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Energy Savings and Radon Mitigation with Heat exchanger ventilation system in Residential Buildings

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Abstract
Balanced ventilation with heat recovery has strongly effects on radon mitigation and energy saving in residential buildings.

While reducing radon by means of forced ventilation, it is necessary to increase outdoor supplied air, and this in turn raising energy use. Also through ventilation systems energy losses is inevitable by exhaust fan or another ways, but by heat recovery technology it is possible to recover most of this heat loss.

Heat recovery ventilation systems which recover exhaust air can reduce ventilation loss significantly and with balancing indoor air pressure play a good role on effectiveness of ventilation to reduce and mitigate radon level.

This paper deals with the effects of heat exchanger on radon concentration and energy consumption in a detached house in Stockholm, as a case study. The performance of heat recovery ventilation system in the viewpoints of radon mitigation and energy saving is investigated with radon concentration measurements and life cycle cost analysis during winter.

The results of measurements and dynamic simulation showed that heat recovery ventilation system can reduce radon level from about 900 Bqm^{-3} to below 100 Bqm^{-3} and 80% energy savings of ventilation loss, amounted about 500 kWh per month in winter and to 37 $kWh/m^2.a$ in cold climate with ventilation rate 0.5 ach and 5000 heating degree days.

1.Introduction

Energy consumption in building sector is increasingly growing and that is about 40% of total final energy consumption in many countries. In Sweden about 61 % of the energy use in this sector is used for producing space heating and domestic hot water [1]. This fact has to be realized in employing energy efficient ventilation system as a radon mitigation strategy to prevent unnecessary energy consumption, especially in cold climate.

The application of heat exchanger as a heat recovery ventilation system has grown increasingly in last 2 decades in residential buildings. These systems because of reducing heating energy consumption and providing indoor air quality can have significant role in improving sustainable society.

Several studies have compared various ventilation systems to show the advantages of heat exchangers, especially in cold climate [2,3,4]. Energy efficiency can be improved up to 67% using a heat recovery system having 80% efficiency, compared to traditional exhaust ventilation system [2]. Wiliam Nazaroff et al, used heat recovery ventilation system to control radon content in residential buildings. They concluded that in air tight houses, installing air-to-air heat exchanger can satisfy energy conservation goals in a cost effective manner without compromising indoor air quality [5]. The comparison made between exhaust fan and heat recovery ventilation systems in cold climate showed that heat exchanger air-to-air ventilation system can save 2710 kWh per year energy consumption related to ventilation system and space heating. This amount meant that about 30% energy efficiency in a insulated house [6]. The results of three different ventilation systems in Swedish dwelling showed that heat recovery ventilation system is the best one to reduce radon level [7].

Roseme has calculated that the expected energy savings by employing air-to-air heat exchanger in the tight single family detached house with total volume 350 m^3, 0.5 ach and 4657 degree hours, and showed that annual energy savings about 6000 kWh and electricity cost 275 dollars per year is obtainable [5].

Besides some advantages mentioned before, energy recovery ventilation systems can reduce the risk of condensation of water vapor in winter time within dwellings [8].

This study aims to investigate about radon mitigation, the life cycle cost analysis and the energy recovery calculation and dynamic simulation of a rotary heat exchanger. This approach can help more than 500,000 dwellings in Sweden which suffer from elevated radon concentration in the ranges of 200- 800 Bqm^{-3}, some 1000,000 dwellings in the ranges of 100- 200 Bqm^{-3}[9] which is necessary to be increased ventilation rate to reduce indoor radon, by means of a cost effectiveness ventilation system. IDA, indoor climate and energy package was employed as dynamic simulation software to predict recovered heat by heat exchanger unit.

2. Energy recovery ventilation systems

Thermal losses of buildings are ventilation losses and transmission losses of the envelope. The former is becoming more and more important and as much as the latter, because of new indoor air quality standards and protective actions against the modern air tight buildings; sick building syndrome. The available technique to reduce ventilation load and control indoor pollution and humidity is energy recovery ventilators. Energy recovery from the exhaust air is a simple process whenever there is controlled ventilation system [3]. Two kinds of recovery ventilators exist; energy recovery ventilator (ERV) which transfers certain amount of water vapor (moisture) along with heat energy and heat recovery ventilator (HRV) which only exchanges heat energy between incoming and outgoing air streams. Transferring water vapor across the heat exchanger core is desirable and useful in the healthy buildings. In winter, indoor humidity stays more constant because some of the moisture from the exhaust air is transferred to the less humid incoming winter air. In the summer, the water vapor in the incoming air is transferred to the drier air leaving the house. If you use an air conditioner, an ERV generally offers better humidity control than an HRV and is usually a better choice in view point of indoor air quality, especially in cold climate.

A recovery ventilator can be the best choice to compromise between radon reduction and energy consumption. Recovery ventilation systems have two air streams provided by a supply and an exhaust fan. The supply and exhaust air streams are connected by means of an air-to-air heat exchanger which acts as a heat transfer system from warm air stream; indoor air, to cold air stream; outdoor fresh air without mixing them.

2.1 Temperature and humidity efficiencies of energy recovery ventilation system

Rotary heat exchangers are also employed as a well proven and efficient means of heat recovery providing up to 80% energy savings. The rotating wheel (rotor) is made up of an air permeable heat transfer matrix which picks up heat from the exhaust air and releases it as the wheel passes through the cooler supply air. Depending on the air conditions and using desiccant coated rotors the heat recovery wheel can also transfer moisture providing both sensible and latent energy recovery. Figure 3 indicates the incoming and outgoing air streams towards the wheel.

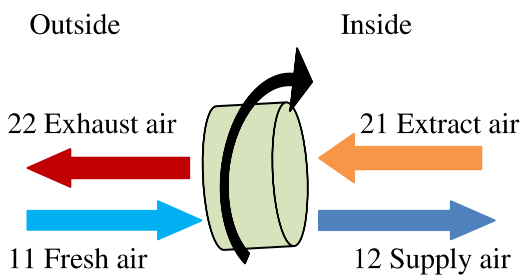

Fig. 3 Air streams direction to/from rotary heat exchanger unit

The primary key factors for evaluating the performance of rotary heat exchangers are temperature and humidity efficiency. They are defined as the ratio between the air condition change achievable by the rotary heat exchanger and the maximum possible condition change of the air. These factors are defined as:

Temperature efficiency η_t:
$$\eta_t = \frac{t_{12}-t_{11}}{t_{21}-t_{11}} \qquad (1)$$

Moisture efficiency η_w:
$$w_t = \frac{w_{12}-w_{11}}{w_{21}-w_{11}} \qquad (2)$$

where, $t =$ Temperature in °C, w = Water content of air in g/kg

11 = Fresh air condition before heat exchanger (Outdoor),

12 = Supply air condition after heat exchanger (Indoor),

21 = Extract air condition before heat exchanger (Indoor),

22 = Exhaust air condition after heat exchanger (Outdoor)

3. Case study description

3.1The Building

The hose selected for this study is a detached one family house in Stockholm, built in 1970. This house is 2-storey structure, which is placed one meter below the ground and volume of each storey is about 230 m^3. The foundation of this building is located on bedrock. The firstly radon level was about 4000 Bqm^{-3} originated from the sources of the ground and buildings material in the first floor, 70% and 30 respectively. The final radon level decreased to about 600 Bqm^{-3} after sealing some part of floor and using sump radon in this storey.

3.2 The ventilation system

For this study a mechanical ventilation system with air-to-air heat exchanger unit provides fresh air to the building. This unit is a rotary energy recovery system, which is recovered both heat (sensible) and humidity (latent) energy. Figure 1 illustrates the installed heat exchanger system inside the house.

The operating points of the unit can be determined from the diagram shown in figure 2. This diagram which is prepared by the manufacturer consists of a number of curves and axes.

Fig.1.The rotary heat exchanger installed in the building

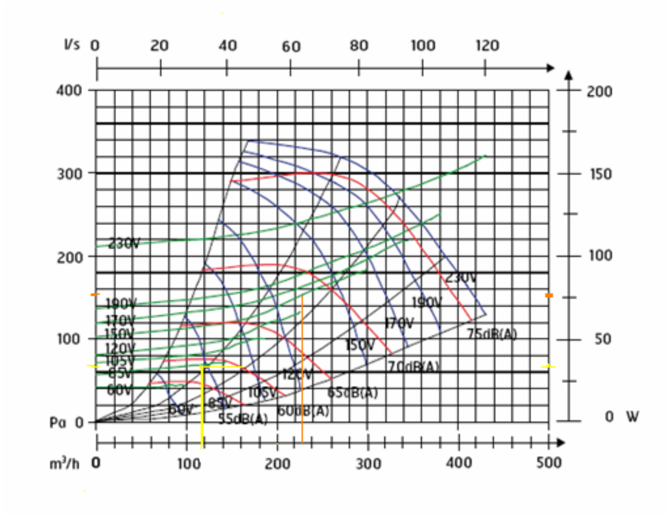

Fig 2. The characteristics curves of fan air supply
1. Capacity curves (blue), 2. Operation curves (black), 3. Power consumption curves (green) 4. Sound curves (red), taken from FLEXIT company

Given the ventilation rate, it is possible to find operating points of pressure, noise and fan(s) electric energy consumption. These values are shown in table 1.

Specifications	Operating rating
2 Fans power rating	100W
Efficiency	80%
Ventilation rate	0.5 ach (35 l/s)
Noise	50 dBA(quiet)

Table 1.The operating rating of the unit.

The temperature and humidity efficiencies of this rotary heat exchanger unit are 80%. This unit provides fresh air at three levels; 0.25, 0.5 and 1 ach.

The outdoor and indoor conditions (t_{11},t_{21}, $RH_{Outdoor}$ and $RH_{Intdoor}$) were measured and another conditions; w_{11}, w_{12}, t_{12}, w_{21} were calculated by equations 1 and 2 or were taken from Mollier diagram, see figure 4.

These data for are also collected in table 2. As it can be observed, improving of indoor air quality, from 2 to 4.24 gkg^{-1} of indoor moisture, and decreasing of the difference between indoor and outdoor temperature, from -7.4 to 14.5 °C, are two significant reasons of using heat recovery exchangers. It means that energy recovery ventilation system provides additional comfort in the winter by adding moisture from the outgoing air to the incoming air to help avoid excessively dry indoor conditions.

Since outdoor temperature has a long variation during the year, the temperature and humidity efficiencies are not constant and so a dynamic simulation tool is a good means to determine the recovered heat during a month or whole year.

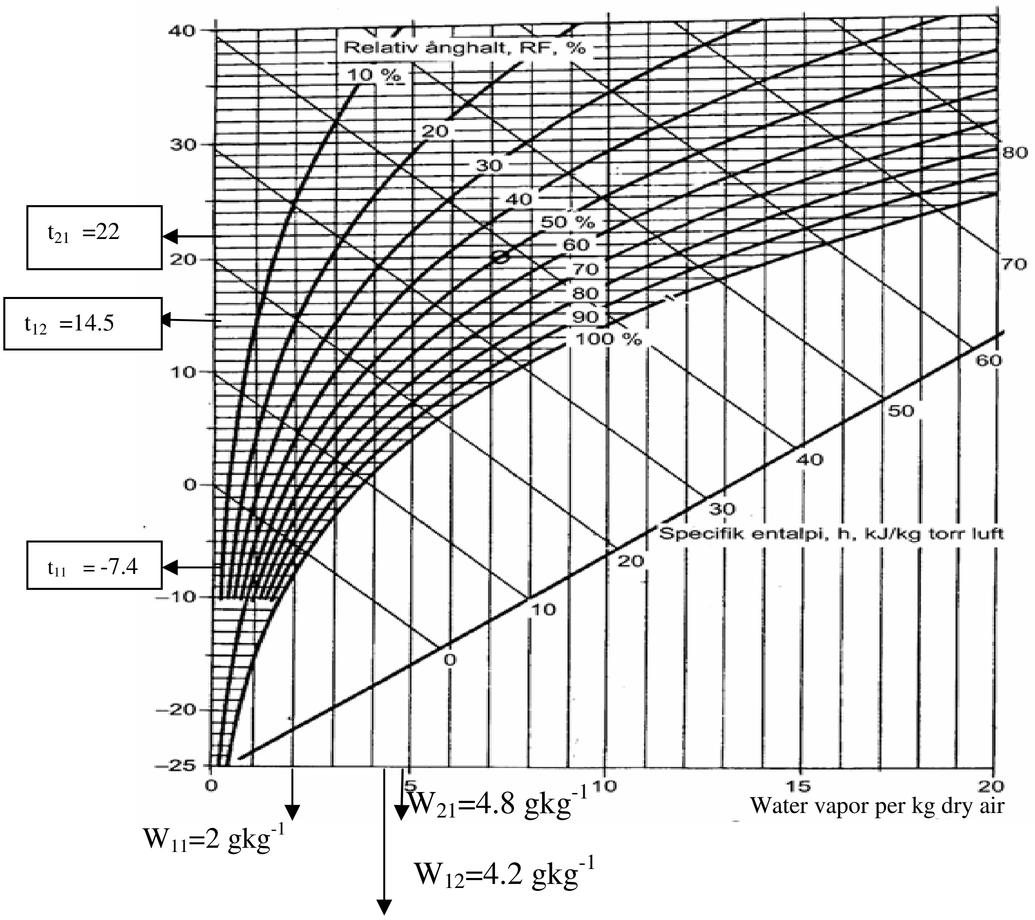

Fig. 4 Air conditioning process for heating operation

Temperature	Relative Humidity	Moisture in air	Position
t_{11}=-7.4	98%	w_{11}= 2 gkg^{-1}	Fresh air condition
t_{12}=14.5	40%	w_{12}= 4.24 gkg^{-1}	Supply air condition
T_{21}= 22	30%	w_{21}= 4.8 gkg^{-1}	Extract air condition

Table2. Air conditions before and after recovery ventilation system

3.3. Radon measurements

Radon concentrations were measured constantly during the winter, both with a continuous meter (CRM) and alpha track detector (ATD). Table 3 shows the results of these measurements.

Date and period	ATD	CRM	Ventilation rate	Ventilation type	Remedial action
2008-2 (2 weeks)	3580 $\pm$380 Bqm$^{/3}$	----------	0.25 ach	Extract fan	No action
2010-01 (3 month)	1280$\pm$160 Bqm$^{/3}$	1580 $\pm$ 158 Bqm$^{/3}$	0.25 ach	Heat recovery	Sump and sealing
2010-04	100 $\pm$20 Bqm$^{/3}$	-----------	0.5 ach	Heat recovery	3 connected sumps

(3 weeks)					
2010-3-14 (2 days)	------------	97$\pm$10 Bqm$^{/3}$	0-5 ach	Heat recovery	-----------
2010-3-18 (2 days)	-----------	65$\pm$6 Bqm$^{/3}$	0.5 ach	Heat recovery	----------
2010-4-22 (2 days)	-----------	36$\pm$4 Bqm$^{/3}$	0.5 ach	Heat recovery	-----------

Table 3. Measurements results

3.4. Analytical analysis

If it is assumed that the radon generation rate (G) is constant, the radon content level 1 meter below the ground is calculated analytically [10] as:

$$G = Ae\rho\lambda\frac{1-p}{p} \qquad (3)$$

$$C = \frac{G}{n} \qquad (4)$$

where, C = radon concentration(Bqm^{-3}), G = radon generation rate while air ventilation rate is zero,

n= air change rate(h^{-1}), G=radon generation rate (Bqm^{-3}s^{-1}), λ = radon decay constant (2.1×10^{-6}s^{-1}), A

= radium activity (Bqkg^{-1}), e = radon emanation fraction (0.3), ρ = soil density(kgm^{-3}), p = porosity

(0.4).
If A= 20 Bqkg^{-1} , ρ = 1000 kgm^{-3} and n= 0.25, 0.5 and 1 ach, equations 3 and 4 give,

$G = 18.9\times10^{-3}$ Bqm^{-3}s^{-1} and with ach$\cong$0, maximum indoor radon would be C_{max} = 4500 Bqm^{-3}. This

value is also is comparable with data measured with low ventilation rate in 2009.
Equation (4) gives C for different ventilation rate; then $C_{0.25} = 140$, $C_{0.5} = 70$, $C_1 = 34$. Comparing

these analytical data with measured data gives about 15% error.

Radon concentrations were measured with changing ventilation rate in three levels. Figure 5 shows the results of in three different air change rates, trough CRM radon monitor instrument. This CRM measurements results has +/- 10% uncertainty.

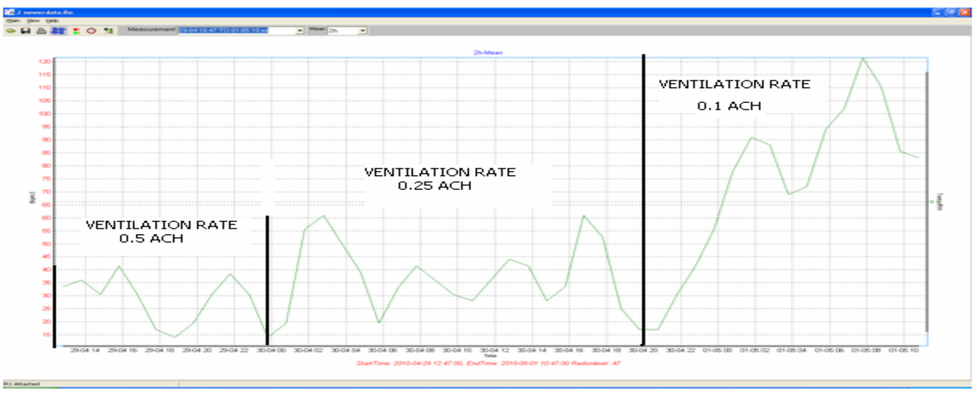

Fig. 5. Continuous radon concentration levels measured with CRM

4. Dynamic simulation

For a long term assessment of the heat recovery ventilation efficiency is needed to consider complete time series of outdoor temperature and all buildings loses and gains during heating period. The variations of outdoor temperature and ventilation rate may change the heat recovery temperature and humidity efficiencies. All these time dependent effects are taken into account with the use of dynamic programs.

5. Economic analysis

In order to calculate which costs and energy losses imposed by the heat recovery unit as a radon mitigation and ventilation system to the utility costs of the residential building, we need to know about ventilation loss, operational energy cost and future energy price, climate, fan(s) energy consumption, heat energy cost, indoor air temperature and ventilation rate (as a life style of occupants) and unit initial and installation costs. In the industry and academics heating and cooling degree days is a useful method which has been used for decades [11]. In cold climate high heating degree days is very important in view point of energy recovery and multi propose as radon mitigation ventilation system.

5.1 Energy loss and life cycle costs analysis

Usually, energy loss and initial costs of a ventilation system to reduce radon content is concern of home owners. In order to install a radon mitigation system, some costs should be considered:
1-Direct electrical energy cost relevant to unit power to operate the ventilator; fans, motor, preheating
2-Operating energy costs of ventilation and infiltration losses and thermal transmission losses 3-Efficiency of ventilation unit
4- Noise of ventilation unit
5- Whole life time of ventilation unit
Since ventilation system is installed indoor place, usually the size of the system is a concern from the homeowners' point of view.

As a general and accepted approach to calculate recovered energy is the outside temperature cumulative curve during the heating and cooling period. The seasonal recovered energy recoverable energy while the room temperature is set constant can be easily determined. The outside temperature cumulative curve for Stockholm winter is illustrated in fig 6.

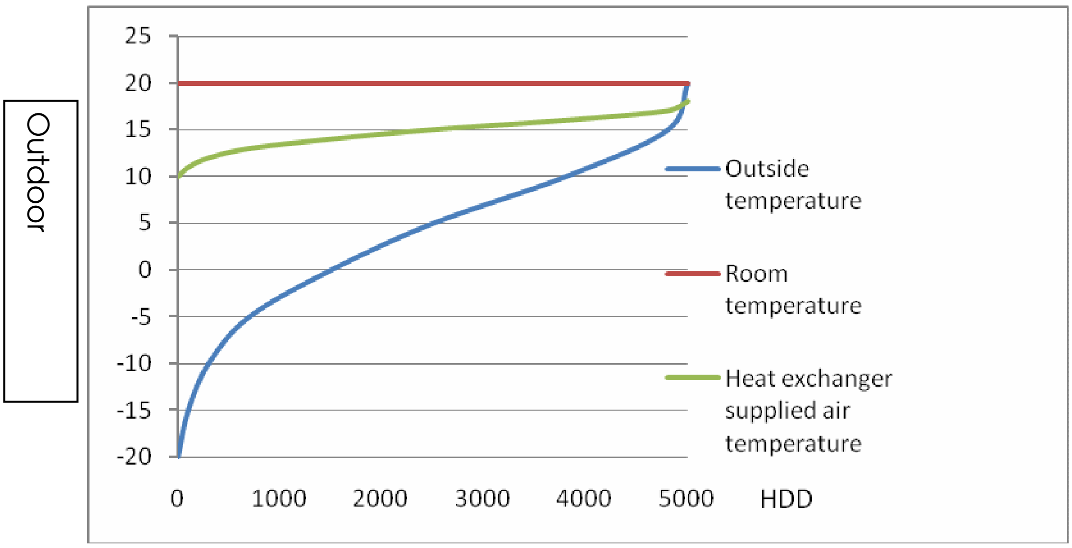

Fig. 6 Cumulative heating degree days in Stockholm

The normal range of the ventilation rate and heat degree days (HDD) in some cold climate change from 0.25-1 ach and 4000-6000 degree days respectively, the total energy consumption through ventilation would change from 2000- 8000 kWh per year. Heating Ventilation loss for the detached house with 0.5 ach and HDD=4819 for Stockholm, is 3990 kWh, which can be calculated from equation (5) as following:

$$Q = ach \times V \times 0.33 \times 24 \times HDD \quad (5)$$

Where ventilation rate= 0.5 ach, building volume=V=230 m^3, HDD=4819 degree days

Recovered Q by the heat exchanger: $Q_{\text{recovered}}$ =4389*80%= 3511 kWh/ year (37kWh/m^2.a) and annually energy savings is; 3511-766= 2745 kWh.

The annually energy saving is varied by changing the ventilation rate and HDD, this values are illustrated in figure 7. The two key factors which a radon mitigation system adds to the utility costs of the residences are outside environment and the house air exchange rate (ach).If it is considered 30-50% of raising energy consumption is due to a radon mitigation system, it can be seen that as much as this energy consumption could be saved through recovery and this kind of radon mitigation method is cost effective.

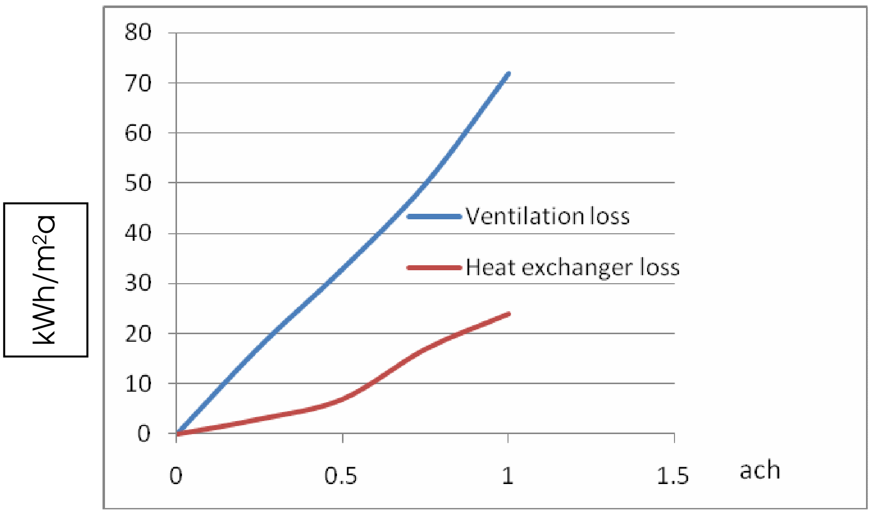

Fig. 7 Ventilation loss and recovered energy by heat exchanger

The IDA dynamic simulation results, are shown in the table 4. Comparing these simulation results with calculated results, shows an agreement between data with error of 12% at 0.5 ach.

Ventilation rate	Heat recovery	Fan energy use
1.0 ach	8033 kWh	1322 kWh
0.5 ach	4035 kWh	661 kWh
0.25 ach	2027 kWh	331 kWh

The whole year predicted result of dynamic simulation is indicated in figure 8. This figure shows that the heat exchanger ventilation can damp the long variation of outdoor and keep indoor air at set point temperature with short variation during a year.

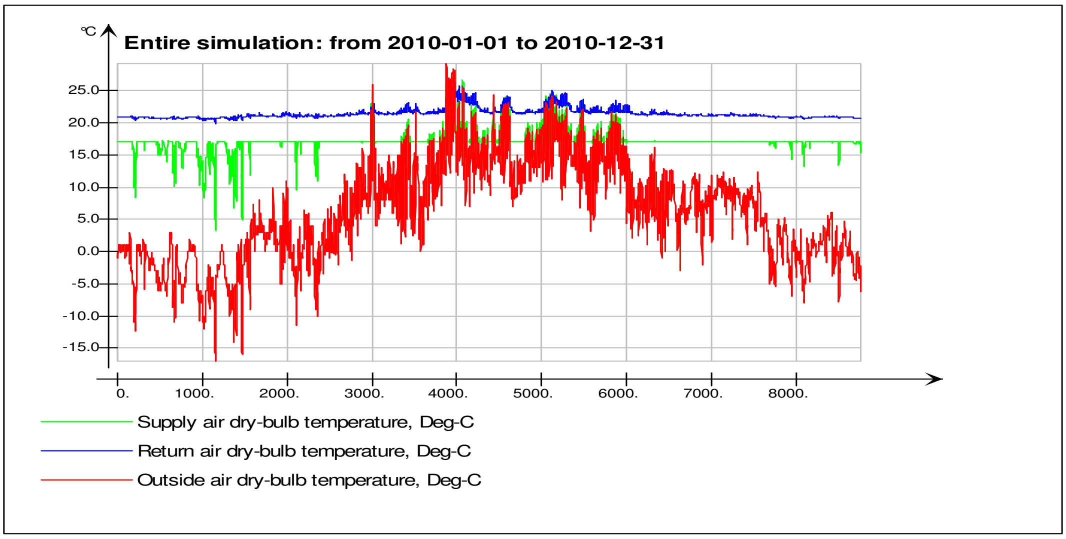

Fig.8.The difference variation between the temperatures of outside air, supplied air by heat recovery and return air

5.2. Energy life cycle costs

The initial capital investment and installation costs of this rotary heat exchanger unit is about 25,000 SEK with 25 years life time and has low energy consumption and annually maintenance. The energy use to operate the 2 fans is 766 kwh per year and the costs of 2 filters for about one year is 500 SEK. Energy cost is Sweden is roughly about1 SEK/kWh include tax and VAT.

Net present value method (NPV) is one of the different techniques to evaluate the cost-effectiveness of an investment in the future. Energy costs in the future can be calculated as:

NPV = Costs of recovered energy per year- Annually cost (2426 SEK-500 SEK) ×I, where I(NPV factor) = $\frac{1-(1+i)^{-n}}{i}$, n=25 and i (interest rate) =4%

I= 15.6221, NPV= 30088 SEK, while initial investment =A_0=25,000 SEK, since NPV> A_0 enterprising is cost-effective. Because of rising energy price annually, if these changes of energy price take into account, NPV calculation is as:

$$I_q = \frac{1-\left(\frac{1+q}{1+i}\right)^n}{\frac{1+i}{1+q}-1}$$

where q= 2% is the annually rate of changing energy price and is the interest rate. From this equation $I_q = 19.6146 > I$ and then NPV with energy price increment would be NPV=38659 SEK. Regarding to rising annually energy price, about 15 years this investment would have payback.

6. Results and discussion

Some 30% of Swedish residences have elevated radon higher than 100 Bqm^{-3} and about 500,000 dwellings with concentration 200-800 Bqm^{-3} [9] and they need to be improved indoor air quality only by providing cost-effective ventilation system in order to consider energy savings implications. This study showed that the best choice is energy recovery units, which is manufactured in Europe and the small sizes suitable for single family buildings are in the range of 17000-30,000 SEK.

Analytical and dynamic simulation results showed that, using this kind of ventilation system to mitigate radon level, Swedish buildings can have energy savings in the range of 36 to 52 kWh/m^2a for different heating degree days from 4000 to 6000. If it is considered each building of 500,000 buildings, has at least 50 m^2 floor areas, annually energy savings roughly would be 1000 GWh.

Usually, radon level cannot reduce lower than a specific value; this equilibrium value is combination of outdoor radon and building materials, which is called background level [12].Reducing radon lower than background level by maximizing ventilation rate, only leads to add unnecessary energy consumption and make much more noise to the house. In order to minimizing the radon level, some variables like energy losses, noise of ventilation system, should be optimized along with, and the efficiency of heat recovery unit must be considered.

The economic evaluation of the heat exchanger from the exhaust air depends on the volume and duration of the ventilation. The payback decreases when the annual utilization hours increase. It means that heat recovery ventilation systems are more advantageous for long and sever winters like Sweden or hot summers.

7. Conclusion

The first set of conclusion of using balanced heat exchanger ventilation system is relevant to indoor air quality of radon concentration; balancing between supply air and exhaust air prevents sucking of radon from the ground to inside the building. In contrary extract fan ventilation system with making negative pressure draws outdoor air gas from everywhere which is possible. Energy recovery ventilation system also because of humidity efficiency and latent energy recovery reduce dampness and mold growth causing by high levels of relative humidity.

The second advantages set of conclusion of heat exchanger is related to energy savings. In comparison with exhaust fan ventilation, this study proved that, heat exchangers ventilation system can save energy of ventilation loss up to 80%. The colder climate, the more energy can be saved and recovered.

The economic calculations of NPV method and energy life cycle cost showed that capital investment is cost-effective even though if the energy price is unchanged in the future years. In cold climate the investment cost indeed can be balanced by energy savings, because the more heat degree days (more energy demand) leads to more energy savings.

The best characteristic of heat exchanger is quiet outdoor temperature dependent, unlike exhaust fan ventilation.
In Sweden because of long winters, high value of heating degree days and elevated radon level in residential buildings, heat exchanger ventilation system is the cost-effectiveness strategy for both energy saving and indoor air quality.

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