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Technologies for increasing CO₂ concentration in exhaust gas from natural gas-fired power production with post-combustion, amine-based CO₂ capture

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Abstract

Enhanced CO₂ concentration in exhaust gas is regarded as a potentially effective method to reduce the high electrical efficiency penalty caused by CO₂ chemical absorption in post-combustion capture systems. The present work evaluates the effect of increasing CO₂ concentration in the exhaust gas of gas turbine based power plant by four different methods: exhaust gas recirculation (EGR), humidification (EvGT), supplementary firing (SFC) and external firing (EFC). Efforts have been focused on the impacts on cycle efficiency, combustion, gas turbine components, and cost. The results show that the combined cycle with EGR has the capability to change the molar fraction of CO₂ with the largest range, from 3.8 mol% to at least 10 mol%, and with the highest electrical efficiency. The EvGT cycle has relatively low additional cost impact as it does not require any bottoming cycle. The externally fired method was found to have the minimum impacts on both combustion and turbomachinery.

Keywords:

CO₂ concentration in exhaust gas, gas turbine cycles, amine-based CO₂ capture, exhaust gas recirculation, air humidification, supplementary fired cycle, externally fired cycle

1 Introduction

CO₂ capture and storage (CCS) is one of the most important technologies for the CO₂ emission mitigation. The power sector has CO₂ large point sources, and therefore offers opportunities to apply CCS at a large scale. The main barriers concerning the applications of CCS are high electrical efficiency penalty and high CO₂ avoidance cost. Therefore, the integration of novel power generation cycles and different CO₂ capture technologies is an essential topic to bring CO₂ capture technologies closer to realization.

CO₂ capture usually requires a specific process for separating CO₂ from the reaction mixture. The technologies differ in utilized pressure and temperature levels and in the content of CO₂, impurities and inert gases. Thus, a specific CO₂ capture technology can be well-suited for certain power cycles while infeasible for others. Currently, the technology of reactive absorption by amines, e.g. monoethanolamine (MEA), methyldiethanolamine (MDEA), has been commercialized [1-4]. Such processes are based on the CO₂ chemical absorption which enhances absorption rates and hence can be used with relatively low CO₂ partial pressure in

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exhaust gases. The main disadvantages of chemical absorption arise from the high thermal energy needed to regenerate the solvent and extract the CO₂, and problems with corrosion and solvent degradation. It has been verified that the reboiler duty of the stripping column is sensitive to the CO₂ concentration of exhaust gas [5, 6]. As shown in Figure 1, for a CO₂ concentration increase from 1 to 6 mol %, the specific reboiler duty decreases sharply, from 7.5 to 3.76 MJ/kg CO₂. Beyond this range, the specific reboiler duty continues to decrease at a much lower rate. Continuous decrease in energy demand with increasing CO₂ concentration is mainly caused by the higher CO₂ partial pressure, which increases driving forces, enables higher effective loading, and hence favors the capture reaction.

Figure 1 Energy demand of stripper at different feed CO₂ concentrations

The use of gas turbines for power generation has been increasing during the last decades and is likely to grow further in the medium term. Many advanced power generation cycles have been developed to take advantage of the thermodynamic characteristics of gas turbines. However, the maximum temperature attainable in the Brayton cycle is limited by the metallurgical constraint, resulting in large excess air in the combustion stage, hence highly diluted CO₂ in the exhaust gas (about 3.3 vol% dry). This is a challenge for amine-based CO₂ capture as a full-scale absorption plant will have to treat large volumes of dilute gas.

Increasing CO₂ concentration in exhaust gas may provide an efficient method to reduce the high electrical efficiency penalty caused by chemical absorption. Four methods for increasing CO₂ concentration applicable to gas turbine based power plant cycles have been selected and studied. These are: 1) exhaust gas recirculation (EGR), 2) humidification (EvGT), 3) supplementary firing (SFC), and 4) external firing (EFC). The scope of the present work is to review and evaluate their potential applications in the gas turbine cycle integrated with MEA-based chemical absorption. Features and challenges related to the integration of these technologies are addressed according to their impacts on cycle efficiency, combustion, gas turbine components, and cost.

2 Input data and assumptions of simulations

In this work, gas turbine cycles have been simulated with the commercial software PRO/II [7] developed by Simulation Science Ind. PRO/II process simulation software is a steady-state simulator enabling improved process design and operational analysis. It is designed to perform rigorous mass and energy balance calculations for a wide range of chemical processes.

The input data and assumptions of simulations were defined following our previous work [8]. The compositions and properties of main streams are summarized in Table 1. The input data and assumptions for the simulations of gas turbines, compressors and CO₂ transport are given in Table 2. The input data to simulate MEA-based chemical absorption are shown in Figure 1.

Table 1 Compositions and properties of streams

Stream	Unit	Value
<i>Fuel stream</i>		Natural gas [9]
LHV	MJ/kg	48.252
<i>T</i>	°C	15
<i>P</i>	bar	1
Composition		
CO	mol%	0.5
CH ₄	mol%	94.4
C ₂ H ₆	mol%	3.1
C ₃ H ₈	mol%	0.5
C ₄ H ₁₀	mol%	0.2
C ₅ H ₁₂	mol%	0.2
N ₂	mol%	1.1
<i>Air stream</i>		
<i>T</i>	°C	15
<i>P</i>	bar	1
Composition		
N ₂	vol%	78.99
O ₂	vol%	20.65
Ar	vol%	0.921
CO ₂	vol%	0.04
Relative humidity	%	60
<i>CO₂ stream to be transported</i>		
<i>T</i>	°C	20
<i>P</i>	bar	150

Table 2 Input data and assumptions about the simulations of chemical absorption and combined cycle

Parameter	Unit	Value
<i>Gas turbine</i>		
Pressure ratio		20
Turbine inlet temperature	°C	1250
Isentropic efficiency	%	91

<i>Steam power cycle</i>		
Maximum steam turbine inlet T	°C	460
HP steam inlet pressure	bar	111
HP turbine isentropic efficiency	%	92
IP steam inlet pressure	bar	27
IP turbine isentropic efficiency	%	92
LP steam inlet pressure	bar	4
LP turbine isentropic efficiency	%	89
<i>Compressors</i>		
Type		Isentropic
Isentropic efficiency	%	85
Intercooling T	°C	30
Stage number of air compression		1
Stage number of CO ₂ compression		3
<i>Other parameters</i>		
Pump efficiency	%	75
Pressure drop in heat exchangers	%	3
Combustor outlet temperature	°C	1328
Pressure drop in combustor	%	5
$\Delta T_{\min}$ gas/gas	°C	30
$\Delta T_{\min}$ gas/liquid	°C	20
<i>Simulation Tools</i>		
Cycle		PRO/II

By correlating the simulated results, the following equation is used to predict the specific reboiler duty at different feed CO₂ concentrations [6]:

$$Q=3.3162+0.0154*y_{\text{CO}_2}+2.0383/y_{\text{CO}_2}+2.1432/(y_{\text{CO}_2})^2 \quad \text{Equ. 1}$$

Where y_{CO_2} is CO₂ mole concentration in percentage ($y_{\text{CO}_2}\text{mol\%}$). Considering the reboiler temperature that is about 118°C at a stripping pressure of 1.8 bar, the thermal energy required by the reboiler is provided by the steam extracted from the IP steam turbine outlet so that the saturated-steam temperature matches that of the reboiler and the defined $\Delta T_{\min}$ for heat transfer.

3 Selected methods for increasing the CO₂ concentration of exhaust gas

3.1 Exhaust gas recirculation (EGR)

A method for increasing CO₂ concentration in the gas stream at the inlet of chemical absorption units is EGR, which at the same time can reduce the corresponding volume flow. Peeters et al. [10] predicted the potential future performance of post-combustion CO₂ absorption in combination with a natural gas combined cycle (NGCC). In [10], EGR was considered as an important technology for reducing energy penalty of CO₂ capture, improving net cycle efficiency and reducing capital cost (CAPEX), cost of electricity (COE) and CO₂ avoidance cost (COA) in the short, medium and long terms.

A system scheme of a combined cycle integrated with EGR and chemical absorption is shown in Figure 2. After passing through the bottoming cycle, a partial stream of the exhaust gas is extracted downstream of the exhaust gas condenser and mixed with the inlet air upstream of the compressor. Here, EGR ratio is defined as:

$$EGR = \frac{\text{volume flow of recirculated exhaust gas}}{\text{volume flow of exhaust gas}} \Big|_{\text{after condensation}} \quad \text{Equ. 2}$$

Figure 2 Scheme of a combined cycle integrated with EGR and amine-based CO₂ chemical absorption

3.1.1 EGR impacts on amine-based chemical absorption

Based on simulation results, Figure 3 shows the CO₂ concentration and the mass flow of the exhaust gas entering the absorption column at different recirculation ratios. As can be observed, CO₂ concentration increases and the mass flow decreases significantly as the EGR ratio increases. Compared to a cycle without EGR, a recirculation ratio of 55% could increase CO₂ concentration from 3.8 mol% to 8.7 mol% and reduce the mass flow of the absorber feed stream by 56.2%. As a result, the total thermal energy consumption of the reboiler is reduced by 60%, and the mass flow reduction may allow for smaller sizes of absorption and stripper columns, thus contributing to a reduction in capital cost. According to Røkke [11], an EGR ratio of 50% could reduce CAPEX of an amine plant by 21.1%. Even though EGR affects the specific reboiler duty significantly, its impact on the electrical efficiency is not obvious as the recirculated exhaust gas would increase the compression work, A change of EGR ratio from 0

to 55% increases the overall efficiency from 50.1 to 50.4% of natural gas (NG) LHV according to the simulations performed in this study.

Figure 3 CO₂ concentration and mass flow of exhaust gas at the absorber inlet as function of EGR ratio

3.1.2 EGR impacts on combustion

Since there is less oxygen available in the exhaust gases than in ambient air, O₂ concentration before and after combustion decreases with increasing EGR ratio. As shown in Figure 4, in order to achieve complete combustion, EGR cannot theoretically exceed 60%, at which stoichiometric combustion is reached.

Figure 4 O₂ concentrations in the recirculated exhaust gas at different EGR ratios

However, from the viewpoint of combustion, it is of importance to control oxygen concentration before combustion. Burners and combustors are generally designed for air

containing 21 mol% oxygen, and by recycling exhaust gas the global oxygen concentration at the combustor inlet decreases considerably, to for example 11 mol% at 55% EGR ratio. With vitiated air, severe problems are prone to occur regarding combustion stability, efficiency and emission, particularly in gas turbine combustors, characterized by high velocity and low residence time. Elkady et al. [12] studied the behavior of combustion in a 10 bar Dry Low NO_x (DLN) combustor with 35% EGR. This combustor was proposed for the plant design in order to avoid potentially challenging gas turbine operating regimes with respect to combustion. The results indicated that low oxygen concentration could 'reduce the reaction rates, allow for combustion to spread over a large region and reduce the peak flame temperature, which is not in favor of the oxidation of CO to CO_2 ; on the contrary, reduction in oxygen levels combined with supplementary CO_2 in the oxidizer leads to changes in the heat release process via CO_2 dissociation'. Ditaranto et al. [13] experimentally studied the effect of O_2 vitiation in an atmospheric laboratory-scale setup, showing that even though the flame could be sustained at O_2 concentration as low as 14% in the oxidizer, the levels of unburned hydrocarbons and CO were excessively high when the O_2 concentration reached 16%. Taking that limit as an indication, Figure 4 shows that EGR exceeding 40% could be difficult to obtain. This limit can, however, be pushed further by technical adaptation of the engine and combustor arrangement that would allow for additional O_2 injection or different air distribution spilt as suggested in Li et al. [6].

On the other hand, the low oxygen concentration is beneficial with respect to NO_x formation, as the latter depends on oxygen concentration as well as flame temperature, which are both reduced as EGR ratio increases. In addition, recycling minor species as NO and CO into the combustion zone tends to reduce their concentrations through, for example, the potential NO reburning mechanism [13]. In the study of Elkady et al [9] the NO_x emissions decreased with increasing EGR levels by more than 50% with 35% EGR. For the chemical absorption process, the presence of oxygen could cause degradation of amines, and the byproducts lead to corrosion problems. Hence, EGR could also minimize the need for chemical inhibitors or process modification involving deoxidation of the CO_2 -rich amine [14].

3.1.3 EGR impacts on turbomachinery

Figure 5 shows the gas turbine inlet mass/volume flow at different EGR. As can be observed, both mass and volume flows decrease with increasing EGR ratio. The decrease of gas turbine inlet mass flow can be explained by the fact that the recirculated exhaust gas has a higher temperature (40°C) than air (15°C). In order to achieve the same preset combustion temperature (1328°C), a smaller mass flow is required when some of the colder air is replaced by the hotter exhaust gas. However, the impacts of EGR on the gas turbine inlet mass flow are not obvious. An EGR of 50% varies the mass flow only by 1.04 wt%, and correspondingly the volume flow by 1.61 vol%. In addition, the specific heats of O_2 , N_2 and CO_2 are close. Hence, for gas turbines and compressors, it is likely that the aerodynamic and thermodynamic changes due to the changes in composition of the working fluid may be handled without modifications.

Figure 5 Gas turbine inlet mass/volume flows at different EGR

3.2 Gas turbine humidification

The driving forces for gas turbine humidification have been the potential of high electrical efficiency and specific power output, reduced specific investment cost, reduced NO_x emissions, reduced power output degradation caused by high ambient temperatures or low ambient pressures (i.e. at high elevations), and improved part-load performance compared with combined cycles. Humidified gas turbines have a thermodynamic potential of electrical efficiencies similar to or higher than that of combined cycles (CC) [15] and can be divided into three categories: (I) gas turbines with injection of water that evaporates completely in or after compressors, (II) gas turbines with injection of steam (STIG), and (III) gas turbine cycles with injection of water in a humidification tower, with a recirculation water loop (EvGT).

When water or steam is introduced in the cycle, a part of air is effectively replaced by steam. Since steam could be easily separated from exhaust gas by condensation, gas turbine humidification could have a higher CO_2 concentration than the conventional gas turbine cycle, which would favor the CO_2 capture process by chemical absorption.

EvGT integrated with MEA-based chemical absorption was studied by Li et al. [16] and a system scheme is shown in Figure 6. Water is heated close to the saturation point by the compressed air in the aftercooler and by exhaust gas in the feedwater heater and economizer. The heated water enters at the top of a humidification tower and is brought in contact counter-current with the compressed air that enters as the bottom of the tower. The tower is a column with a packing that is either structured or dumped. Some of the water is evaporated and the air is humidified, and the evaporation occurs at the water boiling point corresponding to the partial pressure of water in the mixture, that is, below the boiling point that corresponds to the total pressure in the tower. Hence, low temperature heat can be recovered in an EvGT cycle. Since the water vapour content in the air increases as the air passes upward through the tower,

the boiling temperature also increases. This ensures a close matching of the air and water temperature profiles, and small exergy losses compared to evaporation in a conventional steam boiler [15]. Moreover, as the heat involved in exhaust gas is recovered back to the cycle by evaporating water in the humidification tower, there is no need for a bottoming steam cycle in an EvGT system, thus lowering the investment cost.

Figure 6 System scheme of EvGT cycle integrated with amine-based CO₂ capture

With the same parameters of the gas turbine cycle, EvGT integrated with MEA-based chemical absorption were simulated at different water/air ratio (WAR) defined as:

$$\frac{W}{A} = \frac{\text{mass flow of evaporated water}}{\text{mass flow of air}} \Big|_{\text{humidification tower}} \quad \text{Equ. 3}$$

WAR is of great importance for the electrical efficiency of an EvGT cycle. For every case with constant combustion air temperature, there always exists an optimum point [17].

3.2.1 Impacts of gas humidification on amine-based chemical absorption

As shown in Figure 7, the CO₂ concentration in exhaust gas of EvGT cycle could be raised to above 5mol% after condensation. However, injecting water increases water concentration of the condensed exhaust gas at the same time. The molar fraction of H₂O is raised from 4.3mol% in the simple cycle to 7.4mol%. The high water content of exhaust gas would bring more water into absorber and dilute the MEA solution, resulting in an increased specific reboiler duty. An optimized value of electrical efficiency regarding WAR is 41.6% of NG LHV at WAR=0.115 [16]. However, compared to a combined cycle integrated with chemical

absorption, in which electrical efficiency is calculated to 50.1% of NG LHV, EvGT does not show any promising results in the present work.

Figure 7 CO₂ concentrations in the dehydrated exhaust gas at different WAR

Figure 8 Oxygen concentration before combustion and water concentration in the gas turbine inlet stream

3.2.2 Impacts of gas humidification on combustion

As a part of air is replaced by water steam, EvGT cycles are characterized by lower oxygen concentration prior to combustion and higher water concentration at the gas turbine inlet, compared to conventional gas turbine cycles. The extent to which O₂ and H₂O vary is shown in Figure 8 as a function of WAR. As H₂O acts as a diluent, the effects are similar to those of EGR, that is, reduction of NO_x and potential increase in CO and unburned hydrocarbons. At

In general, a supplementary fired plant inherently has lower efficiency than that of a conventional plant, however the ability to produce more power output during periods of high electricity prices gives it an economic advantage depending on the demand for the electricity

and the number of hours when the high prices exist [18]. The benefits of supplementary fired combined cycle plant depend on a number of factors: plant design, cost of capital, cost of fuel, marginal cost of electricity production, and hours of operation are the most important. Since many variables are involved, most notably plant design and regional wholesale electricity prices, any particular application should be analyzed in detail to determine the full merit of adding a supplementary firing unit.

3.3.1 Impacts of supplementary firing on amine-based chemical absorption

From the viewpoint of post-combustion CO₂ capture, supplementary firing shows potential advantages. Similarly to EGR, supplementary firing could increase the CO₂ concentration in exhaust gas. Compared to a cycle without EGR, the CO₂ concentration is increased from 3.8 to 6.7mol%. However, supplementary firing results in an increased mass flow of exhaust gas, which is the opposite effect from that of EGR. The increase in mass flow counteracts the benefit of high CO₂ concentration and hence, SFC has a somewhat lower electrical efficiency of 48.1% of NG LHV, according to the simulations conducted in this paper. Another factor contributing to lowered efficiency is the high temperature difference for the HRSG heat exchangers. Hence, a bottoming cycle with higher temperature, for instance a supercritical bottoming cycle, may contribute to improved efficiency.

3.3.2 Impacts of supplementary firing on combustion

A similar characteristic between EGR and SFC is low oxygen concentration in exhaust gas. However, the high temperature generally compensates for the low levels of oxygen concentration, around 12mol%, and stabilisation is often insured with simple burner ramps. In addition, high NO_x reductions have also been observed in gas turbines with supplementary firing units [13].

If higher combustion temperature can be applied, instead of the assumption ($T_{\text{combustion}} = 1328^{\circ}\text{C}$), CO₂ concentration can be further enhanced. Figure 10 shows the CO₂ concentration in the condensed exhaust gas while Figure 11 shows the oxygen concentrations before and after combustion in the supplementary firing unit. At stoichiometric combustion, CO₂ concentration approaches the theoretical maximum value, which is 11.3mol%. Furthermore, the oxygen concentration before the supplementary combustion declines with the increase of combustion temperature, but not significantly, and the increased combustion temperature could mitigate the problem of low O₂ concentration.

Figure 10 CO₂ concentrations in exhaust gas and electrical efficiency of SFC at different supplementary combustion temperatures

Figure 11 Oxygen concentrations before and after combustion in the supplementary combustor at different combustion temperatures

3.3.3 Impacts of supplementary firing on cycle efficiency and gas turbine

As mentioned above, the increase in mass flow counteracts the benefit of high CO₂ concentration. Consequently, along with the increase of supplementary combustion temperature, the cycle efficiency drops and approaches the lowest level at stoichiometric combustion, which is only 41.9% of NG LHV, as shown in Figure 10.

As the exhaust gas discharged from the high-pressure gas turbine stage can be re-heated indirectly in the supplementary combustor to improve the gas turbine cycle efficiency, the

material of gas turbine does not represent a problem as long as turbine inlet cooling and a high temperature-tolerant heat exchanger are applied. More details about high-temperature heat exchangers are given in section 3.4, but a new design of gas turbine to satisfy the recuperation of exhaust gas is required. In addition, if the system is simplified by skipping exhaust gas recuperation, turbine machinery would be kept unmodified and the cycle efficiency reduced by only 0.3% of NG LHV at a supplementary combustion temperature of 1320°C.

3.4 Externally Fired gas turbine Cycle (EFC)

As analyzed in the previous sections, there are potential problems associated with integration of conventional gas turbine cycles with EGR or air humidification, such as unstable combustion caused by low oxygen concentration, new design requirements of gas turbines to handle altered exhaust gas composition, and mass mismatch. These problems may be avoided with the application of external firing technology.

The EFC has been studied for coal since the 1930s, as summarized by Keller [19]. In the 1950s and 1960s, several works were conducted regarding the externally fired combined cycle concept [20,21]. Six coal and peat-fired air heaters built between 1956 and 1961 were used to understand the features of EFC. [22].. From 1990, research interest was directed towards the application in the combined heat and power plants utilizing biomass [17,23,24].

Whereas in conventional gas turbines the compressed air-fuel mixture is burnt in the combustor and subsequently expanded in the turbine, the combustion gases do not pass through the turbine in an externally fired gas turbine cycle. As shown in Figure 12, heat from the hot exhaust gas is transferred to the compressed air in an indirect contact heat exchanger. The externally fired gas turbine unites several advantages, such as the possibility of burning so-called 'dirty' fuel and employing a low-temperature cleanup system. It also avoids problems related to changes in gas characteristics through the compressor and turbine. Furthermore, the combustion unit does not need to be under the high-pressure environment as is the case for a conventional gas turbine.

Figure 12 Scheme of externally fired gas turbine cycle

The main technical impediment of EFC is the high-temperature heat exchanger, which requires robust materials in order to operate at required temperature levels for a high-efficiency cycle. Because metallic heat exchangers used in the earlier versions of the cycle did not allow sufficiently high turbine inlet temperatures for profitable power production, ceramics that can stand temperatures above 1400°C in corrosive coal combustion gas environment was used instead. Hague International conducted a series of experiments with ceramic materials in the 1970s [25]. Most of the work during this period was focused on heat recovery equipment for the secondary metals industry. To date, their low-pressure ceramic air heaters have accumulated over two million hours of successful operation in corrosive, high-temperature industrial environments. Also in the early 1980s, Hague International initiated work to increase the pressure capability (up to 100bar) of the ceramic heat exchangers [22].

3.4.1 Impacts of externally firing on amine-based chemical absorption and cycle efficiency

If CO_2 is to be captured by amine-based chemical absorption, EFC provides potential advantages. For an externally fired gas turbine cycle, since the power generation and combustion units are separated, it may not be necessary to keep the combustion at as high excess air levels as for conventional gas turbines. Hence, the flue gases can be less diluted, resulting in lower volumes to treat in an amine scrubber. In this study an EFC was simulated under the conditions listed in Table 1 and 2, except for the combustion temperature. The resulting variation in CO_2 concentration and mass flowrate of the condensed exhaust gas at different levels of excess oxygen are shown in Figure 13. As a result, the net electrical efficiency increases as the excess air ratio approaches stoichiometric condition, as shown in

Figure 14. In the theoretical case of stoichiometric combustion, CO_2 concentration would be increased to 11.8mol% and the mass flow reduced to 17.1kg/s, leading to an electrical efficiency of 44.3% of NG LHV.

3.4.2 Impacts of external firing on combustion

Figure 14 shows the adiabatic combustion temperatures of EFC at different excess oxygen, and equals 2031°C at stoichiometric combustion conditions. Conventional furnace could be used in externally firing cycle which generally operates at 3% excess O_2 . The major impact would be at the gas/air heat exchanger and the selected materials.

Figure 13 CO_2 concentrations and mass flow of the condensed exhaust gas at different levels of excess oxygen

Figure 14 Electrical efficiency and combustion temperatures of EFC at different levels of excess oxygen

4 Discussion

Based on the above analysis, Table 3 summarizes the characteristics of different technologies considered in this work, including advantages, challenges and key parameters. Furthermore, the calculated electrical efficiencies of the different cycles are displayed in Figure 15.

Figure 15 Calculated electrical efficiencies of the different cycles in consideration

according to the simulation results of this study, EvGT has the lowest electrical efficiency, while EGR has the highest. One of the important advantages of EvGT lies in the augmentation of the gas turbine flowrate obtained through water evaporation. However, when integrated with amine-based chemical absorption, this technology becomes less advantageous due to several reasons. As amine regeneration inherently consumes large amounts of heat, less heat is available to humidify air. Thus, the amount of water evaporated in the humidification tower is reduced sharply. Furthermore, as EvGT requires high-temperature exhaust gas for the supply of thermal energy to the reboiler, the large temperature difference at the heat transfer sections will further contribute to efficiency losses. In addition, as the exhaust gas pressure is close to atmospheric, a large amount of latent heat of water condensation cannot be utilised in the stripper reboiler as normally done in combined cycles due to the low condensing temperature. This further reduces the cycle efficiency. EGR shows higher efficiency than SFC and EFC due to more energy-efficient thermal integrations between the involved sub-processes. Compared to SFC, EGR is characterized by smaller temperature differences between the exhaust gas and the maximum steam turbine inlet temperature in the HRSG, for the EGR case around 40°C while 480°C for SFC. Finally, compared to EFC, internal combustion with compressed air has a higher thermal efficiency than external combustion with indirect heat transfer from the combustion products to the internal gas turbine cycle.

For the power cycles considered in the present work, further modifications can potentially improve the overall efficiencies. In the case of EvGT, efficiency may be improved by integrating a bottoming cycle running at low temperature, such as organic Rankine cycles working with R113 and R245 whose maximum working temperatures are in the range of 200–

320°C [26,27]. For SFC, a supercritical bottoming cycle may utilise thermal energy more efficiently than a subcritical cycle due to the high exhaust gas temperature. In the case of EGR, higher EGR ratios can further increase CO₂ concentration and reduce the mass flowrate of exhaust gas to be treated in a chemical absorption plant. However, in order to reduce EGR impacts on combustion, local oxygen enrichment may be required. Hence, integrating a low-purity oxygen air separation unit (ASU), cryogenic or possibly utilising oxygen membrane technology, could be a potential way to improve the overall efficiency of EGR with CO₂ capture.

5 Conclusions

As enhanced CO₂ concentration in exhaust gas being a potentially effective method to reduce the high electrical efficiency penalty caused by chemical absorption, four technologies enabling increased CO₂ concentration have been reviewed and evaluated: exhaust gas recirculation, gas turbine humidification, supplementary firing and external firing.

From the viewpoint of improving capture conditions, exhaust gas recirculation can potentially increase the molar fraction of CO₂ from 3.8 mol% to 10 mol% or possibly higher, while air humidification may increase the CO₂ fraction to around 5 mol%. For supplementary firing and externally fired cycles, the theoretical maximum CO₂ concentrations are 11.3 mol% and 11.5 mol%, respectively, in the case of stoichiometric combustion.

As far as electrical efficiency is concerned, the simulation results presented in this paper show that the system integrated with EGR shows the best performance while the system integrated with air humidification shows the lowest efficiency.

Regarding investment cost, EvGT cycle has a relatively low cost due to the absence of bottoming cycle, while supplementary firing has a relatively high cost due to its additional burner. And comparatively, externally fired technology has the minimum impacts on both combustion and turbomachinery.

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Table 3 Summary of the characters of different technologies

Character		Technology			
		EGR	EvGT	SFC	EFC
Impact on amine-based chemical absorption	CO ₂ -enriched exhaust gas	+++	+	++	++
	Exhaust gas mass flow reduction	++	+	-	+
	Low O ₂ %	++	+	++	++
Impact on combustion	Reduction of NO _x	+	+	+	-
	Demand of extra oxygen	+	-	-	None
	Potential problems	Stability, CO/UHC	Stability, CO/UHC	Unstable combustion	None
Impact on turbine	Potential problems	High CO ₂ concentration	High H ₂ O concentration, mass mismatch	None	None
Impact on efficiency	Thermal integration	+	-	-	-
	Possible electrical efficiency (% NG LHV)	50.1-50.5	39.7-41.6	41.9-48.9	42.8-44.3
Impact on cost reduction		+	++	-	+
Key parameter		Recirculated mass flow	WAR	Supplementary combustion temperature	Excess O ₂
Additional requirements/problems		New design of combustion chamber	Humidification tower, make-up water system	Supplementary duct burners, high temperature heat exchanger	High temperature heat exchanger, material selection

NOMENCLATURE

P	Pressure
Q	Specific reboiler duty (MJ/kg CO ₂)
T	Temperature
y _{CO2}	CO ₂ mole concentration in percentage
λ	Excess air ratio

Abbreviations:

CC	Combined cycle
CCS	CO ₂ capture and storage
COA	CO ₂ avoidance cost
COE	Cost of electricity
DLN	Dry low NO _x
EFC	Externally Fired cycle
EGR	Exhaust gas recirculation
Equ	Equation
EvGT	Evaporative gas turbine
HP	High pressure
HRSG	Heat recovery steam generator
IP	Intermediate pressure
LHV	Lower heating value
LP	Low pressure
MDEA	Methyldiethanolamine
MEA	Monoethanolamine
NG	Natural gas
NGCC	Natural gas combined cycle
ORC	Organic Rankine Cycles
SFC	Supplementary Firing Cycle
SRK	Soave-Redlich-Kwong
STIG	Gas turbines with injection of steam
TET	Turbine exit temperature
TIT	Turbine inlet temperature
UHC	Unburned hydrocarbon
vol	Volume
WAR	Water air ratio
wt	Weight

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