Influence of residential ventilation on Radon mitigation with energy saving emphasis

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Abstract:
There are many indoor pollutants in the residential buildings. High insulation and tightness in buildings in order to increase energy efficiency and to lower energy costs is led to the indoor air quality problems. To provide sufficient fresh air and to promote indoor air quality at acceptable level, it is needed to increase ventilation rate to overcome such pollutants.

The aim of this paper is to study about energy efficient mechanical ventilation to overcome poor indoor air quality and energy consumption associated with radon ventilation.

Ventilation is a good method to dilute radon contaminant and maintain indoor air quality, but in the other hand ventilation is account for about 50 percent of energy use in residential buildings. Designing the required rate and location of ventilation systems and also choosing the best type of ventilation strategies can be provided both indoor air quality (IAQ) and building energy savings (BES).

Computational fluid dynamics technique as a useful tool can be used to simulate and visualize radon treatment and mechanical ventilation rates for optimizing energy consumption and achieving to indoor air quality.

Results show that the exhaust fan installed in the middle another one in the left side have different impacts on distribution of radon contents in the room. Also when the rate of ventilation is changed from 7.5 l/s to 35 l/s the radon concentration will be decreased. By choosing the optimum features of ventilation system, energy saving can be obtained.

1. Introduction:

Radon, which is emitted from soils, rocks and buildings material in many countries, has adverse health problems and can be led to lung cancer and it must be controlled and mitigated under limitation level.

Pollutant control can be obtained using ventilation to dilute pollutant concentrations. Pollutant concentrations are inversely proportional to ventilation rates. Thus reducing concentrations 50 percent (1/2 of the original values) require twice the initial ventilation. Reducing the concentration by 90 percent (1/10 of the original value) would require ten times the ventilation [1].

The more fresh air is brought into the indoor environment, the better the indoor air quality (IAQ) can be achieved, if the fresh air comes from non polluted ambient source. However ventilation can consume a lot of energy more than 50% of energy in building section, especially in cold climate same as Sweden, energy consumption could be much more. But pollutants control is important for health and comfort of occupants to maintain IAQ aspect.

Ventilation has also an impact on the outdoor pollution level. Building related pollution sources represent about 40% of the total pollution load. Due to the increased thermal insulation levels of buildings, including envelope tightness, the importance of the ventilation related energy use is increasing and may represent up to 50% of the total energy use of a building, particularly for certain typologies such as office buildings [2].

To compromise between indoor air quality (IAQ) and building energy saving (BES), there are several methods that they can be used, with respect to special situations, like local or spot ventilation displacement ventilation versus mixing ventilation, floor heating instead of radiator system or even heat recovery ventilation by using heat exchanger.

Computational fluid dynamics (CFD) as an alternative of experimental method can help with simulating and visualizing airflow patterns, thermal comfort and concentration distributions of pollutants in a space to find optimum energy consumption and limited pollutants levels, at much less cost.

In this study, Fluent CFD software program is used for simulation of radon behavior and air flow in a room.

2. Review of radon mitigation and energy conservation

To prevent extra energy use versus radon mitigation, some studies [3] conducted by energy conservation measures (ECMs) method and the results showed that with ventilation rate of 7.5 liter per second per person during occupied periods, implementing ECMs could offset any increase in energy consumption resulting from higher ventilation rates related to radon mitigation. ECMs could be reduced total annual energy costs 10-36.8% in school buildings. The heating, ventilation and air conditioning (HVAC) systems have been shown to impact the radon concentration [4].

Operation and maintenance of a building's (HVAC) system at proper design, and how it influences indoor air quality can be beneficial in determining the management strategy for a radon problem. Very often the problem can be solved without the need for extensive and sometimes costly radon mitigation systems. A slightly positive pressure within the building can prevent radon from entering a building while negative pressure can pull radon into the building [4, 5].

An indoor thermal comfortable space is independent on the use of energy for ventilation, heating and cooling, while heating has traditionally been the major cause for energy consumption in most cold climate countries. Thermal comfort may be achieved with thermostat settings 2 or 3 degrees lower because it warms people and objects directly as opposed to heating air. In most cases radiant floor heating systems can provide energy savings of 20 to 40% over alternative types of heating system.

Ventilation system type can have a significant impact on energy use. Building energy uses account for approximately 40% of total primary energy use in several countries. Of this, the residential sector consumes more than 50 percent of which is used for space conditioning [6]. As building insulation levels have increased in recent years so too has the fraction of the energy consumed for heating or cooling ventilation air --- now between 30 to 50% of the energy used for space conditioning. Thus, there is the potential to conserve nearly 10 percent of total primary energy use via reduced or more efficient ventilation strategies [7].

Traditionally there is a focus on maintaining a fixed ventilation rate where the optimum is approached between the indoor air quality and the energy consumption as given in figure 1. Too low flow rates lead to insufficient IAQ, whereas too high flow rates lead to increasing energy demands [8].

In most buildings, ventilation is probably the greatest component of the total energy consumption. This is usually in the range of 29_59% of the building energy consumption [9].

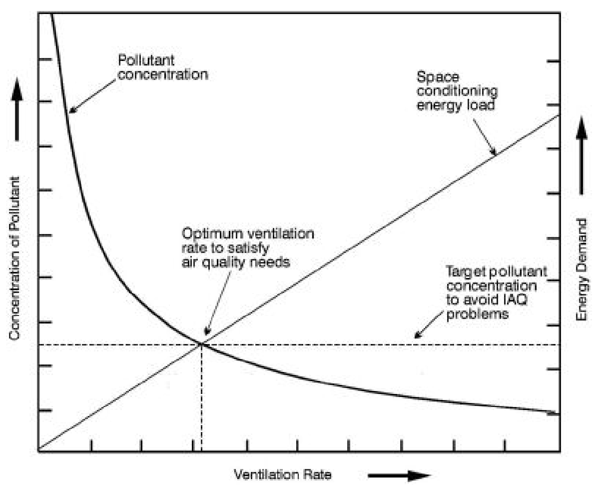

Fig 1, pollutant control versus ventilation rate and energy consumption, source: www.aivc.org

Nuess and Prill (1990) carried out an experimental pressurization control system in Spokane, and concluded that if heat recovery is used to enhance energy efficiency, this action for energy saving there isn't over cost for radon mitigation [10].

Displacement ventilation (DV) can enhance IAQ in the lower level by separating polluted and warmed air from clean and cool air through the stratification. As a result, the DV system has the advantage of energy saving over mixing ventilation (MV) system and in the same time the IAQ in occupied zone can be efficiently controlled. Many investigators have reported such advantages of DV theoretically and experimentally for various HVAC applications. It was also reported that for 100,000 ft^2 offices, the cooling load was reduced by 25-30 percent using DV. Consequently, DV reduced the supply air volumetric flow rate to 70 percent of what is required in conventional MV in the same situation. When heat sources are also the contaminant sources, compared to the MV system, the ventilation efficiency of the DV is much higher [11].

To control and reduce radon contents, the effectiveness of ventilation (εv) is a good parameter to choose the ventilation strategy. Of different ventilation types, displacement ventilation has an upper effectiveness than others; as such it can be used as energy efficient ventilation system [9].

Sometimes by using special ventilation systems such as spot ventilation, heat recovery ventilation or energy efficient system energy saving could be achieved. For instance using floor heating can conserve about 20% relative to radiator heating. Energy saving implications will be discussed in future studies. Besides the potential to control indoor pressure, the principal advantage of balanced ventilation systems is the ability to incorporate a heat exchanger that transfers energy between outgoing indoor air and incoming outdoor air. Depending on the climate and the efficiency of the heat exchanger, such heat- or energy-recovery units can significantly lower the operating costs associated with conditioning ventilation air.

2 Literature review on Computational Simulation in indoor air quality

Computational fluid dynamics (CFD) makes it possible to simulate airflow patterns, thermal comfort and concentration distributions of pollutants in a space at much less cost. This technique, allowing the simulation and the visualization of environmental problems, represents a powerful tool to motivate, guide and educate about the environment. [12]

CFD involves the solutions of the equations that govern the physics of the flow. Due to the limitations of the experimental approach and the increase in the performance and affordability of computers, CFD provides a practical option for computing the airflow and pollutant distributions in buildings.

A more practical approach is to subdivide the space inside the room into a number of imaginary sub-volumes, or elements. These sub-volumes usually do not have solid boundaries; rather, they are open to allow gases to flow through their bounding surfaces.

The goal of the CFD program is to find the temperature, concentrations of contaminants, and the velocity throughout the room, for each of the sub-volumes. This will reveal the flow patterns and the pollution migration throughout the room.

To produce a solution, the CFD program solves the equations describing the process in the room. Each of the sub-volumes involves the conservation of mass, energy, momentum and chemical/biological species.

Since each of the equations for the conservation of mass, energy, momentum, and chemical/biological species involve the pressure, temperature, velocity, and chemical/biological concentration of an element and its neighbors, the equations for all of the elements must be solved simultaneously.

Due to the development in CFD modeling and computer technology, the CFD tool becomes more and more popular for IAQ and thermal comfort studies. [13]

CFD analysis tools solve the system of mass, energy, and momentum conservation equations known as the Navier- Stokes equations to determine the air velocity, temperature and contaminant concentration at each of these nodes.

W. Zhuo (2000) used computational fluid dynamics (CFD) to study the concentrations and distributions of indoor radon (222Rn) and thoron (220Rn) as well as their progeny in three dimensions. According to the simulation results, in a naturally ventilated room, the activity distribution of 222Rn is homogeneous except for the places near air diffuser (supply and exhaust) locations. The concentration of 220Rn exponentially decreases with the distance from the source wall which is considered independently. However, as the ventilation rate increased, the concentrations of both 222Rn and 220Rn decreased and their activity distributions become complicated due to the effect of turbulent flow. It suggests that the impact factors of monitoring conditions (sampling site, airflow characteristics, etc.) should be taken into account in obtaining representative concentrations of 222Rn for dose assessment. Both the simulation results of activities and their distributions agreed well with the experimental results in a laboratory room. [14]

Whereas Computational Fluid Dynamics (CFD) gives more accurate picture of contaminant concentration behavior, the setting up of the boundary conditions and other input parameters makes CFD prohibitively difficult. CFD solves the partial differential equations governing mass, momentum and energy transport on a fine grid. But unfortunately, CFD codes are complex, expensive and quite difficult to use.

Ventilation is supply to and removal of air from a space to improve the indoor air quality. The idea is to capture, remove and dilute pollutants emitted in the space to reach a desired, acceptable air quality level. Existing ventilation guidelines or standards in European countries and elsewhere assume that the occupants of a space are the dominating or exclusive polluters.

3 Governing Equations

3.1 Continuity and Momentum Equations in FLUENT [13]

FLUENT can model the mixing and transport of chemical species by solving conservation equations describing convection, diffusion, and reaction sources for each component species. For all flows, FLUENT solves conservation equations for mass and momentum. For flows involving heat transfer or compressibility, an additional equation for energy conservation is solved. For flows involving species mixing or reactions, a species conservation equation is solved or, if the non-premixed combustion model is used, conservation equations for the mixture fraction and its variance are solved. Additional transport equations are also solved when the flow is turbulent.

3.1.1The Mass Conservation Equation

The equation for conservation of mass, or continuity equation, can be written as follows:

$$/ \quad + \quad .(\vec{\ })= \qquad (1)$$

This Equation is the general form of the mass conservation equation and is valid for incompressible as well as compressible flows for laminar flow. The source is the mass added to the continuous phase from the dispersed second phase (e.g., due to vaporization of liquid droplets) and any user-defined sources.

3.1.2Species Transport Equations

When you choose to solve conservation equations for chemical species, FLUENT predicts the local mass fraction of each species, , through the solution of a convection-diffusion equation for the th species. This conservation equation takes the following general form:

$$-(\quad)+\quad(\quad\vec{\ }\quad)=-\quad.\vec{\ }+\quad+ \qquad (3)$$

Where, is the net rate of production of species by chemical reaction (described later in this section) and is the rate of creation by addition from the dispersed phase plus any user-defined sources. An equation of this form will be solved for N-1 species where N is the total number of fluid phase chemical species present in the system. Since the mass fraction of the species must sum to unity, the Nth mass fraction is determined as one minus the sum of the N-1 solved mass fractions. To minimize numerical error, the Nth species should be selected as that species with the overall largest mass fraction, such as N2 when the oxidizer is air.

In Equation (3), $\vec{\ }$ is the diffusion flux of species , which arises due to concentration gradients. By default, FLUENT uses the dilute approximation, under which the diffusion flux can be written as

$$\vec{\ }=-\quad , \qquad (4)$$

Here $_{,}$ is the diffusion coefficient for species in the mixture.

In turbulent flows, FLUENT computes the mass diffusion in the following form:

$$\vec{\ }=-\quad , \quad +\frac{}{} \qquad (5)$$

Where, is the turbulent Schmidt number ($\frac{}{}$ where is the turbulent viscosity and is the turbulent diffusivity). The default is 0.7. Note that turbulent diffusion generally overwhelms laminar diffusion, and the specification of detailed laminar diffusion properties in turbulent flows is generally not warranted.

3.2 Ventilation rate

A factor which is very important in determining ventilation rates is the ventilation effectiveness "εv" which is defined as:

$$\varepsilon_v = (c_o - c_i)/(c - c_i) \times 100\% \quad (6)$$

where,

C_i =pollution concentration in the supply air, ppm or mg m^{-3}

C_o =pollution concentration in the exhaust air, ppm or mg m^{-3}

c=mean pollution concentration in the occupied zone, ppm or mg m^{-3}.

The value of εv depends on the ventilation strategy used, i.e. location of air supply and extract openings\ the momentum and turbulence of the supply air and the room heat load and its distribution. Values of εv can only be obtained by measurements or simulation of the air movement using computational fluid dynamics (CFD), or may be found in handbooks or guidelines for certain air distribution strategies. As an example, a typical value of εv for high level mixing ventilation might be around 70%, whereas for floor displacement ventilation it is somewhere in the region of 120%. Hence, theoretically at least, based on these values a displacement system should require only about 58% of the ventilation rate of a high level system. [12]

ASHRAE Standard 62-1989R gives two methods of determining ventilation rates, the prescriptive procedure and the analytical procedure. In the prescriptive procedure, tables of ventilation rates required diluting the pollution produced by people and buildings are given for different types of buildings. In the analytical procedure, the ventilation rates are calculated using data for pollution sources and the effectiveness of the ventilation system [14].

The expression below can be used to calculate the ventilation rate, Q, required maintaining the concentration of a particular pollutant within a desired value. [12]

$$\mathbf{Q} = \mathbf{G} / \{\varepsilon_v.(c_i - c_o)\} \times 10^6 \, m^3 s^{-1} \quad (7)$$

Where,

G=pollutant generation rate, m^3 s^{-1}or kg s^{-1}

C_i =indoor concentration that can be tolerated, ppm or mg kg^{-1}

C_o =outdoor concentration of the pollutant, ppm or mg kg^{-1}

εv=effectiveness of ventilation system

ASHRAE Standard 62 (ASHRAE, 2003) says living areas need "0.35 air changes per hour but not less than 15 cfm (7.5 L/s) per person." In other words, the standard is 0.35 AC/h or 15 cfm per person, excluding those with the presence of known contaminants. Whichever is greater; the first guideline is based on building volume, the second on occupancy. When actual occupancy is unknown, as in the case of production homes under construction, occupancy is usually (but not always) assumed to be one more than the number of bedrooms, i.e., two occupants in the master bedroom and one in each additional bedroom. [15]

Here it is used the building volume guideline (0.35 AC/h), rather than assumed occupancy to determine minimum ventilation rates because the actual occupancy of any home will fluctuate over time. Also, the occupancy guideline is more appropriate when occupants are the principal pollutant sources, while the building volume guideline is more appropriate when the building itself is a significant source of air contaminants, as same as here which radon is a significant pollution. However, this or any "standard" ventilation rate is necessarily somewhat arbitrary, controversial, and subject to change. ASHRAE's 0.35 AC/h is a minimum rate, and some consider 0.60 AC/h a practical upper limit for mechanical ventilation because as the ventilation rate increases, so do the conditioning costs [16].

3.3 Transport radon through building material

The indoor radon sometimes comes from the building materials. The reason is that the building materials were usually made of granite or tails of uranium mines. In this paper is assumed that the indoor radon only comes from the surface of the building materials and the outdoor air and the radon emanation rate of the building materials are kept constant. Indoor radon concentrations are dependent on radon production, ventilation and outdoor radon concentration.

Ventilation of a room can significantly influence radon measurement. The relationship between radon concentrations and indoor air exchange rate is given by Thomas C. W. Tung J. Burnett [17] and at the steady state situation, if the radon exhalation from the building material is known; the indoor radon content can be calculated for different rates of ventilation [18] air change as equation (7):

$$= \frac{\Sigma}{(\quad)} \qquad (7)$$

Where,

= indoor radon from building material Bq/m^3,

λ = radon decay constant (=0.00755) 1/h or 2.1e^{-6} 1/s, note that λ is very smaller than .

= rate of air change 1/h

= volume of the building or room m^3

= exhalation rate of building part *i* Bq/m^{2}h

= area of building part *i* m^2

The radon decay constant *λ*=2.1e-6 1/s, since the order of ventilation rate is much more than *λ*, therefore is inversely proportional to , i.e. when is increased, is decreased inversely.

4 Data used in this study:

C_∞=270 Bqm^{-3}, λ=2.1e^{-6}s^{-1}, radon diffusivity, D=1.0e^{-6} m^{2}s^{-1}, air viscosity=1.75e^{-5}Kgm^{-1}s^{-1}, radon viscosity=1.8 e^{-5}Kgm^{-1}s^{-1}, room volume=V=110m^3

1 Bqm^{-3}=1.75e^{-19} kgm^{-3} *(22)*

1 kg radon=5.7e^{18} Bq [19]

Radon action level in residential buildings in some countries and organizations is about 150 *Bqm^{-3}* [20].

5 modeling procedure

5.1 Three dimension, Boundary conditions and initial values

Geometry is a room with sizes 5*10*2.2=110 m^{3,} outdoor temperature 273 K and indoor temperature 293 K.

It is assumed that the radon concentration inside the room at steady state is 270 *Bqm^{-3}* [21] and from equation (7), with $\sum A_i$ = 66 m^2, the value of E= 0.094 e^{-2}≈ 10^{-3} *Bqm^{-2}s^{-1}*.

Radon emissions from the walls are 66 m^2 and 110 m^3,but in Fluent the boundary defined with volume 5.74 m^3(one slice of the walls with 0.1m thickness).The emanation rate (E) from the surface of this volume has to calculate again, from equation (22), E= 1.75*10^{-19}*10^{-3}=1.75*10^{-22} *Kgm^{-2}s^{-1}* for 110 m^3 , since the surface area is 66m^3 , E.A= 115.5*10^{-22} *Kgs^{-1}*, then the radon value within volume 5,74 m^3 will be C=(115.5/5.74)*10^{-22}=2*10^{-21} *Kgm^{-3}s^{-1}*.

Initial values are supposed as:

Velocity = 0, radon concentration=0, temperature=293 K.

The simulations have been performed with Fluent V.6.3. Since the Reynolds number is about 1000, the model of air flow is chosen as laminar model.

Fluent has run twice, with different ventilation rates and different locations of ventilation, for the first case the left exhaust fan1 was on and the ventilation rate defines as 35 l/s(0.037 Kg/s),and the others were off and the inlet vent was the middle door. In the second case the middle exhaust fan3 was on, with a ventilation rate about 7.5 l/s (a quarter of the first case), and instead of door, used an inlet supply.

Iterations and grid size were 10,000 and 89783 cells respectively for both cases (figure 2).

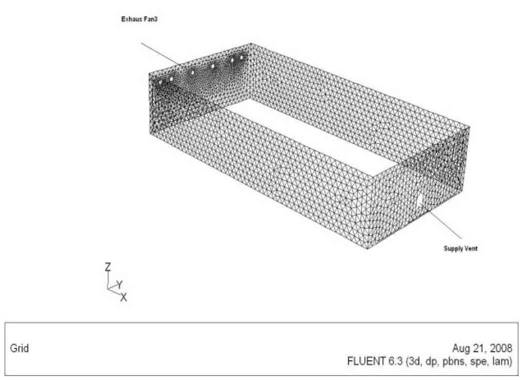

Fig.2, 3 dimension geometry and grid

5.2 Two dimension boundary condition

In 2 dimension modeling, FLUENT program software runs with different cases, and with changing ventilation rates and types to observe the outcome of radon mass fraction.

Figure 5, shows the geometry, grid and boundary conditions.

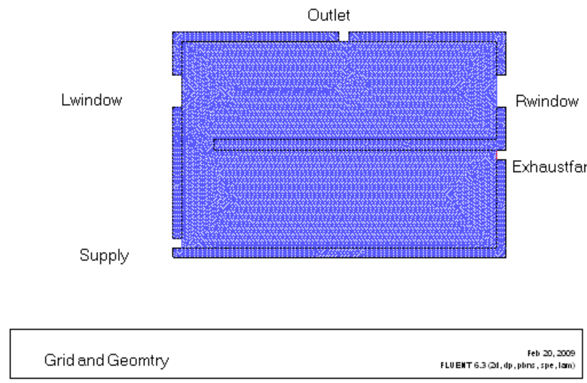

Fig.3, 2 dimension geometry and boundary condition

6 Results and discussion

6.1 ventilation influence on radon concentration

Fig 4 and 5 show the results of ventilation on radon distribution with different ventilation rates and locations. As we can see with different supply and changing the exhaust fan location the results will be changed and radon maximum level and distribution patterns are changed. In the figures 3and 4, maximum radon contents are about 24 and 41 Bq/m^3 respectively and the zones with maximum levels are different with each other.

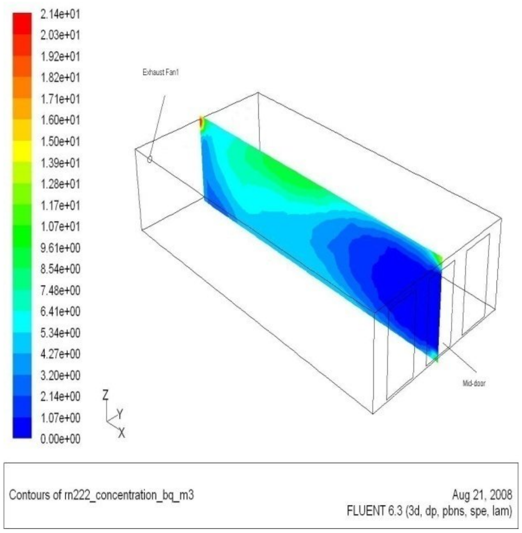

Fig.4 radon concentration on y=0, door inlet and

left exhaust fan

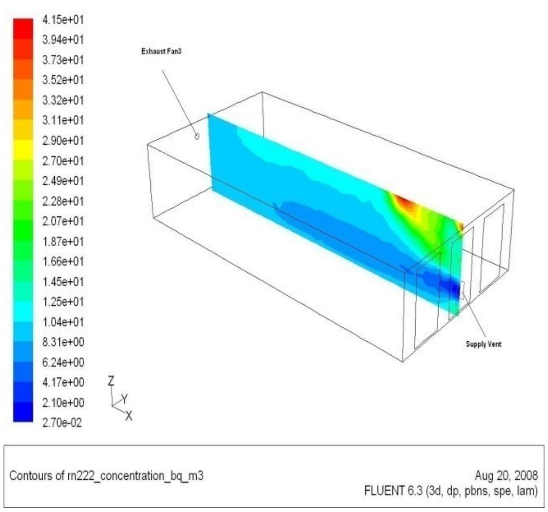

Fig.5 Radon concentration on y=0, supply inlet and

middle exhaust fan

6.2 radon mitigation and energy efficient ventilation

The boundary condition and initial values are defined as bellow:

In figure 6, supply =velocity inlet at 0.4 m/s, exhaust fan =wall, outlet=exhaust fan at 3 Pascal and windows=wall

Max v=0.57, Max radon=$3.6e^{-19}$.

Figure 6, set as displacement ventilation (DV), with supply fan as a fresh air diffuser near the floor in which it can be seen almost there is not any polluted region in the first floor, but in the second floor there is a region near the second floor in which radon content is at high level and at this point the air velocity is also in the minimum rate.

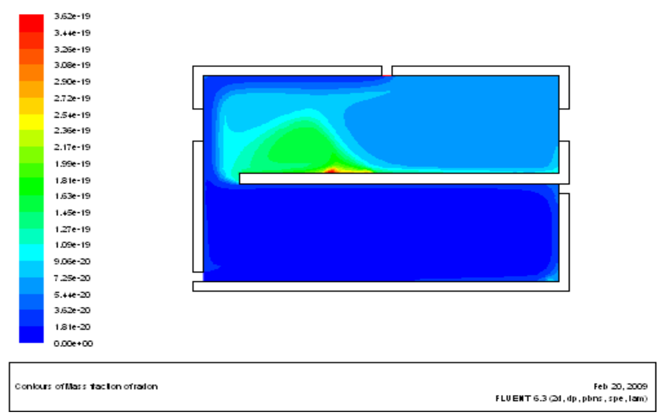

Fig .6, Radon mass fraction in displacement ventilation

In figure7, supply =exhaust fan at pressure jump 3 Pascal, exhaust fan =outlet= velocity inlet at 0.3 m/s and windows=wall

Max v=0.7, Max radon=4.5×10^{-19}

This case is set as mixing ventilation (MV), as we can see the radon content distribution are very different in MV and DV.

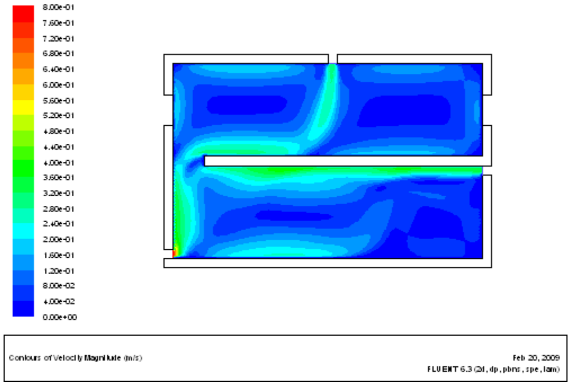

Fig .7, Radon mass fraction in mixing ventilation

With Comparing figure 6, displacement ventilation, and figure 7, mixing ventilation, the results indicate that the maximum level of radon is lower in first case such that confirmed the preference of DV for removing contaminants in the residential building, also observed that the ventilation rate is lower than MV, which means this case uses lower energy and it is can be used from energy saving view point.

7 Conclusions

This study confirms that with increasing ventilation rate, the radon concentration is decreased, but the position of ventilation system is also important. From the simulation, it is observed that some places, are good for living and somewhere is more polluted.

With using CFD we can predict the radon distribution and polluted areas and designing ventilation system for achieving comfort situation and energy efficiency point of views.

The model developed with FLUENT simulated radon entry through the material of a house in 3D and 2D models. The results showed that indoor radon concentrations are dependent on radon production, ventilation rates and its location. Therefore ventilation of a room can significantly influence radon measurement.

Also displacement ventilation because of effectiveness and lower energy consumption is preferred to mixing ventilation.

Since we can visualize the indoor radon distribution and temperature contours and also air flow velocity, CFD can help us to design energy efficient ventilation to optimize energy use and overcome to poor indoor air quality.

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