 5 shows the December and June load for detached houses and weekday, indicating the effect of the varying lighting demand.
Fig. 5. An example of output from the model when applied to SCB 1996, showing how the power demand for lighting varies between months. The remaining power demand is the same in the two figures. The figures show total load curves, averaged over all households, for detached houses and weekday, for the month of December (a), and for the month of June (b). The morning peak for lighting, distinctive in the winter, almost disappears in the summer.

5. VALIDATION

Ideally, the model should be validated against measured electricity load in the same households as where the time-use data were collected. This is possible for the small number of households that took part in the time-use subproject in the Swedish Energy Agency’s measurement survey. When applying the model to the SCB 1996 data, no such measurements are available, neither on the surveyed households, nor on any households with the required level of detail. The aim has therefore been to validate the mean output from the SCB 1996 data and parameters reflecting today’s ‘standard’ appliance ownership against the preliminary mean results of the Swedish Energy Agency’s measurement survey. While the first type of validation shows the model errors, the second reflects both model errors and errors from using SCB 1996 data for predicting today’s electricity use. These errors are described in more detail below.

5.1 Possible errors

The whole process from the collection of the SCB 1996 time-use data to the validation of the final model output contains a number of possible sources of errors. These are important to identify in order to interpret the validation results correctly. The most important are the following:

(1) Bias in the household selection process.

(2) Diary-writers not reporting with care.

(3) Problems with interpreting exactly the diary-writer’s notice and applying activity scheme to it.

(4) Modeling assumptions.


(6) Non-representativity of the surveyed households relative to the targeted households when validating.

5.2 Comparison with measurements
Two comparisons with measurements were made: (a) between total average load curves from the model and the Swedish Energy Agency’s preliminary results, and (b) between model output and measurements for a household where both time use and electricity use were followed. The first comparison shows how well the model estimates the electricity demand of today when applied to SCB 1996. Differences between model output and measurements can then be caused by any of the above error sources. The second comparison shows how well the model works when the households with time-use data and the targeted measured households are the same. In this case, bias errors (1) and non-representativity problems (6) are irrelevant. Differences are only due to error sources (2) – (5).

Figure 6 shows the correspondence between model output and measurements for detached houses and apartments on weekdays and weekend days.

Fig. 7. Comparison between the output average load from the model when applied to SCB 1996 (—) and the measured average load from the Swedish Energy Agency’s measurement survey (- - -). The figures show total load curves, averaged over all households, for detached houses and apartments on weekdays and weekend days. The generally close agreement between measurements and model output is evident. Source of measurement data: Peter Bennich, Swedish Energy Agency, personal communication.

A close overall correspondence can be observed for all four cases in figure 7. The main difference is that the model output is more variable while the measured data curve is smoother. This is because the number of households is larger in the measurement survey (200 detached houses and 200 apartments in the measurement survey, compared to 103 detached houses and 64 apartments in the time-use survey) and because the number of days per household is much greater in the measurement survey.
(months or years in the measurement survey and one day per household in the time-use survey). Considering this, and the above overview of possible sources of differences between model output and actual energy use, the model gives very good resemblance with measured data. What is of importance is that the general pattern is captured by the model, for example that the power demand is generally lower in apartments than in detached houses, and that the morning load is shifted towards mid-day on weekend days.

A comparison was also made between each appliance/activity category. For ease of comparison, the model categories were rearranged to match those of the Energy Agency. An estimate of total annual use was calculated by scaling the daily values output by the model to annual values and weighting the weekend and weekday figures appropriately for each month. The result of this comparison, shown in figure 7, indicates once again that the model yields reasonable results.

![Fig. 7. Comparison between predicted annual electricity demand per household from the model and measured annual means per household from the Energy Agency’s survey. Categories are A: cold appliances, B: lighting, C: cooking, D: dishwashing, E: washing and drying, F: TV, VCR, DVD, etc., G: computer, H: audio appliances, I: additional. The ‘additional’ category includes cleaning and ironing in the modeled data. Source of measurement data: Bennich, 2007.](image)

Although the exact magnitudes differ somewhat, the general pattern is the same for the measured and modeled figures. Note for example that the relative magnitudes of cold appliances, lighting and cooking are roughly the same in both detached houses and apartments. The most obvious difference between measurements and model output is the computer category. This is probably a non-representativity problem, reflecting the increased use of computers since 1996.

The result of comparison (b) between measured electricity demand and model output for a single household, where both time use and actual electricity demand were followed, as described above, is shown in figure 8.
Fig. 8. Comparison between measured electricity demand and the model output for a single household. The model gives considerably good correspondence with measurements although the standard parameters are used.

The figure shows the total load curves for the four successive days covered in the time-use data for the household. The correspondence between measured and modeled load is not perfect, but follows the same overall pattern. The number of peaks and the height of the peaks are approximately the same. The biggest difference occurs on the third day and is due to misplacement of the power demand for cooking (error source 4) and non-reported dishwashing (error source 2). The cooking power misplacement is not surprising, given that it is the roughest model assumption. Quite contrary, it is surprising that the modeled load curve shows such similarity to the measurements on single household level, although the modeling assumptions are kept simple and the standard appliance set is used. It should also be noted that there are four other households to validate the model against. This will be covered in more detail in a coming Elforsk report.

To summarize the validation results, the overall resemblance between measurements and model output is good, especially considering the simplicity of the model structure and parameters. The preliminary measurements should not be considered as true either, being subject of a selection process with possible bias. Combining the results of the two comparisons, these indicate that error sources (2) – (5), reflecting the modeling assumptions and time-use data quality, do not have any substantial effect on the model results, while error sources (1) and (6) seem to have some impact on single appliance categories, computer use being the most obvious one.

6. DISCUSSION

The aim to use simple and transparent assumptions to model household electricity loads while keeping the results sufficiently accurate has evidently been achieved for the 1-hour resolution output. Comparing with previous models, like the Capasso model, the assumptions are few. An obvious difference, which is a main reason behind this, is of course that this model is not stochastic. Although it would be possible to create such an extension of the model, for example by creating synthetic activity data, there is a point in not doing so and instead keep the original activity data. With the whole pattern of activities kept intact, it is possible to analyze activity use in context, one of the benefits of using activity data, as mentioned in the introduction. Methods for such systematic analyses
of activity patterns are currently being developed for the Visual-TimePAcTS program (Vrotsou et al., 2007).

It is possible to identify a number of uses for the model. Mentioned briefly in the introduction was the possibility to use the model as an alternative to actual measurements of electricity use. With data on the specific household appliances and detailed time-use data describing the use of them, it should be possible to model the electricity use with reasonable accuracy, as indicated by the validation of the model. Both the model and the time-use survey method could then be improved, the latter by making it more specific and restricted to the use of household appliances.

In the near future, the usefulness of the model will be shown in a number of coming papers. Hot water demand is modeled from the same data in a parallel study (Lundh, 2007). Since there are no available statistics covering hot water and electricity demand in the same households, a model providing such data would be beneficial. Other studies that utilize the modeled load curves in simulations are under way. Options for load matching in households with photovoltaic generation are currently being investigated, as well as the limits to the penetration level of distributed photovoltaics in low-voltage distribution grids in Sweden.

7. CONCLUSION

The main conclusion is that the proposed model gives sufficiently accurate results with a minimum of assumptions. When validating the model against preliminary results from the Swedish Energy Agency’s on-going survey of household electricity, the model applied to time-use data from 1996 yielded data in good agreement with the mean measurements for all households. When applying the model to a household with both time use and electricity use measured, it also showed good overall agreement, with a few explainable discrepancies.

ACKNOWLEDGEMENT

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REFERENCES


DIFFERENCES IN ELECTRICITY AND HOT WATER CONSUMPTION IN APARTMENTS OF DIFFERENT SIZES

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ABSTRACT

Measurements of electricity and hot water consumption were performed in 24 apartments during the years 2005 and 2006. Buildings, located in Västerås, Sweden, are characterized by the fact that energy costs are included in the rent. Data obtained from the company renting out apartments MIMER were analyzed in order to find out if there were any general trends interrelated with the level of surface area, number of rooms, or the main driving force is the individual behaviour of tenants. It was found that the analysis by various parameters is as important as analysis of each individual apartment. Some tendencies were well defined such as increase of total electricity consumption during the winter months and lowest both electricity and hot water consumption in June and July. The number of rooms at equal surface area could not be accepted as a criterion of electricity consumption. Bearing in mind the interactive contact between the energy company and the respective tenants, a positive trend of lowering both studied parameters was well manifested if a comparison of data obtained during 2005 and 2006 was carried out. Obviously, further improvements in company-tenants relations in terms of more detailed mutual information would probably change tenants’ behaviour thus improving energy saving tendency in both buildings.

INTRODUCTION

For the EU-25 as a whole, growth in electricity consumption was particularly strong in the service sector, followed by households (European Environmental Agency, 2007). However, over the period from 1990 to 2004, this increase is less than 1 % for Sweden. Energy consumption particularly in the building sector accounts for 39 per cent of Sweden’s total final energy consumption and for about 50 per cent of total electricity consumption in Sweden (Swedish Energy Agency, 2007). The energy is used to heat areas and water, as well as to operate various types of equipment. Although energy consumption in the buildings has remained relatively stable since the early 1970s, heating and hot water account for more than 60 per cent of energy consumption in this sector. During the last 10-15 years, a significant improvement in the energy use in the household has been achieved through introduction of modern, energy-saving and available technologies. Nevertheless, it is widely accepted that interventions that target consumer behavior should be reinforced as it presents large number of possibilities within the sustainable development (Wood and Newborough, 2003). In fact, ssustainable energy consumption is a key element within sustainable development approach. The hot spot in sustainable energy consumption is mainly oriented to reducing consumption through tenants’ behavior analysis and further measures to efficiently change it.

Two points should be considered when assessing energy consumption in multifamiliar buildings in Sweden. The first one concerns the fact that the cost of utilities (heating, electricity, cold and hot
water) forms part of the total rent per apartment. Therefore, tenants are not encouraged to save energy like in individual households (individual houses or apartments where tenants pay for utilities). For example, results showed that apartments for which heat is included in the rent in are kept warmer than those where tenants pay for heat. The temperature differences is largest when no one is home, indicating that tenants who pay for heat are more likely to take simple conservation measures such as turning down the thermostat when leaving home (Levinson and Niemann, 2004).

The second important point is that in Sweden, information related to individual energy consumption is not available without tenants’ permission which makes difficult deeper data analysis (5). From a logical point of view the hypothesis that the energy usage in apartments correlate well to the size of a household seems reasonable. On the other hand, based on the literature analysis we may consider individual habits as more important factor. A reason for this is that the public company renting out apartments in Västerås, MIMER, has seen that the overall electricity as well as heating energy consumed in one area with “energy for free” is almost 50% higher than in a similar area where the inhabitants pay individual consumption directly. Similarly, in the USA it was recently demonstrated that tenants who rent apartments with utilities included behave differently than they would if they paid heating costs separately from rent: they use more heating and turn back thermostats less when away from home (Sjogren et al., 2007).

Therefore, to investigate the above hypothesis we have studied the usage of electricity and hot water in apartments in Västerås. There is a plan to install individual measurements of both electricity and hot water in about 1300 apartments, and thus this information can later be compared to those who have already had an individual metering for several years. This study was performed in the frame of a larger project for the development of a method for interactive (between tenants and local energy companies) information on energy consumption in individual apartments. It is also interesting to see if information about the individual energy usage can lead to a decrease of the usage.

TECHNICAL BACKGROUND

Data included in this study were collected during two years (2005 and 2006). Measurements were carried out for both electricity and hot water consumption on hourly basis. Further, data was sent to central database using a server existing at MIMER and at Metrima (the company which provided the meters and collects the hourly values). Presented to the inhabitants by displays placed next to fusebox.

The buildings included in the study were constructed in 2001 and, therefore were provided with energy efficient facilities to fulfil modern comfort standards as well as with the state of the art with respect to energy conservation. Data on energy and hot water consumption were available from apartments situated in the Östra Mälarstrand area at the shore of the lake Mälaren, Sweden. The total amount of apartments with individual measurements was 24 with a total surface of 1894 m². Of these, 8 were with 2 room and 62 m², 1 with 2 rooms and 79 m², 1 with 3 rooms and 79 m², 6 with 3 rooms and 80 m², 8 with 3 and 95 m², and 2 with 4 rooms and 95 m². In each building there were 12 apartments, occupied by 10 and 21 tenants, respectively. Consequently, the average number of persons is two per apartment.
RESULTS AND DISCUSSION

In Table 1 we can see the annual consumption of electricity and hot water for different groups of apartments independently of the number of rooms during 2005 and 2006 years.

**Table 1. Total electricity and hot water consumption during 2005 and 2006 years**

<table>
<thead>
<tr>
<th>Apartment group (m²)</th>
<th>Electricity (kWh) 2005/2006</th>
<th>Hot water (kWh) 2005/2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>62 (average/apt)</td>
<td>1922/1813</td>
<td>2829/2756</td>
</tr>
<tr>
<td>(total, all apts)</td>
<td>15376/14504</td>
<td>22632/22048</td>
</tr>
<tr>
<td>79 (average/apt)</td>
<td>3809/3489</td>
<td>6558/6886</td>
</tr>
<tr>
<td>(total, all apts)</td>
<td>7618/6978</td>
<td>13116/13772</td>
</tr>
<tr>
<td>80 (average/apt)</td>
<td>3537/2669</td>
<td>2707/1912</td>
</tr>
<tr>
<td>(total, all apts)</td>
<td>21222/16014</td>
<td>16247/11472</td>
</tr>
<tr>
<td>95 (average/apt)</td>
<td>5688/5210</td>
<td>7545/6775</td>
</tr>
<tr>
<td>(total, all apts)</td>
<td>45504/41680</td>
<td>60360/54200</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(average/apt)</td>
<td>14957/13183</td>
<td>19638/18330</td>
</tr>
<tr>
<td>2 Builds (24 apts)</td>
<td>89720/79176</td>
<td>112355/101492</td>
</tr>
<tr>
<td>1894m² all apts (per m²)</td>
<td>47/41</td>
<td>59/53</td>
</tr>
</tbody>
</table>

Analyzing the data achieved a general trend for increasing the average electricity and hot water consumption per apartment should be noted with increasing the apartment surface. However, data from 80 m²-apartments, particularly obtained for hot water, were no responding to this observation. Another interesting trend was the decrease of both parameters during 2006 year for all apartments excluding hot water consumption in 79 m²-apartments. This difference was more pronounced in 80
m²-apartments where 5 208 and 4 775 kWh less electricity and hot water total consumption were reached. Overall, average values of 47 and 41 kWh of electricity and 59 and 53 kWh of hot water per m² were consumed in 2005 and 2006 year, respectively. These values are far lower than 150-230 kWh/m² of annual energy consumption in the EU and even than 120-150 kWh/m² in low-energy buildings in some Scandinavian countries (Balaras et al., 2000).

**Fig. 1 a, b. Comparative data on electricity monthly consumption by different groups of apartments (averaged per apartment)**

Data, presented on Fig. 1 (a, b) show a well defined tendency of high total electricity consumption in winter months (December, January, and February). Apartments of higher surface, mainly of 95 and 80 m² consumed more electricity compared with apartments of lower surface area. The lowest level of electricity was registered in July independently of the year. Some exceptions should be mentioned that were not related to the surface area. For example, within the group of 95 m², it seems that apartments with 4 rooms consumed significantly higher amount of electricity during the 2005 and particularly in the “cold” months in 2006 while maximum of monthly electricity usage during 2006 was noted in apartments of 79 m².

**Fig 2 a, b. Comparative data on hot water monthly consumption by different groups of apartments**

(averaged per apartment)
Data obtained for hot water monthly consumption are presented on Fig 2 a, b. In general, the usage of hot water along the respective 2005 and 2006 year was more stable in comparison with that of electricity. Lowest consumption was observed in both July and August. Again, as in the case of electricity total consumption, there were two groups of apartments with higher level of hot water usage (95 and 79 m²).

Table 2. Maximum electricity (EC) and hot water (HWC) consumption during 2005 and 2006 on monthly and hourly basis (taken for individual apartment basis)

<table>
<thead>
<tr>
<th>Apartment size (m²)</th>
<th>Maximum EC (monthly)</th>
<th>Maximum EC (hourly)</th>
<th>Maximum HWC (monthly)</th>
<th>Maximum HWC (hourly)</th>
</tr>
</thead>
<tbody>
<tr>
<td>62</td>
<td>474/444</td>
<td>9,9/9,8</td>
<td>716/704</td>
<td>24/36</td>
</tr>
<tr>
<td>79</td>
<td>686/692</td>
<td>3,8/3,5</td>
<td>684/650</td>
<td>19/20</td>
</tr>
<tr>
<td>79</td>
<td>169/94</td>
<td>1,9/1,1</td>
<td>664/735</td>
<td>13/16</td>
</tr>
<tr>
<td>80</td>
<td>743/515</td>
<td>9,9/9,3</td>
<td>676/308</td>
<td>19/17</td>
</tr>
<tr>
<td>95</td>
<td>442/469</td>
<td>9,6/2,8</td>
<td>540/420</td>
<td>24/22</td>
</tr>
<tr>
<td>95</td>
<td>568/494</td>
<td>9,2/1,8</td>
<td>1448/660</td>
<td>39/23</td>
</tr>
</tbody>
</table>

Taken on individual basis per each group of apartments, data for maximum values of electricity and hot water monthly and hourly consumption offers another possibility for analysis. For example, it appears that the number of rooms affects the consumption but in different manner. For apartments of 95 m² increase in number of rooms caused a logic enhancement of consumption of both electricity and hot water although single maximum measurement data did not correlate with this trend. On the other hand, apartments of 79 m² demonstrated totally different trend as a higher consumption was registered in apartments with lower number of rooms while single maximum measurement data correlate with the maximum monthly consumption.

If we take as indicator the total monthly consumption of electricity and hot water for an average apartment (Table 3), independently of its surface, data confirmed the observations already discussed (Fig 1a, b and Fig 2a, b) – higher consumption during the winter months (a trend better pronounced for electricity and 2005) and lower consumption in June, July and August for both electricity and hot water.
Table 3. Total monthly electricity and hot water consumption for average* apartment during 2005 and 2006

<table>
<thead>
<tr>
<th>Month</th>
<th>Electricity</th>
<th>Hot water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2005</td>
<td>2006</td>
</tr>
<tr>
<td>January</td>
<td>317</td>
<td>278</td>
</tr>
<tr>
<td>February</td>
<td>259</td>
<td>236</td>
</tr>
<tr>
<td>March</td>
<td>258</td>
<td>244</td>
</tr>
<tr>
<td>April</td>
<td>235</td>
<td>197</td>
</tr>
<tr>
<td>May</td>
<td>206</td>
<td>200</td>
</tr>
<tr>
<td>June</td>
<td>176</td>
<td>155</td>
</tr>
<tr>
<td>July</td>
<td>139</td>
<td>116</td>
</tr>
<tr>
<td>August</td>
<td>187</td>
<td>133</td>
</tr>
<tr>
<td>September</td>
<td>202</td>
<td>163</td>
</tr>
<tr>
<td>October</td>
<td>240</td>
<td>212</td>
</tr>
<tr>
<td>November</td>
<td>238</td>
<td>224</td>
</tr>
<tr>
<td>December</td>
<td>270</td>
<td>264</td>
</tr>
</tbody>
</table>

* Total consumption /24 apartments=average monthly consumption per apartment

More detailed view on electricity and hot water consumption for each individual apartment during 2005 and 2006 is presented on Fig. 3a, b and Fig. 4a, b. It is important to note that individual apartments in general follow the same trend in consumption if we compare 2005 with 2006 years. There were several exceptions as for example apartment Nº 16 which showed significantly lower consumption of both electricity and hot water in 2006 compared to those in 2005. On contrary, data of hot water consumption of apartment Nº 23 was significantly higher in 2006 that that consumed in 2005.
Fig. 3a, b. Electricity consumption for 2005 and 2006 for each individual apartment

3a

3b

Fig. 4a, b. Hot water consumption for 2005 and 2006 for each individual apartment

4a
Another important parameter that should be taken into account and further studied is the ratio between average and median values, both calculated per year for each individual apartment (data not shown).

Some of the apartments showed significant difference in their consumption compared to the rest of the apartments studied. For instance, there were 3 apartments, one of 62m² and two of 95m², with respective ratios of 0.50, 1.36 and 1.62 (for electricity consumption, 2005) compared to 0.98 to 1.02 for the rest of the apartments. For the electricity consumption 2006, the situation was similar to the previous year - two apartments, one 62m² and one 95m², showed ratios of 0.84 and 1.38, respectively.

Considering hot water consumption, 2005, there were eight apartments with ratios varying between 0.89 and 1.2. For hot water, 2006, the apartments with higher difference in their ratios were six, being the lower ratio value 0.89. In all these cases (hot water, 2006) the median was higher than the average and therefore all the ratios are below 1.0.

GENERAL DISCUSSION AND CONCLUSIONS

Analyzing the results presented in this work, it should be concluded that each group of data is important, alone but also within the frame of overall interrelations with all other groups. First of all, increasing the surface area causes enhancement of both hot water and electricity. A well defined tendency of increased total electricity consumption during the winter months and lowest both electricity and hot water consumption was observed in June and July for all groups of apartments. The number of rooms can not be accepted as a criterium of consumption as different groups of apartments demonstrated different behaviour using this parameter. One very important observation concerns the generalized tendency of each apartment to follow in 2006 the same consumation as that registered in 2005 although at lower level. This conclusion is probably the most important as it confirms the statement that the individual habits are the dominating reason for the consumption profile of each apartment although all other parameters should be taken into account when assessing the detailed electricity and hot water usage. In any case, the system applied in these two buildings from the real estate, MIMER obviously resulted in decrease in energy consumption if we compare it in 2005 with 2006. Bearing in mind the presented data analysis and conclusions, further work should be oriented towards changing consumption behaviour of tenants on individual basis and considering data obtained from each individual apartment but with its peculiar characteristics such as surface area and number of rooms amongst others. Interactive relation between individual tenants and energy companies and/or the renting apartments company presenting energy savings and respective money savings will
probably provoke further changes in tenants’ habits that may decrease electricity and hot water consumption. In this sense, our group is preparing a computerizing system that will enable each tenant to be well informed about his particular instantaneous consumption.

**FURTHER WORK**

Further work will focus on continuation of the observation of electricity and hot water consumption of these two buildings. It would be also interesting the creation and distribution of some questionnaires that will be given to the tenants. The households will also be informed by diagrams and figures (some of them presented in this article) about their consumption during 2005/2006.

Afterwards consumption during 2008 will be compared with data studied in this paper and both possible change in behavior patterns and a lowered consumption will be expected.

**ACKNOWLEDGEMENT**

We want to thank the Swedish Energy Agency for financial support, as well as Mimer, Mälarenergy, Eskilstuna Kommunfastigheter and Eskilstuna Energi och Miljö for support.

**REFERENCES**


DESIGN SAFER AND MORE PRODUCTIVE OCCUPIED BUILDINGS

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ABSTRACT
The results from implementing building intelligence technologies and processes are buildings that cost less to operate and are worth more to their occupants. For projects that are owner occupied, such as corporate, government, and institutions, the benefits of an intelligent building provide an immediate ROI in terms of higher employee productivity and reduced operating expenses. For commercial developments, these projects are expected to result in above market rents, improved retention, higher occupancy rates, and lower operating expenses. Intelligent buildings designing are an important title in last decades. The definition of an ‘intelligent building’ depends on point of view. Two last decades building intelligence was constrained by both technology limitations and economic viability. Recently a whole series of Internet and network communications developments truly elevated average structures to Intelligent Buildings.

From this vantage point, it is clear that Intelligent Buildings are a reality. Often people confuse Intelligent Buildings with High-Tech Buildings. This is totally wrong. An intelligent building is not gadget-oriented. It must be designed to suit the present needs of the occupants. A major problem in the study of intelligence is: Are we talking about intelligence as an abstract set of capacities, or as a set of biological mechanisms and phenomena? These two questions set up two dimensions of discussion about intelligence.

The first dimension: Is intelligence separable from other mental phenomena?

And the second dimension in discussions about intelligence involves the extent to which we need to be tied to biology for understanding intelligence. Can intelligence be characterized abstractly as a functional capability which just happens to be realized more or less well by some biological organisms?

This piece of work discusses the above aspects as a goal of creating buildings with adaptive environments of high quality, energy efficiency, security and safety, permitting optimized internal and external communications to qualify the actual meaning of intelligence.

This issue is followed by analyzing different buildings which already located in order to place the multiplicity of proposals into perspective.

Keywords: building, design, intelligent, façade, envelope

INTRODUCTION
The word "intelligent" was first used to describe buildings at the beginning of the 1980s, and its use has been accompanied by the American term "smart", used to imply the same kind of abilities in materials, structures and buildings. Other synonymous expressions are used, such as “Home System”, “Smart House” and “Home Automation”. Another expression is “Integrated House”. Many of the
early examples of buildings called "Intelligent Buildings” IB simply represented an attempt to portray and exploit the prevailing trend for incorporating increasing quantities of information technology into buildings.

The idea of the intelligent building has, for many people means the use of information technology and control system to make the functioning of the building more useful to its occupants, in relation to its management, or in respect of the building's operational purposes.

The Intelligent Building Institute has proposed: "an intelligent building is one that provides a productive and cost-effective environment through optimization of its four basic elements - structure, systems, services and management - and the interrelationships between them. Intelligent buildings help business owners, property managers and occupants to realize their goals in the areas of cost, comfort, convenience, safety, long-term flexibility and marketability” [1].

To be able to asses the degree of intelligence we have to look at the specific needs of a specific building. Today, architects and designers are beginning to look toward developments in new "Smart" or "Intelligent" materials and technologies for solutions to long-standing problem in building design [2].

Intelligence can be used to improve the performance of the building fabric by making it more capable, so as to reduce the need for imported energy for heating, cooling, lighting and ventilation. Thus, the goal is to reduce the operating cost of the building while maintaining the desired environment for the building occupants [3].

The façade of a building can account for between 15% and 40% of the total building budget, and may be a significant contributor to the cost of up to 40% more through its impact on the cost of building services.

So, the builders are giving the customers a chance to maintain a comfortable and healthy home environment without taking a huge bite out of their monthly budget [4].

**Envelope of the building:**

The main relevant design feature which affects some interactions of the building with the environment is the envelope (skin) of the building.

In dealing with the subject of the building’s envelope there are many perspectives of effects such as:

1. Natural ventilation          2. External color of the building envelope.

**Natural ventilation:**

In all climatic regions of the world there are times when the outdoor temperature is pleasant and natural ventilation can be simplest and most effective way to provide indoor comfort [5].
Natural ventilation takes place mostly through windows, so that building design for natural ventilation means decisions by the designer concerning the location, number, size, orientation and design details of the windows [5].

The main design features which affect the indoor ventilation conditions are [5]:

1. Type of the building which determines the options of providing effective cross-ventilation.
2. Orientation of buildings and openings to provide good natural ventilation at least one of the walls of the unit should face the wind.
3. Vertical location of windows: the height of the inlet opening may determine the level of the main indoor air flow. When openings are near the ceiling, poor ventilation conditions may exist in the occupied zone unless the flow is directed downward by the openings details of the inlet.
4. Windows types and ways of openings: different types of windows, when serving as inlets, produce different patterns of indoor air flow and provide different options for controlling the direction and level of the flow.
5. Subdivision of the interior space, because of the reduction of the flow rate air has to pass through more than one space. Therefore, if internal subdivision of the building enables independent cross ventilation of individual spaces, better over all ventilation is produced.

Building skin color:

The color of the external walls and the roof has a tremendous effect on the solar impact on the building and its indoor climate. Such a solution can be provided by careful design of some building elements and a selective choice of colors for different parts of the building. With very light colors of the walls and the roof, the indoor average temperature is close to that of the outdoor average so that of the small indoor diurnal swing can result in a maximum significantly than the outdoors’ maximum. However, with dark colors of walls and the roof, the indoor average may be about 4°C-5°C (7.5°F-9.5°F) above the outdoors’ average. Also the wind speed mainly affects the external surface temperature of dark walls or roofs, while the wind speed effect in case of light colored walls is much smaller.

As a result from the effect of the envelope color on the walls and the roof affect greatly cooling load of the building and the need for thermal insulation in hot regions [5].

Shading devices:

It is divided as follows:

- **Operable shading devices:**
  The common feature to all external operable devices is that they can be adjusted to either exclude or admit solar radiation; they can reduce solar heat gain to about 10% to 15% of the radiation impinging on the wall while enabling day lighting to enter. Most of the operable shading devices can be applied with about the same effectiveness to all orientations and to any shape of window. Their color may have little effect on their thermal performance unless they are completely closed. They also usually need maintenance to keep them in good condition.

- **Fixed shading devices:**
The different efficiencies of the fixed shading devices, influences how the shape of a window shaded by such devices affects its thermal performance; There two types of fixed shading devices: horizontal (over hang) and vertical (fins), they can also be combined in different combinations.

Fixed shading is usually an integral part of the building’s structure. Once built their patterns depend only on the incident angle of the sun’s rays, but with proper design the over all performance can be reasonably good. The advantage of fixed shading is that it needs no handling by the occupants and is also free, it can be considered as an "Intelligent Element".

- **Building materials:**
The new materials should be used in buildings design to save as much energy as possible. The materials of which a building, and especially its envelope, is constructed determine the relation ship between the outdoor temperature and solar radiation conditions, and the indoor temperature (non-air conditioned buildings) when saving energy consumption is required.

To day, the availability of modern insulating materials, together with application of passive cooling systems, makes it possible to maintain indoor temperatures significantly below the average of the outdoor air temperature with such design details it is possible to provide natural comfort through longer periods of the year and to use less energy.

The thick and heavy structure of the walls and the roof suppress the swing of the external temperature at a level of the external surfaces of the building’s envelope.

In hot areas traditional buildings are built of high mass, thick walls made of heavy materials, such as stone, bricks, adobe and mud. Vaulted roofs, with flat impervious external finish covered with earth, also provide high mass to the building. Windows are usually small and protected from the sun by the thickness of the wall in which they are placed and may be provided with wooden shutters.

- **Windows:**
Windows fulfill many functions in building, such as providing visual and auditory contact with the outdoors, natural ventilation and daylighting. In addition they can serve as elements in passive solar heating and cooling system[5].

A correctly selected window system can provide the following benefits:

- Reduce and eliminate air conditioning cooling load.
- A lower lighting load: glazing systems with a high value for this luminous efficacy can reduce energy use for lighting.
- Superior comfort to occupants.
- Less fading damage caused by UV light transmission.

Often, selecting a window is based on only some of the many possible considerations. A decision to purchase a window can be based on the basic style, operating type, and initial cost. The problem with this approach is that there is no certainly of performance. Often, the energy-related aspects of the window are not factored into the decision. While this approach may save money on the initial purchase, it may result in considerably more expense over the life of the window. Efficient windows also protect against possible future energy price increases.

Designers must learn new technologies that improve window performance and reduce wasteful energy use and make "Intelligent Choices".

- **Effect of orientation:**
When a window is unshaded its quantitative effect on the indoor temperature depends on its orientation. A study has demonstrated that when window are effectively shaded, by shading devices exterior to the glazing, their orientation has very little effect on the heat gain of the building and its indoor temperatures[5]. Therefore, unshaded windows should be avoided as much as possible.
Case studies:

The purpose of the case studies is to describe the range and variations of "Natural Intelligence" (NI) employed to moderate energy flows through the building’s skin.

The Environmental Building [14]:

BRE’s Environmental Building provides a model for offices for the 21st century. Innovative and environmentally advanced, it demonstrates the way for the future based on a platform of new low-energy targets.

Location: Garston, UK
System: Operable solar shading and stack ventilation
Architect: Fielden Clegg

• Project Background:

The building aims not only to provide a working office with low energy consumption in use (fig.1), but also to serve as a large-scale experimental facility for evaluating various innovative technologies.

The design strategies (fig.2) used in response to the specification are summarized on the following points:

- Energy consumption.
- Quality and comfort of the internal environment.
- Day lighting levels.
- Performance of glass louvers.
- Airflow in stacks and floors.
- Air change rates.
- Open plan space utilization.

• Stresses in superstructure from construction and occupancy loads.

• Project Description:

The new Environmental Building at Garston has been built as a demonstration building for the Energy Efficient Office of the Future (EOF) performance specifications; Air conditioning is not used in the new building - the major energy consumer in many existing office buildings. Other savings will be made by making better use of day lighting and by using the building's 'thermal mass' to moderate temperatures.

The floor plan is divided into open-plan and cellular offices allowing cross ventilation in the open plan arrangement while the 4.5-meter-deep cellular offices are located on the north side with single-sided natural ventilation (fig.3). A shallow open-office plan is coupled to a highly glazed façade. A wave-form ceiling structure is used. At the high point of the wave, a clerestory window allows daylight to effectively penetrate the space. A duct providing space conditioning and ventilation was...
placed within a hollow core at the low point of the wave-form structure.

- **Ventilation and cooling:**
  A key feature of this building is the integration between natural ventilation and daylighting strategies. The most striking feature of the building when seen from the south side is the five distinctive ventilation shafts running up the façade. These form a key part of the energy-saving natural ventilation and cooling system (fig.4).

  Working rather like a greenhouse, the summer sun shines into the glass-fronted shafts, warming the air inside. This warmed air naturally rises out of the stainless steel 'chimneys' and causes air from inside the building to be drawn through to replace it. On a breezy day the movement of air across the tops of these chimneys increases this 'stack' effect. On very warm, still day's low-energy fans in the tops of the stacks can be turned on to give greater airflow.

  A stack ventilation system was designed as an alternative ventilation strategy for the open plan offices during extreme cooling conditions. Vertical chimneys were designed to draw hot air through the duct in the wave-form structure as well as through bottom-hung, hopper, etched windows. The exterior of the stacks are glazed with etched glass blocks, allowing daylight admission. Low-resistance propeller fans were mounted at the top-floor level, to provide minimum ventilation and to flush internal heat gains during the night (fig.5).

  This air moving out from the building draws cooler, fresh air in from outside through ventilation openings. On still, windless days the air is taken from the shady north side of the building, coming in through high-level windows. On warmer or windy days (when it's windy the air on the north side is not as cool), air is drawn in through passages in the curved hollow concrete floor slabs. Because of its bulk - or thermal mass - the concrete cools the incoming air by absorbing heat from it (fig.6).

  Additional cooling can be achieved by circulating cold water through the slab. Cold water is drawn from a 70 meters deep bore hole where the temperature is constantly around 10 Celsius. This is passed through heat exchangers to chill water that is circulated through under floor pipe work. The borehole water is returned to the ground via a second, shallower borehole, so no water is 'wasted'. Overnight, the control systems can open ventilation paths right through the concrete slab to cool it further, storing this 'coolness' for the following day (fig.7). The exposed curved ceiling gives more surface area than a flat ceiling would, acting as a cool 'radiator', again providing summer cooling without energy-consuming air conditioning. During the winter months the water circulating through the concrete slab is heated to give gentle under floor heating. This is supplemented when necessary by conventional radiators around the perimeter of the office area. The water is heated by condensing gas boilers which are 30% more
efficient than ordinary boilers, mainly by recovering much of the heat that is usually wasted in the flue gases.

- **Solar control and day lighting:**

To make maximum use of available daylight the building has a large glass area, carefully optimized to provide high light levels but low heat losses and solar gain. To prevent excessive heating and glare from the sun shining in - the 'blinds down, lights on' situation common in many offices on sunny winter days - the building has a system of Colt motorized glass louvers on the south façade to control the daylighting levels (fig.8). Each louver has a translucent ceramic coating on the underside which obscures the direct sunshine whilst still letting diffuse light through. During the day the angle of the louvers changes according to the position of the sun. At times when direct sunshine is not a problem the louvers are angled to act as 'light shelves' - reflecting light off their smooth upper surface onto the ceilings of the offices. This reduces the amount of artificial lighting needed in the parts of the offices furthest from the windows.

**Commerzbank Headquarters [15]:**

This building is the “world’s first ecological high-rise tower”, which reflects a modern translation of an ancient concept. This translation provides the benefits of energy efficiency and high-quality indoor environments, through the thoughtful use of climate adaptive building skins.

- **Project Background:**

The design addressed sustainability issues such as: ambient energy used as much as possible to reduce the dependency on fossil fuels by an innovative façade and building system that uses natural ventilation; maintaining health and happiness for the users by daylighting office space and allowing them to enjoy the outdoors by operable windows and planted sky gardens (fig.9).

- **Project Description:**

The Tallest building in Europe – 299 meters, 53 floors, steel framing and green Design.

The Commerzbank building uses a combination of opaque and transparent double-curtain walls with internal shading to provide daylighting, natural ventilation, shading in summer, and passive solar heating in winter. This system is so energy-efficient that it is compared to ordinary boilers, mainly by recovering much of the heat that is usually wasted in the flue gases.
effective that the building relies solely on natural ventilation and daylighting for about 70% of the year.

Four-story sky gardens, set at different levels on each of the three sides of the tower, are the visual and social focus for village-like clusters of offices. The gardens are places to relax and socialize, bringing richness and humanity to the workplace, and from the outside they give the building a sense of transparency and lightness (fig.10).

- **Daylighting:**
Every office in the tower is daylight and has openable windows, resulting in energy consumption levels equivalent to half those of conventional office towers. Daylight is provided directly to the outside offices through the windows, and indirectly to offices facing the gardens that are lit both from the side and above (fig.11).

The climate façade is a custom made double skin envelope system that mediates the weather between the interior and exterior of the building. It is also this innovative design that allows for individuals to control their surroundings by operable windows and a sunshade system. This invention allows natural ventilation to be viable in a skyscraper. It is composed of a solid pane of laminated glass on the outer layer, which deflects strong winds and rain.

- **Natural ventilation:**
Natural ventilation is achieved across the 16.5m floor plates by controlled perimeter windows. The 14m high garden facades can also be opened in good weather to ventilate the atrium space (connected to two other gardens) and indirectly provide fresh air to the offices facing the atrium. Outdoor-facing offices are ventilated directly from outside (fig.12).

**CONCLUSIONS**

The environmental designs are not new but were recently featured in Intelligent Architecture (IA). Intelligent Skins (IS) is a valuable tool for Architects, Engineers, Surveyors, and Designers, so by proper design of the Building Skin the size of the energy consumption system can be reduced bringing down the initial investment, as well as reducing the operating cost the building over its lifetime [5].

This paper is intended to help architects make more informed decisions that will be important to Intelligent Building’s Future Comfort and Finances. Also, the paper outlines a new methodology which takes account of the Intelligent Architecture (IA) and illustrates the application of this methodology to the analysis of a particular project, showing how this might be achieved.
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I.C. MariAnne Karlsson
Chalmers University of Technology, Product and Production Development
ABSTRACT

Installed DCS system in Jajarm alumina production factory in Iran, help to us for transferred the signals from equipments to simulators. The simulators can help to operator for control, monitoring and training. Authors have tried to find a new simulator using ASPEN plus™ software and write a new protocol for discussed tasks.

Aspen Plus™ by Aspen Technology is one of the major process simulators that are widely used in alumina process industries today. It specialises on steady-state analysis.

For implementation, simulation and interpretive of the alumina process flowsheet in jajarm factory was used from the Aspen Plus simulator. We have tried to be able to provide a list key operating and design parameters and equipment selection criteria for a limited set of unit operations and processes. And so for determination the economic potential of a process and to identify the operational variables that affect the economics we have studied the process and flowsheets.

Using the general information of factory, process informations same as temperature, measured pressure and so PFD, cinitic informations and finallay clin, bauxite and sodium sulphate informations we have design a new simulation method for digestion and control process in Jajarm factory. The process has implemented on LCR1,PU08, PU10 and PU11 units.

Key words: simulation, boxite, alumina, process

INTRODUCTION

Aluminum is considered to be the most abundant metallic element in the earth’s crust and it’s the third most common element around. It is not found in its elemental form but always tenaciously held in many compounds, most of which contain oxygen or silica, or both. The most important aluminous ore for the manufacture of aluminium is bauxite. It consists of several hydrous aluminium oxide phases [gibbsite (Al(OH)₃), boehmite (AlOOH) and diaspor (Al₂O₃.H₂O)] as well as normal impurities such as Fe₂O₃, SiO₂ and TiO₂. The difference in composition between the minerals lies in different geographical locations.
Jajarm line production description

Factory process is shown in flowsheet form in the appendices. Extracted bauxite stone from Jajarm mine transport to stone breacker units by trucks. The output is the less than of 20 mm, around of 0.15 cm. Clin and Na$_2$SO$_3$ mixed in rod and ball mill in PU08 unit. Mill outputs were controlled by spiral classifiers. Less than 90 micron materials exit from classifier and send to PU09 unit, for removing of silice. Greater than of 90 micron were milled again. In PU10 using high pressure pumps, slurry pressure reach to 100bar and then send to PU11, digestion unit. Slurry temperature reaches to 275 centigrade degree and then sends to piped reactors and digesters. After silica removing in PU12, liquid with aluminium, for phase separation of liquid from solid, transmit to thickning of separator unit (PU13). Overflow thickener that is a soluble with alumina, after filtrization transmit to soluble cooling unit, PU17A. Underflow output of tinker is called red flower. After many steps washing, in PU14 unit after sulphate sodium refunding, concentrated and finally send to the waste dam. Transmitted sluable to cooling unit, vent to the PU16 unit after cooling. This unit done the precipitation in 2 steps, and finally create the aluminium hydrate crystals. After filtration on liquir with alumimium in PU17, created the aluminium hydrate cacke Al$_2$O$_3$.3H$_2$O and send to the hydrate store, PU19. Produced hydrate, transmit to PU21 unit (calcinations unit) for producing of AL$_2$O$_3$, alumina powder. Final product transmits to PU15 unit for storage.

In table 1 main parameters of process design compared in 3 cases:

- reported parameters by first designer (TEX)
- reported parameters before changing by NFC
- reported parameters after changing by NFC

<table>
<thead>
<tr>
<th>Table 1: main parameters of process</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al$_2$O$_3$ content in bauxite</td>
<td>47.8%</td>
<td>48.8%</td>
<td>48.8%</td>
</tr>
<tr>
<td>Silica ratio of bauxite</td>
<td>4.51</td>
<td>4.61</td>
<td>4.61</td>
</tr>
<tr>
<td>Caustic concentration Na$_2$Ok</td>
<td>175 g/l</td>
<td>171 g/l</td>
<td>190 g/l</td>
</tr>
<tr>
<td>αk of digested liquor</td>
<td>1.48</td>
<td>1.50</td>
<td>1.42</td>
</tr>
<tr>
<td>N/S of digested red mud</td>
<td>0.32 w/w</td>
<td>0.36 w/w</td>
<td>0.34 w/w</td>
</tr>
<tr>
<td>A/S of digested red mud</td>
<td>1.2 w/w</td>
<td>1.21 w/w</td>
<td>1.24 w/w</td>
</tr>
<tr>
<td>Digestion temperature</td>
<td>310 C</td>
<td>275 C</td>
<td>275 C</td>
</tr>
<tr>
<td>Addition of Lime</td>
<td>4.0%</td>
<td>12.5%</td>
<td>12.0%</td>
</tr>
<tr>
<td>LOI of digested red mud</td>
<td>8.54%</td>
<td>8.54%</td>
<td>8.54%</td>
</tr>
<tr>
<td>Diluted concentration Na$_2$Ok</td>
<td>130 g/l</td>
<td>133 g/l</td>
<td>140 g/l</td>
</tr>
<tr>
<td>Caustic ratio of pregnant liquor</td>
<td>1.58</td>
<td>1.58</td>
<td>1.49</td>
</tr>
<tr>
<td>αk in spent liquor</td>
<td>3.04</td>
<td>2.94</td>
<td>2.90</td>
</tr>
<tr>
<td>Soluble soda loss in mud,Na$_2$O</td>
<td>3.1 kg/t-dry mud</td>
<td>kg/t-dry mud</td>
<td>kg/t-dry mud</td>
</tr>
<tr>
<td>Moisture of red mud cake</td>
<td>45%</td>
<td>45%</td>
<td>45%</td>
</tr>
</tbody>
</table>
Main flows rates of factory are shown for production of 1 ton alumind in 3 cases.

Table2:main flow rates for production of 1 ton alumina

<table>
<thead>
<tr>
<th>Name of flow</th>
<th>Unit</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bauxite (dry)</td>
<td>t</td>
<td>2.844</td>
<td>2.919</td>
<td>2.915</td>
</tr>
<tr>
<td>Lime</td>
<td>t</td>
<td>0.673</td>
<td>0.37</td>
<td>0.350</td>
</tr>
<tr>
<td>Slurry to digestion (PU11)</td>
<td>m³</td>
<td>12.23</td>
<td>13.00</td>
<td>10.88</td>
</tr>
<tr>
<td>Flashed water from PU11</td>
<td>t</td>
<td>3.640</td>
<td>2.883</td>
<td>2.342</td>
</tr>
<tr>
<td>Slurry after diluted (PU12)</td>
<td>m³</td>
<td>19.30</td>
<td>20.67</td>
<td>18.45</td>
</tr>
<tr>
<td>Red mud wash water</td>
<td>t</td>
<td>9.47</td>
<td>5.705</td>
<td>5.270</td>
</tr>
<tr>
<td>Red mud to disposal</td>
<td>t</td>
<td>2.235</td>
<td>2.227</td>
<td>2.200</td>
</tr>
<tr>
<td>Pregnant Liquor</td>
<td>m³</td>
<td>15.07</td>
<td>15.44</td>
<td>13.55</td>
</tr>
<tr>
<td>Hydrate wash water</td>
<td>t</td>
<td>0.80</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>Evaporated water in PU18</td>
<td>t</td>
<td>2.313</td>
<td>2.035</td>
<td>2.188</td>
</tr>
<tr>
<td>Caustic make up 50% NaOH</td>
<td>t</td>
<td>0.281</td>
<td>0.328</td>
<td>0.307</td>
</tr>
<tr>
<td>Alumina product</td>
<td>t</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Process Description

The process is based on the Gladstone Alumina refinery. Shown in figure1 is the block diagram of the process

Figure 1: Block Diagram of Alumina Manufacturing Process

Bauxite Preparation
The bauxite entering the refinery must be uniform and sufficiently fine so that the extraction of the \( \text{Al}_2\text{O}_3 \) and other operations are successful. In most modern plants, the bauxite is mixed with a portion of the process solution and is ground as slurry to prevent a dusty working environment. Rod mills and ball mills are used most frequently, for mill of stone to less than 20 mm. The ground slurry is then passed over screens or through cyclones, with the finer particles (less than 0.15 cm) progressing and the course ones being returned to mills.

An innovation recently adopted is to hold ground slurry for several hours in agitated tanks. These tanks are operated so that plant feed is uniformly blended. Sometimes, bauxites are dried to improve handling or washed to remove clay.

**Digestion**

In digestion, all of the \( \text{Al}_2\text{O}_3 \) in the bauxite must be extracted. It works by the principle that gibbsite and boehmite are soluble in sodium hydroxide (NaOH), the solubility being temperature, concentration of NaOH and bauxite characteristic dependent.

Most of the impurities in bauxite are not soluble in NaOH, except reactive silica (\( \text{SiO}_2 \)), which forms a quite insoluble compound during processing. The following describes the two important reactions occurring during this stage.

**Reaction 1 – Digestion**

\[
\begin{align*}
\text{Al}^3+ \text{Na}^+ \text{OH}^- & \rightarrow \text{Al}^3(\text{OH})_2^- + \text{Na}^+ \\
\text{AlOOH} \text{NaOH} \text{H}^+ \text{O} & \rightarrow \text{Al}^3 \text{OH}^- \text{Na}
\end{align*}
\]

It was found that the solubility of gibbsite is higher than boehmite; hence the conditions for digesting boehmitic bauxite must be more severe. The temperature and/or NaOH concentration must be increased. For diasporic bauxites, CaO is charged to allow digestions at lower temperature.

**Reaction 2 – Causticization**

\[
\begin{align*}
\text{CaO} \text{H}_2\text{O} & \rightarrow \text{Ca(OH)}_2 \\
\text{Ca}^2+ \text{Na}_2 \text{CO}_3 & \rightarrow \text{CaCO}_3 + 2\text{NaOH}
\end{align*}
\]

The reason for this reaction is primarily to make up the NaOH losses. Lime (CaO) is added to the digest. \( \text{Na}_2\text{CO}_3 \) is formed by decomposition in the digest of organic material from the bauxite and \( \text{CO}_2 \) adsorbed into process solutions from the atmosphere.
**Clarification**

The next major step in the process is to separate the solid residue from the sodium aluminate solution. This separation must be as complete as possible as any remaining solids will cause contamination to the product.

The slurry is fed into the center of thickening tanks (also called settlers), each 40 m in diameter. The velocity of the slurry becomes very slow as the solution flows radially across the thickener. The solids, having a higher specific gravity than the solution, sink to the bottom of the thickener. The fine solids behave as a relatively stable colloidal suspension, hence they settle slowly if not treated further. Flocculants are added to improve the clarity of the thickener overflow, the solids content of the underflow, as well as the settling rate of the solids.

The particle size distribution of the residue solids is usually bimodal. The term sand is used to describe coarse fraction over 100 μm in diameter whereas the rest of the solids are finer than 10 μm.

The settler underflow first has sand removed in sand traps, which is recycled to bauxite grinding. With the residue concentrated in the thickener underflow, the next task is to wash it with fresh water so that it can be discarded within environmental standards. This is done in countercurrent washing thickeners similar in design to those used for settling. Fresh water is use to recover the soda and alumina content in the residue before being pumped to large disposal dams. This result in minimising the total costs of the soluble salts lost due to incomplete washing and the cost of evaporating the dilution introduced.

The final stage of clarification is polish filtration of the overflow settler solution. This stage is to remove the few particles of solids remaining to protect product purity. Heavy cotton cloth provided the early filter medium, but it was easily damaged and slowly attacked by the caustic solution. Polypropylene is the current fabric choice and is unaffected by process conditions. The plant uses Kelly-type constant pressure filters.

On occasions, small quantities of Al(OH)₃ or DSP will partially blind the cloth. Hence, lime is added to produce a filter aid – tricalcium aluminate (3CaO.Al₂O₃.6H₂O) to promote the formation of a porous, rigid filter cake.

**Precipitation**

With all the solids removed, the liquor leaving the filter area contains alumina in clear supersaturated solution. This filtered solution must be cooled before precipitation. This is done by flash evaporation whereby a steam jet pump is used to remove noncondensable gases from the system to create vacuum. Steam is given off and is used to heat spent liquor (from classifiers) returning to digestion.

Precipitation of crystals is used to recover dissolved alumina from the liquor. The reaction is the reverse of the first digestion reaction:

\[ \text{Al} \text{O}_3 \text{Na} + \text{Al} (\text{OH})_3 \rightarrow \text{Al}_2 \text{O}_3 + \text{NaOH} \]

The above reaction is done in rows of precipitation tanks that are seeded with Al(OH)₃ to promote crystal growth.
The first objective in precipitation is to produce Al(OH)$_3$ that, when calcined, meets the product specification. The second objective is to obtain high yield from each volume of the solution. Care must be taken to achieve this as the number of new particles generated in precipitation must equal the number of particles leaving as product for the system to remain balanced. This requires balancing nucleation, agglomeration, growth, and particle breakage, so a combination of science and art has developed. In the plant, the precipitation tank is agitated, with a holding time each of about 3 hours.

During the 25 – 30 hours pass through precipitation, alumina of various crystal sizes is produced. The entry temperature and the temperature across the row, seed rate and caustic concentration are control variables used to achieve the required particle size distribution in the product. Consequently the process moves slowly from being too fine to too coarse and back again. The aim is to minimise the frequency and amplitude of the changes.

Slurry leaving the precipitators is led to three stage ‘gravity’ classification tanks to be separated into three size ranges. The primary classifiers collect the coarse fraction, which becomes the product. The intermediate and fine crystals from the secondary and tertiary classifiers are washed and returned to the precipitation tanks as seed.

The spent caustic liquor, which is essentially free from solids, from the overflow of the tertiary classifier is returned through an evaporation stage. This liquor will be heated and reconcentrated, to be recycled back to dissolve more alumina in the digesters. Fresh caustic soda is added to the stream to make up for process losses.

**Calcination**

The final operation in production of alumina is calcination. The temperature of Al(OH)$_3$ is raised above 1380 K resulting in the reaction:

$$2Al(OH)_3 \rightarrow Al_2O_3 + H_2O$$

The product from the primary classifier is washed on horizontal-table vacuum filters to remove process liquor. The quality of the wash water is of some concern because such impurities as calcium and magnesium can be adsorbed on the surface of the product. The resulting filter cake is then fed to a series of calcining units to remove both free moisture and chemically-combined water. The calcining units are made up of rotary kilns each 100 m long and 4 m in diameter. They are mounted on bearings and rotate about an axis inclined at a small angle to the horizontal. Damp Al(OH)$_3$ from the filters enters the upper end and slowly tumbles toward the lower end, travelling against a stream of hot gas formed by the combustion of natural gas at the discharge end.

Cooling the alumina is first carried out in rotary or satellite coolers, which preheat the secondary combustion air for kilns; and then in fluidised-bed coolers for further cooling.

The final product – pure alumina is discharged on to conveyor belts, which carry it to storage buildings where it is stockpiled for shipment.

For this project, the composition of the bauxite used is as follows (table 3):
Table 3: Composition of Bauxite [7]

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Monohydrate Grade (wt %)</th>
<th>Trihydrate Grade (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al₂O₃</td>
<td>55</td>
<td>50</td>
</tr>
<tr>
<td>Available Al₂O₃</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>17</td>
<td>12</td>
</tr>
<tr>
<td>SiO₂</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>TiO₂</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Other (mainly H₂O)</td>
<td>25</td>
<td>26</td>
</tr>
</tbody>
</table>

For the monohydrate grade, of the available Al₂O₃, 40% is from gibbsite and 10% is from boehmite. Whereas for the trihydrate grade, all available Al₂O₃ consists of gibbsite.

Aspen model diagram

The simulation is based on Gladstone Alumina refinery with the following feed rate:

Table 3: Amount of feed rate

<table>
<thead>
<tr>
<th>Component</th>
<th>Flow rate (tons/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monohydrate grade bauxite</td>
<td>725</td>
</tr>
<tr>
<td>Trihydrate grade bauxite</td>
<td>90</td>
</tr>
<tr>
<td>CaO</td>
<td>20</td>
</tr>
<tr>
<td>Ca(OH)₂</td>
<td>14.7</td>
</tr>
<tr>
<td>NaOH</td>
<td>73.52</td>
</tr>
</tbody>
</table>

The product will be a smelting-grade alumina with the following specification:

Table 4: Smelting grade alumina

<table>
<thead>
<tr>
<th>Item</th>
<th>Normal range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size</td>
<td>10 – 200 μm</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td></td>
</tr>
</tbody>
</table>
Many of the simulated units are simplified. For example, only one flash unit is being simulated while realistically, there should be a series of flash vessels. Assumptions and basis also has to be included for the simulation. Below gives the description, assumptions and basis for each block.

<table>
<thead>
<tr>
<th></th>
<th>0.01 – 0.04 wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>0.01 – 0.03 wt%</td>
</tr>
<tr>
<td>CaO</td>
<td>0.02 – 0.08 wt%</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.002 – 0.005 wt%</td>
</tr>
</tbody>
</table>

Figure 2: Aspen model block diagram for manufacture of Alumina in the bottom and PFD model of PU11 unit in down
Digestion (B1 to B4)

B1 (Mixer)

This is used to simulate part of the bauxite preparation whereby the raw feed is mixed together with the caustic and slaked lime to form slurry.

Assumptions – the bauxite has been pre-grounded in compartment rod/ball mills to allow better solid and liquid contact during digestion.

B2 (Rstoic)

This block simulates the digestion units. The units are operated at a temperature of 573K and a pressure of 3500kPa.

Assumptions – only the following reactions take place:

1. \(2\text{NaOH} + \text{Al}_2\text{O}_3 \rightarrow \text{NaAlO}_2 \text{H}_2\text{O}\) Digestion

2. \(\text{CO}_2 + \text{NaOH} \rightarrow \text{Na}_2\text{CO}_3 \text{H}_2\text{O}\) Carbonation

Digestion – this reaction has been described earlier. For this simulation, it is assumed that 97% of \(\text{Al}_2\text{O}_3\) has been converted to \(\text{NaAlO}_2\).

Carbonation – this reaction occurs naturally with the carbon dioxide from the atmosphere. This reduces the effectiveness of the liquor (caustic liquor) to dissolve alumina.

B3 (Mixer)

This allows the addition of \(\text{Ca(OH)}_2\) which will be used for the later reactions in the digesters.

B4 (Rstoic)

This block again, simulates the digestion units whereby only causticization reaction occurs.

1. \(\text{Na}_2\text{CO}_3 + \text{Ca(OH)}_2 \rightarrow \text{CaCO}_3 + 2\text{NaOH}\) Causticization

Causticization – as mentioned previously, the above reaction is to regenerate \(\text{NaOH}\) and \(\text{CaCO}_3\) will be removed later. It is assumed that all \(\text{Na}_2\text{CO}_3\) has been reacted.

B5 (Flash2)

Flash units are simulated in this block. Flash tanks are used for heat recovery purposes.

The simulation is done with an outlet temperature of 383K and outlet pressure of 250kPa.

Clarification (B6 to B8)

B6 (Sep)

This block is used to simulate settlers.

All unreacted raw feed (\(\text{Al}_2\text{O}_3\), \(\text{Fe}_2\text{O}_3\), \(\text{SiO}_2\) and \(\text{TiO}_2\) and \(\text{CaCO}_3\)) is considered as solids.

This simulation is run with an underflow containing 25% solids.
B7 (Sep)

. This block is used to simulate Kelly-type constant pressure filters whereby all remaining solids are separated and the liquid leaving the filter area contains alumina in a clear supersaturated liquid.

B8 (Mixer)

. This simulates the washer units. The underflow from the previous settler is mixed together with water from the heat recovery sections. The product is called mudwaste.

Precipitation (B9 to B11)

B9 (Flash2)

. The resultant supersaturated liquid needs to be cooled before precipitation. This is done in vacuum flash vessels, which is simulated by this block.

The target outlet temperature is 345K.

B10 (Rstoic)

. This block is used to simulate precipitators. The following ‘crystallization’ reaction takes place:

\[ 2NaAlO_2 + H_2O \rightarrow Al_2O_3 + 2NaOH \]

. Precipitation

It is assumed that all NaAlO_2 has been crystallized to Al₂O₃.

B11 (Sep)

. Slurry leaving the precipitators is being separated in 3 classifiers, namely, primary, secondary and tertiary. But for simplicity, 1 single unit is being simulated.

It is simulated on an overflow concentration of about 3 g/L of alumina.

The resultant overflow liquid is termed as spent liquor and is heated before being recycled back to the digesters.

Calcination (B12 and B13)

B12 (Heater)

Calcination equipment (rotary kilns) is simulated for this block. The underflow from the primary classifier (B10) is heated to temperatures above 1373K to remove water.

B13 (Heater)

The product is then cooled in a series of equipment (initially in rotary coolers and then, in fluidised-bed coolers) to room temperature.
**Heat Recovery System (B14 and B15)**

B14 (Mixer)

This is used to simulate a mixer whereby fresh NaOH solution is added to the caustic liquor recycled from the classifier (B10).

B15 (Heatx)

The flash heat generated from flasher units (B5) is used to preheat incoming caustic liquor in tubular heat exchangers. Condensate from these heat exchangers is used to wash the mudwaste (B22).

**Mass and Energy Balance**

A Process Flow Diagram has been done for the above process. The following abbreviations are used for the equipment:

- CR – Crusher; V – Vessels; R – Digesters (Reactors); S – Settlers and Clarifiers; F – Filter; HX – Heat exchangers; PR – Precipitator; CL – Calcine; M – Mixer; C - Cooler

**Optimisation of the Process**

The critical operating unit for the process is the temperature and pressure of the digester units. As different operating values will have different conversions for Al₂O₃, this will affect the final yield of the product.

From the simulation, another important variable is the flash temperatures and pressures.

At the moment, the flash temperature and pressure used are 383K and 250kPa respectively. A change in either of the variables will affect the composition of the vapour and the liquid streams, namely, the water and NaAlO₂ concentrations. It would be ideal to have as low concentration of NaAlO₂ at the vapor stream. When increasing the temperature, it was found that water concentration has been increased in the vapour stream, but NaAlO₂ concentration did not changed much. An increase in pressure will however result in both concentration decreases in the liquid stream. Classifier’s overflow composition can also be changed to control the amount of NaOH return to the digesters. This will in turn affect the amount of NaOH recycled back to the digesters for reaction.

**Conclusion**

It has been shown that it is possible to simulate processes using Aspen software. To be as realistic as possible, operating values for each unit is required. Otherwise, heuristic assumptions have to be made. Process has been simplified and scenarios were introduced into the implementation protocol and simulator.

Many phases, robust informations bank and general equations help to designer for cover the all of systems. This software can help to us for simulation of liquors with solid included, electrolyte and more, these capability are the major competences on HYSYS software an so others. Using software
we have designed the process flow diagram, and so with choose the inputs in software get the outputs and in the first view it have been shown the good accuracy, between measured and simulated profiles.

Recommendations for further work on the above are as follows:

To simulate the above process as a solids handling process. This will then include the pre-treatment process of crushing and particle size distribution (PSD) will have to be specified. This will make the simulation more realistic.

Impurities such as Na₂O should be considered.

REFERENCES

[1]. Caroline Crosthwaite, 1E202 Process systems analysis study guide, Department of Chemical Engineering UQ, 2000, pages 4 and 5.


[7]. Queensland Alumina Limited Company brochure – The Gladstone Alumina Refinery, Queensland Alumina Ltd


APPENDICES:

Degrees of Freedom Analysis

Number of Components, \(n = 12\) (Al₂O₃, SiO₂, FeO₂, TiO₂, NaOH, CO₂, CaO, Ca(OH)₂, NaAlO₂, CaCO₃, Na₂CO₃, H₂O)

Number of reactions in B₂, \(r = 2\) while B₄ and B₁₀, \(r = 1\)

B₁: \(\text{Mixer} = n(c + 2) = 5c + 10\)

B₂: \(\text{Rstoic} = c + 4 + r = c + 6\)
B3: Mixer = n(c + 2) = 2c + 4
B4: Rstoic = c + 4 + r = c + 5
B5: Flash = c + 4
B6: Sep = 2c + 2
B7: Sep = 2c + 2
B8: Mixer = n(c + 2) = 3c + 6
B9: Flash = c + 4
B10: Rstoic = c + 4 + r = c + 6
B11: Sep = 2c + 2
B12: Heater = c + 4
B13: Heater = c + 4
B14: Mixer = n(c + 2) = 2c + 4
B15: Heatx = 2c + 7
Therefore, total = 27c + 69
Interconnecting streams = 21(c + 2) = 21c + 42, Hence, remaining = (27c + 69) – (21c + 42) = 99

Specifications:

Feed 1 (Monohydrate) = 9 (Pressure, Temperature, all 0% except Al2O3, SiO2, FeO2, TiO2 and H2O (Composition))
Feed 2 (Trihydrate) = 9 (Pressure, Temperature, all 0% except Al2O3, SiO2, FeO2, TiO2 and H2O (Composition))
Feed 3 (CaO) = 13 (Pressure, Temperature, all 0% except CaO)
Feed 4 (CO2) = 13 (Pressure, Temperature, all 0% except CO2)
Feed 5 (Ca(OH)2) = 13 (Pressure, Temperature, all 0% except Ca(OH)2)
Feed 6 (NaOH) = 13 (Pressure, Temperature, all 0% except NaOH)
B2 (Rstoic) = 4 (Pressure, Temperature, % conversion of both reactions)
B4 (Rstoic) = 3 (Pressure, Temperature, % conversion)
B5 (Flash) = 2 (Pressure, Temperature)
B6 (Sep) = 5 (Bottom composition - 25 % of Al2O3, SiO2, FeO2, TiO2 and CaCO3)
B7 (Sep) = 4 (Bottom composition – all Al₂O₃, SiO₂, FeO₂, TiO₂)

B9 (Flash) = 2 (Pressure, Temperature)

B10 (Rstoic) = 3 (Pressure, Temperature, % conversion)

B11 (Sep) = 1 (Top composition – 3 g/L of Al₂O₃)

B12 (Heater) = 2 (Pressure, Temperature)

B13 (Heater) = 2 (Pressure, Temperature)

B15 (Heatx) = 1 (No vapor in the cold stream)

Total = 99

Degrees of Freedom = Remaining – Specifications: = 99 – 99= 0

Therefore, the model is solvable.
ABSTRACT

Power transformer is a complex and critical component of the power transmission and distribution system. System abnormalities, loading, switching and ambient condition normally contribute towards accelerated aging and sudden failure. In the absence of critical components monitoring, the failure risk is always high. For early fault detection and real time condition assessment, online monitoring system in accordance with age and conditions of the asset would be an important tool.

This paper presented an algorithm on the estimation of the hot spot temperature within a transformer, addressing some issues concerning the accuracy of their results. Included are summaries of articles on modelling techniques and the reasons offered by their authors regarding their effectiveness, focussing on their advantages and disadvantages. The paper also engages in some discussion on the current use of Artificial Intelligence (AI) systems on the dissolved gas analysis (DGA) results of transformer oils, and how similar AI systems are being adopted to estimate hotspot temperatures. Finally, some mention is made of the application of fibre temperature probes that have been recently developed. Such technology has been valuable to corroborate results and secure the validity of works done in this area. But there are limitations on their application, and these are discussed, highlighting the economic and safety implications.

1 INTRODUCTION

Insulation is the major component, which plays an important role in the life expectancy of the transformer. Transformer life known to us is based on the designed parameter with respect to normal operation and climate conditions. To determine the performance and aging of the asset, insulation behavior is a main indicator. Most of the transformers in a system, around the world are exceeding their designed life. In the absence of insulation assessment, good number of transformer failed due to insulation problems, before reaching to their designed technical life. It is important to investigate the cause(s) of the insulation degradation with respect to age. Average age of the transformers that failed due to insulation deterioration during the last ten years was 17.8 years. A good number of aged transformers are still performing well, it is vital to monitor the insulation behavior rather then replacing with new one. Transformer insulation behavior is different with respect to operation mode, climate (ambient condition) and frequency of subjected faults. Load growth has influence on the insulation degradation. The insulation degradation trend
needs regular assessment. An accurate analysis of the insulation can suggest operating condition, de-rating of the transformer will increase the life expectancy. The unit can be proposed for relocation, subjected to less stress. Cost effective maintenance strategies can be developed.

Insulation aging in transformer is a complex and irreversible phenomena. To ensure higher reliability and safety, insulation condition monitoring and trend analysis are of major concern. Insulation trend analysis ill conclude type of failure as well as severity of the fault. This will make easy to understand type of maintenance required, loading constraints and future management required.

The analysis will predict the life expectancy of the asset. It is significant to recommend insulation assessment for the aged and suspicious behaviour transformers. With perfect condition monitoring the rate of aging can be reduced. Online insulation condition monitoring, proper diagnostics and accurate interpretation/ analysis will provide realistic decision for economical operation and cost effective maintenance strategies.

The overall integrity of the asset can be assessed, with minimum risk of sudden failure. The environmental risk can be reduced. Effect of aging rate on the life expectancy can be established. Condition monitoring provides information on the developing insulation problems and incipient faults. Thus early warning of any abnormality can avert the catastrophic failure.

Put into perspective, power transformers are probably the single most expensive asset within an electrical transmission and distribution network [1], and that alone justifies the requirement of developing appropriate reliable systems ensuring their availability and reliability.

They are designed with a nominal life expectancy in years, evaluated for a rated load under ideal conditions as indicated by their nameplate. Excluding unusual circumstances unrelated to the normal functioning of a power transformer, failure is expected to occur as the windings’ paper insulation erodes past its limit to sustain appropriate structural and electrical stresses. The degradation is cumulative and adversely affected by the presence of both heat and oil contaminants, including gases and water [2].

Limited excessive loading beyond the transformer’s nameplate rating is permissible and often experienced during emergency conditions, but the trade-off is an accelerated demise of the transformer towards an end-of-life condition.

In Australia, the privatisation of the electricity utilities has met with increasing pressure by investors and shareholders to maximise Return-On-Investment (ROI). Utilities in the electricity industry must now re-examine operating strategies on long term, back up and failure procedures balancing the demands for both reliable and economic performance. Obviously, under utilised equipment, especially at the size of expense of power transformers, is undesirable. Ultimately the target will be to set transformers to run at “Full Warp Drive” as the normal mode of operation.

However, the techniques used to predict a transformer’s loading limits are still too primitive to provide any guarantees. Any inadvertent abuse, where the transformer’s temperature thresholds are exceeded will compromise the performance of the transformer, a result caused by the application of stresses beyond the anticipated design limits, and possibly generating undetected incipient faults. Albeit the transformer may survive, avoiding premature failure, there will remain a high level of doubt concerning its state of reliability.

An obvious resolution to this matter lies in the ability to accurately predict the safe limitations of power transformers and the associated loss-of-life trade-off. Such calculations will enable operational strategies that address economic and reliability issues without exceeding those thresholds that result in transformer damage or failure.

Since 1885 transformers (0.15 MVA) are serving the power industry and are being produced with higher rating (> 2000MVA). Majority of transformer population is serving in many of the
Transmission and distribution utilities are 20 to 40 years old. As an example, the installed power transformer (United States) capacity has reduced from 185 GVA (Giga Volt Amperes) to 50 GVA per year over the past twenty-five years.

The average load growth rate observed is approximately 2%. Transformer utilization has increased by 22% on average, causing oil hot spot temperature to increase by approximately a 48%, at normal peak load.

Due to gradual increase in the temperature, peak load insulation life will be reduced by a factor of approximately 8. Economic pressures and factors such as an increasing proportion of aged power transformers are combining to dictate more efficient plant maintenance management. Life assessment is becoming increasingly important as the average age of the asset increases, due to economic pressures and a relatively low load growth, with fewer major re-development projects.

A scientific remnant life assessment would be an important tool towards higher reliability of the system and asset management. After determining the critical indicator responsible for aging as well as asset technical assessment, the rate of ageing can be reduced by implementing the correct operational and maintenance strategies. The early and failures due to aging can be effectively minimized. Better asset management system can be implemented (timely relocation/replacement can be planned). The transformer's condition assessment can be broken down into the following areas of concern:

- Operating performance to design criteria
- Aging of insulating materials due to stress imposed both thermal and electrical.
- Chemical deterioration from moisture, oxygen and acidity and other contaminations.
- Mechanical strength of the solid insulating and bracing materials.

Transformer assessment is mainly based on dissolved gas analysis (DGA), in particular Rogers Ratio method.

C2H2/C2H4, CH4/H2 & C2H4/C2H6

The important issue is trending of combustible gases.

\[
R = \frac{(S_T - S_O) \times V \times 10^{-6}}{7.5 \times T}
\]

(1)

Where,

- \( R \) = Rate (ft3/day)
- \( S_O \) = First sample (ppm)
- \( S_T \) = Second sample (ppm)
- \( V \) = Tank oil volume
- \( T \) = Time (days)
The other important parameter is rise in winding and top oil temperature. The analysis outcome mainly depends on the test accuracy and correct interpretation.

Core, windings, insulation oil, bushing and on-load tap changer are the main active parts of the transformer insulation chain. The degradation of insulation systems is accompanied by phenomenon of changing physical parameters or the behavior of insulation systems. The degradation of insulation systems is a complex physical process. Many parameters act at the same time thus making the interpretation extremely difficult.

The aging process in the oil/cellulose insulation system under thermal stress and their measurable effects are due to chemical reactions in the dielectric. The temperature of the oil/paper dielectric is the critical aging parameter to cause enough change in the mechanical and electrical properties of the material. Apart from high temperatures, other important parameters affecting the aging of the solid and liquid insulation include the presence of water and oxygen in the system [6, 7].

The monitoring and assessment of such components is vital to achieve better reliability of the system. By implementing correct operational and maintenance strategies the insulation aging/degradation process can be controlled and the asset life can be extended effectively. Asset’s critical component monitoring (strict) is required for the technical assessment (normal to end of life) to ensure economical and safe operation. Also better asset management polices can be implemented.

The types of failures which may occur within the transformer tank are many, one with serious concerns to identify the effectiveness of diagnostics tests and various condition monitoring techniques are listed below. The types of failures which may occur within the transformer tank are many, one with serious concerns to identify the effectiveness of diagnostics tests and various condition monitoring techniques are listed:

- Overheating breakdown
  Overheating breakdown in core plate insulation leads to circulating currents and usually sparking at the fault.

- Core bolt and Core clamping structure
  Breakdown of insulation between parts of clamping structure results in circulating current, possibly sparking. Breakdown of insulation between core and core clamps and the tank leads to spark (fault).

- Windings and inter-winding insulation
  Overheating due to poor joints is a common fault in any part of the electrical circuit. Breakdown of inter-strand insulation results in circulating current causing overheating of insulation and hot spots at point of fault. This can be a result of winding movement. A turn to turn fault produces a similar effect but with much more energy and can usually be detected and identified, whereas there is currently no diagnostic test to identify a strand to strand fault.

Partial discharge faults can develop between various parts of the insulation structure as a result of contamination (including moisture) or due to poor impregnation or overstressing.

Overheating of stress shields results in breakdown and circulating current. A fault between windings - usually results in serious damage and a fault from line to ground also usually results in serious damage.
Tank, flux shields, and fittings
The breakdown of insulation between portions of the tank shields or between the shields and tank can lead to circulating current, this will be a function of load current. Partial discharges may emanate from the ground potential surfaces of the tank and parts mounted on the tank. Circulating current in the tank due to proximity of heavy current conductors can produce hot spots in the tank and across gasket joints.

Deterioration and Failure Factors
The factors responsible for failures and accelerated deterioration are categorized as:

- Operating environment (electrical)
  Operating voltage (50/60 Hz), transient over-voltages,
  load current, short circuits (fault currents), lightening and switching surges.

- Operating environment (physical)
  Temperature (operating full load with high ambient temperature-humidity index), wind, rain, seismic and pollution.

- Operating time
  Time in service and time under abnormal conditions or extreme condition (Load variation, change in thermal stresses).

- Number of operations of tap changer
  Number of on-load tap changer operation.

- Vibration effect
  Sound and material fatigue.

Contaminants
Moisture (water content in oil), presence of oxygen and particles in oil.

2 DYNAMIC LOADING
A transformer’s loading capacity is related to the exposure of its insulation to heat, the highest temperature of which is referred to as the Hot Spot Temperature (HST). The HST’s effect on the windings’ paper insulation is used to quantify the limit of its temperature range over a calculated period of time. The problem, however, is that these limits are dynamic due to the changing transformer characteristics, and varying ambient climate conditions.

3 ACCURATE HOT SPOT ESTIMATION IMPORTANCE’S
Development of an accurate method of estimating the dynamic loading limitations, and consumption of service life of a transformer, has economical and operational benefits.

Economically, deferral of expenditure on expensive plant by “driving them harder”, has always been recognised as a wise business strategy. Conversely, but equally wise, being able to correlate the cost of depreciation on a transformer with usage in kilowatt hours (kWhs) allows for a more
financially equitable method for assessing asset performance, thereby enabling the calculation of the most appropriate time for retiring older equipment. It also assists in planning for network growth and reducing expensive risks.

Similarly, strategic maintenance and operational procedures are best formulated where the performance of existing plant has been accurately assessed. Unexpected failures are rarely welcome, especially with increasing pressure to minimise backup resources such as redundant transformer capacity.

4 CONDITION MONITORING

Over recent years, condition monitoring of power transformers has become a far more affordable exercise; in actual fact, the true cost of not having adequate online monitoring is arguably much greater, especially if an avoidable incident should occur resulting in damage and injury. Several companies have already developed monitoring systems with simple algorithms that activate alarms and protection devices when monitored inputs have exceeded static thresholds. These thresholds are unquestionably conservative, perhaps through lack of confidence, which intuitively reduces any risk of damage or failure, but also under utilises the transformers’ true performance.

5 THE STANDARDS

Several Standards have been developed to estimate the temperature of hotspots within a transformer as a function of current load and ambient climate conditions. Many electricity companies have used these as the basis of their operating procedures, developing tables and charts that highlight their exposure to risks within their network. As previously mentioned, there is often a policy among decision makers in this field to bias all errors on the side of caution. In this paper are presented two such Standards: IEC 354:1991 and IEEE Std. C57.91-1995.

5.1 IEC standard

IEC 354:1991

“IEC: Loading guide for oil-immersed power transformers”

The IEC Standard [3] provides a series of simplified equations that describe a mathematical model for the calculation of operating temperatures in a transformer. The assumptions listed in these standards include: a linear temperature rise in the oil from the bottom of the tank to the top, a parallel temperature rise in the windings, and an allowance for stray losses that is used to assess the HST.

As these Standard points out, for large power transformers, the results for hotspot temperatures (based on temperature rise tests) may not be valid due to the significance and complexity of the contribution of flux leakage to the heating of the windings. Therefore, this method has a limited use, restricted at or below the transformers rated capacity.

A further note in this Standard adds that corrections to account for load losses and oil viscosity, can be dismissed as either insignificant, or that the effects cancel each other.

5.2 IEEE standard
IEEE Std C57.91-1995

“IEEE Guide for Loading Mineral-Oil-Immersed Transformers”

In the IEEE [2] Standard there are two methods of calculating the HST. The first method, as with the IEC Standard, is a mathematical model. In the calculation there is the assumption that the oil temperature across the windings is equal to that of the top oil temperature. However, at the commencement of the Standard there is an admission on the validity of this assumption. After measurements were taken with recently available direct thermocouple and fibre optic devices, it was revealed to be incorrect. A paper written by Lesieutre et al. [4] also points out that the method does not adequately account for variations in the ambient temperature for which they [4] have suggested a modification and claimed to have verified.

The second method in the IEEE Standard (Annex G) takes into account these observations and attempts to correct them, including thermal effects and liquid viscosity during overload conditions.

6 MODELLING

While Mathematical Models, as those represented in IEEE [2] and IEC [3] Standards are based on the simplified observation of the exponential cooling of lumped heated bodies, others such as Swift et al. [5] have suggested that a thermodynamic and heat transfer approach would be more appropriate.

They explain that by incorporating the significance of the heat transfers between mediums such as the transformer oil and transformer tank-wall, a more practical and accurate estimation is probable. But even this model suggests the need for accurate parameter estimation and the assumption that the transformer is operating in an environment that supports nominal operation.

7 ARTIFICIAL INTELLIGENCE (AI)

Owing to the complexity and variations in transformer design and operation, the expectation that a reliable and accurate “one size fits all” mathematical model is possible, is questionable. In any case, isolated experiments conducted using this method have met with the requirement for precision that is impractical, as discovered by Tylavski et al. [6]. Ultimately, such models are not capable of identifying and adjusting for the effects of aging, inaccurate inputs, and incipient faults. The identification of these difficulties has ignited particular interest in two categories of AI: Fuzzy Logic and Neural Networks.

As a research tool, the Fuzzy Inference System (FIS) has been applied to a variety of similar projects where there has been a need to address the issue of inaccurate information and also apply heuristic reasoning [7].

Similarly, Artificial Neural Networks (ANN) has found implication where dynamic parameters are difficult to define mathematically [7] where training of the model can recognise trends and the dynamic nature of some of the parameters that might once had been believed to be constant.

8 FIBRE OPTIC TEMPERATURE PROBES

Fibre Optic Temperature Probes are the obvious new technology, hailed as the easy, cost effective remedy for determining transformer HSTs. But seen objectively, the ultimate task of transformers is to provide reliable, efficient operation at the lowest possible cost. At the bare minimum, a transformer is little more than an iron core, wrapped with windings, bathed in a tank of oil.
Anything else adds complexity and cost through design, maintenance and supervision. It is from this premise that the addition of measuring equipment may not always be the most advisable approach.

Also, whilst for new transformers the task of embedding fibre optic cable into its windings is a seemingly easy and inexpensive task, it provides no reprieve for the vast majority of older transformers, many of which have operated undisturbed for the past few decades, and for economic reasons, may be wisely left that way.

A multi-channel fiber optic temperature monitoring system for power transformer hot spot measurements is shown in figure1. The new system has been developed with long-term performance and stability in mind. This fiber optic temperature monitoring system for power transformers offers accuracy, toughness and long-term resistance to failure.

Coupled fiber-optic temperature probe provides accurate and direct temperature monitoring of transformer windings. This solution provides a realistic, real-time view of winding conditions that is quicker and more accurate than top oil thermocouple measurements, and greatly complements indirect measurements based on thermal models. System gives the exact temperature of probes in 165 millisecond per channel. Peak load or emergency overloads are thus detected almost instantaneously. With newest technology, utility can have a new tool to optimize high-voltage transformer performance and life expectancy.

System can specifically designed to meet power transformer industry requirements: extended intervals between servicing, low maintenance, rugged components and the ability to withstand the harshest conditions. All components could be specifically selected for long term performance, including the light source that has an MTBF superior to the life of the transformer. Moreover, compared to other technologies available on the market, like fluorescent decay, a sensor, based on solid state semi-conductor, do not fade or drift over time, allowing a constant and absolute temperature measurement of utility transformer windings over the lifespan of the equipment.

The fiber-optic probes are made only with dielectric materials and are designed to withstand initial manufacturing conditions, including kerosene desorption and heat runs, as well as long term oil immersion and vibration. Moreover, the new temperature probes are interchangeable and no calibration or inconvenient gage factors are required when changing sensors.
The newest system is available with 1 to 16 channels. It can be mounted in an optional enclosure with a see-through window door. The system is based on the proven solid state GaAs technology. An original algorithm is used to analyze the signal and provide repeatable and reproducible measurements.

The system is available with a data logging option that relies on removable flash cards. This option allows recording of temperature data points and alarms status information directly into the system without the need for permanent connection to a remote acquisition system or to a PC. Data collected by the system monitoring is saved in a standard SD multimedia flash card. The system can accept memory cards of up to 128 megabytes, which is sufficient to log over 6 millions data points. This represents more than twenty years of data logging for a transformer instrumented with 8 temperature probes! The SD card can be read by any PC through a standard SD card reader. Moreover, data points are saved with a time stamp that comes from the internal real-time clock of the monitoring system.

The newest system has 16 Form-C (SPDT) industrial relays with galvanic isolation which can also be set up as Form-A or Form-B relays by user. The system can be easily connected to any acquisition system, like a SCADA, through its built-in OPC server, its RS-232C communication port or by the standard 4-20 mA analog outputs (0-10 Volts on request). The monitoring system may also be ordered with DNP 3.0 and IEC 61850 connectivity.

System’s configuration is made through the industrial grade front panel keypad or the communication port. The monitoring front panel features 4 lines by 20 characters backlight LCD display.

9 DGA USING AI SYSTEMS

A common method for identifying developing faults in power transformers is the Dissolved Gas Analysis (DGA) [8]. Analysis of ratios of specific dissolved gas concentrations, their generation rates, and the measure of total combustible gases are used as the attributes for classification. Thresholds are designed to partition the attributes into intervals. Specific combinations of these intervals are then used to identify the fault. However, in much the same way as determining hotspots, the results can differ, dependent on the thresholds used, coupled with the almost infinite variations and combinations of factors that influence the results. These are the classic characteristics that advocate the use of Fuzzy Sets (FS) and Artificial Neural Network (ANN) systems.

For a case study, in service transformer (132/33 kV, 60 MVA,) was investigated for its abnormal routine dissolved gas analysis behavior. Unit was commissioned in 1981 and first oil was sampled for DGA in 1996. The key combustible gases (C2H2 & H2) were found in higher concentration. According to the limits described in the IEEE guide for interpretation of gases, the transformer total dissolved combustible gas (TDCG) exhibits normal conditions. C2H2 & H2 identify IEEE condition two [Figure 2]. This shows that an active fault (early) is present. No further investigations carried out except the transformer oil was reprocessed and the unit was energized.
10 CONCLUSIONS

A variety of models and techniques have been assessed over the years, with claims of improvement and higher dependability. Works done in this area by D.J. Tylavsky et al. [8] convincingly show that there is a balance between complexity and accuracy of results, and that in fact the major sources of error occurred from imprecision at the input.

AI systems are customarily designed for these types of problems. Coupled with physical and mathematical models would assist in the development of a system that was both accurate and simple to implement.

With strict monitoring, accurate diagnostics interpretations and realistic operational/ maintenance strategies Implementation the following would be achieved effectively:

- Asset economic loading conditions identification and assessment for maximum practicable operating efficiency.
- Premature failures risk minimisation.
- Remnant life estimation and timely asset replacement/ retiring planning.
- Asset life extension by implementing correct operational and cost effective maintenance strategies
- Improvement in the system performance ensuring good reliability as well as plant availability.
- Minimization of the long-term operational cost.
- Cost saving by eliminating the unplanned maintenance.
- Minimizing the outage period.
- Relocation/ retirement planning.
- In time procurement of spare parts to get competitive rates.
- To enhance the over all reliability of the system
- Accurate risk assessment.
- Low insurance premiums.
It will also benefit the end user to have power supply without interruption, in particular the industrial sector. It will reduce the risks to human kind and the environmental damages.

11 REFERENCES


ABSTRACT

Iran is an important country in oil and gas production in the world. Iran’s economy relies heavily on oil, gas export revenues. It is obvious that Iran is a considerable country in energy consumption and CO₂ production. These are our main reason for energy assessment in Iranian side. Author has evaluated the Iranian energy production and consumptions and its role in the world.

Key words: Iran, energy, oil, production, consumption

INTRODUCTION

Although Iran is a main oil producing country, due to following reasons, renewable energy (RE) is important:

To be in line with the world efforts to curb the world environmental problems

To improve energy accessibility for remote and isolated places in the country

To pave the way, among other things, for controlling urban air pollution

Main Policies in this paper:

Supporting private sector for dissemination of RE applications that are approaching economical viability, such as wind, geothermal and biomass energy.

Supporting manufacturers for transferring and localization of RE technologies which are expected to become competitive in medium terms, e.g. PV systems and solar thermal power plants.

Supporting there search centres to expand their research programs for RE technologies that are becoming competitive in longer than 10 years period.

Providing sustainable and accessible energy to the poor and isolated areas. It is worth mentioning that at present more than 96% of people in rural areas of the country has access to national electrical grid.

Building capacity; training, supporting research centres, encouraging manufacturers to produce required RE equipments, organizing suitable institutional framework, …

Legislation for RE development; the government is obliged to purchase electricity from private RE power plants with the price of three times higher than the amount paid by end users.
Raising public awareness;
Pilot projects by the government; to clear the ground for the private sector to come forward.
Potential assessment studies; of RE resources with continuous upgrading of the results.

Iran's economy relies heavily on oil export revenues, with such revenues representing around 80-90 percent of total export earnings and 40-50 percent of the government budget. Strong oil prices the past few years have boosted Iran’s oil export revenues and helped Iran's economic situation. For 2005, Iran's real GDP increased by around 6.1 percent. Inflation is running at around 16 percent per year, though unofficial estimates place the figure at 40-50 percent. Iran’s oil export revenues have increased steadily, from $32 billion in 2004, to $45.6 billion in 2005, with 2006 became at $46.9 billion. In 2007 it became more than $60 billion. Despite higher oil revenues, Iranian budget deficits remain a chronic problem, in part due to large-scale state subsidies on foodstuffs and gasoline. Thus, the country's parliament (the Majlis) decided in January 2005 to freeze domestic prices for gasoline and other fuels at 2003 levels. In March 2006, parliament reduced the government's gasoline subsidy allocation for FY 2006 /07 to $2.5 billion, compared with a request of $4 billion and costs of over $4 billion for imports last year. As of July 2006, the Iranian government is still debating how to handle gasoline subsidies. NIOC has said it has used nearly all of its $2.5 billion budget for gasoline imports, but legislators have stated their opposition to providing the additional $3.5 billion necessary to pay for imports through the end of the fiscal year, in March 2007.

Another problem for Iran is the lack of job opportunities for the country’s young and rapidly growing population. Unemployment in Iran is around 11 percent, but is significantly higher among young people. Iran is attempting to diversify its economy by investing some of its oil revenues in other areas, including petrochemicals production. In 2004, non-oil exports rose by a reported 9 percent. Iran also is hoping to attract billions of dollars worth of foreign investment to the country through creating a more favorable investment climate by reducing restrictions and duties on imports and creating free-trade zones. However, there has not been a great deal of progress in this area. Foreign investors appear to be cautious about Iran, due to uncertainties regarding its future direction under new leadership, as well as the ongoing international controversy over the country's nuclear program.

In June 2005, Iran held Presidential elections in which the conservative mayor of Tehran, Mahmoud Ahmadinejad, won a surprise victory. Ahmadinejad succeeded Mohammad Khatami, a moderate reformist, who had been President since August 1997. Ahmadinejad ran on a populist platform and pledged to share Iran’s oil wealth more broadly and to reduce the nation’s income gap between rich and poor. However, policies implemented in the economic realm since President Ahmadinejad took office are cited by analysts as responsible for high (unofficial) inflation rates, depressed housing and stock markets, and rising unemployment. According to FACTS, reduced confidence in the Iranian economy and the ongoing dispute with the international community has combined to cause an estimated $50 billion of capital to flow out of Iran in the last year.

As of 2004, Iran had installed power generation capacity of about around 34.3 gigawatts (GW). Of this total, over three-quarters was natural gas-fired, with the remainder either
hydroelectric (7 percent) or oil-fired. For 2005, Iranian power generation capacity is expected to reach 36 GW).

**Sector Organization**

Although the government has considered privatization, at present Iran's power sector is run by the state-controlled Tavanir organization. Power plant construction is handled by the Iran Power Development Company (IPDC), a wholly owned subsidiary of Tavanir. Eventually, Tavanir may be broken up into smaller companies as part of a privatization package. In addition to power generation, Tavanir also is responsible for electrical transmission. Iran has three main power distribution networks: 1) the Interconnected Network, which serves all of Iran except for remote eastern and southern areas, using 440-kV and 230-kV transmission lines; 2) the Khorassan Network, which serves the eastern Khorassan province; and 3) the Sistan and Baluchistan Network, which serves the remote southeastern provinces of Sistan and Baluchistan. The government goal is to join these three networks into one national grid. Currently, around 94 percent of Iran's rural population has access to electricity.

**Recent Capacity Additions**

With power demand growing rapidly (7-9 percent annually; to 145 billion kilowatt hours in 2005), Iran is building significant new generation capacity, with the goal of adding 18 GW over the next five years. As a result of significant state investment in this sector, a number of new power plants (mainly hydroelectric and combined cycle) have come online in recent years.

![Figure 1. Iran’s power generation capacity by type](image)

**Hydro**

Currently, the largest hydropower projects are the 2,000-megawatt (MW) Karun 3 plant, the 2,000-MW Godar-e Landar facility, and a 1,000-MW station in Upper Gorvand. Iran plans to add 6.4 GW of hydroelectric power generating capacity over the next five years. 550 MW of new capacity was
expected to be brought online in the current Iranian year via additions of new units at the Karoun3, Lourak, Yasouj and Menj hydropower stations. The additions will raise Iran’s hydropower capacity from 4.8 GW in 2005 to 11.2 GW by 2011.

**Natural Gas-Fired**

New thermal projects include two 1,040-MW combined cycle plants in the South, a 1,300-MW combined cycle plant at Arak, a 1,000-MW facility in Bandar Abbas, and a 1,000-MW combined cycle plant being built by the Tehran Regional Electricity Company (TREC) in Qom. This latter project is significant, as it is being privately financed and built by a regional - as opposed to national - company. The plant is expected to be completed in 2007. In May 2004, a 494-MW gas-fired power plant was inaugurated in Abadan. In January 2006, it was reported that Iran is to build a 1,000-MW gas power plant in the western province of Khorramabad. Construction work is planned to start by the end of the current Iranian fiscal year and will be completed within four years.

**Build-Operate-Transfer (BOT) Projects**

Iran has received offers for investment in the form of loans and build-operate-transfer (BOT) contracts, but progress has been slow. BOT contracts allow the investing company to build and operate the generating facility for a period of 15-20 years, after which time the plant is turned over to the Energy Ministry. Negotiations have taken place with international energy firms on expansion plans for power plants at Bandar Abbas, Shahid Rajai, Alborz, Ramin, and Kerman.

In June 2006, Iran’s first BOT power plant became fully operational, when the last of six 159MW open cycle gas turbine generating sets comprising the Chehelsotun power plant in South Isfahan were brought online. The 950MW gas-fired plant, the first to be completed in Iran under a BOT agreement, was developed by a 50:50 joint venture between the Iranian investment house IHAG and local power contractor Mapna. The first unit at the Chehelsotun plant was brought online in 2005.

In addition to BOT plants, Iran has attempted to promote a build-own-operate (BOO) model for the 2,000-MW, Zanjan 1-4 independent power project (IPP). In September 2004, the BOO plan was dealt a setback due to a lack of bidders, and may be re-bid. Overall, Iran is planning 5,800 MW of BOT projects and 7,000 MW of BOO projects.

**International Trade**

Overall, in 2004, Iran imported around 2.2 billion kilowatthours (Bkwh) per year, up from 1.5 Bkwh in 2003,, and exported just under 1.9 Bkwh. Iran trades electricity with Afghanistan (exports to the western part of the country), Armenia (exports and imports), Azerbaijan (exports and imports), Pakistan, Turkey and Turkmenistan (exports and imports). In April 2003, Iran said that it would be willing to supply Iraqi cities with electricity as well. In December 2004, a protocol was reached on synchronizing the power grids of Iran, Azerbaijan, and Russia, with 500 MW being exchanged beginning in 2006. In August 2004, Turkmenistan began power exports to Iran via a new transmission line (Sarhaz). Annual exports of 375 million kilowatt-hours, worth $7.5 million, are expected. This line adds to previous electric export capacity from Turkmenistan to Iran via the Balkanat-Gonbad line started up in June 2003. Another line is to be constructed in the short-term, bringing total power exports from Turkmenistan to Iran to 2.4 billion kilowatt-hours per year.
Oil

According to the Oil and Gas Journal, as of January 1, 2006, Iran held 132.5 billion barrels of proven oil reserves. This figure, which includes recent discoveries in the Kushk and Hosseineih fields of Khuzestan province, means Iran holds roughly 10 percent of the world's total proven reserves. The vast majority of Iran's crude oil reserves are located in giant onshore fields in the southwestern Khuzestan region near the Iraqi border. Overall, Iran has 40 producing fields – 27 onshore and 13 offshore (see table below for major fields). Iran's crude oil is generally medium in sulfur and in the 28°-35° API range.

During 2005, Iran produced about 4.24 million bbl/d of total liquids. Of this, 3.94 million bbl/d is crude oil, roughly 5 percent of world crude production. Iran's current sustainable crude oil production capacity is estimated at 3.8 million bbl/d, which is around 310,000 bbl/d below Iran's latest OPEC production quota of 4.110 million bbl/d. Through the first half of 2006, Iran’s crude oil production was at 3.75 million bbl/d. Iran's domestic oil consumption, 1.5 million bbl/d in 2005, is increasing rapidly as the economy and population grow. Iran subsidizes the price of oil products heavily, which contributes to rising domestic consumption.

Iran's existing oilfields have a natural decline rate estimated at 8 percent onshore and 10 percent per year offshore. The fields are in need of upgrading, modernization, and enhanced oil recovery (EOR) efforts such as gas reinjection. Current recovery rates are just 24-27 percent, compared to a world average of 35 percent. Iran also needs to increase its search for new oil, with only a few exploration wells being drilled in 2005.
With sufficient investment, Iran could increase its crude oil production capacity significantly. The country produced 6 million bbl/d of crude oil in 1974 but has not come close to recovering to that level since the 1978/79 Iranian revolution. Still, Iran has ambitious plans to increase oil production to more than 5 million bbl/d by 2010, and 8 million bbl/d by 2015. The country will require billions of dollars in foreign investment to accomplish this.

**Exports**

Currently, Iran exports around 2.5 million bbl/d of oil, of which OECD countries import 60 percent (or 1.6 million bbl/d). Iran's main export blends include Iranian Light (34.6° API, 1.4 percent sulphur); Iranian Heavy (31° API, 1.7 percent sulphur); Lavan Blend (34°-35° API, 1.8-2 percent sulphur); and Foroozan Blend/Sirri (29-31° API).

![Iranian Crude Oil Exports by Blend (2004)](image)

![OPEC Total Crude Oil Production (Million bbl/d)](image)

**Crude Swaps**

Iran's desire to become a player on the Caspian oil front has led it to push forward in the area of oil "swaps." This arrangement involves the delivery of Caspian oil to refineries, via the Caspian port town of Sari in northern Iran, for local consumption (See map below). An equivalent amount of Iranian oil is then exported through Persian Gulf terminals such as Kharg Island. Shippers normally pay a "swap fee" of $1.50-$2.00 per barrel, with swaps handled by Naftiran Intertrade Co. (Nico), the Swiss-based trading arm of NIOC. Crude swaps have increased rapidly in recent months, with a July 2006 report by the Oil Export Terminals Company placing the level at 130,000 bbl/d. As recently as June 2006, Abdolrahman Kheylai, Manager of NIOC’s Sari Oil Products Export Terminal, stated that average daily Caspian exports to Iran were about 117,000 bbl/d, consisting
mainly of Turkmen and Kazakh oil. The surge in crude swaps is attributed to higher oil prices and the increased willingness of the Caspian Sea littoral states to offer oil in the form of direct sales.

Currently, from sari, just over 40,000 bbl/d of import oil is sent to Tehran by the existing 180,000-bbl/d capacity Neka-Tehran pipeline, and roughly 80,000 bbl/d is sent to Tebriz. Eventually, Iran hopes to upgrade its facilities in order to greatly expand oil swaps capacity first to 370,000 bbl/d and then to 500,000 bbl/d. Iran further intends to increase storage capacity at the terminal from 1.5 million barrels to 2.5 million barrels. As a further part of Iran’s efforts to compete on costs with the 1-million-bbl/d Baku-Tbilisi-Ceyhan (BTC) pipeline, Mr. Kheylai reported that Iran plans to build a submerged turret offshore oil loading terminal in the Caspian Sea. The technology offers a flexible and cost-effective solution for mooring of vessels applied as shuttle tankers or storage vessels. Mr. Kheylai stated that while currently 7,000 deadweight (dwt) tankers can bring Caspian oil to Neka, the new turret will be able to service up to 63,000 dwt tankers.

In July 2005, Iran and Iraq signed an MOU on a swap agreement involving construction of a 24-mile, 350,000-bbl/d oil pipeline from Basra to the Abadan refinery in southwestern Iran. In exchange, Iran would ship refined products back to Iraq. In addition, Iran could allow Iraq to export crude through the Kharg Island terminal and to import refined products through the Iranian port of Bandar Mahshahr. One potential problem with this deal revolves around the ability of the Abadan refinery to process Basrah Light in significant volumes. Another problem is Iran already faces a severe shortfall in its own domestic gasoline supplies, making additional exports of gasoline difficult.

**Export Terminals**

Iran exports crude oil via four main terminals: Kharg Island (by far the largest), Lavan Island, Sirri Island (reopened on April 13, 2003 for the first time since 1988, when it was damaged by an Iraqi air raid), and Ras Bahregan. Refined products are exported via the Abadan and Bandar Mahshahr terminals. Many Iranian oil export terminals were damaged during the Iran-Iraq War, but all have been rebuilt. Iran operates OPEC’s largest oil tanker fleet, comprising roughly 29 ships, including Very Large Crude Carriers (VLCCs). The fleet is run by the National Iranian Tanker Company, which is a subsidiary of NIOC. In 2003, Iran commissioned six vessels for Caspian routes, to promote Iran’s position as a transit option for regional crude, along with 12 LNG tankers.

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<th>Top Ten Iranian Crude Oil Export Destinations</th>
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<td>(Thousand bbl/d)</td>
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State-owned National Iranian Oil Company (NIOC)'s onshore field development work is concentrated mainly on sustaining output levels from large, aging fields. Roughly 60 percent of Iran’s oil production comes from fields more than half a century old, with some dating back to the first oil discoveries in the Middle East. Consequently, EOR programs are underway at a number of fields, including Marun and Karanj.
In February 2004, a Japanese consortium led by Inpex signed a final agreement on the $2 billion Azadegan oilfield development project. Azadegan was discovered in 1999, representing Iran's largest oil discovery in 30 years. It is located onshore in the southwestern province of Khuzestan, a few miles east of the border with Iraq. Reportedly, Azadegan contains proven crude oil reserves of 26 billion barrels, but the field is also considered to be geologically complex, making the oil more challenging and more expensive to extract. In January 2001, the Majlis approved development of Azadegan by foreign investors using the so-called "buyback" model (see below). Inpex, which has no upstream experience of its own, has brought in Total on the project for its technical expertise. Initial production of medium-sour crude oil from Azadegan could come in 2009, ramping up to 160,000 bbl/d by 2012 and 250,000 bbl/d by 2014/15. At its peak, Azadegan production could account for as much as 6 percent of Japan's oil imports. However, little forward progress has been made on Azadegan, including the lack of an operating agreement with NIOC. In September 2005, Iran sharply criticized Japan for the slow progress. Japan maintains that further clearing of mines leftover from the Iran-Iraq war is needed for work to go forward and that because of an increase in the price of field development tools, notably steel, the contract should be revised. Iran claims the field is 96 percent clear of mines and has threatened to develop the field themselves if a final agreement is not reached by September 2006.

In February 2001, NIOC announced the discovery of a very large offshore oil field, named Dasht-e Abadan, in shallow waters near the port city of Abadan. According to a top NIOC official, Dasht-e Abadan could contain reserves "comparable" in size to Azadegan.

Since 1995, NIOC has made several other sizable oil discoveries, including Darkhovin onshore oilfield. Located near Abadan, which contains low sulfur, 39° API crude oil. In late June 2001, Eni signed a $1 billion, 5 1/2-year buyback deal to develop Darkhovin, with the added incentive of a limited risk/reward element that linked payment to production capacity. Darkhovin came online at 50,000 bbl/d in July 2005, with production expected to reach 160,000 bbl/d in 2007.

Another oil discovery in western Iran was made recently by Norsk Hydro, the Anaran field, which contains reserves of 2 billion barrels. According to Norsk Hydro, Anaran could produce more than 100,000 bbl/d of oil, possibly starting in 2010. Lukoil is a minority partner in the field. Reportedly, development of Anaran is complicated by the need to clear landmines in the area.

| Major Iranian Oil Fields (est. production, bbl/d) |
|---------------------------------|-----------------|
| **Onshore**                     | **Offshore**    |
| Agha Jari (200,000 bbl/d)       | Abuzar (140,000 bbl/d) |
| Ahwaz-Asmari (700,000 bbl/d)    | Dorood (130,000 bbl/d, to increase to 180,000 bbl/d) |
| Bangestan (around 245,000 bbl/d current production, with) | Salman (100,000 bbl/d, to increase) |
plans to increase to 550,000 bbl/d or more) to 150,000 bbl/d)

Bibi Hakimeh (130,000 bbl/d, to increase to 175,000 bbl/d) Sirri A&E (95,000 bbl/d)

Gachsaran (480,000 bbl/d, to increase to 600,000 bbl/d) Soroush/Nowruz (87,000 bbl/d)

Karanj-Parsi (250,000 bbl/d)

Marun (520,000 bbl/d, to increase to 600,000 bbl/d)

Pazanan (35,000 bbl/d)

Rag-e-Safid (180,000 bbl/d)

NIOC also would like to develop five oil and natural gas fields in the Hormuz region: Henjam A; the A field near Lavan Island; the Esfandir field near Kharg Island; and two structures near the South Pars natural gas and condensate field. Iran and Oman have discussed the possibility of joint development of the Henjam A field. According to NIOC, the five Henjam fields hold an estimated 400 million barrels of oil and have a production potential of 80,000 bbl/d. Other Iranian oil fields slated for increased development include Doroud, Nosrat, Farzam, and Salman.

As a further part of Iran’s expansion efforts, in May 2006, the head of Petroleum Engineering and Development Company (PEDEC), Mehdi Bazargan, said that Iran will tender the development of 10 additional oilfields in its oil-rich southern provinces, including the Parsi, Shadgan, Pazenan, Gachsaran, Karanj, Northern Azadegan, Jofair, Marun, and Mansuri fields. According to Mr. Bazargan, the development of the fields will require roughly $7 billion dollars of investment.

**Storage Capacity**

In June 2006, Crude oil storage capacity at Kharg Island, the country’s largest export terminal, had been increased over the past six years from 7 million barrels to 12 million barrels. Iran has begun a $218 million expansion program to raise the terminal’s storage capacity to 22 million barrels. Iran’s immediate aim should be to increase storage capacity to 10 - 15 days worth of exports, and in the longer term to 30 - 35 million barrels.

In April 2006, NIOC planned to begin construction during 2006 of strategic crude oil storage tanks in a number of producing regions, with a total capacity of 10 million barrels. Construction costs are estimated at $1.165 million. NIOC had previously announced plans to construct 15 crude oil storage tanks at the following locations: four tanks at Ahwaz with total capacity of 2 million barrels of crude oil; three tanks at Omidiyeh with total capacity of 3 million barrels; six tanks at Goura with total capacity of 4 million barrels; one 500,000 barrel tank on Sirri Island; and one 500,000 barrel tank at Bahregansar.

**Foreign Investment/Buybacks**
The Iranian constitution prohibits the granting of petroleum rights on a concessionary basis or direct equity stake. However, the 1987 Petroleum Law permits the establishment of contracts between the Ministry of Petroleum, state companies and "local and foreign national persons and legal entities." Buyback contracts, for instance, are arrangements in which the contractor funds all investments, receives remuneration from NIOC in the form of an allocated production share, then transfers operation of the field to NIOC after a set number of years, at which time the contract is completed.

The first major project under the buyback investment approach became operational in October 1998, when the offshore Sirri a oil field, then-operated by Total and Malaysia's Petronas, began production at 7,000 bbl/d. The neighboring Sirri E field began production in February 1999, with production at the two fields expected to reach 120,000 bbl/d. Under the 1995 agreement, as the two fields came on stream, the National Iranian Oil Company (NIOC) gradually took over as operator after five years; but TOTAL will still be involved in the operations until its investment has been fully recovered.

In March 1999, France's Elf Aquitaine (now Total) and Italy's Eni were awarded a $1 billion contract for a secondary recovery program at the offshore, 1.5-billion-barrel Doroud oil and natural gas field located near Kharg Island. The program is intended to boost production from around 136,000 bbl/d to as high as 205,000 bbl/d. Total is operator of the project, with a 55 percent share, while Eni holds the other 45 percent. In April 1999, Iran awarded Elf a buyback contract to develop the offshore Balal field, which was turned back over to NIOC in January 2003 when the field reached its contract designated level of 40,000 bbl/d. Eni is also involved, with a 38.25 percent stake. The field, which contains some 80 million barrels of reserves, started producing in early 2003 with currently has output of 40,000 bbl/d.

On March 18, 2005, a contract to develop the giant Bangestan field was awarded to Petro Iran Development Co., after having been delayed several times since 2001. Bangestan contains an estimated 6 billion barrels of oil reserves and produces about 158,000 bbl/d of oil, but the field is one of the oldest in the country, requiring investment and technological applications to compensate for natural decline. While development of Bangestan could cost $3 billion over 10 years, and aims to raise output to 600,000 bbl/d, currently production at the field has dropped by roughly 50 percent from peak levels and may drop a further 50 percent due to lack of gas re-injection.

In May 2002, Iran's Oil Ministry signed a $585 million buyback contract with NIOC subsidiary PetroIran to develop the Foroozan and Esfandiar offshore oilfields. Currently producing 40,000 bbl/d, PetroIran is expected to increase production at the fields to 65,000 bbl/d. The two oilfields straddle the border with Saudi Arabia's offshore Lulu and Marjan fields.

The Cheshmeh-Khosh field, which previously had been awarded to Spain's Cepsa for $300 million, was re-awarded in January 2004 to state-owned Central Iranian Oil Fields Company (CIOFC). In December 2003, Cepsa and OMV withdrew from lengthy negotiations after a reported failure to agree on development costs and buyback terms. It remains possible, however, that Cepsa and OMV could still be involved at Cheshmeh-Khosh in some way. The objective is to raise crude production at the field from 40,000 bbl/d currently to 80,000 bbl/d within four years.

In late May 2002, Canada's Sheer Energy became the first foreign company since Eni's Darkhovin deal to reach agreement to develop the Masjed-I-Suleyman, or MIS, field. Sheer's goal was to boost MIS production from 4,500 bbl/d to 20,000 bbl/d at the historic field, which, discovered in 1908,
peaked at 130,000 bbl/d in the 1930s. However, the company was replaced by China's CNPC, which bought the subsidiary of Sheer working on MIS. CNPC began work on the field in June 2005.

The buyback system has drawbacks for both sides: by offering a fixed rate of return (usually around 15-18 percent), NIOC bears all the risk of low oil prices. If prices drop, NIOC has to sell more oil or natural gas to meet the compensation figure. At the same time, companies have no guarantee that they will be permitted to develop their discoveries, let alone operate them. Finally, companies find the short terms of buyback contracts unfavorable.

In response, Iran has considered revisions to buyback terms, including extending the length of contracts and allowing for continued involvement of oil companies after the field is handed over to NIOC. However, these proposals have been controversial and generally have not moved forward. While modest changes have been made, such as increases in the number of years of buybacks and additional incentives for E&P projects, political opposition continues to prevent any sizeable reforms. The last major buyback left is the Eni-led development of the onshore Darkhovein oil field, which is due to reach its targeted plateau of 160,000 bbl/d by the end of 2006.

**Offshore Developments**

The Doroud 1&2, Salman, Abuzar, Foroozan, and Sirri fields comprise the bulk of Iran's offshore oil output. Iran plans extensive development of existing offshore fields and hopes to raise its offshore production capacity significantly.

In late 2001 and early 2002, Shell brought part of the $800 million Soroush-Nowruz development online. The two fields are located offshore, about 50 miles west of Kharg Island, and contain estimated recoverable reserves of around 1 billion barrels of heavy oil (20° API). The heaviness and high sulfur content (3 percent) of the oil has made marketing Soroush-Nowruz oil difficult; in 2005 and again in the second quarter of 2006, Iran reportedly diverted Soroush-Nowruz production into storage rather than try to sell the oil at a steep discount. In addition, production has been limited to 27,000 bbl/d at Nowruz and 60,000 bbl/d at Soroush, despite goals of 57,000 and 65,000 bbl/d, respectively. In an attempt to sell more of Nowruz/ Soroush crude, NIOC has recently begun blending the crude with South Pars condensate. The combined batch is then being fed into the Bandar Abbas refinery for domestic consumption. In July 2006, Iran reported that it had processed 2 million barrels of Soroush and Nowruz crudes at Bandar Abbas. In May 2006, NIOC secured a 60,000 bbl/d term contract for Nowruz/ Soroush crude with India’s Reliance.

Another area believed to have significant potential is offshore near Bushehr, where Iran claimed in July 2003 to have discovered three fields with potential reserves of 38 billion barrels of oil. In March 2004, the Iranian Offshore Oil Company (IOOC) awarded a $1.26 billion contract for recovery of NGLs and natural gas from Soroush, Nowruz, Foroozan, and Abuzar to Japan's JGC Corporation. Ethane from the gas will feed an ethylene complex at the Kharg petrochemical complex. Elsewhere, in May 2004, Brazil's Petrobras signed a 3-year, $32-$34 million deal to develop the Tousan fields of the Persian Gulf.
Caspian Sea Region

Aside from acting as a transit center for other countries' oil and natural gas exports from the Caspian Sea, Iran has potentially significant Caspian reserves of its own. Currently, Iran has no oil or natural gas production in the Caspian region. In early 2004, a 3-D seismic survey of the southern Caspian was conducted by Iran's Oil Survey Co.; the work yielded a number of potentially prospective blocks, including Blocks 6, 7, 8 and 29. In June 2006, Masoud Jahdi, Director of the state-run Caspian Sea Exploration Company, stated that Iran has completed 3D seismic work of 1,550 sq mile of the sea, and a further 11,580 sq miles has been swept in 2D surveys. According to a 1998 study by Eni, Shell and KEPCO, the Iranian sections of the Caspian Sea have significant potential. A tender for exploration is expected to follow after the seismic work is complete. Among the foreign firms that have indicated their interest in the area are Statoil, Norsk Hydro, Petrobras, Petronas and CNOOC.

At the present time, Iran continues to maintain that regional treaties signed in 1921 and 1940 between Iran and the former Soviet Union, which call for joint sharing of the Caspian's resources between the two countries, remain valid. Iran has rejected all unilateral and bilateral agreements on the utilization of the Sea. As such, Iran is insisting that either the Sea should be used in common, or its floor and water basin should be divided into equal (20 percent) shares. Under the so-called "condominium" approach, the development of the Caspian Sea would be undertaken jointly by all of the littoral states. However, using the equidistant method of dividing the seabed on which Kazakhstan, Azerbaijan, and Russia have agreed, Iran would only receive about 12-13 percent of the Sea. As yet, no agreement has been reached among all Caspian Sea region states on the legal status of the area.

Refining

According to Oil and Gas Journal, Iran has a combined capacity of 1.64 million bbl/d. Major refineries include: Abadan (400,000-bbl/d capacity); Isfahan (265,000 bbl/d); Bandar Abbas (232,000 bbl/d); Tehran (225,000 bbl/d); Arak (150,000 bbl/d); and Tabriz (112,000 bbl/d). Gasoline demand is forecasted to be growing at around 11.4 percent per year. Iran plans to increase its refining capacity to 2.54 million bbl/d by 2010. One goal of this expansion is to allow Iran's refineries to process a heavier crude slate, while decreasing the fuel oil cut. Currently, Iran's refineries produce around 30 percent heavy fuel oil and just 16 percent gasoline. In addition, diesel sulfur levels are slated for a major reduction from 500 parts per million to 50 ppm by 2010, requiring significant additional hydrotreating capacity.

The National Iranian Oil Refining and Distribution Company (NIORDC) plans to begin construction work as early as September 2006 on three units aimed at increasing gasoline production from the Isfahan refinery. Currently, technical proposals are being reviewed for the construction of three units: a 32,000 bbl/d continuous catalytic reformer (CCR) unit; a 27,000 bbl/d isomerization unit; and a 62,000 bbl/d hydrotreater. Construction is expected to cost $300 million. NIORDC is negotiating with bidders to reduce construction time from 36 months to 30 months.

In June 2004, Japan's JGC reached an agreement with Iran to expand Arak to 250,000 bbl/d by 2009. In addition, in 2005 it was announced that a new 180,000-bbl/d-capacity refinery is being
planned for Abadan. Bandar Abbas is being expanded in several phases and is on schedule to meet goals of adding around 250,000 bbl/d of capacity by 2010. Two planned grassroots refineries include a 225,000-bbl/d plant at Shah Bahar and a 120,000-bbl/d unit on Qeshm Island. Under Iranian law, foreign companies are permitted to own no more than 49 percent of Iranian oil refining assets.

Iran plans to boost capacity at its northern refineries at Arak, Tebriz, and Tehran in order to process additional Caspian oil. In August 2003, a $500 million tender was issued to upgrade the Tehran and Tabriz refineries in order to handle 370,000 bbl/d of high sulfur Caspian crude. This follows a $330 million project, completed by a Sinopec-led consortium in late 2003, to expand storage at Neka and to upgrade the Tehran and Tabriz refineries.

**Gasoline Imports**

Iran has imported refined products since 1982, and these imports have been increasing rapidly. Currently, gasoline costs less than 40 cents per gallon in Iran, far below international levels, contributing to a rapid (8-10 percent per year) growth rate in gasoline consumption. In addition, the country imports around one-third of its gasoline. In volume terms, Iran is the second largest importer of gasoline in the world after the United States. In 2005, Iran imported 150,000 bbl/d out of total consumption of 400,000 bbl/d. For 2006, FACTS estimates Iran will consume 462,000 bbl/d of gasoline and import 188,000 bbl/d, or roughly 41 percent of total consumption. According to *Petroleum Argus*, around 60 percent of this comes from European oil trader, Vitol, with another 15 percent coming from India’s 600,000-bbl/d Reliance refinery. However, although Iran imports large amounts of gasoline, it is an overall net petroleum products exporter due to its large gross exports of residual fuel oil.

Through the summer of 2006, there was heated debate among Iranian politicians as to how to balance expanding gasoline needs and the corresponding increase needed for gasoline subsidies. NIOC has said it has used nearly its entire $2.5 billion budget for gasoline imports but legislators have stated their opposition to providing the additional $3.5 billion necessary to pay for imports through the end of the fiscal year, in March 2007. Options put forward for addressing the issue included ceasing gasoline imports in September 2006 when many contracts expire and rationing gasoline, or implementing a two-tier price system whereby each car is allotted 2.5-3 liters a day at the subsidized price of 8.7 cents per liter, with consumption beyond that at 60-65 cents per liter.

Going forward, FACTS reports that Iran will complete construction of three 120,000 bbl/d condensate splitters by 2009. The facilities will produce an estimated 200,000 bbl/d of gasoline. Along with other projects, it is possible that Iran will cease being a gasoline importer by 2010.

**Environment**

Given its heavily energy-centered economy, environmental issues in Iran generally have ranked as a relatively low priority. However, ongoing and severe air pollution in urban areas have highlighted the need to improve Iran's environmental record. The rush to develop oil and natural gas resources in the Caspian Sea makes oil pollution in the Caspian a real environmental threat.
Huge increases in energy consumption over the past 20 years have contributed greatly to pollution levels as Iran's carbon emissions have nearly tripled over the same time span. Large numbers of old, inefficient cars on the road lacking catalytic converters account for much of the country's air pollution. Energy prices are kept artificially low in Iran through heavy state subsidies, resulting in highly inefficient and polluting consumption patterns. In addition, Iran's abundance of fossil fuel resources has tended to discourage the country's incentive to shift to cleaner alternative energy sources for its energy needs.

**Ongoing in alternative energy area**

Iranian energy minister have decided to establish of renewable and so green energy production systems in Iran, same as solar power plant, Wind Turbine, PV systems, geothermal power plant, sea waves energy, biomass system and micro hydro power plant.

As of 2004, Iran had installed power generation capacity of about around 34.3 gigawatts (GW). Currently it is above of 45 GW. Of this total, over three-quarters was natural gas-fired, with the remainder either hydroelectric (14.7 percent) or oil-fired. For 2005, Iranian power generation capacity is expected to reach 37 GW).

It has reported [1] that the electricity production in Iran per person is 2621 KWH, and power per person is 604 W.

Compositions of power plants in Iran are: steam station 15554 MW (37.9%), Gas station12,050 MW(29.4%), combined cycle 6832MW(16.7%), hydropower 6037MW(14.7%) and Wind and Diesels are 530MW(1.3%). Tavanir reported that in 2005 Iranian nominal capacity of power station conclude production by ministry of energy (38,038MW) and another parts was above the 41,003 MW, and average produced power was 37,054 MW, but maximum prepared load was 31,306 MW, and maximum mitigated load was 32,302MW.

Based on Tavanir report In 2006 average electricity production in Iran was 43,610MW, in 2007 will be 49,112, in 2008 so 62,722, in 2009 so 72,799, in 2010 so 78,275 and in 2011 will be 80.026 MW.

Iranian try in this area are discussed in following:

Wind Mapping Iran, Wind turbine production facilities in Iran
The goal of the project is to achieve a detailed understanding of the wind regime over Iran and to define the basis for the purpose of wind park projects development in Iran.

For compilation of the wind map the KLIMM model is applied. The standard software tools for wind maps are based on the WAsP model. The limitations of this program especially for complex and semi-complex terrain are well known and have been published in numerous publications. With the application of the three dimensional numeric mesoscale atmosperic model of KLIMM the long term wind data at the upper boundary (geostrophic wind) and the temperature stratification of the atmosphere can be used as input for the meteorological data. Site orography and roughness data is
used to model the site conditions. A nation-wide measurement campaign. With the installation of 50 meteorological stations will provide the near ground wind data for model calibration and fine adjustment. This procedure guarantees high accuracy and a representative character of the calculated wind conditions. The applied calculation model is among the most powerful calculation procedures available for wind energy practice.

**Main Data:**

Land-covering wind map with a grid resolution of 200 to 1000 m for an area of 1400 km x 1200 km

Complex terrain

3D mesoscale atmospheric modelling with KLIMM

Wind map design

Transferability of measurements of ground wind

Identification of suitable wind park sites

**Services:**

Data collection and processing

Wind potential analysis

Computation of wind map using the 3D atmospheric model KLIMM

Print of wind map, incl. geographical information

Training program for local staff

Preparation of a digital wind data base

Support of wind monitoring program

Identification of suitable wind park sites

**Iran Governmental energy policy and renewable energy**

Iran policy about fossil fuels consumption for energy supply will be continued. However in renewable energy resources Iran Policy is to supply 1 percent of Electricity with renewable resources until fiscal year 2010. This amount of energy is about 550 MW electricity. This capacity will be gained from different renewable resources as follows:

1-Renewable Power Plants which are constructed by Ministry of Energy (300MW):

- 55 MW Geothermal Power Plant in Sabalan (North West of Iran)

- 60 MW Wind Power Plant in Jarandagh( Center of Iran)
- 100 MW Wind Power Plant in Manjil (North of Iran)
- 10 MW Biomass Power Plant (Urban solid waste)
- 25 MW Wind Power Plant in Binalood (East of Iran)
- Photovoltaic systems in rural areas (50 MW Total Capacity)

2-Renewable Power Plants which are constructed by private sector (250 MW):

Electricity produced by these power plants will be bought by government higher than 3 times of fossil electricity price. Government considers this law (Article number 62) for promoting private sector to erect renewable power plants.

**Availability of Biomass in Iran**

Considering the availability of all types of Biomass resources in Iran, Power Ministry did a research to evaluate the potential to use biomass for renewable energy. This research was done in 1976 and conclusions are as follows:

1. Quantity of accessible Animal Waste in Iran is 74946000 ton; Biogas could be produced by this amount is 8668 Million M3 and energy equivalent this biogas is 193299 TJ. (TJ = 10^{12} J)

2. Quantity of accessible Urban Waste in Iran is 10605000 ton; Biogas could be produced by this amount is 1645.7 Million M3.

3. Quantity of accessible Biogas from Urban Waste Water in Iran is 98.855 M3/day. (Waste Water specifications are: 160 Litter per capita per day and BOD per capita is 33-40 gr/d.c)

4. Quantity of accessible Methane from Industrial Waste Water in Iran is 167664199 M3/year. Energy equivalent this quantity is 6153 TJ per year. (This Waste Water is from Big Food Industry in Iran.)

5. Total gross energy potential from Agricultural and Wood Waste is 411.896 PJ from 3285.50 Million M3 Methane and 33943344 M3 Ethanol which could be produced.

**Case Study on Use of biomass for renewable energy**

We analyze two case studies here: Mashhad Landfill Power Plant and Saveh Biogas Plant.

*Design and Implementation of the First Landfill-Gas Power Generation Unit in Mashhad (Iran)*

The first Landfill-Gas (LFG) power generation project was initiated in Mashhad, the second largest city in Iran, through a memorandum of understanding between “Renewable energy Organization of Iran (SUNA)” and “Waste Recycling and Processing Organization of Mashhad Municipality (WRPO)”. Based on the mentioned memorandum, SUNA took the responsibility of preparing technical investigations and tender documents and follow-up the electricity purchase contract.
between Mashhad LFG power plant and Ministry of Energy. Investment for power plant and commissioning was accepted by WRPO. Feasibility studies, conceptual design and tender documents preparation were consequently allocated to Renewable Energy Department of NRI.

The first phase of this project, included design criteria for engineering landfills and gas extraction systems and transmission lines, introduction to energy conversion and power generation technologies for LFG, field investigations and measurement methods and monitoring of LFG. The next phase was feasibility study for installation of power generation unit in Mashhad Landfill, in which, estimation of landfill gas theoretical yield for Mashhad municipal solid wastes, LFG generation modeling and gas flow prediction for long term periods, evaluation of confident power capacity for Mashhad Landfill, technical assessment of power generation equipments for LFG and introduction of more appropriate commercial generating sets for utilization of LFG in Mashhad Landfill, were performed. In the third phase, economical studies, three alternatives were selected on the base of feasibility study results. These alternatives were assessed as economical aspects and finally, installation of generating sets near the guard room of Mashhad Landfill, which is located near to irrigation station and a 20kV line, was selected as the most useful option for utilization of the whole gas which can be collected through the existing gas extraction systems. The generated electricity in this unit will be sold to power network at an average price of 616 Rls. per kWh.

The phase of conceptual design included: pipeline design for LFG transmission to central gas station, gas blower station, gas treatment process, foundation and structure of generating house, power generation unit arrangement and grid interconnection system plus protection and confidential instruments. Technical characteristics and tender documents were consequently prepared on conclusions. The contract for construction and start-up of Mashhad Landfill power generation unit will be as an Engineering Procurement Construction (EPC) contract.

**Project Results:**

- Pipeline and collection systems were designed on the basis of 13 years useful operation period of a biogas fueled generating set, and LFG generation modeling results, for average gas flow rate of 550 Nm3/h and maximum gas flow rate equal to 660 Nm3/h. A minimum power capacity of 435 kWe is expected to be achievable until the end of 2018 by existing gas extraction systems.

- The power capacity can be increased to at least 715 kWe if Mashhad Municipality develop the gas extraction systems to recent buried layers of solid wastes which are dumped in period of 2004-2006.

- Generating sets with LFG fueled internal combustion engines are the best option for Mashhad Landfill, furthermore, a list of qualified manufacturers of these equipments, has been presented in the project documents.

- Economical assessment results showed the best alternative is the installation of power generating unit in near of Landfill irrigation station.
A case study with capacity of 400 kWe (due to capacity of commercial models) will have the generation cost of electricity relevant to discount rates of 8%, 12%, 16% and 20% equal to: 293, 320, 350 and 382 Rials per kWh, respectively.

- LFG power plant interconnection with regional power grid is feasible through the existing 20kV line in Mashhad Landfill. Electrical circuit drawing and single-line diagram for connection to 20kV network were obtained and presented in project documents.

**Saveh Power Plant**

The city of Saveh is in the central province, 150 km from Tehran with a population of 120,000. It has a Semi-arid climate and the temperature during different seasons of the year fluctuates within the range of –10°C to 40°C. In order to establish the Bio-gas power plant in this city, the usable pollutants in Saveh were studied and they were divided into four groups:

- Household garbage, sludge of sewage treatment, slaughter house waste water and sludge of leaching pit. Through statistical studies, separation operation, sampling and executing physical, and chemical tests, quantity and quality specifications of each of the four types of pollutants were determined.

Some of the ongoing projects:

1. Two parabolic trough solar thermal power plants with the total capacity of 17.25 Mw plants

This project consists of a 250 kW parabolic trough solar thermal power plant which has been designed and is under construction and an integrated solar combined cycle with the solar share of 17 MW. Recently the first loop of the solar collectors of the 250 kW power plant has been tested successfully.

2. Geothermal power plant with final capacity of 55 MW

This power plant is going to be installed near Mount Sabalanin the north-west of Iran
3-398 MW Wind farms in five different locations

1st location: 55.68 MW Manjil Wind Farm,

2nd location: Binalood Wind Farm in the north-east of Iran: total capacity 17 MW, These projects consist of 660 kW turbines whereas some parts including turbine blades are manufactured in Iran.

3rd location: Jarandaq Wind Farm 100 MW

4th location: Binalood Wind Farm 100 MW

5th location: Siapush Wind Farm 125 MW

For these three sites private investors have completed their feasibility studies and are in the final stage of contract agreement. The power purchase agreements of these projects are available and had been presented to the investors together with the available wind data.

4- 90 MW Small hydro power plants in different regions

a) With public investment: 10 MW (under study)

b) Private power plants:

1-City of Mashad, landfill technology 0.4 MW (PPA preparing)

2-City of Sari, plasma technology 15 MW (under way)
3-City of Shiraz, landfill technology 1.1 MW (under way)

6- PV systems for 40 isolated village households

In this project 40 off-grid PV systems each with the capacity of 1.1 kW would be installed and tested in different village households in order to pave the way for installation of about 12000 of those systems in the isolated and remote areas of the country with total installed capacity of 13 MW.

Main Achievements

Enabling Iranian enterprises for RE systems design and also manufacturing of wind turbines, hydro power plant equipments, solar water heaters, parabolic trough concentrators, PV cells, panels and systems. Experiencing geothermal drilling in harsh climate areas.

Building confidence in private sector investors for producing electricity, especially through wind farms.

Considerable up bringing of the knowledge of universities in RE fields.

CONCLUSION

Iran’s energy production, consumption and export are evaluated. Iran swap the crude oil and gas in Caspian sea side and so Persian golf. Iran's economy relies heavily on oil export revenues, with such revenues representing around 80-90 percent of total export earnings and 40-50 percent of the government budget. Strong oil prices the past few years have boosted Iran’s oil export revenues and helped Iran's economic situation. For 2005, Iran's real GDP increased by around 6.1 percent. Inflation is running at around 16 percent per year, though unofficial estimates place the figure at 40-50 percent. Iran’s oil export revenues have increased steadily, from $32 billion in 2004, to $45.6
billion in 2005, with 2006 became at $46.9 billion. In 2007 it became more than $60 billion. Finally:

Due to capital intensive nature of renewable systems its large scale application is a burden to the national economy and therefore a supportive international financing mechanism is required.

RE technologies are mostly immature and need improvement as well as breakthrough which is only possible through regional and international research cooperation and assistance.

We must work harder to prepare ground for private sector effective investment in the field of renewables which is a key factor in making RE cost-effective and competitive as well as bring about innovation, creativity and dynamism.

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AP Worldstream

APS Review Gas Market Trends

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INVESTIGATION ON CHARACTERISTICS OF THERMAL CONDUCTIVITY FOR Al₂O₃-H₂O NANOFLUIDS

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ABSTRACT

Nanofluids have been attractive for the last few years with the enormous potential to improve the efficiency of heat transfer fluids. In this study, the thermal conductivity of Al₂O₃–water nanofluids was measured by a Hot Disk Thermal Constants Analyzer, and the effects of pH value, sodium dodecylbenzenesulfonate (SDBS) concentration and nanoparticle concentration on the thermal conductivity of Al₂O₃ nanoparticles in deionized water were discussed. The results showed that the thermal conductivity enhancements of Al₂O₃–water nanofluids are highly dependent on pH values, the weight fraction of nanoparticle and SDBS dispersant concentration of nano-suspensions. The Al₂O₃–water nanofluids with an ounce of Al₂O₃ have noticeably higher thermal conductivity than the base fluid without nanoparticles. For Al₂O₃ nanoparticles at a weight fraction of 0.0015 (0.15 wt %), thermal conductivity was enhanced by up to 10.1%, with an optimal pH value and SDBS concentration for the highest thermal conductivity. Therefore, the combined treatment with both the pH and chemical dispersant is recommended to improve the thermal conductivity for practical applications of nanofluid.

Key words: Nanofluid, Alumina nanoparticle, Zeta potential, Thermal conductivity

INTRODUCTION

Heating or cooling fluids are important to many industrial sectors, including transportation, energy supply and production and electronics. The thermal conductivity of these fluids plays a vital role in the development of energy-efficient heat transfer equipment. However, conventional heat transfer fluids have poor heat transfer properties compared to most solids. In fact, an amount of studies of the effective thermal conductivity of suspensions consisting of solid particles have been conducted. However, these studies have been confined to those produced with millimeter or micrometer-sized particles. The lack of stability of suspensions that involve coarse-grained particles is undoubtedly a primary reason why the fluids with dispersed milli- or micro-sized particles have not been applied to any industrial sectors.
It was proposed that fluids containing nanometer-sized particles can be a new class of engineered fluids with high thermal conductivity. The nanoparticle suspended fluids, named nanofluids, have been produced as the nanotechnology producing nanoparticles developed rapidly. Extensive research conducted on the preparation and processing technology of nanofluids in recent years has provided an opportunity to apply this emerging nanotechnology to thermal engineering. It cannot only solve the problems such as sedimentation, cohesion and corrosion which happen conventionally in heterogeneous solid/liquid mixture with millimeter or micrometer particles, but also increase the thermal performance of base fluids remarkably. Suspensions containing a small amount of metal (e.g., Cu) or nonmetal (e.g., SiC, Al₂O₃, and CuO) nanoparticles have been reported to have substantially higher thermal conductivities than those of the base fluids [Hong et al., 2006; Li et al., 2006; Li et al., 2007; Hwang et al., 2007]. Anomalously, Patel et al. [Patel et al., 2003] concluded that 5%–21% enhancement of the thermal conductivity of nanofluids for water with citrate in the temperature range 30–60 °C at a very low loading of 0.00026 vol% of Ag particles. For a loading of 0.011% of Au particles, the improvement of thermal conductivity was around 7%–14%. Kumar et al. [Kumar et al., 2004] reported an enhanced thermal conductivity of about 20% for a nanofluid of only 0.00013% Au nanoparticles in water. Since such an anomalous enhancement is expected to have wide applications in thermal engineering, nanofluids have received considerable attention in thermal science and engineering. However, it is very difficult to understand why nanofluids would have such a high thermal conductivity. Meanwhile, there are large differences among the thermal conductivities reported by different researchers. Keblinski et al. [Keblinski et al., 2005] further pointed out that the most exciting experimental results have not been reproducible. Therefore, it is necessary to reconsider the reliability of the measurements reported so far.

In the present study we measured the thermal conductivities of the Al₂O₃-H₂O nanofluids. The effects of the weight fraction of the dispersed Al₂O₃ particles, the pH value of the aqueous suspension, SDBS concentration, and the thermal conductivity of the base fluid on the enhanced thermal conductivity ratio have been investigated. It is expected to provide guidance to design nanofluids with excellent performance.

**EXPERIMENTAL**

**Chemical**

The Al₂O₃ powder (Alfa Aesar, Ward Hill, MA, USA) with alumina content > 99.9 % was used in the study. It has a BET surface area of 100 m² g⁻¹, and a median particle size of 15-50 nm, and a density of 3965 kg m⁻³. The surface area was determined using the Micromeretic Tristar 3000. The particle size was measured using the X-ray Disc Centrifuge Particle Size Analyser Ver. 3.49. The transmission electron micrograph (TEM) of alumina powder is shown in Fig.1. In the Fig.1, there are a few larger particles, which are likely aggregates of the smaller ones, but the whole distribution of the particles is relatively well-dispersed. The particles are basically spherical or near spherical.

An anionic surfactant, sodium dodecylbenzenesulfonate (referred to as SDBS) in chemical grade, from Guangzhou Chemical Reagent Factory (China), was used. The water was purified by a Milli-Q Academic Millipore system. The pH was controlled using hydrochloric acid (HCl) and
sodium hydroxide (NaOH) in analytical grade. All chemicals were used as received without any further purification.

![TEM micrograph of nano-alumina sensor](image1)

![Schematic diagram of TPS](image2)

**Fig 1. TEM micrograph of nano-alumina sensor**

**Fig 2. Schematic diagram of TPS sensor**

**Measurement of zeta potential and particle size**

The experiments were conducted using 0.05 wt% alumina nano-suspensions. Different concentrations of the dispersant were added to the suspensions, which were stirred thoroughly and ultrasonicated (KQ2200DE Ultrasonic Cleanser, 100W, Kunshan of Jiangsu Equipment Company, China) for at least 15 minutes, 2–4 ml of suspensions was transferred into a measuring cell. Then zeta potential and particle size were measured by a Malvern ZS Nano S analyzer (Malvern Instrument Inc., London, UK). The measurement was run at V=10 V, T=25°C with switch time at t=50 s. Each experiment was repeated at least ten times to calculate the mean value of the experimental data. The pH value of system was adjusted with HCl and NaOH solution by precise pH Meter (PHS-25, China).

**MEASUREMENT OF THERMAL CONDUCTIVITY OF NANOFLOIDS**

**Transient plane source (TPS) theory**

Thermal conductivity of nanofluids is measured by means of the TPS method [Rodríguez-Pérez et al., 2003]. In this method, the TPS element behaves both as temperature sensor and heat source. This novel method offers some advantages such as fast and easy experiments, wide range of thermal conductivities (from 0.02 to 200 W/m K), no sample preparation and flexible sample size.

The TPS element consists of an electrical conducting pattern of thin nickel foil (10 μm) in the form of double spiral, which resembles a hot disk, embedded in an insulating layer made of kapton (70 μm). (see Fig.2)
A Kapton insulated probe is dipped into the suspensions. A constant electric power is supplied to the sensor and the increase in temperature $\Delta T(\tau)$ is calculated from the variation in the sensor resistance with time $R(t)$ by using the equation:

$$\Delta T(\tau) = \frac{1}{\alpha} \left( \frac{R(t)}{R_0} - 1 \right)$$  \hspace{1cm} (1)

where $R_0$ is the hot-disk resistance in the beginning of the recording (initial resistance), $\alpha$ is the temperature coefficient of resistance of the nickel foil, and $\Delta T(\tau)$ is the temperature increase of the sensor expressed in terms of an only variable $\tau$, defined as:

$$\tau = \sqrt{\frac{t}{\theta}} , \quad \theta = \frac{a^2}{\kappa}$$  \hspace{1cm} (2)

where $t$ is the measurement time, $\theta$ is the characteristic time, which depends both of parameters of the sensor ($a$ is the sensor radius) and the sample ($k$ is the thermal diffusivity of the sample).

In the case of a disk geometry, consisting of $m$ concentric ring sources, an exact solution of equation (1) is possible. The increase of temperature is:

$$\Delta T(\tau) = P_0 \left( \pi \frac{a^2}{\lambda} \right)^{-1} D(\tau)$$  \hspace{1cm} (3)

where $P_0$ is the total output power and $D(\tau)$ is a geometric function. By fitting the experimental data to the straight line given by equation (3), the thermal conductivity can be obtained by calculating the value of slope for the fitting line \( P_0 \left( \pi \frac{a^2}{\lambda} \right) \).

**Measurement process of the thermal conductivity of nanofluids**

Different concentration nano-suspensions were prepared, which were stirred thoroughly and ultrasonicated (KQ2200DE Ultrasonic Cleanser, 100W, Kunshan of Jiangsu Equipment Company, China) for half of an hour. A Kapton insulated probe (design 7577) was successively dipped into the different nano-suspensions. The diameter of the sensing spiral in the probe was about 2.001 mm and the Kapton insulation on both sides of the spiral had a thickness of 13 $\mu$m. Then the thermal conductivity was measured by a Hot Disk Thermal Constants Anlyser (Hot Disk Inc., Uppsala, Sweden). The measurement was run at $V$=0.02 V, $T$=25°C with switch time at $t$=5 s. Each experiment was repeated at least ten times to calculate the mean value of the experimental data. The pH value of system was adjusted with HCl and NaOH solution by precise pH Meter (PHS-25, China).

**RESULTS AND DISCUSSION**

**Influence of pH on thermal conductivity of Al$_2$O$_3$-H$_2$O nanofluids**

Fig.3 shows the change of zeta potential and particle size for Al$_2$O$_3$-H$_2$O suspensions with SDBS dispersant as a function of pH. According to the zeta potential values of alumina powders, pH 8.0-9.0 can be selected as an operating pH for the suspensions with SDBS dispersants. Because, in the pH, the absolute values of zeta potential for Al$_2$O$_3$-H$_2$O suspensions with SDBS dispersants is higher, so
there are more surface charges around the particles. On the other hand, the particle size of alumina particles in water is smaller at pH 8.0-9.0, which can lead to better dispersion and stability of the nanofluids.

Fig. 3 shows the change of thermal conductivity ratio for Al₂O₃-H₂O suspensions with SDBS dispersant as a function of pH. It can be seen that the thermal conductivity ratio increases as pH increases from 3 to 8.0-9.0. As addressed in the literatures [Xie et al., 2003], such abnormal enhancements are not explained by any pre-existing model. When the nanoparticles are dispersed into water, the overall behavior of the particle–water interaction depends on the properties of the particle surface. At the point of zero change (PZC), the repulsive forces among alumina particles is zero and nanoparticles will coagulate together under this pH value. Therefore, when the pH value is equal to or close to the PZC, alumina particle suspension is unstable according to the DLVO theory [Russel et al., 1989; Hunter et al., 1987; Elimelech et al., 1995]. The hydration forces among particles increase with the increasing difference of the pH value of a suspension from the PZC, which results in the enhanced mobility of nanoparticles in the suspension. The microscopic motions of the particles cause microconvection that enhances the heat transport process. So we attempt to link the concept of surface charges to the change in thermal conductivity ratio of nanofluids. The point to mention is that the charged surface sites seemingly provide much more effective passages through which heats or phonons are going more efficiently. Lee et al. [Lee et al., 2006] showed that surface charge states are mainly responsible for the increase of thermal conductivity in the present condition by a surface complexatio model for the measurement data of hydrodynamic size, zeta potential, and thermal conductivity. Xue et al. [Xue et al., 2003] showed from molecular dynamic simulation that phonons felt much less resistance during travel from particle to liquid at stronger interfacial bonding. Therefore, it looks reasonable to infer that optimizing pH or higher surface charging condition facilitates phonon transport through increases of effective sites and transport efficiency.

As depicted in Fig. 3, as the pH goes away from the PZC, the surface charge increases because of more frequent attacks to the surface hydroxyl groups and phenyl sulfonic group by potential-determining ions (H⁺, OH⁻ and phenyl sulfonic group), leading to an increase in the zeta potential on the alumina powder surface. In this way, we can infer that there are more surface charges at pH...
8.0-9.0, at which the dispersion behavior is better and the thermal conductivity is higher. As expected, the surface charge is minimum at the PZC.

**Influence of the SDBS concentration on thermal conductivity of Al₂O₃-H₂O nanofluids**

Fig. 5 presents the thermal conductivity ratio of the Al₂O₃-H₂O suspensions and the base fluid with respect to the concentration of SDBS dispersant at pH 8.0-9.0. The weight fraction of the Al₂O₃-H₂O suspensions is 0.1 wt%. For the base fluid, the thermal conductivity ratio starts to decrease after a certain value of the dispersant concentration. In the present experiments, the highest thermal conductivity appears at 0.02 wt% water solution, which means when an ounce of SDBS dispersant is added, the thermal conductivity at 0.02 wt% water solution is higher than that of pure water. In the 0.1 wt% Al₂O₃-H₂O suspensions, the trend of the variation of the thermal conductivity is very similar to those in the base fluid with dispersant only. However, the thermal conductivity ratio decreases slowly as SDBS concentration increases from 0.02 wt% to 0.10 wt%, and then decreases very quickly with an increase in the SDBS concentration. Obviously, for the Al₂O₃-H₂O suspensions and the base fluid, when more SDBS is added into the systems, the thermal conductivity ratios decrease very quickly. Owing to this trend, the addition of more dispersant seems noneffective in the Al₂O₃-H₂O suspensions. This is because the heat transfer area becomes narrower due to the amount of the surfactants on the particle surface. Taking into account the combined effect of dispersion behavior and thermal conductivity, the 0.10 wt% SDBS can be selected as an optimizing concentration for the 0.1% alumina nano-suspensions. Therefore, it can be concluded that the application of nanofluid with optimizing chemical dispersant is a better way among the considered enhancement techniques in the viewpoint of the effectiveness of dispersion behavior and thermal conductivity.

**Influence of alumina concentration on thermal conductivity of Al₂O₃-H₂O nanofluids**

Fig. 6 shows the enhanced thermal conductivity ratio of Al₂O₃-H₂O suspensions with the optimizing SDBS concentration as a function of the weight fraction of nanoparticle. pH 8.0-9.0 can be selected as an operating pH for different weight fraction suspensions. The results show that an ounce of nanoparticle suspensions have noticeably higher thermal conductivities than the base fluid without nanoparticles. The thermal conductivity of Al₂O₃-H₂O nanofluid is enhanced approximately nonlinearly with the weight fraction of the alumina nanoparticle, it implies that Al₂O₃-H₂O suspensions can enhance the heat transfer performance. The maximum thermal conductivity enhancements of up to 10.1% is observed at the 0.15 wt% suspension. Fig. 6 also shows that the comparison between the experimental data for Al₂O₃-H₂O nanofluids and the values calculated from Hamilton–Crosser model. The results show (see Fig. 6) that the measured thermal
conductivities are higher than those calculated from Hamilton–Crosser model. Hamilton–Crosser model is known as following equation [Yu et al., 2004]:

$$\frac{k_{\text{eff}}}{k_f} = \frac{k_p + (n-1)k_f - (n-1)\varphi(k_f - k_p)}{k_p + (n-1)k_f + \varphi(k_f - k_p)}$$

(4)

The notations of $\text{eff}$, $p$, and $f$ represent nanofluid, particle and base fluids, respectively. $\varphi$ and $k$ represent the volume fraction and thermal conductivity, respectively. Where $n$ is the empirical shape factor given by $n = 3/\psi$ and $\psi$ is the sphericity. For the spherical and cylindrical shape particle, the sphericity ($\psi$) is 1 and 0.5, respectively.

Besides H-C model, other traditional models also underpredict the effective thermal conductivity of nanofluids because these models do not completely account for particle size, particle Brownian motion, nanolayering, and effect of nanoparticles clustering and pH condition, which are important to nanoparticles in nanofluids. Thus, new assessments and mathematical models of the effective thermal conductivity for nanofluids will need to be proposed.

CONCLUSIONS

This paper is concerned with the thermal conductivity of Al$_2$O$_3$-H$_2$O nanofluid under different nanoparticle concentration, pH values and sodium dodecylbenzenesulfonate (SDBS) concentration. Key conclusions can be summarized as follows:

1. We have shown that the pH of the nanofluid strongly affects the thermal conductivity of the suspension. As the pH of the nanofluid goes far from the PZC, the surface charge increases because of more frequent attacks to the surface hydroxyl groups and phenyl sulfonic group by potential-determining ions ($\text{H}^+$, $\text{OH}^-$ and phenyl sulfonic group ), and the colloidal particles get more stable and eventually alter the thermal conductivity of the fluid. In this way, we can infer that there are more surface charges at pH 8.0-9.0, at which the thermal conductivity is higher.

2. The use of Al$_2$O$_3$ nanoparticles as the dispersed phase in water can significantly enhance the thermal conductivity, and the enhancement increases with particle concentration under the conditions of this work. The maximum thermal conductivity enhancements of up to 10.1% is observed at the 0.15 wt% suspension. The experimental results are compared with H-C model and indicate that the experimental results are remarkably higher than predicted by H-C model for nanofluids. The comparisons also indicate that it is needed to take into account several possible factors in enhancing the heat transfer performance of nanofluids, for example, higher charging condition facilitates phonon transport through increases of effective sites and transport efficiency.

3. The thermal conductivity can be improved by adding optimizing SDBS dispersant. However, the combined treatment with both the pH and chemical dispersant is recommended to improve the thermal conductivity for practical applications of nanofluid.
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