Simulation of Radon Mitigation in Residential Building with Ventilation

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Abstract

There are many indoor pollutants in the residential buildings. Of those radon is a major and harmful indoor pollutant in most countries. Radon sometimes entries to the house through building materials. High insulation and tightness in order to increase energy efficiency and to lower energy costs is led to the indoor air quality problems.
Ventilation is a good method to dilute radon contaminant and maintain indoor air quality. The more fresh air is brought into the indoor environment, the better the indoor air quality can be achieved, if the fresh air comes from non polluted ambient source. However ventilation can consume a lot of energy (currently 29-59% of energy building use), especially in cold climate same as Sweden, energy consumption could be much more. Though for coping with high energy consumption the building tightness is acted very well, but for ventilation plays against. This contradiction makes a poor indoor air quality. The aim of this paper is to simulate and visualize radon treatment and mechanical ventilation rates for achieving to indoor air quality.
The Fluent (CFD) program software is employed for simulation.

1 Introduction

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. Since whole-building ventilation is a significant contributor to annual energy use, the massive changes in ventilation rates that would be required to cause substantial changes in pollutant concentrations are not common.

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.

CFD is a microscopic modeling technique that provides a more detailed representation of the airflow, temperature, and contaminants in a zone using hundreds or thousands of nodes per zone.
Ventilation is a good method to maintain indoor air quality. The more fresh air is brought into the indoor environment, the better the indoor air quality can be achieved, if the fresh air comes from non polluted ambient source. However conditioning fresh air can consume a lot of energy (currently 29-59% of energy building use), especially in cold climate same as Sweden, energy consumption could
be much more. Though for coping with high energy consumption the building tightness is acted very well, but for ventilation plays as a bad role, i.e. reducing natural ventilation and increase mechanical ventilation with more energy use. This contradiction makes a poor indoor air quality. With respect to radon risks in polluted Swedish building is more dangerous, because radon breathing leads to lung cancer. Fluent CFD software program will be used for simulation of radon behavior and air flow in a room.

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. [1]
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. [2]

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. [3]

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.

It is well documented that ventilation has a strong influence on indoor radon concentration. Chao and his colleagues concluded that the indoor–outdoor radon ratio approached unity if the air exchange was greater than $3h^{-1}$. [4]

From view point of this paper, ventilation has two functions; the first is enhancement of IAQ and establishment of thermal comfort and the second is mitigation of contaminants; i.e radon.

Among from many mitigation methods to reduce radon in residential buildings, the ventilation method was chosen because of capability, facility and lower costs.

3 Governing Equations

3.1 ventilation rate

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

$$\varepsilon_v = (c_o - c_i)/(c - c_i) \times 100(\%) \qquad \textbf{(1)}$$

where

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

co=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. [5]

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. The expression below can be used to calculate the ventilation rate, Q, required maintaining the concentration of a particular pollutant within a desired value. [5]

$$Q = G/\{\varepsilon_v(c_i - c_o)\} \times 10^6 \text{ m}^3 \text{ s}^{-1}$$ **(2)**

where

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

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

Co=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. 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.

Researchers have studied the relationships between ventilation rates and indoor radon levels. Increasing the natural ventilation rates could reduce the indoor radon levels effectively (Chao et al., 1997). This outdoor air requirement mainly addressed the odour criteria with respect to human bio-effluents, including carbon dioxide. Although the ‘Indoor Air Quality Procedure’ should be considered for restricting the concentration of contaminants, it is a reasonable investigation to verify the extent of this guideline serving the purpose of radon mitigation (EPD, 2003). [6]

3.2 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. [7]

The indoor concentrations **C** at time t be expressed in terms of outdoor radon concentration $\boldsymbol{C_o}$, initial radon concentration of the room $\boldsymbol{C_i}$, the air exchange rate of the room $\boldsymbol{q}$, the effective volume of the room $\boldsymbol{V}$, the radon-222 decay constant $\boldsymbol{\lambda}$, and the generation rate $\boldsymbol{\Omega}$ of the room, $\boldsymbol{C}$ is then given by Equation (3).

$$C = \left[C_i - \frac{qC_o + \sum E_i A_i}{V((q/V) + \lambda)}\right] e^{-((q/V)+\lambda)t} + \left[\frac{qC_o + \sum E_i A_i}{V((q/V) + \lambda)}\right]$$ **(3)**

or,

$$C = (C_i - C_\infty)\, e^{-((q/V)+\lambda)t} + C_\infty$$ **(4)**

$\boldsymbol{\Omega = \Sigma E_i A_i}$ **(5)**

$$C_\infty = \frac{qC_o + \sum E_i A_i}{V((q/V) + \lambda)}$$ **(6)**

Determination of the sampled room leakage and decay rate ***(q/v+ λ), M:*** The equilibrium level of radon in the room sampled is dependent on the leakage rate, radon production rate and the outdoor radon concentration.

The room leakage rate can be deduced from the leakage and decay rate, ***M***. The value ***M*** is obtained by transformation and use of a linear regression technique

on Equation (41), as follows:

$$\ln|C_\infty - C| = -\left(\frac{q}{V} + \lambda\right)t + \ln(C_\infty - C_i)$$ **(7)**

or,

$$\ln|C_\infty - C| = -Mt + \ln(C_\infty - C_i)$$ **(8)**

where ***M*** is the absolute value of the slope of Equation (9), that is

$$M = \left(\frac{q}{V} + \lambda\right) \quad (9)$$

Quantifying the sampled room radon generation rate, **Ω**

The radon generation rate of the room can be expressed in terms of ***M***, ***C_o*** and ***C_i***, for which Equations (5), (6) and (9) are used to create the expression:

$$C_\infty = \left(\frac{q}{V} + \lambda - \lambda\right)\left[\frac{C_0}{((q/V)+\lambda)}\right] + \frac{\sum E_i A_i}{V((q/V)+\lambda)} \quad (10)$$

Substituting Equations (5) and (9) into Equation (10) and rearranging gives:

$\Omega = [C_\infty - (1 - \lambda/M)\, C_o] VM$ **(11)**

The relationship between the equilibrium indoor radon concentration ***C_∞***, and ***Ω*** from Equation (11) can be expressed by Equation (12):

$C_\infty = (1 - \lambda/M)\, C_o + \Omega/VM$ **(12)**

Replacing the leakage rate and equilibrium indoor radon concentration from Equation (10) by ***(q_n/V)*** and ***$(C_\infty)_n$***, respectively, gives:

$(C_\infty)_n = (1 - (\lambda/(q_n/V) + \lambda)\, C_o + \Omega/ V((q_n/V) + \lambda)$ ***(13)***

where ***(q_n/V)*** is a given air exchange rate and ***$(C_\infty)_n$*** is the equilibrium indoor radon concentration at a given air exchange rate and ***Ω/ V** is define as **G** generation rate per m³*.

$(C_\infty)_n = (1 - (\lambda/(q_n/V) + \lambda)\, C_o + G/ ((q_n/V) + \lambda)$ ***(14)***

For C_o=0 and (q_n/V) =0 *equation (14) simply reduced to:*

$(C_\infty) = G/\lambda$ ***(15)***

4 Exposure limits (Action levels) in some countries and organizations:

4.1 Sweden

Existing buildings (approximately 0.11 WL)*	400 Bq/m³
Remodeled or renovated houses (approximately 0.054 WL)*	200 Bq/m³
New houses (approximately 0.02 WL)*	70 Bq/m³

4.2 World Health Organization (WHO)

Existing buildings	0.11 WL

4.3 U.S.A.

148 Bq/m³ (less than 4 pCi/L or approximately 0.02 WL

Environmental Protection Agency 148 Bq/m³ 4 pCi/L or approximately 0.02 WL)

* 1 WL is taken to correspond to 100 pCi/L of radon concentration in the air.
1 pCi/L = 37 Bq/m³
0.02 WL = 148 Bq/m³ = 4 pCi/L
Source of data: Canadian Centre for Occupational Health and Safety

5 Data used in this study:

C_∞=250 Bq/m³, λ=2.9838e⁻⁶ s⁻¹, G= 5.246e⁻⁴ Bqm⁻³s⁻¹, radon diffusivity, D=10e⁻⁶ m²s⁻¹, air viscosity=1.75e⁻⁵Kgm⁻¹s⁻¹, radon viscosity=1.8 e⁻⁵Kgm⁻¹s⁻¹

1 Bqm^{-3}=1.75e^{-19} kgm^{-3}

1 kg radon=5.7e^{18} Bq [8]

Geometry: a room with sizes 5*10*2.2=110 m³,

Outdoor temperature 0 º C and Indoor temperature 20 º C

Radon emissions from the walls with 66 m², in Fluent the source terms defined with volume 5.74 m³ (one slice of the walls with 0.1m thickness).The total generation rate given from equation (15) with the specific volume of source terms can be calculated as:

G= 9.18e^{-23} $kgm^{-3}s^{-1}$*for 110 m³, then for 5.74 m³, G yields 1.77e^{-21}* $kgm^{-3}s^{-1}$

6 Simulations with FLUENT 6.3

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 ventilation positions, 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 quarter of first case ventilation rate(about 7.5 l/s), and instead of door, used an inlet supply.
Iterations were 10,000 and grid size 89783 cells for both cases.

6.1 Simulation results and visual comparison between cases:

Note: each figure has two pictures; the up picture relates to first case.

7 Results

CFD is a suitable and available tool for visualizing the behavior of harmful contaminants with low cost in comparison with the other methods same as gas tracer. The model developed with FLUENT simulated radon entry through the material of a house thar is located in basement. Indoor radon concentrations are dependent on radon production, ventilation and outdoor radon concentration. Ventilation of a room can significantly influence radon measurement.

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

In the second case with q/v=7.5 l/s, the average concentration yields 13.2 Bqm^{-3} and the maximum 329 Bqm^{-3}(Fig. 3, 4), this means that an exhaust fan with low exchange rate is suitable and adequate for the sampled room, whereas in the places in the right of the supply vent, there is a small area with the maximum pollution.

Fig. 1 Grids and meshes

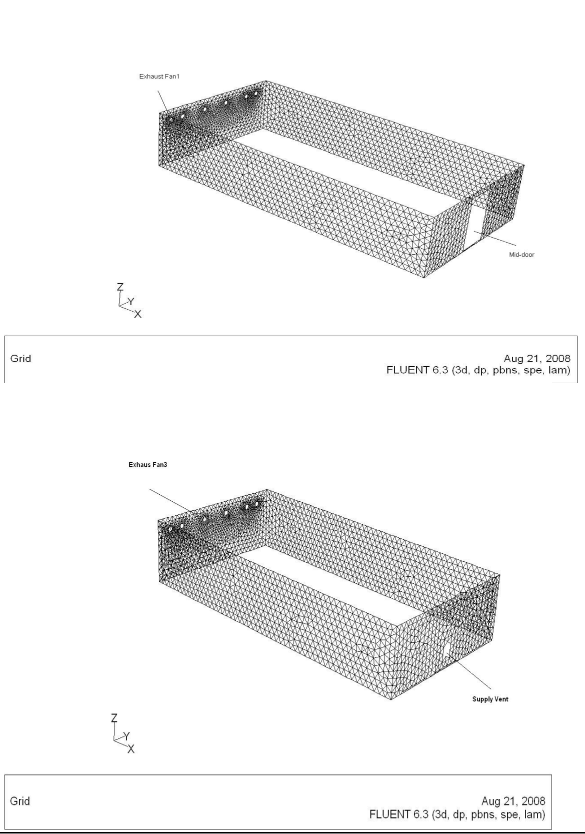
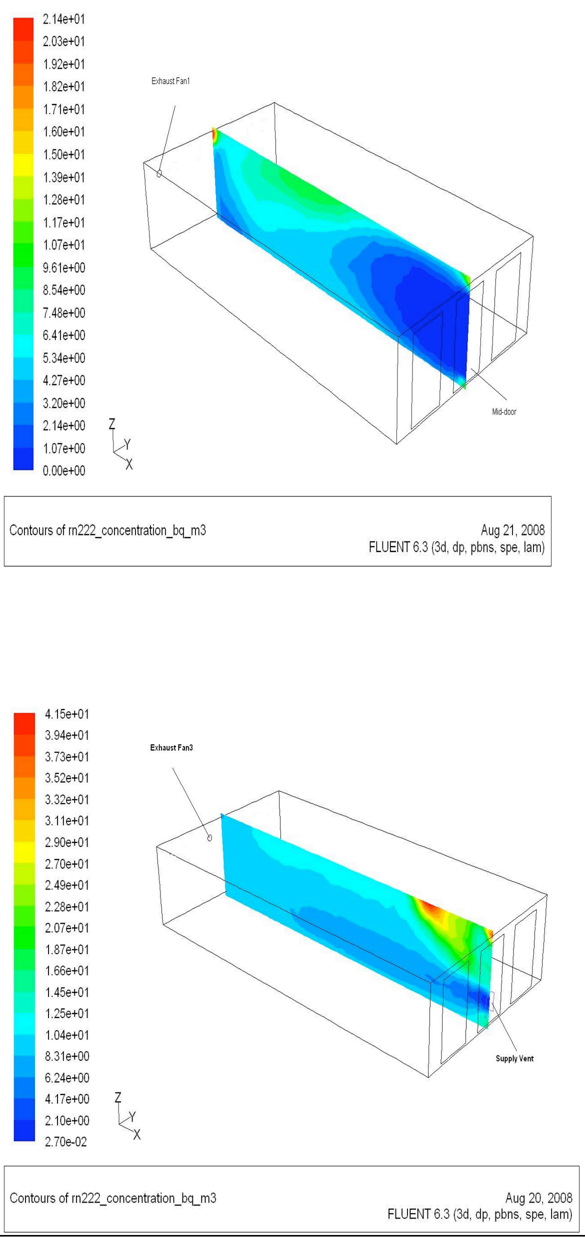


Fig. 2 radon concentration on y=0



8 References

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Figure 3, radon concentration near the floor

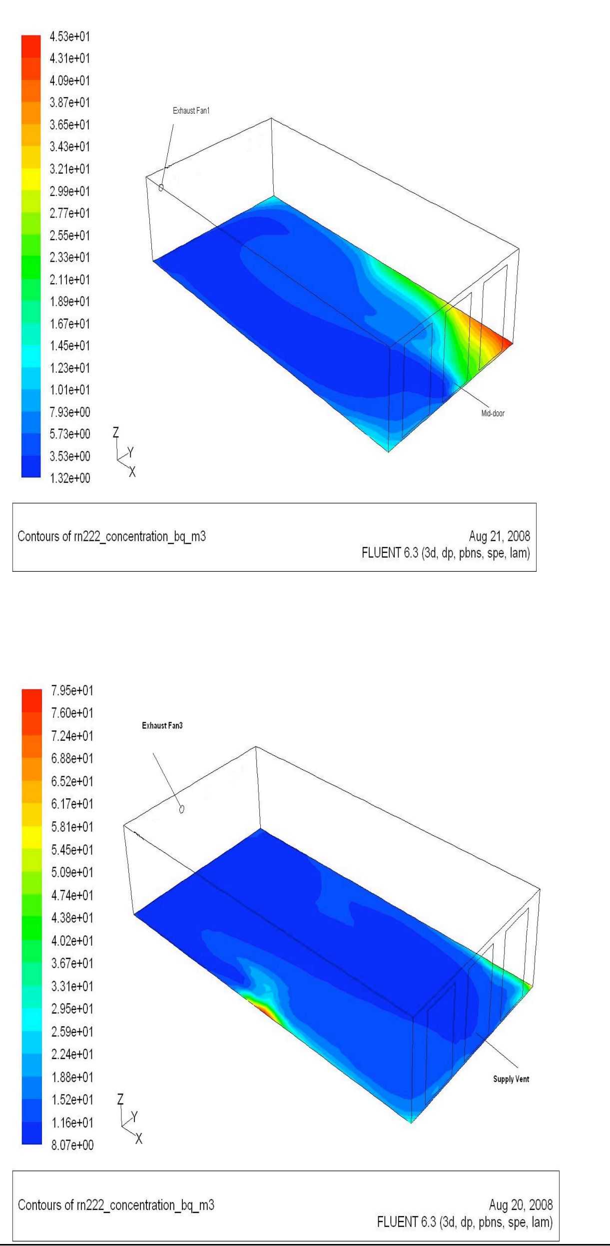

Fig. 4 Radon concentration at z=1.1m

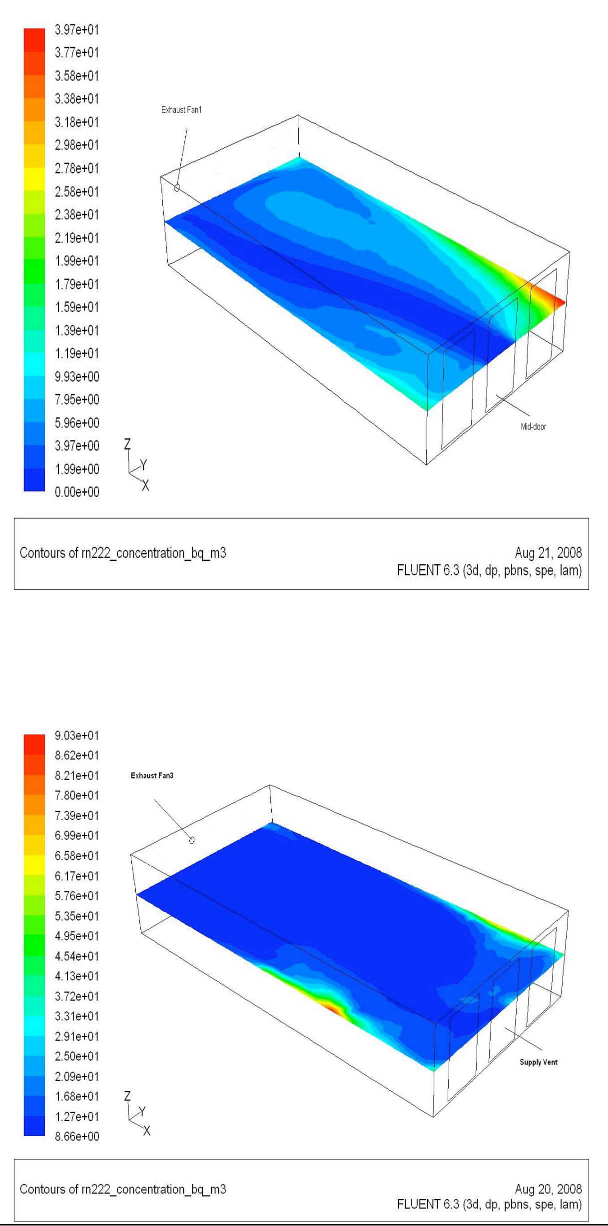

Fig. 5 Radon concentration near the ceiling