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IMPACT OF RADON VENTILATION ON INDOOR AIR QUALITY AND BUILDING ENERGY SAVING

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ABSTRACT

More than 90 percent of people in developed countries do live and work in closed and confined places; offices and residential buildings. This is why in this new world more fresh air which is generally provided by forced ventilation plays a vital role in living of human being. Furthermore due to exiting of different indoor pollutants, like radon and a lot of artificial pollutants, the amount of needed outdoor fresh air and in turn the energy consumption has been increased. Nowadays energy consumptions related to ventilation even has reached up to about 30-50 percent of energy used of building sector's share. So making interaction between indoor air quality (IAQ) and optimization of energy saving is a necessary research study.

Radon as a natural pollutant is occurred in environment and in many countries threatens people health whereas radon risk is known as the second causes of lung cancer. For reducing radon concentration in residential building at the standard level, forced ventilation is used usually.

The aim of this thesis is to study the impact of ventilation on indoor radon by using Computational Fluid Dynamics (CFD) to achieve indoor air quality and energy efficiency. Application of CFD as a new technology, because of its cost and time savings, and on the other side, of its flexibility is increasingly grown and can be used as a very important and valuable tool for the prediction and calculation of air and radon distribution in a ventilated room.

Currently, measurement techniques and standards and regulations of indoor pollutants and ventilation, particularly related to indoor radon cannot be able to provide a secure, safe and energy efficient indoor climate. This is why the indoor airflow distribution is very complex and with changing building geometry and operation condition, the treatment of air flow pattern, substantially will be changed, whereas the rules are usually independent of the buildings features. Furthermore, the indoor standards and regulations are based on average amount of pollutants in a room, whereas the pollutant distributions aren't identical and are varied throughout the room. Then the current techniques aren't exactly valuable and acceptable.

From different methods which are prevalent to control pollutants, ventilation method is applicable in existing buildings. Designing effective ventilation can reduce radon concentration to very level low with regarding energy conservation remarks.

This thesis presents results from experimental and simulation studies on ventilation and radon mitigation in residential buildings, in view points of indoor air quality and energy savings. The CFD technique is applied to predict, visualize and calculate of mixture radon-air flow. The distribution of indoor radon concentration, air velocity and room temperature also have considered together for achieving indoor air quality and energy saving. The results are also compared with the experimental data and related previous research studies.

In this thesis, it is assumed that some factors like ventilation rates, inlet and outlet locations and types of ventilation strategies can influence indoor radon distribution. It was found that with increasing ventilation rate, the radon concentration is decreased, but the location of ventilation system is also important. Displacement ventilation versus mixing ventilation can improve both IAQ (i.e. radon mitigation) decrease energy consumption. From the simulation results, it is observed that within the ventilated room, there are some zones, which are good for living and somewhere is more polluted. The traditional radon detectors basically show the average value of radon content in $1m^3$ of air. That is why detector measuring is not exact and safe. Simulation results proved that underfloor heating can be improved ventilation effects and it is useful to reduce radon content and energy consumption with lower ventilation rate. This research shows that with a rule of thumb, it is estimated, using the methods discussed here 30% energy saving is achievable.

SAMMANFATTNING

Syftet med denna uppsats är att undersöka effekterna som ventilation har på radon i inomhusmiljöer med hjälp av Computational Fluid Dynamics (CFD) för att uppnå kraven när det gäller inomhusluftens kvalitet och energieffektivitet.

Tillämpning av CFD som en ny teknik, på grund av dess kostnader och tidsvinster, dess flexibilitet och precision är allt som odlas och kan användas som ett mycket viktigt och värdefullt verktyg för att förutse och planera mätning av radon distribution i ett ventilerade byggnaden.

Traditionella mätmetoder och förslag till godtagbar standard och reglering av inomhusföroreningar och ventilation, särskilt i samband med inomhus radon kan inte ge ett säkert och energieffektivt inomhusklimat. Luftflödets distribution är mycket komplext och föränderlig med byggnaders geometri, driftförhållanden, luftflödets mönster och behandling och borde ses över.

Av de metoder som har privilegiet att kontrolleraföroreningar, ventilation metod är i befintliga byggnader. Attplanera en effektiv ventilation kan minska radonhalten nivåmycket låg med om energisparande.

Denna avhandling presenterar resultaten från Simuleringar över hur ventilationen påverkar radon i bostadshus, med tanke på inomhusluftens kvalitet och energibesparingar. CFD-teknik har tillämpats för att förutsäga, visualisera och mäta radon-luft-blandningar. Trots att fördelningen av inomhus radonhalten, lufthastighet och rumstemperatur skulle beaktas tillsammans för att uppnå inomhusluftens kvalitet och energibesparing.

Det konstaterades att radonhalten minskade med ökad ventilation, men placeringen och utformningen av ventilationssystemet är också viktigt.

Från simuleringens resultat kan det konstateras att inom det ventilerade utrymmet finns vissa områden som går bra att bo inom och andra som är mer förorenade. De traditionella radon detektorerna visar det genomsnittliga värdet av radon i luften. Därför är inte dessa mätningar så exakta och tillförlitliga.

Resultatet av simuleringarna visade att golvvärme kan stödja Ventilationrens verkan och påskynda omblandningen. Golvuppvärmning förstärker flytkraftsegenskaperna effekt, vilket är användbart för att minska radon i golvet (sittområde) och sedan lägre ventilationsgraden kan tillämpas.

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List of papers

This thesis is based on the following papers:
Paper I- Keramatollah Akbari, Jafar Mahmoudi, ***Experimental and Numerical Study of Radon Mitigation and Ventilation Effects,*** submitted to Indoor Building and Environment Journal, Ref. No.: BAE-D-09-00702

Paper II- Keramatollah Akbari, Jafar Mahmoudi, ***Simulation of Radon Mitigation and Ventilation in Residential building,*** printed in the 49th Scandinavian conference on Simulation and Modeling (SIMS 2008), ISBN-13-978-82-579-4632-6.

Paper III- Keramatollah Akbari, Jafar Mahmoudi, Robrt Öman, ***Ventilation Strategies and Radon Mitigation in Residential Buildings,*** submitted to Indoor Air International Journal of Indoor Environment and Health, ID: INA-09-09-156

Paper IV- Keramatollah Akbari, Jafar Mahmoudi, ***Influence of residential ventilation on Radon mitigation with energy saving emphasis,*** Scientific Conference on "Energy system with IT" March 2009, Stockholm, ISBN number 978-91-977493-4-3

Nomenclature and abbreviations

Latin and Greek letters

A	surface area [m^2]
C, C_b, C_∞	radon concentration [Bqm^{-3}]
C_p	specific heat capacity [j $kg^{-1}.k^{-1}$]
D_h	hydraulic diameter [m]
E	radon exhalation (emanation) rate [$Bqm^{-2}s^{-1}$]
G	radon generation rate [$Bqm^{-3}s^{-1}$]
H	convective heat transfer coefficient [$Wm^{-2}K^{-1}$]
K	turbulent kinetic energy [m^2s^{-2}]
M	room decay and leakage rate
M_w	molecular weight
P	pressure [pa]
q, q_v, q_n	ventilation rate [h^{-1}or s^{-1}]
Re	Reynolds number
T	temperature [K]
U,v	velocity [ms^{-1}]
V	volume [m^3]
h_c	heat transfer coefficient [$Wm^{-2}K^{-1}$]
y^+	normal-distance Reynolds number (y plus)
Sc_t	turbulent Schmidt number
D_t	turbulent diffusivity [m^2s^{-1}]
k	thermal conductivity [W/m-K]
j_d	diffusive flux density [$Bq\ m^{-2}s^{-1}$]
D, D_e	effective diffusion coefficient [m^2s^{-1}]
λ	radon decay constant [s^{-1} or h^{-1}]
ρ	density [kgm^{-3}]
ε	turbulent dissipation rate [m^2s^{-3}]
ε_v	ventilation effectiveness
μ	molecular viscosity [Pa. s]
μ_t	turbulent viscosity [Pa. s]
ν	kinematic viscosity [$m^2\ s^{-1}$]

Abbreviations

ASHRAE	American society of heating, refrigerating and air conditioning engineering
Ach	Air change
BES	building energy saving
BRI	building related illnesses
CFD	computational fluid dynamics
CFM	Cubic feet per minute
DNS	direct numeric simulation
HVAC	heating, ventilation and air conditioning
IAQ	indoor air quality
LES	large eddy simulation
Rn	Radon-222
SBS	sick buildings syndrome
VOCs	volatile organic compounds
2D	two dimensions
3D	three dimensions

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Chapter 1

Introduction

People in developed countries, usually spend more than 90 percent of lifetime in confined and closed places, i.e. in homes, offices and transportation vehicles, particularly more than two thirds of this time is spent in residential buildings. Buildings must protect people from heat, cold, sunshine, noise, pollutants and any other inconveniences as a shelter, these human shelters are not safe now, because there are many indoor pollutants in the residential buildings. All pollutants make indoor air quality problems by affecting human health, productivity and comfort conditions and they are increasing in time [1, 2]. Poor indoor air quality leads to two types of building illnesses: sick building syndrome (SBS) and building related illness (BRI) [2].

Buildings task is to provide a healthy and comfortable indoor environment in which people can do work and live. The indoor environment must provide a pleasant thermal comfort, have enough fresh air, draughts and acceptable level of pollutants; generally building ventilation is responsible to provide these tasks [3].

Indoor air quality is an important issue related to human being health and productivity. An acceptable indoor air quality is defined as air in which there are no known contaminants at harmful levels and to which a substantial majority of the people are not dissatisfied. The quality of the indoor air depends on both the quality of the outdoor air and on the strength of emissions from indoor sources. To satisfy comfort and health needs, indoor air must have a required quantity of tempered and clean outdoor air without any chemical or microbiological hazardous contaminants. Building operation, occupant activity and outdoor climate substantially affect indoor air quality [4]. Generally ventilation can be used to keep and maintain an acceptable level of IAQ.

The purpose of ventilation is to provide indoor air quality and thermal comfort. Providing a desired ventilation system to achieve these factors are important concerns for occupants and building constructors because ventilation affects health, comfort and productivity within residences. In viewpoint of energy consumption ventilation systems give concerns about economy. Occupants normally tend to decrease ventilation rates, and this in turn leads to poor IAQ problems. Energy saving policies, which started in the early 1970's resulted in air tightness of building envelopes and constriction of supply air inlets to lower the energy consumption, consequently with deteriorating indoor air quality.

There are several kinds of indoor pollutants with different effects of comfort and health that influence the quality of indoor air. The pollution sources are divided into following categories as: Occupants, smoking, building products and furniture, radioactive ground and building materials, office equipment, pets and other sources of allergen, and outdoor pollutants [3- 5].

Radon in our environment is as radioactive ground gas which exists in soil, water, air and some natural gas. It is almost 7.5 times heavier than air and comes from the normal decay of uranium. Because it is a gas, it can easily move through soil and water and enter the atmosphere. It is an invisible and natural radioactive gas and like Carbon Monoxide, it is also colorless, odorless and tasteless, so the only way to know about elevated radon gas concentrations is to test. Radon is a naturally occurring radioactive noble gas which exists in several isotopic forms. Only two of these isotopes occur in significant concentration in the general environment: radon with molar weight 222 gram (usually referred to as "radon (Rn)"), a member of the radioactive decay chain of uranium-238, and radon with molar weight 220 gram (often referred to as "thoron"). Radon can easily leave the place of production (soil, rock and building materials) and enter the indoor air. The contribution made by thoron to the human exposures in indoor environments is usually small compared with that due to radon, because of its much shorter half-life (55 seconds vs 3.82 days) [6].

Radon gas itself is rather harmless but for the alpha particles emitted by short lived decay "daughters" can make adverse health problem and has been identified as the second largest cause of lung cancer after smoking. Contaminated air of radon products can irritate cancer of respiratory tracts and lungs and settle on the walls of these organs. These decay products are not inert and often attach themselves to airborne particulates which may then enter the lungs and it caused respiratory tract and lung cancer. Sometimes, the alpha radiation will decay as a radon product while the gas is inside the respiratory system. In the long term (15-40 years), alpha radiation may give rise to lung cancer [2, 5, 6].

Radon concentration in SI unit is measured in becquerels per cubic meter of air (Bq/m^3), and the unit more commonly used in the United States, is picocuries per liter (pCi/L), 1 pCi/L is equal to 37 Bq/m^3. One Bq/m^3 is defined as one radioactive atom disintegrated per second per cubic meter of air. A radon concentration value of 4 pCi/L or about 150 Bq/m^3 is usually used as a maximum permitted level for calculating ventilation rates, this value usually called threshold limit value or action level [2, 5].

Studies have done during the past thirty years show the wide-scale presence of radon in residences throughout the world. The sources of radon have been understood and mitigation systems are used in many countries [7].

The major sources of radon are soil and rocks with a high content of uranium. The radon concentration of the ground depends on location, its permeability and radon decay products. The foundation of building can introduce radon to the indoor air by infiltration. Radioactive building material (shale based lightweight concrete) is also source of radon of indoor air. These particles normally have small penetration depths and they only form a health risk if inhaled, damage to the lining of the lungs could occur posing the risk of cancer. Radon levels vary widely, but the gas is particularly prevalent in areas of granite or limestone, especially where these rocks make up the building materials. [6].

Radon in soil and rocks mixes with air and rises to the surface where it is quickly diluted in the atmosphere. However, radon which enters enclosed spaces and buildings, can reach relatively high concentrations in some circumstances, especially in buildings with insufficient ventilation. Some studies have shown, even buildings with double pane windows have much radon rather than one pane windows [8].

Elevated radon level is one of the major and harmful indoor pollutants in most countries, for examples in the Scandinavian countries, the U.S., U.K, Hong Kong and etc. 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. Building materials are generally the second main source of radon indoors. High insulation and air tightness in buildings in order to increase energy efficiency and to lower energy costs has been led to the indoor air quality problems. Radon is estimated accounts for more than 3000 and 20000 lung cancer deaths in the UK and US each year, respectively [5, 7].

The general methods to control level of indoor pollutants are: source control, e.g. removal, replacement by an alternative material, sealing, dilution or removal by ventilation and air cleaning. Of these ventilation method is a cost effective and applicable method to dilute radon contaminant and maintain indoor air quality in existing buildings. The more fresh air is brought into the indoor environment, the better the indoor air quality can be achieved, if the fresh air lacks of any polluted outdoor sources. Sometimes ventilation in the form of exhaust fan or stack vent can reduce of radon entry from soil through depressurization of subfloor spaces [6].

Ventilation blows fresh outdoor air within the room and with its mixing and dilution can decrease the pollutant concentrations. Pollutant concentrations are inversely proportional to ventilation rates [9]. Providing fresh and clean air by means of ventilation is a necessary factor for survival of human beings, however ventilation can consume a lot of energy especially in cold climate as in Sweden. Increased ventilation rates will in turn increase energy consumption.

Currently in most countries energy consumption in building section is more than 40 percent and the contribution of ventilation is in the range of 29- 50 percent. It is important from energy conservation point of view that ventilation rates should not be excessive, but at the same time an adequate supply is needed to ensure good indoor air quality. The preferred method for controlling the level of pollution depends on the pollutant(s) of concern. If the main pollutants are bio-effluents from human beings, dilution by ventilation is the only realistic method of improving the air quality. In contrast, combustion products are most efficiently removed by local ventilation at the point of generation. The preferred methods may also vary for different building types [3]. It is approved that ventilation has considerable influence on indoor radon concentration. For example for air exchange more than $3h^{-1}$ the indoor radon can be equal to outdoor radon content [10].

Computational fluid dynamics (CFD) can be used as a useful tool to simulate indoor air flow and designing ventilation rate to improve IAQ and energy saving implications. This technique, allows simulation and visualization of environmental problems at low cost [11]. Indoor environmental design requires detailed information about air distribution, such as airflow pattern, velocity, temperature, humidity, and pollutant concentrations. As experimental measurement cannot be a practical design tool, various numerical methods have been developed to simulate these details within the indoor environment [12].

Although some studies have been conducted to predict and measure indoor air flow and pollutants concentration in residential buildings by numerical methods and using CFD techniques but these are in the primary research stage.

There are several limitations about CFD modeling of indoor air pollutant concentrations [13] and also in this work it is supposed some assumptions made for simplicity and computational ability. These limitations and assumptions can be developed by the other CFD methods and considering more complicated building or room in the future studies.

1.1 Problem definition

In some residential buildings, radon is a significant problem in view points of IAQ, health adverse effect and for achieving IAQ much more energy consumption is also needed which is wasted and extracted by means of forced and natural ventilation. Breathing radon for a long times causes lung cancer which is the second largest cause of lung cancer throughout the world. Improving the air tightness of a building is accepted as a common strategy to reduce energy consumption, unfortunately it leads to poor IAQ and in the case of radon; building tightness threatens occupants' health. So radon mitigation and keeping it at limited level is a mandatory regulation for the government in most countries.

Radon sometimes comes into the buildings through building materials and in winter time reaches to higher level than other time because of closing air inlets, i.e. doors and windows, especially in cold climate, like Sweden.

Currently, the common method for testing and reducing radon content is installing radon detectors in some points of into the polluted rooms, these detectors show the average level of indoor radon per a cubic meter of indoor air, in a short or long times, generally from a couple of weeks to a couple of months. After determining of average radon level, by providing required ventilation rate, the radon concentration is measured again to reach a limited or standard level. This method is time consuming and with respect to IAQ and energy saving may not so accurate. Because in spite of achieving to the average limited level of radon, there are still some areas with upper standard pollution or sometimes over ventilation may be occurred.

The replacement of current methods for predicting and designing indoor air quality and studying air flow by CFD are widely used. Since CFD techniques besides of high speed of today computers could overcome air flow complexity into the room with spending lower cost and time and it is possible to design accurate ventilation system in view point of energy saving measures and IAQ.

The CFD technique can be used as a tool to optimize energy consumption and compromise between energy saving and IAQ. The goal of the CFD program is to find the temperature, concentrations of contaminants, and the velocity throughout or each required point of the room. This will reveal the flow patterns and the pollution migration and distribution throughout the room.

In this thesis CFD method is employed as a complementary tool to simulate and visualize radon concentrations in ventilated room. With this method, it is possible to calculate, visualize and predict indoor radon distribution.

1.2 Objectives

The main aim of this thesis is to survey the influence of ventilation on radon mitigation with experimental and numerical methods in viewpoints of energy savings and indoor air quality
Other objectives are as followings:
-Using CFD to simulate and predict of radon distribution in the residential buildings,
-The effect of ventilation systems on indoor radon,
-The effect of ventilation rates and locations on indoor radon and energy saving,
-The comparison of two ventilation principals and radon mitigation and energy saving and
-The effect of underfloor heating on radon mitigation.

Papers I to IV discuss the above objectives and questions. Future studies will focus on heat recovery ventilation and energy saving in residential buildings.
Paper I- Experimental and Numerical Study of Radon Mitigation and Ventilation Effects
Paper II- Simulation of Radon Mitigation and Ventilation in Residential building
Paper III- Ventilation Strategies and Radon Mitigation in Residential Buildings
Paper IV- Influence of residential ventilation on Radon mitigation with energy saving emphasis

1.3 Scope and thesis outline

The scope of this thesis has been focused on indoor air quality and energy saving in residential buildings with specified geometry and constant amount of radon in which emits only through building material, particularly from the basement foundation. Modeling and simulation is carried out by CFD, FLUENT package because of its abilities to solve species model conflation with energy (heat), air flow in two and three dimension. Experimental test and former research studies are used to verify the results.

This thesis comprises 6 chapters as following:
Chapter 1 begins with; introduction, problem definition, objectives, thesis outline and methodology.

Chapter 2 continues with background and review of; radon mitigation methods, ventilation types and standard rates, radon transport trough building materials, energy saving considerations and CFD modeling of indoor air flow and species transportation.

Chapter 3 comprises governing equations of continuity, mass, energy, momentum and species in two and three dimension, materials properties and required calculation of input data to CFD, Fluent package.

Chapter 4 includes numerical solution; geometry, grids, boundary and initial conditions, internal validity.

Chapter 5 includes results and discussion.

Chapter 6 ends with concluding remarks and future work.

1.4 Methodology

In this licentiate thesis, studies were conducted in both numerical and experimental studies. This thesis based on previous related studies on ventilation and radon reduction in residential building, factors such as ventilation rate and location, comparison of two main ventilation principal and effects of floor heating are investigated.

In the numerical study CFD technique was used and FLUENT package employed to establish a particular model by developing and examining the validity of the model. The model is applied to simulate a typical house in which radon migrates in the basement through the floor from the building materials. Such methodology has been used in some related studies about indoor air flow and pollutants concentrations. The experimental data and a previous research study are used for verification of simulation results. The validity of this model is also performed by a series of numerical verifications includes grid independency and convergence tests.

Chapter 2

Background and literature review

This chapter presents details about radon mitigation methods in residential buildings, ventilation strategies and their impact on radon mitigation, Standard rates and effectiveness of ventilation, radon transport mechanisms trough building materials, review of radon mitigation and energy conservation and review of computational fluid dynamics (CFD) techniques in indoor air quality.

2.1 Radon sources and mitigation methods in residential buildings

2.1.1 Radon sources

Radon is a major pollutant and radon exposure is an international problem. Attention to this problem and the associated health risks has been growing throughout the world and more than 50 countries now have ongoing projects and have established regulation mandatory[14]. According to American Environment Protect Agency (EPA), Radon is estimated to cause many thousands (about 21000) deaths each year. Figure 2.1 compares the numbers of deaths from other sources with radon health risks [15].

In most countries like the Scandinavian, the U.S., U.K., Hong Kong, etc., radon sometimes enters to the house through building materials. High insulation and air tightness in buildings in order to increase energy efficiency and to lower energy costs have been led to the indoor air quality problems.

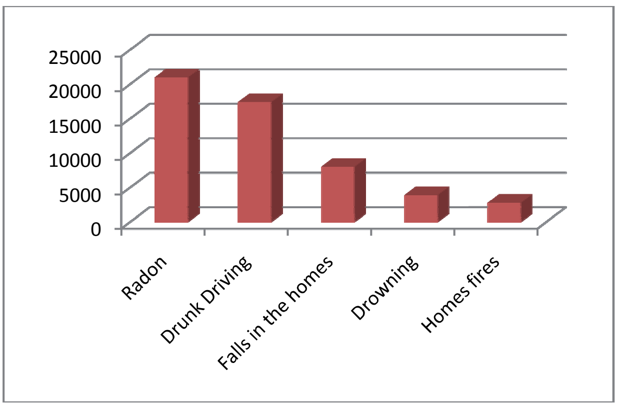

Figure 2.1, Radon health risks [15]

Radon sources are generally from ground, water and building materials. Radon is a serious environmental problem in Sweden that is caused by soil and bedrock. There are large traces of Swedish bedrock consist of uranium-rich granite and pegmatite. A large proportion of the buildings in urban areas are built in districts with uranium-rich rock on high permeability soils. About 300,000 buildings include uranium-bearing building materials in the form of lightweight (blue) concrete has been used for external and internal walls and sometimes also for floor structure. In houses in which a substantial proportion of the building material consists of such concrete, the radon content is always elevated. Radon exhalation (emanation) rate from building materials in some Swedish buildings built during 1929 and 1975 varies from about 0.02 – 0.07 Bq/m^2s [16].

Table bellow shows the radon content in building materials at a number of places built in during 1929- 1975 in Sweden [14].

Material	Radium content Bq/kg	Radon exhalation Bq/m^{2}h
Sand-based lightweight concrete	10-13	1-3
Alum shale-based lightweight concrete	600-2600	50-200

Table 2.1, radon content and exhalation rate in Swedish building materials

Sievert (1956) studied gamma radiation and radon in Swedish dwellings and pointed out in that the radiation dose in the lungs from radon in dwellings could be significant. Swedjemark in 1990 stated that building materials containing radium-rich substances could make a problem for occupants [16].

In Sweden, about of 10 percent of the dwellings are built of a concrete, alum-shale based aerated concrete, containing more radium-226 than normal [7]. In early 1980's, 1975 Swedish homes were measured and the average of radon concentration was 100 Bq/m3. In this distribution 10 percent exceeded 200 Bq/m3 and 1 percent was more than 800 Bq/m3 [17]. It means that radon content of 10 percent of these houses exceeded limited level.

The radon content in dwelling varies during the day and season. This due to various factors as: ventilation rate, building layout, wind influence, temperature difference between indoor and outdoor, which creates stack effect and use of cooker hood which increases the ventilation rate and also indoor humidity and pressure. Concentrations of radon are generally higher at night and during the winter [16].

The content of indoor radon depends on, the entry rate of radon from soil and building materials and the ventilation rate of ambient air having much lower concentration. These parameters are normally influenced by the characteristics (design, location, material of construction, occupant habits, etc.) of the buildings. Since residences are varied in structure and consist of set interconnected rooms, the study of the indoor radon concentration is a complicated task. Because of these complications, it is assumed that the amount of radon flow rate and climate situations are constant.

2.1.2 Radon mitigation methods in residential buildings

Principally, there are three types of radon mitigation methods, sealing entry routes, soil depressurization and ventilation [7]. The first step to develop and choose an effective mitigation strategy for indoor air pollutants is to develop an understanding of the pollutant sources. In this study, it is supposed that the source of radon is only from building materials and thereby ventilation method is used to mitigate radon content in built residential building because it is applicable and cost effective method.

Many studies have been carried out on radon mitigation and influence of ventilation to reduce concentrations in residences. These studies showed sub-slab ventilation could be most effective control strategy to reduction radon concentration with a median reduction of 98 percent (2900 Bq/m^3 to 50 Bq/m^3) [18] and the effectiveness of radon mitigation in subsurface ventilation by pressurization was always more effective than sub-slab ventilation by depressurization in reducing the radon concentrations with using of five different techniques: sealing of cracks and holes; house ventilation with heat recovery, pressurization of the basement; subsurface ventilation (pressurization and depressurization); and crawl-space isolation and ventilation [19].

The result of radon mitigation in some houses in Finland shows a range of 38 to 91 percent indoor radon reduction. Table 2.2, shows summary of results presented by Arvela and Hoving [20].

Strategy	Number of Houses	Median Reduction percent
Sub-slab depressurization (floor)	15	66
Sub-slab depressurization (foundation wall)	32	91
Crawl-space ventilation	7	75
Increased ventilation	34	38

Table 2.2, results of radon mitigation with different strategies

Saum (1991) investigated the use of smaller, more efficient fans for sub-slab depressurization systems and observed that, these systems with a 45 watt fan suggest a 95 percent reduction in indoor radon levels can be achieved. The author proposed that a 10 watt fan should perform closer to the 45 watt fan than to the very weak passive stack systems. With studying an old house with no slab sealing and poor sub-slab aggregate, it was observed a 10 watt "mini-fan" lowered the radon from 370 to 80 Bq/m3 or a 79 percent reduction. A 45 watt fan lowered the radon level to 30 Bq/m3 which is a 92 percent reduction [21].

Nuess and Prill (1990) carried out an experimental pressurization control system in Spokane, USA, and concluded that if heat recovery is used to enhance energy efficiency, there is no extra cost for radon mitigation [22].

Hamel (1995) investigated radon mitigation methods in 18 houses in Germany, and reported that increasing the ventilation rates in the houses improve the radon level and lower to 50 percent [23].

Cavallo and et al (1990) studied the effectiveness of natural ventilation in single family houses. Before natural ventilation radon in the basement was about 3,300 Bq/m^3 and after window opening the level fell to 370 Bq/m^3 [24].

An experimental work of reducing radon concentration in a Swedish single house carried out by JBS AB Company. Two exhaust fans were installed in the cellar; the radon concentration before installation of these ventilators was about 270 Bq/m3 and after using exhaust fans the result was around 150 Bq/m^3 (see appendix A) [25].

Sometimes using plastic-coated wallpaper together with a layer of plaster can decrease radon emission to half. If the surface is also coated with acrylic paint, the radon exhalation will be very low. Note that when one side of the wall is covered with a tighter surface layer, the radon exhalation from the other side will increase substantially [16].

2.2. Energy consumption in building sector

Building energy uses account for approximately 40% of total primary energy use in developed countries. This sector generally uses more energy in comparison with industrial and transportation sectors. Ventilation system type can have a significant impact on energy use. Ventilation plays a crucial role in relation to the indoor pollution levels but it is also of importance in relation to the management of outdoor pollution levels. Ventilation has also an impact on the outdoor pollution level. Building related pollution sources represent about 40% of the total pollution load [3]. As shown in figure 2.1, the building sector consumes more than 50 percent of which is used for ventilation [1].

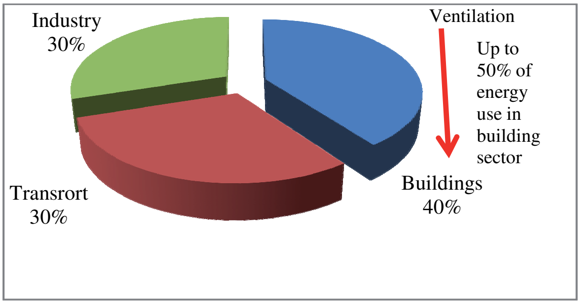

Figure 2.2, Ventilation energy use in building sector; source European commission, Report No 23[1].

Thermal loads connected with the heating/cooling of the air exchanged between outdoors and indoors form a high proportion of thermal loads in buildings. A significant reduction in energy consumption could be achieved if heat losses through the building envelope were decreased (e.g. by thermal insulation, multiple glazing). Energy losses due to ventilation can be reduced by using efficient ventilation technologies (e.g. heat recovery, demand control, etc.).

IN Sweden, the use of electricity for domestic purposes doubled between 1970 and 2005, from 9.2 TWh to 19.7 TWh, with most of the increase occurring during the 1970s and 1980s. This rising use can be explained by an increase in the number of households, greater ownership of domestic appliances and greater ownership of electronic equipment. In 2005, average domestic electricity use amounted to about 6200 kWh in detached houses, and in apartment buildings to about 40 kWh68 per m² and year which, for a 66 m² apartment, means an annual electricity of 2640 kWh/year. To refine this data, the Swedish Energy Agency is carrying out a metering investigation over the period 2005-2007, to break down electricity use into more detailed purposes. The use of electricity for building services systems has increased substantially, from 8.4 TWh in 1970 to 31.1 TWh in 2005. The reasons for this development include rapid growth in the service sector and greater use of office machines and comfort cooling [26].

2.3. Ventilation and radon mitigation

Generally ventilation means fresh air which is necessary for good health, comfort and productivity all the time. A standard amount of fresh air is required by occupants, even though there is no indoor pollutant, which is called standard ventilation rate.

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 [31]. Insufficient ventilation or a very high load of pollutants promotes a sick indoor environment. Infiltration is the air from outside that leaks into a building in an uncontrolled manner and will impact negatively upon the energy efficiency of the building and thermal comfort.

Ventilation of a room can significantly influence radon measurement. The relationship between radon concentrations and indoor air exchange rate is illustrated [10] as shown in figure 2.2.

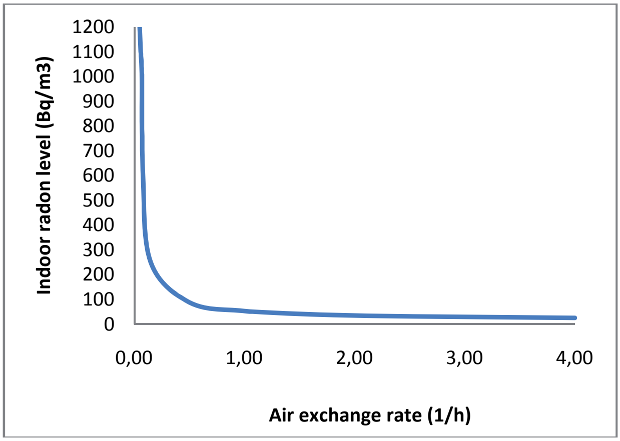

Fig. 2.3, Indoor radon level vs. ventilation rate (source see reference [10])

Pollutant control in most residential buildings is obtained using ventilation to dilute pollutant concentrations. In simplest terms, steady-state pollutant concentrations are inversely proportional to ventilation rates which are determined from equation (3.14). 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 [7,24]. In Sweden maximum permitted level of radon is 200 Bq/m^3 versus about 0.5 Ah^{-1} and ASHREA recommends 150 Bq/m^3 versus about 0.25 Ah^{-1} [27].

Condensation because of relative humidity can increase some indoor pollutants. A ventilation rate of between 0.5 and 1.5 air changes per hour (ach) for the whole dwelling will usually be sufficient to control condensation. In figure 2.2, the required ventilation rate in residential buildings to control some pollutants is specified [28].

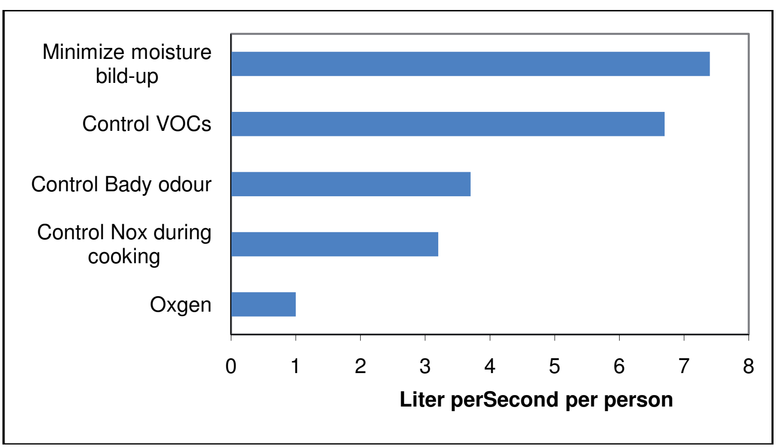

Fig. 2.4, Ventilation rates to control pollutants (Source: derived from Approved Document F (2006)) Energy efficient ventilation in dwellings

The influence of ventilation system on pollutants and energy consumption are described in the following section.

2.4 Influence of Ventilation Systems on pollutants and energy consumption

Ventilation types used for indoor air quality control are; natural ventilation and mechanical ventilation, or combinations of both, called hybrid ventilation. The choice of which to use generally depends on indoor heat gains, occupant usage patterns, energy saving considerations, outdoor noise and air quality and indoor pollutant concentrations.

2.4.1 Natural Ventilation

The basic form of opening of windows and doors is called natural ventilation. This is generally the most cost effective and environmentally friendly form of ventilation. However, windows can cause localized 'discomfort zones' due to draughts and cold radiation in winter or solar gain in summer. Therefore natural ventilation is not recommended for radon mitigation because it is no reliable, hard to control and cannot recover exhaust air energy [29].

2.4.2 Mechanical ventilation

Two main principles of mechanical ventilation in residential buildings are called mixing ventilation and displacement ventilation.

In mixing ventilation usually the outdoor air is supplied into indoor at relatively high velocity, about 1 m/s from near the ceiling space, to produce enough mixtures of supply (fresh) and indoor air (Figure 2.4). Mixing ventilation causes a high degree of mixing to take place within the room, but the temperature and contaminants distribution don't change enough in the whole room. In fact, the main aim of ventilation doesn't meet by means of mixing ventilation system. Compared with the air velocity near diffuser, the air velocity in occupied zone is lower. But for the human body, such velocity sometimes brings draught to people and with the increased heat load indoors, the velocity in occupied zone will be higher. This will mean the mixing ventilation system needs more energy consumption [30].

Fig.2.5. Mixing ventilation regarding to contaminant concentration [30]

In displacement ventilation, clean and fresh air is supplied relatively cool near the floor and at a low velocity about 0.3 m/s (figure 2.5). Supplied air which is normally 3-4 °C lower than the indoor air temperature, spreads and this air from the lower part of the room is induced upward by rising convection flows from heat sources in the room and is then extracted at ceiling level. In this case of ventilation the buoyancy forces created by heat sources, govern the air flow. Using these forces help to supply air at lower temperature in occupied zone. Displacement ventilation is applicable in cooling situations, and is used in buildings with large occupancy and large thermal loads [26, 27]. In this ventilation, when supplied air meets a heat source, a convective thermal plume is generated due to the temperature difference and resultant buoyant force, which acts as a channel through which the warmed and polluted air goes upward to the ceiling area and it exits through the exhaust. This type of ventilation is energy efficient because the air in the room is allowed to stratify "i.e. the air temperature increases with height" which produces the desired temperature in the occupied zone but the extract air temperature is higher. However, in a normal mixing system the extract air temperature is almost the same as the room temperature because of the mixing effect. In practice, this means supplying fresh air at low velocity (typically <0.5 m/s) near the floor directly into the occupied zone with a temperature only a few degrees (up to 4 K) below the room temperature [30].

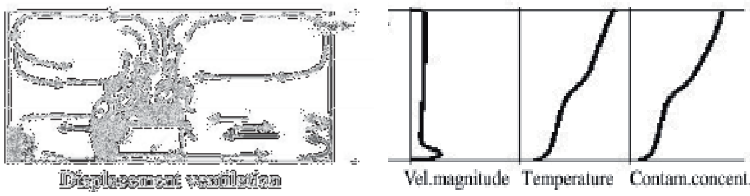

Fig.2.6.Displacement ventilation regarding to contaminant concentration [29]

2.4.3. Balanced and continues ventilation

As in the following are discussed, some ventilation strategies are better to achieve IAQ in residential building in terms of radon, for example balance ventilation and continuous ventilation in view point of radon mitigation.

Balanced ventilation systems use both an exhaust and a supply fan, while unbalanced ventilation systems use either an exhaust or a supply fan. Exhaust and supply fans are functionally identical except for the direction of airflow. ‘Balanced’ systems are not actually balanced unless both fans move air at the same rate and time. Balanced systems do not change indoor pressure relative to atmospheric pressure.

Whenever exhaust fan is used in a house with suspected infiltration of radon from the soil the system should be of the balanced supply-exhaust type. Balancing the system to a neutral pressure, and regular maintenance will be essential. Considering these demands, ventilation can be a good supplementary remedial tool, especially in cases where the building materials contribute significantly to the remaining concentration of radon. Installation of mechanical balanced ventilation in 10 dwellings with infiltration of soil radon resulted in 40 – 90 percent reduction in indoor concentration [7].

Continues ventilation is important not only because people constantly need air to breathe, but also because continuous (non-stop) ventilation is much more effective than intermittent ventilation at reducing concentrations of indoor air pollutants, particularly those of constant source strength as radon emitted through material buildings [7].

As mentioned before, the displacement ventilation 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 displacement ventilation system has the advantage of energy savings over mixing ventilation system and in the same time the IAQ in occupied zone can be efficiently controlled. Many investigators have reported such advantages of displacement ventilation theoretically and experimentally for various HVAC applications. It was also reported that for about 10,000 m^2 offices, the cooling load was reduced by 25-30 percent using displacement ventilation. Consequently, displacement ventilation reduced the supply air flow rate to 70 percent of what is required in conventional mixing ventilation in the same situation. In cold climate when heat sources are also used, the ventilation efficiency of the displacement ventilation is much higher than mixing ventilation [31].

2.5 Ventilation standard rates and ventilation effectiveness

During the three last decades the standard of ventilation rate has been tripled. According to the American society of heating, refrigerating and air conditioning engineering (ASHRAE) 62 standard the level of the minimum ventilation requirements between 1981 and 1989, this value has changed from 2.5 to 7.5 liters per second and person[3]. Living area ventilation rate is very important from viewpoints of health, IAQ and energy efficiency. The first ventilation rate recommended by ASHREA was at least 0.35 air changes per hour (it means that for every 0.35 hour indoor air would be changed), but no less than 7.5 l/s/person. In the next revision, ASHREA decided to make the target ventilation rate in related to the polluted source and determined that one needs to add 10 l/s/100 m^2 to the 7.5 l/s/person. Thus the air change rate requirement will vary by the size of the house and the occupancy. In the other words, the standard is 0.35 AC/h or 7.5 l/s/ person excluding those with the presence of known contaminants [30-32]. The higher pollution leads the higher the ventilation rate and this in turn increases the energy consumption. In fact the ventilation effectiveness can decrease the energy consumption with the lower ventilation rate.

Ventilation does not directly affect occupant health or perception outcomes, but the rate of ventilation affects indoor air pollutant concentrations that, in turn, modify the occupants' health or perceptions.

As mentioned before one of the purposes of ventilation system is to remove the concentration of indoor pollutants. The effectiveness of ventilation ($\boldsymbol{\varepsilon_v}$) provides this objective and is a good parameter to choose the ventilation strategy and to determine ventilation rates. Effectiveness "εv" is defined as [26, 34]: the ratio of average concentration in the room over the concentration in the exhaust air.

$$\varepsilon_v = \frac{(C_o - C_i)}{(C - C_i)} \times 100\% \qquad (2.1)$$

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 ε_v 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. A typical value of ε_v for mixing ventilation might be around 30- 45%, whereas for displacement ventilation is around 50- 80% and it is even 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, 26]. Of different ventilation types, displacement ventilation has better effectiveness than others [19]. Better effectiveness means, in addition to energy savings, improved indoor air quality in the occupied zone and thus improved productivity.

The required ventilation rate in comfort situation depends on such factors same as: the desired IAQ, the indoor generation rate of pollutants, the outdoor quality and the ventilation effectiveness. The expression below can also be used to calculate the ventilation rate, q_v, required maintaining the concentration of a particular pollutant within a desired value [18].

The relationship [5, 6] between the ventilation rate, q_v, required maintaining the concentration of a particular pollutant within a desired value and ε_v is as below:

$$q_v = \frac{G}{\varepsilon_v\,(C_i - C_o)} \times 10^6 \;\; m^3 s^{-1} \qquad (2.2)$$

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}
ε_v = effectiveness of ventilation system
Equation (2.2) shows that when ε_v is low; the required ventilation must be raised for a particular pollutant. Increasing q_v means that energy saving is decreased. Therefore ε_v inversely depends on energy consumption.

2.6. Radon mitigation and energy conservation

To prevent extra energy use versus radon mitigation, Studies [35] conducted by using energy conservation measures methods (ECMs) 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 reduced total annual energy costs 10-36.8% in school buildings. The heating, ventilation and air conditioning (HVAC) systems have shown to impact the radon concentration [36].

The proper design, operation and maintenance of a building's (HVAC) system 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 [35, 36]. However, when increasing indoor pressure in buildings situated in cold climates may lead to moisture problem in the envelope since there is a risk that warm moist indoor air which leaks through the envelope may result in condensation.

An indoor comfortable environment has to rely on the use of energy for lighting, ventilation, heating and/or cooling. Heating has traditionally been the major cause for energy consumption in most cold climate countries. Comfort may be achieved with thermostat settings 2 or 3 degrees lower because it warms people and objects directly when using radiant heating systems as opposed to heating air. For example, radiant floor heating systems may provide energy savings of 20 to 40% over alternative types of heating system [38].

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 [39].

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 2.6. Too low flow rates lead to insufficient IAQ, whereas too high flow rates lead to increasing energy demands [40].

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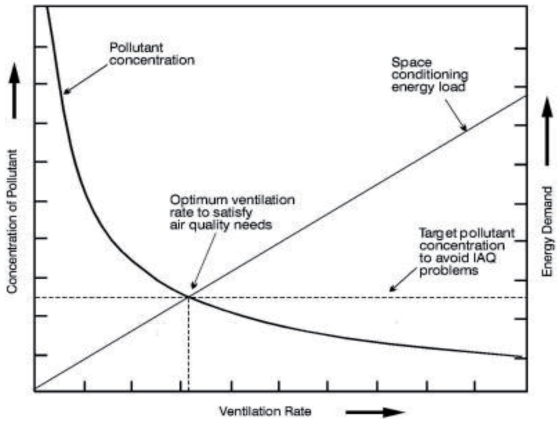


Figure 2.7, Pollutant control versus ventilation rate energy consumption, source: www.aivc.org

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 [28].

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 [38]. Energy saving implications will be discussed in the future works. 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.

2.7. Radon transport mechanisms through building materials

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

Radon migrates through soil and building materials pores by diffusion and advection mechanisms. However, the main entry mechanism is the convective flow from the pores in soil through cracks, and the flow increases with increasing negative differences in pressure across the floor and walls. Radon concentration in soil gas depends on the radium content and the physical characteristics of the soil, such as its grain-size distribution, moisture, porosity and especially the permeability of the soil.

2.7.1 Diffusion mechanism

In order to enter the indoor air, radon gas must first transported through the larger air-filled pores within the building material, so that a fraction of these reaches the building-air interface before decaying and then by the air flow enters indoor. Two basic mechanisms of radon transport within building materials are demonstrated in Figure 2.7. Because of concentration gradient diffusion mechanism in a particular medium before decaying is done by the random molecular motion. Like any fluid substance there is a tendency to migrate in a direction opposite to that of the increasing concentration gradient within the material. Diffusion mechanism is stated by Fick's law [41] and is written as:

$$j_d = -D_e \,.\, \nabla C \qquad (2.3)$$

Where, j_d, is the diffusive flux density in unit of $Bq\, m^{-2}s^{-1}$, D_e, the effective diffusion coefficient and its unit is m^2s^{-1} and C is time-mean concentration of radon.

2.7.2 Advection mechanism

Radon transport through building material by diffusion mechanism has a sufficiently low Reynolds number (Re=0.01), laminar fluxes may be induced due to a pressure gradient. This gradient could be created mainly by changes in environmental conditions by means of ventilation systems and heating and air-conditioned systems in dwellings. Advection mechanism can be represented by Darcy's law [41], which is written as:

$$j_a = -\frac{Ck}{\mu} \,.\, \nabla P \qquad (2.4)$$

Where j_a is the advective flow density in unit of $Bq\, m^{-2}s^{-1}$; k (m^2) is the intrinsic radon permeability; P (Pa) is the pressure field; and μ (Pa s) is the dynamic viscosity of the radon. In this equation the effect of gravity is neglected.

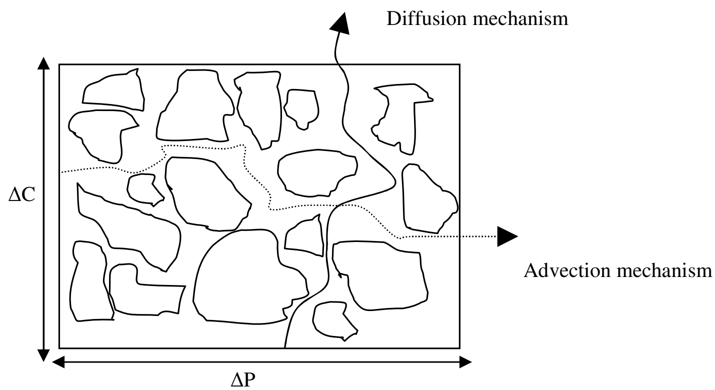


Figure 2.8. Radon transport mechanism through buildings material [41]

2.8 Radon transport and influence of ventilation rate

In this thesis, it is assumed that the indoor radon only comes from the surface of the building materials with constant exhalation rate and the outdoor radon is negligible. Indoor radon concentrations are dependent on radon production, ventilation and outdoor radon concentration.

The relationship between radon concentration and indoor air exchange rate is given by Thomas C. W. Tung J. Burnett [10] and Bertil Clavensjo, Gustav Akerblom [16] as follows:

$$\frac{dC}{dt} = \frac{\sum E_i A_i}{V} + q(C_o - C) - \lambda C. \qquad (2.5)$$

The first term on the right-hand side is a radon generation term, which comes from building materials. The radon emanation rate of material- i and its exposed area are represented by E_i ($Bqm^{-2}h^{-1}$) and A_i (m^2) respectively. The effective volume of the room is V (m^3). The second term comes from the loss due to air leakage, where q is the ventilation rate (h^{-1}) of the room and the unit of radon concentration is Bqm^{-3}. The last term represents the loss due to the process of natural decay of radon gas. The decay constant of radon has a value of 7.55×10^{-3}

h^{-1}. If the initial concentration C_i, of the room is determined, the general solution of equation (2.5) can be expressed as equation (2.6):

$$C = (C_i - C_\infty)e^{-(\lambda+q)t} + C_\infty \qquad (2.6)$$

Or in the other form it can be expressed as equation (2.7):

$$C = \left(C_i - \frac{qC_o}{(\lambda+q)} - \frac{\sum E_i A_i}{V(\lambda+q)}\right) e^{-(\lambda+q)t} + \frac{qC_o}{(\lambda+q)} + \frac{\sum E_i A_i}{V(\lambda+q)} \qquad (2.7)$$

Where, outdoor radon concentration C_o, initial radon concentration of the room C_i, the equilibrium indoor radon concentration C_∞, the air exchange rate of the room q, the effective volume of the room V, the radon decay constant λ.

The second term in the right side of equation (2.7) represents the steady state radon in the room, which can be expressed as equation (2.8):

$$C_\infty = \frac{qC_o}{(\lambda+q)} + \frac{\sum E_i A_i}{V(\lambda+q)} \qquad (2.8)$$

This equation states that, the equilibrium level of radon in the room is dependent on the ventilation rate, radon generation rate and the outdoor radon concentration.

G, radon generation rate (in the unit of $Bqm^{-3}h^{-1}$) is defined as:

$$G = \frac{\sum E_i A_i}{V} \qquad (2.9)$$

In this case radon exhalation rate is constant and is related to the basement floor foundation. In Swedish house radon exhalation rate from the lightweight (blue) concrete is in the range of 50-200 $Bqm^{-2}h^{-1}$ [16].For instant, if E is given as 100 $Bqm^{-2}h^{-1}$, for the basement floor of the one family house mentioned in this work, the value of the G is about 0.1 $Bqm^{-3}s^{-1}$. To apply this value on FLUENT software the unit of G must be changed to $Kgm^{-3}s^{-1}$ as equation (4.2) on chapter 4.

If $C_o = 0$, as in this work, equation (2.8) for different ventilation rates can be also written as equation (2.10):

$$(C_\infty)_n = G/\ (q_n + \lambda) \qquad (2.10)$$

Where, (q_n) is a given air exchange rate and $(C_\infty)_n$ is the equilibrium indoor radon concentration at a given air exchange rate.

In the ventilated room, usually λ is much smaller than ventilation rate, therefore equation (2.10) can be expressed as:

$$(C_\infty)_n = G/\ q_n \qquad (2.11)$$

Equation (2.11) clearly shows the inversely proportional relationship between indoor radon content and ventilation rate.

In non ventilated room; $(q_n) = 0$ and thus equation (2.11) simply is reduced to:

$$(C_\infty) = G/\ \lambda \qquad (2.12)$$

It means that, without using ventilation system the radon concentration in the room is dependent of radon generation rate of type of building materials. Radon generation rate value depends on radon exhalation rate, building volume and wall surfaces.

At the steady state situation, if the radon exhalation from the building material is known, the indoor radon content can be calculated from equation (2.8) for different rates of ventilation [16] air change as equation (2.13):

$$C_b = \frac{\sum E_i A_i}{(\lambda + q)\, V} \qquad (2.13)$$

Where,

C_b = indoor radon from building material Bqm^{-3},

λ = radon decay constant (=0.00755) h^{-1} or 2.1×10^{-6} s^{-1}, note that λ is much smaller than q.

q = rate of air change h^{-1}

V = volume of the building or room m^3

E_i = exhalation rate of building part i $Bqm^{-2}h^{-1}$

A_i = area of building part i m^2

The radon decay constant λ=2.1×10^{-6} s^{-1}, since the order of ventilation rate is much more than λ, therefore C_b is inversely proportional to q, i.e. when q is increased, C_b is decreased inversely.

Chapter 3

Computational Fluid Dynamics (CFD) and indoor air flow

Prediction and calculation of the air flow and any kind of pollutants like radon gas in residential buildings is very important in viewpoints of time and costs given. Simulation techniques by numerical models have been developed to study of the indoor air flow distribution with regard to energy savings and indoor air quality.

Numerical models are based on mass, momentum, concentration and energy conservation equations, also the boundary layer and turbulence hypotheses form the basis of these models. In this work, these equations are used to calculate the characteristics of the ventilation, radon concentration and underfloor heat temperature distribution and FLUENT 6.3 software program is employed as a CFD tool.

This chapter explains the application of computational fluid dynamics (CFD) in indoor air quality and governing equations and numerical characteristics of a CFD fluid flow simulation. The other parts of this chapter are the limitations and validation of CFD techniques.

3.1. Application of computational fluid dynamics in indoor air quality

In the last three decades, many efforts have been done in developing special CFD programs software related to ventilation and spread of pollutants concentration, particularly about calculation of air velocity and temperature distribution in enclosures. In most cases the predicted results have been confirmed when compared with available experimental data [22].

Computational fluid dynamics (CFD) is used to simulate indoor airflow distribution, thermal comfort and species transport at much less cost than measuring. Fortunately with this technique, the simulation and the visualization of environmental problems are applicable [11].

CFD involves the solution of a set of non-linear partial differential equations using numerical methods. These equations express the fundamental physical laws that govern fluid flow and related phenomenon, namely, the conservation of mass, momentum and energy. The equations are discretized and linearized and the computational domain is enclosed with the relevant boundary conditions (e.g. inlet, outlet, solid surfaces, etc). The resultant set of algebraic relations is solved iteratively to predict (at discrete points) the distribution of pressure, temperature and velocity amongst other relevant physical quantities. 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.

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

In CFD the equations have been discretized in order to solve the flow field numerically. The developments in computer capacity have further enhanced the application of this type of simulations. CFD has become an increasing important tool in the prediction of the steady and unsteady state indoor air flow pattern [42].

Negrão (1998) indicated the potential of the combined approach of CFD and whole building simulation. The main restrictions lie in the difficult convergence of the combined flow network and CFD-domain and the high computational effort required [41].

Nielsen (1974) was one of the first who presented an attractive alternative for the empirical research of indoor air flow. CFD opened a route to numerically predict the indoor climate on a detailed level with high flexibility in terms of configurations and boundary conditions. Information on thermal comfort and the effectiveness of the proposed ventilation system can be derived from the calculated indoor air flow pattern, temperature and contaminant distributions [43].

Nowadays CFD is used most often than the experimental approach to study IAQ problems. This involves the solving the flow behavior numerically by using a computer. 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.

W. Zhuo (2000) used computational fluid dynamics (CFD) to study the concentrations and distributions of indoor radon in three dimensions. According to the simulation results, in a naturally ventilated room, the activity distribution of radon is homogeneous except for the places near air diffuser (supply and exhaust) locations. The concentration of radon exponentially decreases with the distance from the source wall which is considered independently. However, as the ventilation rate increased, the concentrations of radon decreased and its activity distribution becomes 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 radon for dose assessment. Both the simulation results of activities and their distributions agreed well with the experimental results in a laboratory room [43].

Other common CFD techniques for indoor air flow are Direct Numerical Simulation (DNS), Large-Eddy Simulation (LES), and the Reynolds Averaged Navier-Stokes (RANS) equations with turbulence models. These techniques are very fine and without approximation and to solve transport equations by these techniques the super computers must be employed or the parallel computers can be used. The current computer capacity is still far too small to solve such a flow. Using these techniques is very expensive right now. DNS for indoor environment simulation is not realistic in the near future [44, 45].

The CFD method with RANS is a very promising and popular tool for IAQ prediction. The most popular RANS model is the standard k-ε model developed by Launder & Spalding. Recently, the RNG k-ε model is the most widely used. The computational method can provide informative results inexpensively [46].

Indoor air flow through mechanical ventilation and in the presence of radon is a complicated problem. Despite of new CFD package and powerful computer, simplifications and approximations are often necessary. This manner has been used by several research studies, for example using two dimensions (2D) instead of three dimensions (3D) and replacement of coarse grids by fine grids [47-50]. In this work these simplifications have been used.

Air flow into the room with mechanical ventilation even though with ventilation rate lower than 0.2 m/s has usually turbulence regime and for solving governing equation, turbulent k-ε model is applied [51].

The standard, k-ε model is a popular method for numerical simulation of room airflow. In a study of comparison among three different turbulent two-equation models, i.e. the RNG (renormalization group), the Standard k-ε, and the Chen-Kim model which is conducted in predicting room air flow and temperature behavior in displacement ventilation, the results show that the prediction of the velocity and the temperature by the three two-equation models is generally satisfactory. The predictions from the RNG and the Chen-Kim model were almost the same and slightly different than the standard k-ε model. The RNG model and the Standard k-ε model are computationally much more stable than the Chen-Kim model. That is why the standard k-ε model is used in this work [51-53].

Although the numerical modeling of ventilation has had considerable improvements, but more research studies are still needed in order to establish CFD as a reliable design and research tool [27].

3.2. Laminar and turbulent air flow in a ventilated room

The radon transport and mitigation with ventilation is affected by the indoor air flow distribution and the air flow characteristics, i.e. temperature, velocity and flow rate is important for achieving indoor air quality. Air flow in ventilated room is a both complicated process and may be highly turbulent, even at very low ventilation rate. Since in the ventilated room, the inertial force is much more than the viscose (shear) force. The Reynolds (Re) number of indoor air flow is defined as:

$$\mathrm{Re} = \frac{\rho U_r D_h}{\mu} = \frac{U_r D_h}{v} \quad (3.1)$$

$$D_h = \frac{2BH}{B+H} \quad (3.2)$$

Where $\mu = \rho\, v$,ρ, air density (1.2 $^{kg}/_{m^3}$), v, is air kinematic viscosity (1.5 × 10^{-5} $^{m^2}/_{s}$,B and H width and height of the room(for typical room 5 and 3 respectively). D_h, hydraulic length of room (about 4 m) and μ, is air viscosity.). U_r= equivalent room air velocity = air flow rate (m^3/s)/ cross sectional area (m^2). If ventilation rate is taken 30 liter per second for 4 persons, then U_r= 0.002 m/s. The Reynolds number with these properties will be, Re = $\frac{0.002\times 4}{1.5\times 10^{-5}} > 10^5$, which is indicated the turbulent model [2].

3.3 Governing equations

All variants of CFD methods are based on the governing equations for fluid flow, which are called transport equations and derived from the laws of conservation of mass, momentum and energy as well as the conservation of species (contaminants) and the turbulence scales of k and ε [34]. All transport equations have the same general form and comprise 4 terms called transient, convection, diffusion and source term which are written respectively. In this work, in steady state model, the transient section is equal to zero and all sources are also equal to zero.

Mass transport in a ventilated room is governed by three processes as:
-Molecular diffusion, which is stated by Fick's law
-Turbulent diffusion, which is the transportation of contaminants by turbulent (eddy) diffusion. Generally turbulent diffusion coefficient is greater than molecular diffusion coefficient.

-Transport by means velocity field; i.e. natural or forced ventilation in the vertical direction caused by a heat source. It is considered that the mixture air-radon in the room is incompressible because of the low air velocity. It means that changes of the mixture density are negligible ($\frac{\partial\rho}{\partial t} = 0$) [34].

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 [54]. 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 also solved. Additional transport equations are also solved when the flow is turbulent.

Transport equations, is the general name for conservation of mass (continuity), momentum (Naviar-Stokes equations), thermal energy and concentration of species. These equations within the ventilated room in turbulent model are described as in the next section.

3.3.1 Conservation of mass

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

$$\frac{\partial\rho}{\partial t} + \frac{\partial}{\partial \mathrm{x}}(\rho u) + \frac{\partial}{\partial \mathrm{y}}(\rho v) + \frac{\partial}{\partial \mathrm{z}}(\rho w) = 0 \qquad (3.3)$$

where ρ, density and $u, v\ and\ w$ are the velocity components in the x, y , z directions respectively.

This Equation is the general form of the mass conservation equation and is valid for incompressible as well as compressible flows for laminar flow.

3.3.2 Conservation of momentum

The momentum equations, which are also called the Navier- Stocks equations, for the turbulent air flow (with turbulence viscosity and diffusion coefficient) in ventilated room, with some simplifying, are expressed in x, y and z directions as:

U-momentum in x direction;

$$\frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial \mathrm{x}}(\rho uu) + \frac{\partial}{\partial \mathrm{y}}(\rho uv) + \frac{\partial}{\partial \mathrm{z}}(\rho uw) = -\frac{\partial \mathrm{P}}{\partial \mathrm{x}} + \frac{\partial}{\partial \mathrm{x}}(\mu_e\, \partial u/\partial x) + \frac{\partial}{\partial \mathrm{y}}\left(\mu_e \frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial \mathrm{z}}\left(\mu_e \frac{\partial u}{\partial \mathrm{z}}\right) + \frac{\partial}{\partial \mathrm{x}}\left(\mu_e \frac{\partial u}{\partial \mathrm{x}}\right) + \frac{\partial}{\partial \mathrm{y}}\left(\mu_e \frac{\partial v}{\partial \mathrm{x}}\right) + \frac{\partial}{\partial \mathrm{z}}\left(\mu_e \frac{\partial w}{\partial \mathrm{x}}\right) \qquad (3.4a)$$

V-momentum in y direction;

$$\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial x}(\rho uv) + \frac{\partial}{\partial y}(\rho vv) + \frac{\partial}{\partial z}(\rho vw) = -\frac{\partial P}{\partial y} + \frac{\partial}{\partial x}\left(\mu_e \frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_e \frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu_e \frac{\partial v}{\partial z}\right) + \frac{\partial}{\partial \mathrm{x}}\left(\mu_e \frac{\partial u}{\partial \mathrm{y}}\right) + \frac{\partial}{\partial \mathrm{y}}\left(\mu_e \frac{\partial v}{\partial \mathrm{y}}\right) + \frac{\partial}{\partial \mathrm{z}}\left(\mu_e \frac{\partial w}{\partial \mathrm{y}}\right) - \boldsymbol{g}(\rho - \rho_0) \qquad (3.4b)$$

W-momentum in z direction;

$$\frac{\partial}{\partial t}(\rho w) + \frac{\partial}{\partial x}(\rho uw) + \frac{\partial}{\partial y}(\rho vw) + \frac{\partial}{\partial z}(\rho ww) = -\frac{\partial P}{\partial z} + \frac{\partial}{\partial x}\left(\mu \frac{\partial w}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial w}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu \frac{\partial w}{\partial z}\right) + \frac{\partial}{\partial \mathrm{x}}\left(\mu_e \frac{\partial u}{\partial \mathrm{z}}\right) + \frac{\partial}{\partial \mathrm{y}}\left(\mu_e \frac{\partial v}{\partial \mathrm{z}}\right) + \frac{\partial}{\partial \mathrm{z}}\left(\mu_e \frac{\partial w}{\partial \mathrm{z}}\right) \qquad (3.4c)$$

where, P is the static pressure, $\mu_e = \mu + \mu_t$ is the air effective(laminar and turbulent) viscosity coefficient, ρ is the air density, ρ_0 is the air dencity at a reference temperature and g is the gravity acceleration in the y direction [27].

3.3.3 The concentration of species equation

When the species transport model is selected and the individual species are defined in the model then the conservation equation including the convection and diffusion is solved for each species, C, through the solution of a convection-diffusion equation for each species. Then mass fraction of the species is predicted by FLUENT and the conservation equation for species transport model is as the following general form:

$$\frac{\partial}{\partial t}(\rho c)+\frac{\partial}{\partial \mathrm{x}}(\rho u c)+\frac{\partial}{\partial \mathrm{y}}(\rho v c)+\frac{\partial}{\partial \mathrm{z}}(\rho w c)=\frac{\partial}{\partial \mathrm{x}}(D_e\, \partial c/\partial x)+\frac{\partial}{\partial \mathrm{y}}\left(D_e \frac{\partial c}{\partial \mathrm{y}}\right)+\frac{\partial}{\partial \mathrm{z}}\left(D_e \frac{\partial c}{\partial \mathrm{z}}\right)+S_c \quad (3.5)$$

In this equation D_e, represents effective diffusion coefficient, ρ is the mixture density, S_c is the generation rate of concentration and c is the- mean concentration [27].

3.3.3.1. Mass Diffusion in Laminar and Turbulent Flows

In Equation (3.13), J_c is the diffusion flux of the species, which arises due to concentration gradients. Effective diffusion coefficient in laminar flow is called D_l, and by default, FLUENT uses the dilute approximation, under which the diffusion flux can be written as:

$$J_c=-\rho D_l . \nabla C \qquad (3.6)$$

Here D_l is the laminar diffusion coefficient for species in the mixture.

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

$$J_c=-(\rho D_e) \nabla C \qquad (3.7)$$

Where $D_e = D_l + D_t$ and $D_t = \frac{\mu_t}{\rho Sc_t}$ is the turbulent diffusivity, Sc_t is the turbulent Schmidt number and μ_t is the turbulent viscosity. The default of Sc_t is 0.7[54].

3.3.4. Conservation of thermal energy

The thermal energy equation [27] per unit volume in ventilated room is as:

$$\frac{\partial}{\partial t}(\rho T)+\frac{\partial}{\partial \mathrm{x}}(\rho u T)+\frac{\partial}{\partial \mathrm{y}}(\rho v T)+\frac{\partial}{\partial \mathrm{z}}(\rho w T)=\frac{\partial}{\partial \mathrm{x}}\left(\Gamma_e \frac{\partial T}{\partial \mathrm{x}}\right)+\frac{\partial}{\partial \mathrm{y}}\left(\Gamma_e \frac{\partial T}{\partial \mathrm{y}}\right)+\frac{\partial}{\partial \mathrm{y}}\left(\Gamma_e \frac{\partial T}{\partial \mathrm{z}}\right)+S_T \quad (3.8)$$

In this equation:
$\Gamma_e = \Gamma + \Gamma_t$ is the effective (laminar and turbulent) diffusion coefficient Where, $Pr = \sigma = \mu / \Gamma$ is the Prandlt number of fluid (in this case room air), and S_T is a thermal source term (W/m3).

3.4. Turbulence modeling

As stated earlier, air flows in the ventilated room are turbulence. Since Reynolds number is enough high (Re> 10^5), it is assumed that the air flow is turbulence, so turbulence modeling is valid for the case in this work. Therefore turbulence modeling with emphasis on the two-equation standard k-ε model is more described.

Three kinds of k-ε turbulent models for indoor air flow modeling are available as follows:

-Standard k-ε model
-Renormalization- Group (RNG) k-ε model
-Realizable k-ε model
The standard k-ε turbulence model is applied in this work, since it is the most widely used because of its applicability to wide-ranging flow situations, stability during simulation time, good predictive accuracy to the flow and its lower computational demand than more complex models that are available [27,52].

3.4.1 Standard k-ε model

Two-equation models are the simplest available means of calculating turbulent stresses in the recirculation flow where the length scale distribution cannot be calculated algebraically. The Standard k-ε model as a two-equation model is a semi empirical model based on model transport equations for the kinetic energy k and its dissipation rate ε. For using this model it is assumed that the flow is fully turbulent and that the effects of molecular viscosity are negligible [27].

Launder and Spalding (1974) proposed a modified version of the k-ε model [55]. The standard *k*-ε model calculates the turbulent viscosity (μ_t) at each point is related to local values of the turbulence kinetic energy, k, and the dissipation rate of turbulence energy, ε from the equation (3.8) as:

$$\mu_t = C_\mu \rho k^2/\varepsilon \qquad (3.9)$$

Where μ_t is the turbulent viscosity, $C_\mu = 0.09$ that is an empirical constant and ρ is the fluid density [27, 42]. The turbulent kinetic energy, k, is determined from the following velocities in three dimensions (3D): $k = ½ (\overline{u}^2 + \overline{v}^2 + \overline{w}^2)$.
The local distributions of k and ε require the solution of two additional transport equations, which are defined from the Navier-Stokes equations. The k-ε transport equations have the same general structure as the momentum and energy equations. They comprise transient, convection, diffusion and source terms.

The k–transport equation for high Reynolds number is given by:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x}(\rho u k) + \frac{\partial}{\partial y}(\rho v k) + \frac{\partial}{\partial z}(\rho w k) = \frac{\partial}{\partial x}\left(\Gamma_k \frac{\partial k}{\partial x}\right) + \frac{\partial}{\partial y}\left(\Gamma_k \frac{\partial k}{\partial y}\right) + \frac{\partial}{\partial y}\left(\Gamma_k \frac{\partial k}{\partial z}\right) + \mu_t\left\{2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right] + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right)^2\right\} - C_\mu \rho \frac{k^{1.5}}{L} + \beta g \frac{\mu_t}{\sigma_t}\frac{\partial T}{\partial y} \qquad (3.10)$$

Where, in this equation $\Gamma_k = \frac{\mu_t}{\sigma_k}$, $\sigma_k \cong 1$, σ_t is the turbulent Prandlt or Schmith number (0.5-0.9) and C_μ is an empirical constant$\cong$ 0.09, and μ_t the turbulent viscosity. Similarly, the ε-transport equation is given by:

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x}(\rho u \varepsilon) + \frac{\partial}{\partial y}(\rho v \varepsilon) + \frac{\partial}{\partial z}(\rho w \varepsilon) = \frac{\partial}{\partial x}\left(\Gamma_\varepsilon \frac{\partial \varepsilon}{\partial x}\right) + \frac{\partial}{\partial y}\left(\Gamma_\varepsilon \frac{\partial \varepsilon}{\partial y}\right) + \frac{\partial}{\partial y}\left(\Gamma_\varepsilon \frac{\partial \varepsilon}{\partial z}\right) + C_1 \frac{\varepsilon}{k}\mu_t\left\{2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right] + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right)^2\right\} - C_2 \rho \frac{\varepsilon^2}{k} + \beta g \frac{\mu_t}{\sigma_t}\frac{\varepsilon}{k}\Gamma_\varepsilon \frac{\partial T}{\partial y} \qquad (3.11)$$

The last terms in equations (3.9) and (3.10) represent the production of turbulence energy by buoyancy, with β as the coefficient of volumetric expantion.
In this equation $\Gamma_{\varepsilon} = \frac{\mu_t}{\sigma_{\varepsilon}}$, where, $\sigma_{\varepsilon} = 1.22$, $C_1 = 1.44$, $C_2 = 1.92$
These constant values were obtained empirically by Launder and Spalding (1974) for a wide range of turbulent flows [27, 55].

3.4.2 Boundary conditions for the k-ε model

The k-ε model calls for further consideration of boundary conditions and near-wall treatments especially in flows with low Reynolds number. The model equation for k and ε are elliptic by virtue of the gradient diffusion term. Their behaviour is similar to other elliptic flow equations and thus gives rise to the need for the following boundary conditions:
- Inlet - distributions of k and ε must be given;
- Outlet or symmetry axis - $\partial k/\partial n = 0$ and $\partial \varepsilon/ \partial n = 0$;
- Free stream - k = 0 and ε = 0; and
- Solid walls - approach depends on Reynolds number.

The main weakness of the k-ε model is its inability to model near-laminar flows, due to the fact that it was originally developed for the analysis of fully turbulent isothermal flow. To improve its capabilities, the traditional k-ε model is extended through an appropriate wall treatment approach to analyze low-Reynolds number flows [56].

3.5 CFD modeling validation

The accuracy of a numerical solution depends on the discretization scheme, computational grid, near wall boundary conditions and the convergence criteria.

In practice, different discretization equations; first order, second order, power law and etc are available. Selection of each scheme depends on the certain problem situations. Grid resolution can change the accuracy of CFD results. Increasing the number of grid points (i.e. fine grid) errors associated with grid resolution may be minimized. In fact, CFD results should be independent of changing with the more refined grid. Convergence test generally must show that the residuals (errors) made by different iterations are in an acceptable value [27]. Validation of the model can be approved by means of experimental and/or previous research studies.

3.6 Near wall boundary conditions

Near the wall a laminar flow is occurred due to the no-slip wall condition and the damping of results. The standard *k*-e model however is only valid for flow regions where the turbulent transport is dominating. Instead the flow nearby walls is solved with wall functions.
Experimental results show that for close to the wall, the Reynolds stresses remain small up to about $y^+ \leq 5$. This region is called the viscous sublayer. In this layer the velocity profile is linear when the Reynolds stresses are neglected [42]. In turbulence modeling FLUENT, itself calculates the normal-distance Reynolds number, y^+.

3.7. CFD modeling limitations

In spite of wide increasingly growth of computational technology and software developments, CFD methods have still some limitations to employ for a whole building air flow, especially buildings with more than one room. Other problems are associated with approximation of discretization scheme, fine grids, near wall treatments and using some empirical constants. To cope with limitations other accurate methods are developed, for instant the direct numerical simulation (DNS) method. In employing DNS method the more power computer is needed, which is used ´only within research study right now [27].

Chapter 4

Numerical solution procedure and experimental data

Computational Fluid Dynamics (CFD) simulations have been performed for the one family house. In this study for solving numerical equations a few models were performed by commercial finite volume analysis package, FLUENT © 6.3. Geometry and meshes made by GAMBIT software. The governing equations solved by Fluent are the Navier-Stockes equation combined with continuity equation, energy equation and specie transport equation. In Fluent, after completing analyses, the resulted data can be easily evaluated by the postprocessor. The measurement data and previous research study are used to validate the numerical model.

To survey indoor air flow and radon treatment in ventilated room, solution of transport equations must be done in analytical or numerical method. Analytical solving of transport equations generally are very difficult, so using of CFD method these equations are solved numerically by discretized equations. This chapter describes model and geometry, boundary conditions and simulation of a one family house with radon, which is emitted through building material from the basement floor. FLUENT © 6.3 program software will be used as CFD tool. With using this package modeling and simulating of ventilation and species transport, simply is available. Also for turbulent modeling of indoor air flow, all kinds of k-ε models are available.

As pointed out before, to study influence of ventilation system on radon mitigation base on given objectives simulation works are investigated as follows:
-The influence of ventilation rate and inlet/outlet location, -comparing two main ventilation system strategies, displacement and mixing ventilation, and -the effect of underfloor heating on radon mitigation.

4.1Model description
Geometry is a one family house with sizes 10×5×7.5=375 m^3. This building is in three floors and volume of each floor is 10×5×2.5=125 m^3. The first floor is called basement.

Figures 4.1, 4.2 and 4.3 indicate a view of the 3-storey building, its geometry and larger view of basement grid feature in FLUENT respectively.

Figure 4.1, The view of the one family house

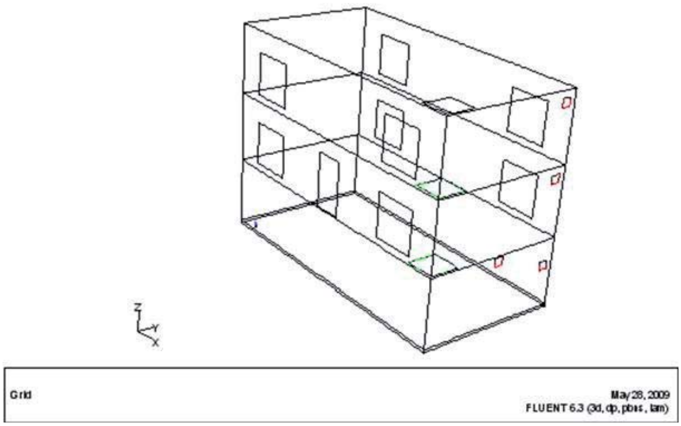


Figure. 4.2.a, Geometry of the 3-storey building

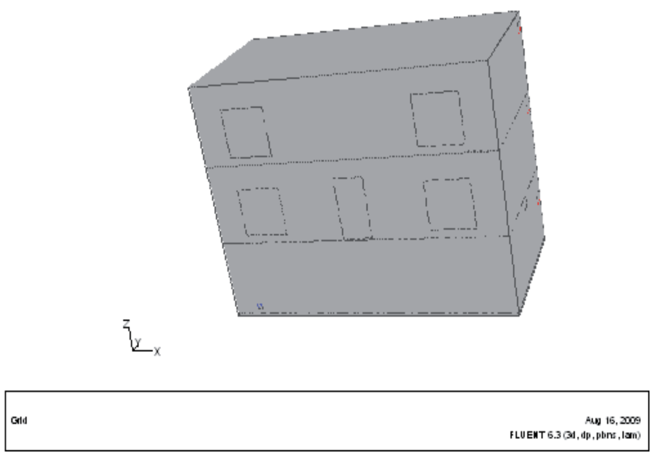


Figure 4.2.b, Grids of the 3-storey building

Domain Extents of building geometry is as:
x- coordinate: min (m) = -5.0, max (m) = 5.0 (the building length 10 m)
y- coordinate: min (m) = -2.5, max (m) = 2.5 (the building width 5 m)
z- coordinate: min (m) = -1.25, max (m)=6.25(the building height 7.5m)

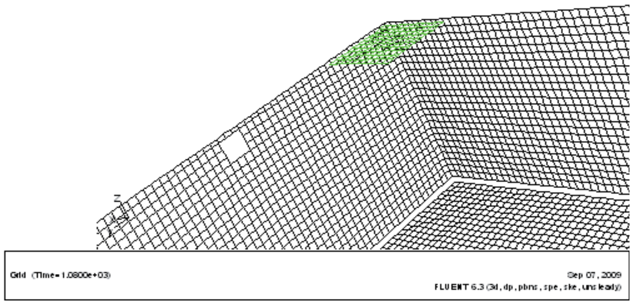


Figure 4.3, 3D Modeling, meshes and boundary conditions of the basement

For solving transport equations, generally fine grids are required. For this building, if that grid interval size takes at least 0. 04, thus the grids number must be exceeded 3,000,000 cells. This grids number are too high and today's computers need long times to solve them. Because of this fact and due to higher radon concentration in the basement floor, which is approved by experimental work, this study focused on the basement, and sometimes because of speed limitation of used computer, instead 2 dimension models were used.

Figures 4.4 and 4.5 show that radon concentration in the building, as it can be observed the radon content is inversely proportional to the building height. It means that the radon content in the basement is much more than the upper floor, in which is agreed to experimental work has been reported by JBS, AB Company (Appendix A).

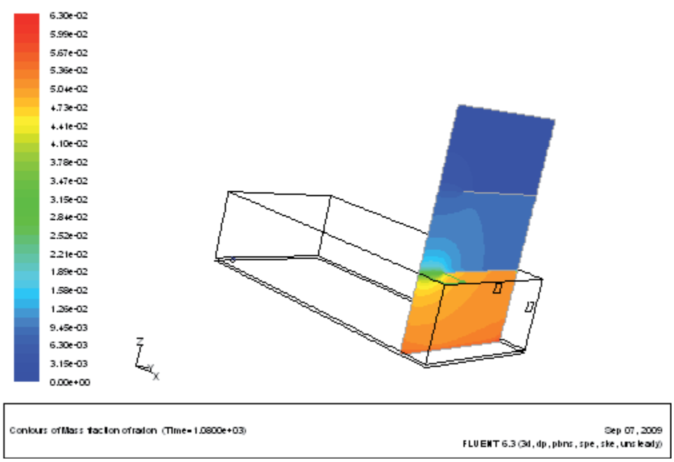


Figure.4.4. Contours of radon variation and building height

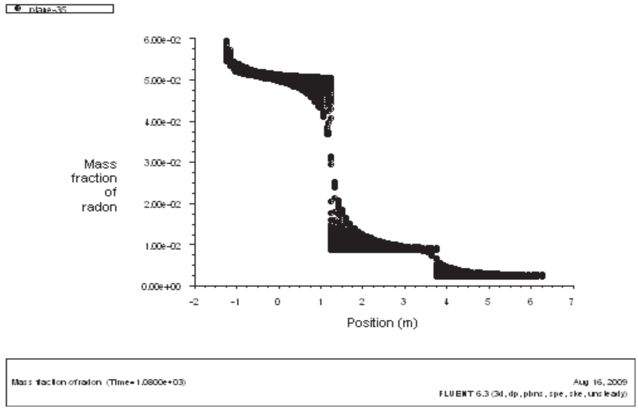


Figure.4.5. Plot of radon variation versus building height

4.2 Required constants and input values

4.2.1 Radon mass fraction

To calculate radon mass fraction in air-radon mixture, radon flow rate (*Kg/m^3s*) is needed for FLUENT as inputs, but the measurement radon unit is Bq$/m^3$. Definition of Bq unit, determines the number of particle which is disintegrated per cubic meter of indoor air per second. Therefore for a given (270 *Bqm^{-3}*) content in *Kg/m^3*, the anticipated radon mass fraction and flow rate calculation are as the following:

The activity (A) of radon is defined [57] by disintegrations per second, of a radioactive substance equals to the product of decay constant (λ), and its number of atoms (N):

$$A = \lambda N \qquad (4.1)$$

For 222Rn,

$$\mathrm{A} = \frac{2.1\times10^{-6}\times6.023\times10^{23}}{222} = 5.7\times10^{15} \quad \mathrm{Bq}$$

It means that one gram of radon in its pure form produces 5.7×10^{15} Bq [57]. Hence;

$$1\ \mathrm{Bq} = \ 1.75\times10^{-19}\ \mathrm{Kg} \qquad (4.2)$$

If indoor radon is supposed 270 Bq/m^3, therefore radon mass fraction can be calculated as:

$$\text{Radon mass fraction } = 270\ {}^{\mathrm{Bq}}\!/_{\mathrm{m}^3} \times \frac{1.75\times10^{-19}\ {}^{\mathrm{Kg}}\!/_{\mathrm{Bq}}}{1.2\ {}^{\mathrm{Kg}}\!/_{\mathrm{m}^3}} = 3.9\times10^{-17}$$

And, if the radon exhalation rate is taken in the range of 5-200 Bqm^{-2}h^{-1}[16], radon flow (generation) rate can be calculated from equation (2.9) with given area and volume of the room. For E= 200 Bqm^{-2}h^{-1},A=50 m^{2}and V=150 m^3 the radon flow rate yields as:

Radon flow rate = $\frac{200}{3600}\ {}^{Bq}\!/_{m^2s} \times \frac{50}{150} \times 1.75\times10^{-19}\ {}^{Kg}\!/_{Bq} = 3\times10^{-21}$ Kg/m^{3}s

In this work, radon flow rate is taken in the range of between 2×10^{-18} to 2×10^{-21} Kg/m^{3}s; this range is also used for to evaluate the sensitivity test.

4.2.2 Mixture properties

Mixture of radon and air is defined as a two fluid which is mixed with different mass fraction; mixture properties are set as shown below:

Mixture (radon and air) species:
In the FLUENT material is setup as follows.
Density: incompressible-ideal-gas, C_p (j/Kg-K): mixing law, Thermal conductivity: 0.0242 W/m-K, Viscosity: 1.75e^{-5} Kgm^{-1}s^{-1}, Mass diffusivity: D=1.0e^{-6} m^{2}s^{-1},

Radon: M_w=222, C_p=900 j/Kg-K, λ=2.1e^{-6}s^{-1}, radon diffusivity, D=1.0e^{-6} m^{2}s^{-1},

Air: M_w =28.8, C_P=1006 j/Kg-K, ρ= 1.2 kg/ m, air viscosity=1.75e^{-5}Kgm^{-1}s^{-1}.
Since h_c=Air heat transfer coefficient = $14.8\,v^{0.69}$, for $0.15 < v < 1.5\ ^{m}/_{s}$, therefore $h_c \cong 15$ W/m^2.K, [30], Outdoor temperature = 265 K, Indoor temperature = 300 K.

Building material of all walls assumes light concrete with, C_p=600 j/Kg-K, Density=1000 kg/m^3, and Thermal conductivity=0.5 W/m-K

4.3 Boundary conditions

4.3.1 Walls

All walls of the basement are modeled adiabatic with zero heat flux, because they are located underground. For the second storey, the walls modeled free convection with h_c =15 and outdoor temperature 265 K (-8° C) wherever is needed.

4.3.2 Floors

Floors are considered as floor heating with heat flux 0, 20 and 40 W/m^2, thickness 0.4 m and light weight concrete material.

4.3.3 Inlet and outlet

Different inlets and outlets are used in this study; inlet vents and out let vent for testing natural ventilation and exhaust fan and velocity inlet for forced (mechanical) ventilation. The air velocity for inlet set in the range of indoor air movement, i.e. from 0.2 to 0.5 m/s and mass flow rate of exhaust fan set to the range 0.02 to 0.04 Kg/s which this range is closed to standard acceptable ventilation rate and thermal comfort.

4.4. Solution of models

Models are defined, incompressible, Pressure based, steady state with energy equation and standard k-ε turbulent model and species transport. Also sometimes wherever the flows were laminar, in natural ventilation, selected models were laminar and unsteady. Models were built 2D and 3D.

4.5. Case study CFD simulations

To show the influence of changing ventilation characteristics on radon mitigation several 2 and 3 dimensions models were preformed. Numerical simulations in 3D were performed on two different models. The boundary conditions and results of numerical studies of first 3D modeling will be discussed first. After discussing second 3d modeling, in the next sections, 2D modeling simulation will be also explained.

The main geometry of first 3D modeling is shown in figure 4.6 and 3 different tests are introduced as:
Test1, to survey influence of changing ventilation rate and location of ventilation systems
Test 2, is set to compare 2 main principal ventilation strategies, i.e. displacement and mixing ventilation
Test 3 is to explain about the underfloor heating effects on radon mitigation.

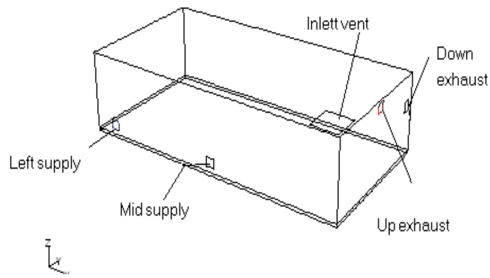


Figure.4.6, Geometry and boundary conditions of basement, first 3D modeling

4.6. The results of first 3D modeling

4.6.1. Influence of ventilation rate and inlet/outlet location

To survey the influence of the ventilation location and the ventilation rate in both natural and forced ventilation, model1 is setup as table 4.1.

Boundary conditions and initial values in cases1 and 2 are the same, except the locations of exhaust fans and ventilation rates. The difference between case 1 and case 2 is only the fan locations, which are moved from down point to up point.

Test1	Floor heat	Inlet	Inlet air T	Outlet	Outlet flow rate
Case1	20W	Inlet vent	293 K	Down exhaust fan	0.04 Kg/s
Case2	20W	Inlet vent	293 K	Up exhaust fan	0.04 Kg/s
Case3	20W	Inlet vent	293 K	Up exhaust fan	0.05 Kg/s

Table 4.1, boundary conditions of ventilation rate and outlet location

Cases 3 and 2 also have the same boundary conditions but with different ventilation rates.

The results of cases 1, 2 and 3 are shown in table 4.2, whereas T, is average temperature within basement, V, is average indoor air velocity magnitude and radon mass fraction is average(mass average) of radon mass fraction.

Test 1	T	V	Radon mass fraction	Minimum	Maximum
Case1	293.06 K	4.34 m/s	7.01 e-21	4.36e-22	2.5e-20
Case2	293.06 K	4.47 m/s	7.23e-21	4.35e-22	2.65e-20
Case3	293.06 K	5.2 m/s	6.53e-21	4.30e-22	1.66e-20

Table 4.2, Influence of ventilation rate and location results

Figures 4.7 and 4.8 indicate the radon distribution related to case1 and case 2 respectively.

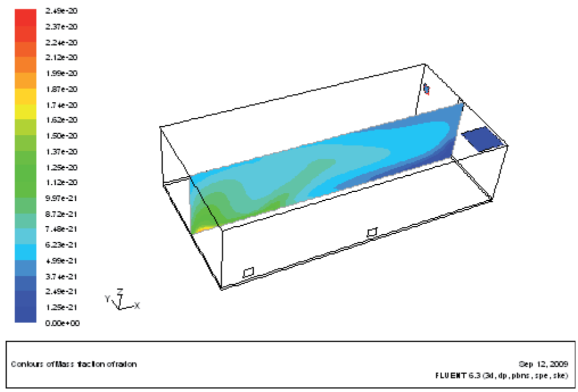


Figure 4.7, case1, Radon mass fraction on y=0, outlet=down exhaust fan and outlet flow rate 0.04 Kg/s

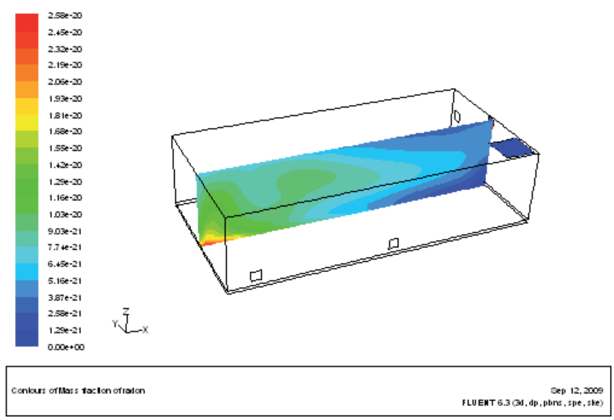


Figure 4.8, case2, Radon mass fraction on y=0, outlet=up exhaust fan and outlet flow rate 0.04 Kg/s

With comparing cases 1 and 2, it can be observed that changing the location outlet, the radon distribution pattern and its average value is changed, from 7.01e-21 to 7.23e-21. These results are agreed with experimental and numerical study conducted by Y. Zhang [2].

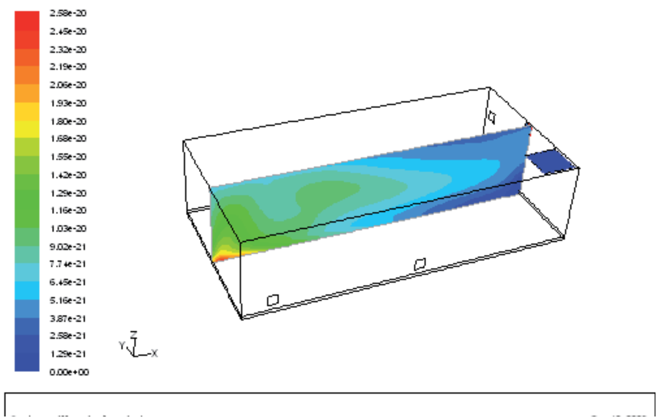


Figure 4.9, Case 3, Radon mass fraction on y=0, outlet=up exhaust fan and outlet flow rate 0.05 kg/s

Figure 4.9 shows that with increasing ventilation rate, the indoor radon content is decreased.

4.6.2 .Differences between 2 main principal ventilation strategies on radon mitigation

Test 2 has been setup to investigate the effects of mixing and displacement ventilation systems on radon mitigation. The boundary conditions defined as table 4.3. In this table boundary conditions for both cases are identical, but the inlet and outlet are vice versa.

Test 2	Floor heat	Inlet	Inlet air T	Outlet	Outlet flow rate
Mixing ventilation	20W	Up exhaust fan	293 K	Left supply	0.04 Kg/s
Displacement ventilation	20W	Left supply	293 K	Up exhaust fan	0.04 Kg/s

Table 4.3, Boundary conditions of mixing and displacement ventilation

Figures 4.10 and 4.11 show the results of radon concentration related to mixing and displacement ventilation respectively. It is observed that the radon level in sitting area in mixing ventilation is more than displacement ventilation. The air velocity and mass average of radon content for these cases are shown in the table 4.4. This table shows that the minimum value of radon in the displacement ventilation is lower than the mixing ventilation (7.36e-19 versus 1.74e-18).

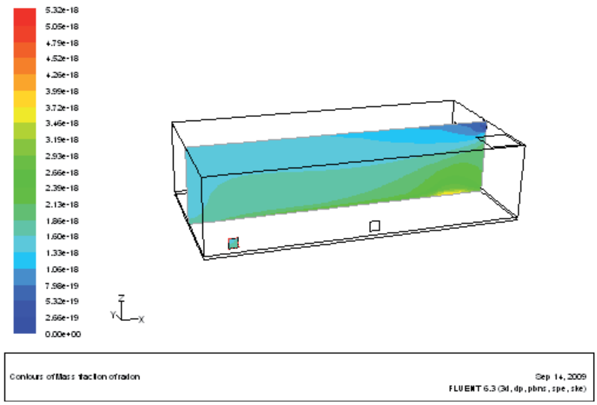


Figure 4. 10 Influence of mixing ventilation on radon mitigation

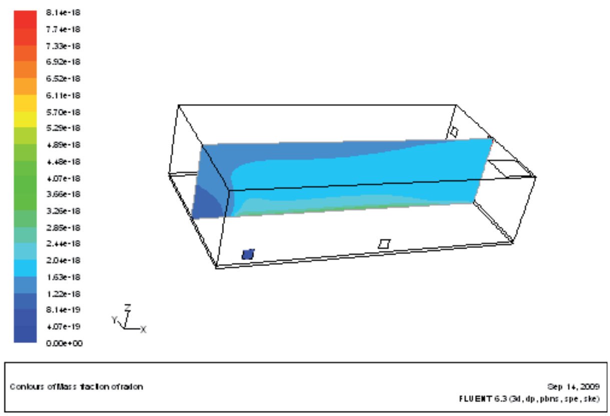


Figure 4.11 Influence of Displacement ventilation on radon mitigation

Test 2	Floor heat	Radon velocity magnitude	radon mass fraction	Min radon mass fraction	Max radon mass fraction
Mixing ventilation	20W	0.02 m/s	2.58e-18	1.74e-18	5.34e-18
Displacement ventilation	20W	0.03 m/s	2.73e-18	7.36e-19	8.12e-18

Table 4.4 Mixing and displacement ventilation results

4.6.3. Underfloor heating effects on radon mitigation

For checking the influence of floor heating on radon mitigation, test3 is configured as table 4.5. This table shows that the difference between 2 cases is only 0 W/m^2 and 20 W/m^2 for cases 1 and 2 respectively and the other parameter are equal.

Test 3	Floor heat	Inlet velocity	Inlet air T	Outlet	Outlet flow rate
Case 1	0W	Left supply 0.4 m/s	293 K	Up exhaust fan	0.04 Kg/s
Case 2	20W	Left supply 0.4 m/s	293 K	Up exhaust fan	0.04 Kg/s

Table 4.5, Boundary conditions of underfloor heating

The two following figures, 4.12 and 4.13 are the results of simulation about underfloor heating on radon mitigation. As shown in these figures and calculated in table 4.6,

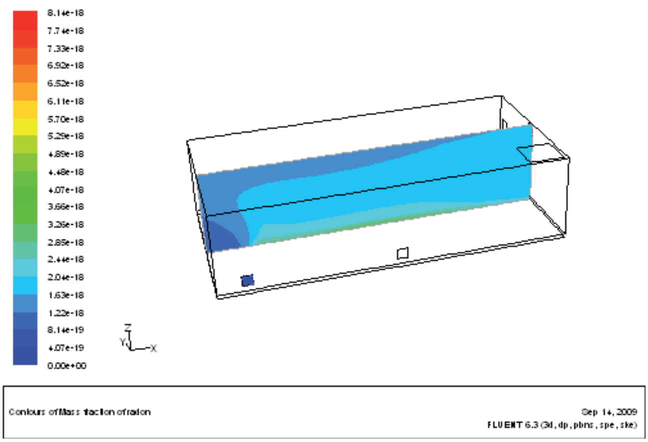


Figure 4.12. Influence of underfloor heating on radon mitigation (0 w/m^2)

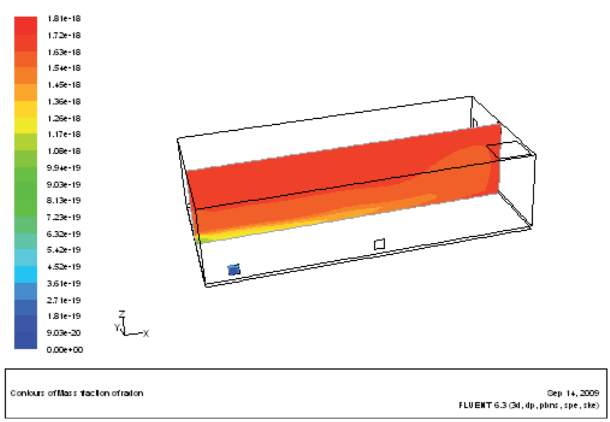


Figure 4.13. Influence of underfloor heating on radon mitigation (20 w/m^2)

The average of radon mass fraction in case 2 (20 w/m^2) is lower than case 1(0 w/m^2). It means that floor heating acts just in direction of improvement the ventilation system.

Test 3	Floor heat	Radon velocity magnitude	radon mass fraction	Min radon mass fraction	Max radon mass fraction
Case 1	0 w/m^2	0.03 m/s	2.73e-18	7.36e-19	8.12e-18
Case 2	20 w/m^2	0.2 m/s	1.45e-18	4.67e-19	1.83e-18

Table4.6, Influence of underfloor heating results

4.7. The results of second 3D modeling

For investigating influence of different inlet and outlet location on radon mitigation, ventilated room is assumed has door, supply and exhaust fan.

Geometry and grids of second 3D modeling is shown as figure 4.14 with different inlets and outlets, which are used as natural and forced ventilation and the results, should be compared to find out the effects of ventilation rates and types on radon distribution in the room.

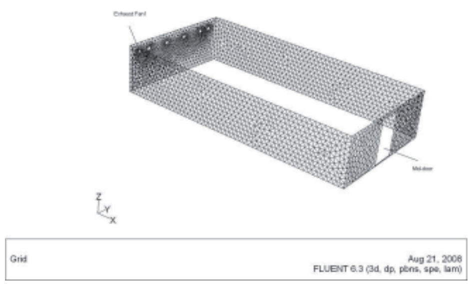
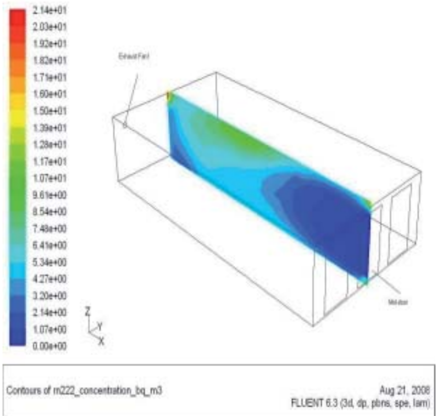


Figure 4.14, Geometry and grids of second 3D modeling

4.7.1 Results of natural ventilation

The radon concentration after natural ventilation through middle door, inlet vent, and left exhaust fan as outlet vent shows that, on surface y=0 the larger the distance from the inlet, there are more radon contents (Fig 4.15.a).On the surface near the floor the radon distribution is like (Fig. 4.15.b), whereas it is observed that, there is high concentration in the area in the right corner, which is located far from the left exhaust fan. Also it is observed that, the maximum radon concentration has been reduced to one-third (about 50 Bq/m3) of its defined content (150 Bq/m3).



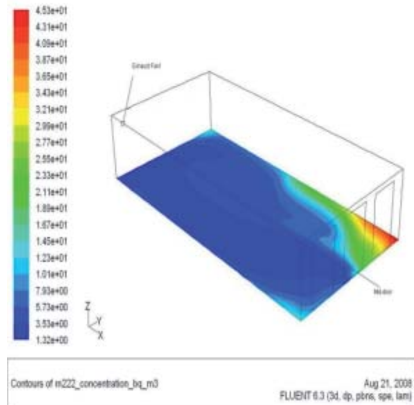
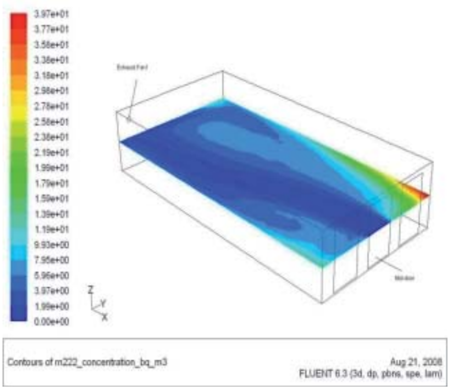


Figure 4.15.a, Radon concentration on y=0

Figure. 4.15.b, Radon concentration near the floor

The above result is also confirmed by the figures 4.16.a,b, i.e. in the areas near the inlet and outlet the radon concentration will be at minimum values.



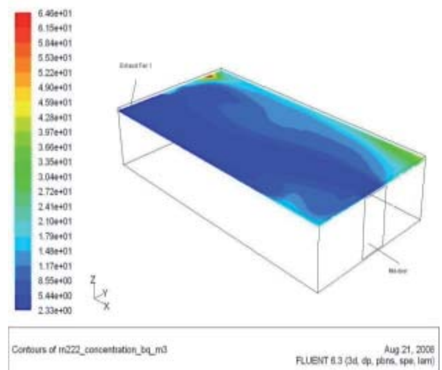


Figure. 4.16.a, Radon concentration at z=1.1m

Figure. 4.16.b, Radon concentration near the ceiling

4.7.2 Results of mechanical ventilation

In figure 5,8, with changing inlet vent to velocity inlet fan and moving the left exhaust fan to middle exhaust fin whereas the ventilation rate was decreased, the concentration of radon is rather increased. This result can be observed in figure 4.17.a,b.

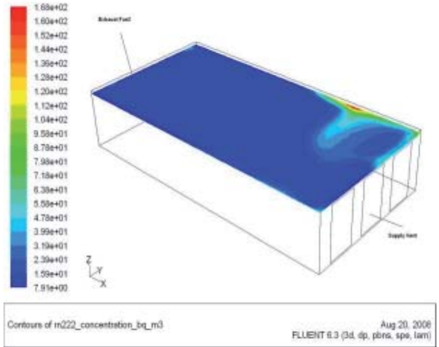


Figure 4.17.a, Radon content on surface near the ceiling

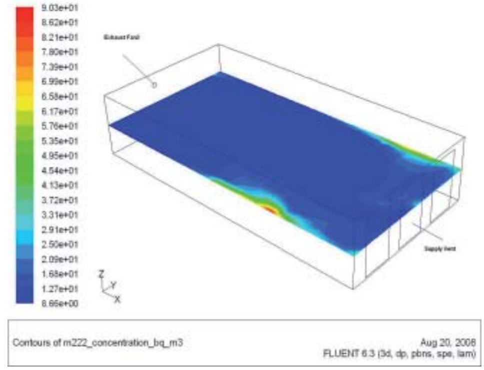


Figure 4.17.b, Radon content at z=1.1 m

Also, this figure confirms that radon distribution can be affected by the changing location of exhaust fan.

4.8. The results of 2D modeling

4.8.1 Results of natural ventilation with different locations

When natural ventilation is applied as figure 4.18.a and b, the radon concentration is decreased, but the content is still high, particularly near the floor. The maximum of radon content in cas1.a is rather lower than case1.b, because the size of inlet vent is bigger and the outlet vent is close to the basement floor. This figure shows that location and size of ventilation are important factor of radon mitigation.

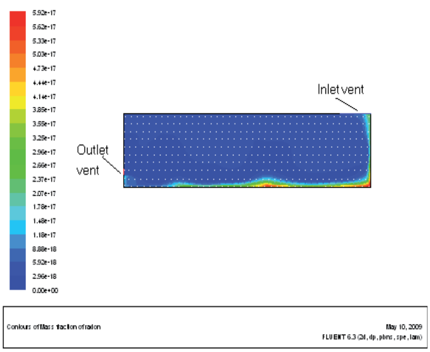


Figure 4.18.a Natural ventilation

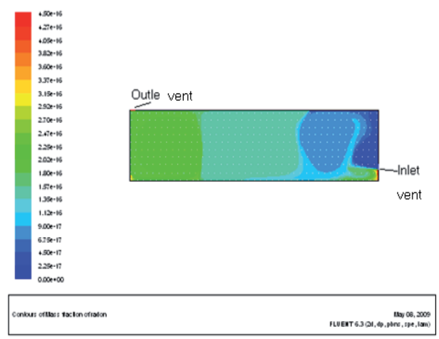


Figure 4.18.bNatural ventilation, with changing size and location

4.8.2 Results of different mechanical ventilation

Figure 4.19, indicates the difference between displacement ventilation figure 4.19.a and mixing ventilation figure 4.19.b, as shown, the displacement ventilation play a better role than mixing ventilation to reduce radon concentration, because of its ventilation effectiveness.

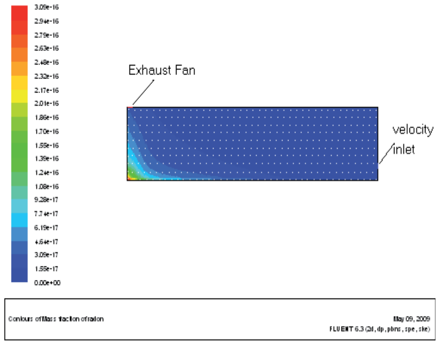


Figure 4.19.a Displacement ventilation

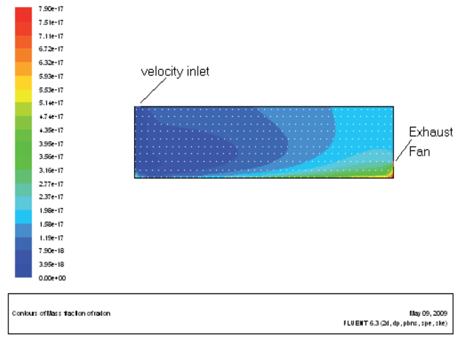


Figure 4.19.b Mixing ventilation

In the real condition, the ventilation used in the basement of this building is as figure 4.20, the inlet vent from the upper floor and using and an exhaust fan. This kind of ventilation so called unbalanced ventilation and usually because off creating negative pressure in the room and taking up of radon from the material building or soil is not a standard and acceptable ventilation strategy. It is observed that in the area near the floor, seat position, the radon content is rather high in comparison to other places.

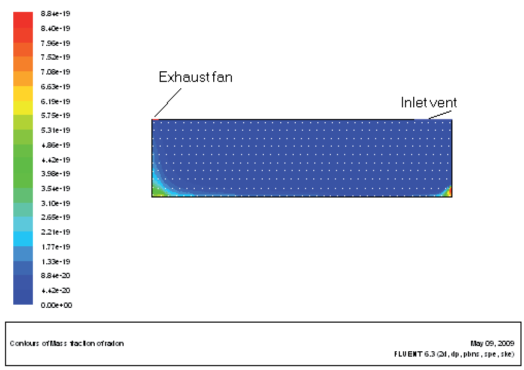


Figure 4.20, Unbalanced ventilation

4.9 Model validation and sensitivity analysis

For confirming the results and testing the sensitivity, we changed the model with different boundary condition values, for example the value of radon exhalation rate, ventilation types and ventilation rate and location. These tests confirmed that the results are different. For checking grids independency, we increase the meshes two times and five times and the results of finer grids were approximately equal. But when the grids are coarse for example; 75×250, the results had about 30 percent deviation. There compared grids were; 150×500 and 300×1000, the comparison of these results will be shown in the next section.

Iterations and grid size were about 10,000 and 17364 cells respectively for all cases. Sensitivity analysis for obtaining grid independency performed and the results were checked with variant grids and the results were very close together.

4.9.1 The different grids comparison and model validation test

In the following figures (4.21.a,b), for 2D modeling, the results of two different grids are demonstrated. As shown, for equal indoor radon concentration, i.e. 2e-18 Bq/m^3, the maximum result of radon content after simulation are 6.88e-19 and 6.90e-19 for grids 150×500 and 300×1000 respectively. It means that about 0.3% error has been occurred in the results between two these grids.

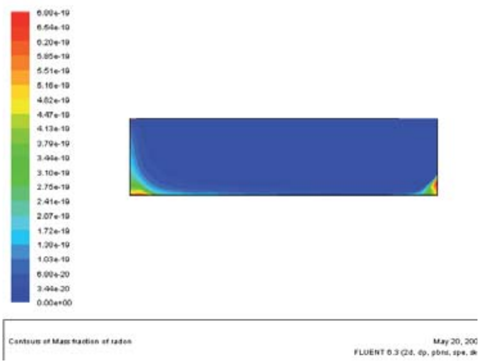


Figure 4.21a, Grids 150×500

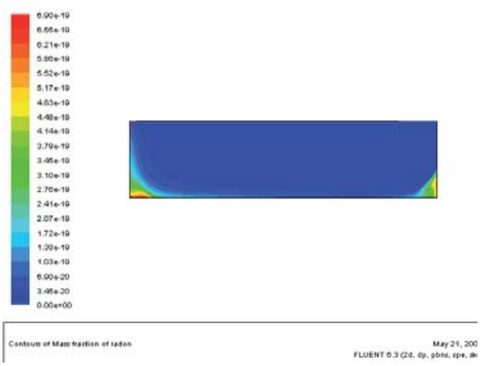


Figure 4.21b, Grids 300×1000

4.10. Experimental works

Studies and experimental works have shown that the location of ventilation inlet and out let and ventilation rate influence the indoor pollutants concentration [2,27]. In this thesis 2 experimental works are investigated and they are used for modeling verification. The first experimental study is related to influence of ventilation rate on indoor radon content, the experimental data used for this section were reported by the municipality of Västerås city in Sweden. The second experimental work is about the effect of changing location of ventilation system on indoor pollutant content which was conducted by Y. Zhang (2004) [2].

4.10.1. Influence of ventilation rate on indoor radon concentration

To examine influence of ventilation rate on indoor radon concentration, about 30 different residential buildings with natural and mechanical ventilation systems are investigated. Tables 4.1 and 4.2 indicate these experimental data which were gathered by environmental section, Vasteras municipality, in Sweden. The last given data (No. 30) was reported by JBS, AB company is related to the case study, a one family house. These data have been adjusted by address, date, and ventilation type, radon concentration before and after ventilation.

No.	Address	Ventilation	Date	BV	AV	AV / BV
1	26293	SJ	19951208	501	126	0.25
2	25705	SJ	19950112	450	310	0.69
3	24520	SJ	19991024	538	204	0.38
4	24899	SJ	20011010	510	260	0.51
5	26001	SJ	20050208	517	290	0.56
6	27777	SJ	20051205	551	150	0.27
7	41764	SJ	20060210	603	399	0.66
8	22437	SJ	20071029	416	284	0.68
9	38940	SJ	19990201	490	80	0.16
10	23821	SJ	20051230	428	306	0.71
11	23875	SJ	19951124	427	184	0.43
12	26745	SJ	19951226	501	149	0.30
13	25753	SJ	20060208	670	278	0.41
14	41412	SJ	20000229	496	343	0.69
15	31483	SJ	20021102	537	285	0.53
----	---------	-----	**Mean**	**509**	**243.2**	**0.48**

Table 4.7, Radon measurement data for natural ventilation system Data; source: Västerås Municipality, Sweden

In tables 4.1 and 4.2: SJ= Natural ventilation, MF= Exhaust fan, **BV** =Results before ventilation (Bqm^{-3}), AV=Results after ventilation (Bqm^{-3}), AV/ BV = ratio AV over BV and all dates are in winter time, 1995- 2008.

No.	Address	Ventilation	Date	BV	AV	AV / BV
16	5920	MF	20071030	618	283	0.46
17	23821	MF	20071214	428	306	0.71
18	42519	MF	20010204	424	276	0.65
19	29581	MF	19990205	586	342	0.58
20	26769	MF	20080107	404	290	0.72
21	29174	MF	19970118	415	124	0.30
22	32391	MF	19970210	580	210	0.36
23	32717	MF	19980307	400	202	0.51
24	29369	MF	20061001	635	380	0.60
25	30384	MF	20061206	561	306	0.55
26	26897	MF	19960126	458	158	0.34
27	54044	MF	19911101	608	356	0.59
28	25302	MF	19941128	660	328	0.50
29	53932	MF	20061018	452	336	0.74
30	--------	MF	20060108	270	150	0.56
---	-------	-----	**Mean**	**550.4**	**281.8**	**0.53**

Table 4.8, Radon measurement data for mechanical ventilation system source: Vasteras Municipality, Sweden

Above tables indicate that natural and forced ventilation systems have reduced indoor radon concentration about average of 50% in this experimental work.

Figures 4.22 and 4.23 also show the natural ventilation and mechanical ventilation results, whereas the result of radon content in Bqm^{-3} before ventilation and after ventilation for each building can be seen respectively. These results represent the influence of natural and forced ventilation on indoor radon concentration.

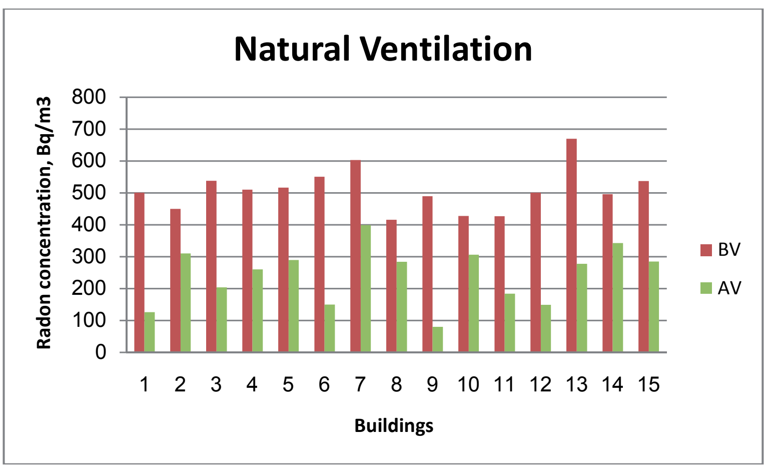


Figure 4.22, Indoor radon content, by means of natural ventilation

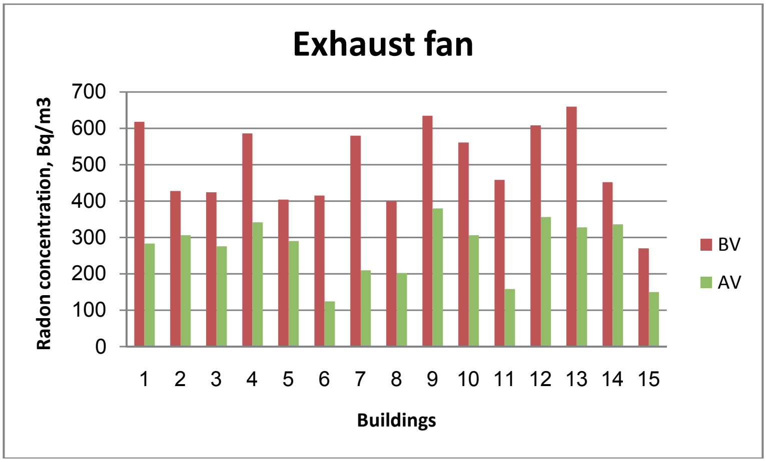


Figure 4.23, Indoor radon content, by means of exhaust fan

Figures 4.24 and 4.25 indicate the radon concentration ratio in natural and forced ventilation respectively. It is observed that the scattering of AV/BV in natural ventilation is more than forced ventilation. The scattering range is from 0.16 to 0.71, it means that indoor radon concentration after ventilation is widely varied. In mechanical ventilation this variation is in range of 0.34 to 0.74. These results also confirm that natural ventilation is an uncontrollable method.

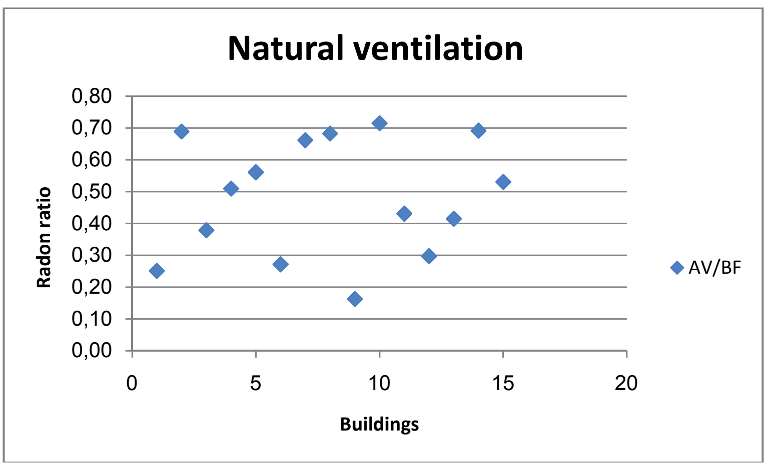


Fig. 4.24**,** Radon ratio AV/BV in natural ventilation

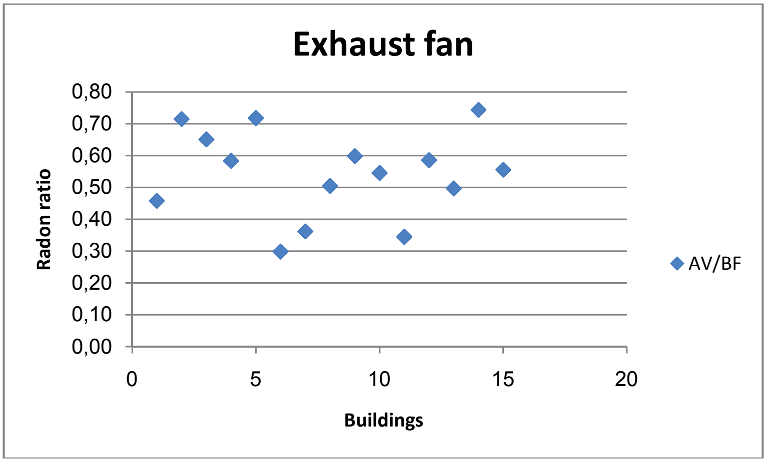


Fig. 4.25, Radon ratio AV/BV in mechanical ventilation

In according with Swedish regulations, as it is figured out in given 30 buildings about 64 percent of those are under ventilation and radon concentration levels are greater that permitted level, i.e. more than 200 Bq/m^3. It seems that it is necessary to increase ventilation rate and in turn to consume more energy to maintain indoor air quality related to indoor radon concentration.

4.10.2. The effect of changing location of ventilation system on indoor pollutant content

Y. Zhang (2004) showed that changing locations of inlets and outlets in the ventilation system can change the air flow distribution and thus locations of ventilation system can influence the pollutant concentration locally. This study has been conducted by experimental test and CFD simulation work for a forced ventilation system [2], see table 4.9. The results indicated that for 2 identical cases in displacement ventilation with changing only the outlet location, the indoor pollutant distribution was changed.

Test cases	Out location	Inlet location	Inlet temp (ºC)	Air exchange rate	Inlet velocity
Case 1	1.3 m from floor, right side	Next to the ceiling, left side	24	19.5	1.78 m/s
Case 2	Next to the floor, left side	Next to the ceiling, left side	24	19.5	1.78 m/s

Table 4.9.The effects of experimental cases of ventilation systems on pollutant distribution [2]

Chapter 5

Numerical and experimental results and discussion

As mentioned in the last chapter, factors same as ventilation rate, inlet/outlet location, mixing and displacement ventilation and underfloor heating were investigated by numerical solutions. The results indicated that these factors affect indoor radon distribution. Also experimental test confirmed that natural and forced ventilation systems can be used as a tool to decrease indoor radon concentration. In this chapter results of numerical simulation and experimental test are discussed.

5.1. Results of changing ventilation rate and inlet/outlet location on indoor radon

Three cases in model1 were investigated to show the influence of ventilation rate and location of inlet or outlet. Results of this numerical simulation showed that with increasing the ventilation rate, the value of indoor radon concentration is decreased (cases 2 and 3). Also it can be observed that with changing the location of outlet from up exhaust fan to down exhaust fan (cases 1 and 2), the average of indoor radon is varied and counters of radon mass fraction show that the distribution pattern of indoor radon for these cases are different (see table 5.1 and figures 4.7 and 4.8).

Model1	T	V	Radon mass fraction	Minimum	Maximum
Case1	293.06 K	4.34 m/s	7.01 e-21	4.36e-22	2.5e-20
Case2	293.06 K	4.47 m/s	7.23e-21	4.35e-22	2.65e-20
Case3	293.06 K	5.2 m/s	6.53e-21	4.30e-22	1.66e-20

Table 5.1, simulation results of changing ventilation rate and outlet location

5.2. Results of mixing and displacement ventilation systems on indoor radon

In this study, it is supposed that the ventilation by displacement because of its inherent nature can be more useful than mixing ventilation to reduce indoor radon content. Model 2 is setup to investigate the difference between these ventilation strategies on indoor radon mitigation. Table 5.2 shows these results which is approved that in the identical boundary conditions, the minimum radon mass fraction in the displacement case is about 40% of mixing displacement. Furthermore simulation results is shown that within the occupied zone (near the floor), in the displacement ventilation is less polluted than mixing ventilation (see figures 4.10 and 4.11). It means that in displacement ventilation with lower ventilation rate (less energy consumption) can be reached to the limited indoor radon level. With regard to indoor air quality the aim of this ventilation is to create supply air conditions in the occupied zone. This is in contrast to the mixing ventilation, where the aim is to dilute air to extract air conditions in the whole space. If it is considered at least 3 degree lower than room temperature it can be saved 15 percent of (heating) energy cost. Thus displacement ventilation because of lower ventilation rate and lower air supply temperature can be useful on indoor radon mitigation and energy savings point of views.

Model 2	Floor heat	Radon velocity magnitude	radon mass fraction	Min radon mass fraction	Max radon mass fraction
Mixing ventilation	20W	0.02 m/s	2.58e-18	1.74e-18	5.34e-18
Displacement ventilation	20W	0.03 m/s	2.73e-18	7.36e-19	8.12e-18

Table 5.2, simulation results of mixing and displacement ventilation systems

5.3. Results of floor heating on indoor radon mitigation

CFD simulation results showed that with increasing the underfloor heat sources the in radon behavior was completely different. Table 5.3 shows that in case 2 with 20 W the radon mass fraction is lower than case 1. The differences between 2 cases are clear from the distribution pattern (see figures 4.12 and 4.13 in the last chapter).

Model 3	Floor heat	Radon velocity magnitude	radon mass fraction	Min radon mass fraction	Max radon mass fraction
Case 1	0W	0.03 m/s	2.73e-18	7.36e-19	8.12e-18
Case 2	20W	0.2 m/s	1.45e-18	4.67e-19	1.83e-18

Table 5.3, simulation results of underfloor heating effects on indoor radon

In addition to the numerical simulation of the last chapter, in order to investigate the effect of floor heat on indoor radon reduction, the heating source of the basement was set 0 and 10 watt/m^2 in the absence of any ventilation. In this way, radon transportation takes place only due to heat; so called stack effect or buoyancy effect. It is necessary to remember that in the operational condition of FLUENT software, the gravity was defined at -9.81 in the z direction. These simulations performed in unsteady solver in order to distinguish the different effects of varying floor heat. Figures 5.1 and 5.2 show the behavior of radon distribution after about one and two hour in unsteady condition respectively. As it is shown the larger time spends the more radon content produces. The maximum value of radon is about 4.10 e^{-16} and 6.10 e^{-14} respectively.

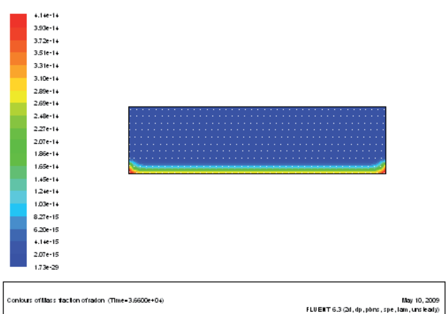


Fig. 5.1, Floor heat at 0 W/m^2 after 10 hours

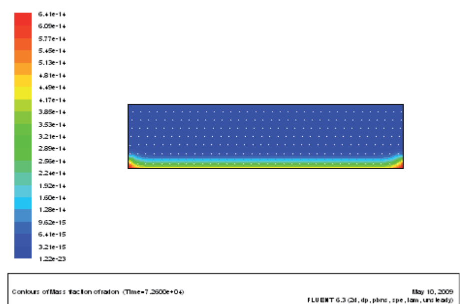


Fig. 5.2, Floor heat 0 W/m^2 after 20 hours

With increasing floor heat to 10 watts/m^2 this effect is projected more clearly. Figures 5.3 and 5.4, show that mixture movement which is reach to the ceiling is much faster in comparison of no floor heating. This is why the floor heat system is usually preferred to reduce indoor radon concentration.

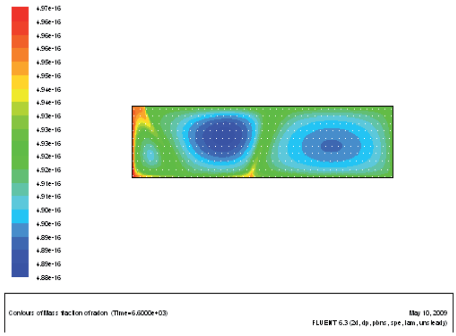


Fig. 5.3, Floor heat 10 w/m^2 after 1 hour

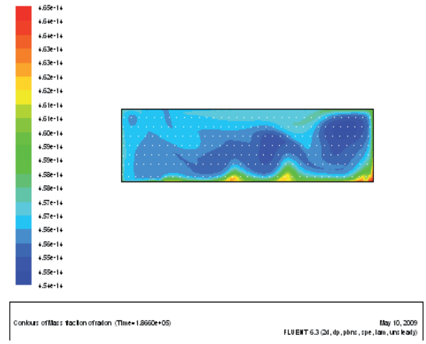


Fig.5.4, Floor heat 10 w/m^2 after 2 hours

From the above findings, one can be estimated that, if displacement ventilation system is used, because of lower ventilation rate (about at least 30%), lower temperature (about 3 degrees ×5%= 15%) and lower heating energy due to buoyancy forces of people ,electrical appliances and underfloor heating sources (20% in comparing with radiator heating system and mixing ventilation strategy). One can be concluded that these options enable energy reduction at least to:

- 30% of energy cost for electrical fans (inlet or outlet vents)
- 35% of energy cost for heating sources

5.4 Experimental test results

In this thesis to make a survey about the influence of ventilation on indoor radon, about 30 different buildings were tested and the values of indoor radon content before and after natural and forced ventilation were measured. These data are indicated that both ventilation systems affect the value of indoor radon concentration. From these experimental data the following results can be concluded as:

- Both ventilation types can affect the indoor radon concentration.
- The average radon reduction in both ventilation systems is about 50%.
- Increasing ventilation rates can decrease the indoor radon content consequently.
- Scatterings range of (radon ratio of A.V./B.V) data related to natural ventilation are more than forced ventilation
- 64% of residential buildings in this experimental test are under ventilation, in which indoor radon concentration after applied ventilation are more that 200 Bqm^{-3}.

- 80% of forced ventilation buildings are needed to be increased ventilation rates. It means that IAQ of the majority of these buildings must be improved.

Chapter 6

Conclusion remarks

6.1 CFD simulation and experimental study on ventilation and indoor radon

CFD is a suitable and inexpensive tool for visualizing the behavior of harmful contaminants like radon and predicting indoor air flow with low cost and time in comparison with the other methods same as gas tracer or experimental methods. The modeling method of radon in FLUENT software is the key factor for solving transport equations in turbulence modeling and enhancing accuracy of the results.

The models developed with FLUENT simulated radon entry through the material of a house that is located in basement in 2D and 3D models. Indoor radon concentrations are dependent on radon production, ventilation and outdoor radon concentration. Ventilation principals, ventilation rate and location of ventilation means can significantly influence radon concentration. Also using underfloor heating can be used as a factor to reduce indoor radon. In this work, mentioned factors were investigated by means of numerical and experimental methods.

Natural ventilation can be used to reduce radon content, but it is non controllable, reliable, particularly in the cold climate like Sweden, and non usable because of adverse thermal comfort in winter.

Simulation results of forced ventilation showed that displacement ventilation acts more efficient than mixing ventilation in view points of reducing radon concentration, i.e. IAQ and energy efficiency.

This study confirms that with increasing ventilation rate, the radon concentration is decreased, but the location of ventilation system is also a significant factor. From the simulation results, it is observed that within the ventilated room, there are some zones, which are good for living and somewhere is more polluted. The traditional radon detectors basically show the average value of radon content in $1m^3$ of air. That is why detector measuring is not exact and safe.

Simulation results proved that floor heat can be supported ventilation effect and speed up the mixture movement. Floor heating reinforces the buoyancy effect, which is useful to reduce radon content in the floor (seating area) and then lower ventilation rate can be applied.

In Sweden in spite of mandatory governing regulations about radon limitation level in residential building, the experimental test underlines that about 80% residential buildings are lack of good IAQ and the indoor radon concentrations exceed of permitted level (i.e. 200 Bqm^{-3}).

It can be concluded that, in case of indoor radon, using displacement ventilation strategy and calculating the suitable location of inlet and outlet by means of numerical simulation and in addition to apply underfloor heating, we can obtain the optimum point of IAQ and more than 30% energy savings in both electrical fans and heating sources.

For confirming the results and testing the sensitivity, we changed the model with different boundary condition values for example the value of radon exhalation rate, ventilation types and ventilation rate and location. These tests confirmed that the results are different. For checking grids independency, we increase the grid two times and five times and the results were approximately equal.

In summary indoor radon affects indoor air quality and energy savings in the residential buildings. Ventilation, especially displacement ventilation, because of its high ventilation effectiveness (ε_v) can play a good role to improve indoor air quality and energy efficiency.
CFD enables researchers to predict, visualize and measure indoor air flow and radon treatment and determine polluted dead zones. They can design desired ventilation system for achieving thermal comfort and energy efficient point of views.

6.2 Future work

This thesis focused on the study of ventilation effects on indoor radon mitigation in residential building, which emits through the building material with emphases on indoor air quality and energy saving approaches. This study should be continued in the future with more details and accuracy in three dimension modeling in the actual building. This study can be improved with considering occupants, thermal comfort and energy savings method using heat recovery ventilation (HRV) by means of heat exchanger and heat pump. External coupling between CFD and BES (Building Energy Simulation) program software is a proper approach for improving both the simulation results and calculation of energy balance.

Very often, there are several pollutants together in residential building, to study all pollutants and ventilating them can be selected as a topic in future research studies. This study can also be completed and validated by exact experimental data and be compared with simulation results.

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Summary of papers

Paper 1:

Experimental and numerical study of radon mitigation and ventilation effects

The main purpose of this article is a feasibility study of CFD for calculating and predicting indoor radon distribution. Designing a suitable model and determining required boundary conditions play a significant role in applying CFD techniques. The other purpose of this paper is a verification of CFD modeling of radon mitigation and influence of ventilation rates and changing locations. The validation of the model is based on some experimental data, analytical analysis and previous researches, grid independency and residual convergence test.

The simulation results showed that with changing of ventilation rates and inlet - outlet locations, the indoor radon concentration will be changed. These results are also in agreement with experimental data and previous research studies.

Paper 2:

Simulation of Radon Mitigation and Ventilation in Residential building

Radon transport in building materials is influenced by ventilation factors and other conditions related to climate and tightness of residential buildings.

Radon after emanating through building materials by advection and diffusion forces comes out and enters within the room space and then is influenced by forced (mechanical) and natural ventilation (buoyancy or thermally effects) and moves throughout the room. To reduce radon concentration level several ways are proposed, but for existing building, ventilation method can be used to dilute radon contaminant and maintain indoor air quality, easily and cost effectively.

The Results confirm that appropriate ventilation can reduce the value of indoor radon concentration and also the location of inlet and outlet vent is influenced the radon content.

Paper 3:

Influence of Ventilation Strategies on Radon Mitigation in Residential Buildings

The aim of this paper is to make a survey of relationships between radon reduction effectiveness with different ventilation principals and to visualize and predict radon content and its behavior in a one family house with computational fluid dynamics (CFD) program software.

Selection of efficient ventilation type is important action to dilute radon contaminant, maintain indoor air quality and energy saving implications. 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. Pollutant concentrations are inversely proportional to ventilation rates.

By means of CFD as a new technology we can design appropriate ventilation in indoor air quality (IAQ) and building energy savings point of views.

Paper 4:

Influence of residential ventilation on Radon mitigation with energy saving emphasis

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 results show the changes of both the outdoor flow rate and the ventilation strategy affect both the indoor radon content and energy consumption. The displacement ventilation over mixing ventilation has better characteristics to reduce indoor radon and energy use because of higher ventilation effectiveness.
It is estimated that using ventilation by displacement and underfloor heating during winter time, at least 30% energy savings can be achieved.