Impacts of Heat Recovery Ventilators on Energy Savings and Indoor Radon in a Swedish Detached House

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Abstract: Heat recovery ventilation systems, because of reducing ventilation loss through recovered exhaust air, can play a good role in the effectiveness of ventilation to reduce energy use.

In this paper, the impact of a heat recovery ventilator (HRV) on the energy use and indoor radon in residential buildings is investigated.

This paper describes the effects of a heat recovery ventilation system on energy consumption in a detached house in Stockholm, Sweden. The performance of the heat recovery ventilation system is examined with respect to radon mitigation and energy saving by measuring the radon concentration and analyzing the life cycle cost of a heat exchanger unit.

In this study, a multizone model of a detached house is developed in IDA Indoor Climate and Energy (IDA ICE 4.0). The model is validated using measurements regarding use of energy for heating, ventilation and whole energy use. The results of the measurements and dynamic simulation showed that heat recovery ventilation system 74% energy savings of the ventilation loss, amounted about 30 kWh.m^{-2} per year. Life cycle cost analysis used for assessing total costs and the result showed that using this system is quite cost-effective and investment would payback during 12 years.

Key-Words: Keywords: Heat Recovery, Ventilation, Energy saving, Radon, Indoor Climate and Energy (IDA)

Nomenclature			
A_0	initial investment	V	volume (m^3)
B_0	all savings in net present value method	η	temperature efficiency
B	annual savings in monetary unit	λ	radon decay rate (h^{-1})
c_p	heat capacity(KJ.kg^{-1}°C^{-1})	λ_v	ventilation rate(h^{-1})
E_{Hex}	Ventilation loss with heat exchanger	ρ	air density
E_{rec}	recovered energy(kW.h)	**Abbreviations**	
E_V	Ventilation loss(kW.h)	AC	alternative current
G_t	heat degree hours	Ach	air change rate
i	interest rate	DC	direct current
M_{water}	water mass(kg)	HRV	heat recovery ventilator
$\dot{m}$	mass flow (kg.s^{-1})	HDD	heating degree days
n	time in year unit	RH	relative humidity
Q_v	specific ventilation loss (w. °C^{-1})	SFP	specific fan power
q	annual energy cost escalation rate		
t	temperature (°C)		

1 Introduction

Energy consumption in the building sector continues to grow steadily, and makes up around 40% of total energy consumption in many countries. Therefore measures of reduction building energy use are a major concern.

In 2007, Swedish Energy Agency reported that electricity use between households, varying from 2000 to 7000 kWh per year for a detached house, and about 61 % of energy use in this sector is used for space heating and domestic hot water [1, 2]. In Sweden, heat recovery from exhaust ventilation in existing buildings is an approach to reduce final energy use per heated area up to 20% below 1995 levels by 2020[3]. Energy in buildings is used to overcome the heat losses due to the ventilation, infiltration and transmission through the buildings envelope. The energy performance of buildings is significantly affected by ventilation and generally accounts for 30–60% of the buildings energy use [4].

The prevalence of heat recovery ventilator (HRV) systems in residential buildings in Sweden has increased over the last few decades. The increase in energy efficiency through heat recovery systems such as these contributes to a more sustainable society.

A heat recovery unit because of saving energy and reducing radon level has two different useful performances. The aim of this study is to show the effectiveness of HRV systems for reducing energy consumption and controlling indoor radon level due to balances between incoming and outgoing air streams.

U sing HRV systems can help many of the more than 500,000 dwellings in Sweden which suffer from elevated radon concentrations in the range 200-800 Bq.m^{-3}, and the 1,000,000 dwellings that have radon concentrations of 100-200 Bq.m^{-3} [5], which need increased ventilation to reduce indoor radon concentrations. Besides of energy use concerns in building sector, more than 30% of Swedish residents live in dwellings which have radon levels above safe level i.e.100 Bq.m^{-3}, which requires remedial actions [5].

Several studies have compared various ventilation systems to show the advantages of heat recovery systems in cold climates [6-8]. One of these studies showed that energy efficiency could be improved by up to 67% compared to a traditional exhaust ventilation system by using a heat recovery system with a nominal temperature efficiency of 80% [6].

The best currently available system for reducing ventilation losses and controlling indoor radon is the recovery ventilator. Heat recovery from the exhaust air in a controlled ventilation system is a simple process [7]. A heat recovery unit with effectiveness at least 50% can save large amount of energy and it can be economically very advantageous [7].

Comparison between an exhaust fan and a heat recovery ventilation system in a cold climate showed that a heat exchanger air-to-air ventilation system can save up to 2710 kWh per year compared to a traditional ventilation system and space heating [9]. This amounts to an increase in energy efficiency of around 30% in an insulated house. This is the best current technology for reducing radon levels [9, 10].

2 Investigation and methods

2.1 Materials and methods

The investigation was conducted in a single family detached house, where radon levels were measured in conjunction with remedial changes to reduce these levels. A rotary heat exchanger unit and radon detectors were employed to measure heat recovery and radon level respectively.

The radon measurement tools included a continuous radon monitor (CRM, R2) produced by Radonelektronik Company [11] which is an electronic devise with 10% error and alpha track detectors. Passive alpha-track detectors contain a plastic sheet of film onto which the alpha particles produced from radon and radon progeny etch lines as they pass through the monitor. These etched lines are then analyzed in a laboratory and the radon concentration is quantified with 10% accuracy. The heat recovery unit (Flexit SL4 R) is an air handling unit with rotor technology produced by Flexit Company [12] with 80% nominal efficiency.

IDA Indoor Climate and Energy (ICE) was used as a multizone dynamic simulation tool to predict energy consumption, heat recovery of the rotary heat exchanger unit analysis, simulation of thermal comfort and indoor air quality in buildings. Research methods applied in this study include analytical analysis, measurement, dynamic simulation, and life cycle cost analysis.

2.2 Case study description

The case study building is a detached one family house in Stockholm and built in 1975. This house is a two storey structure and a volume of about 259 m^3 on each level. This corresponds to a floor area of about 108 m^2, windows (W1, W2 and W3) area 8.8 m^2, main door (D1) area 3.3 m^2 and internal door(s) area 2.2 m^2.Some parts of this house was renovated and sealed in order to energy conservation and radon reduction.

Total energy purchased were 25860 and 22920 kWh per year before and after using heat recovery ventilation system respectively. Figure 1 shows the floor plan of this house.

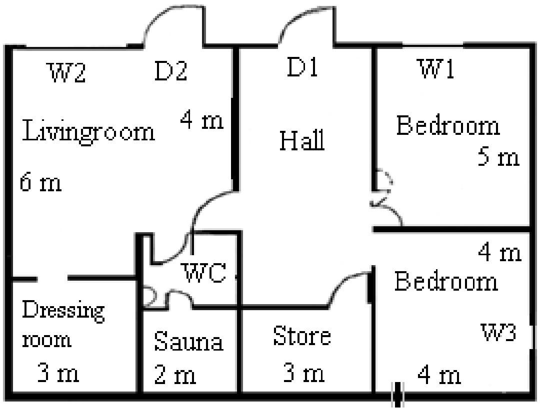

Fig.1.Ground floor plan and zone divisions of the case study house

3 The heat recovery ventilation system

A mechanical ventilation system with an air-to-air heat exchanger unit provides the air supply to the first floor. Fig.2. illustrates incoming and the outgoing air streams the installed heat exchanger system inside the first storey.

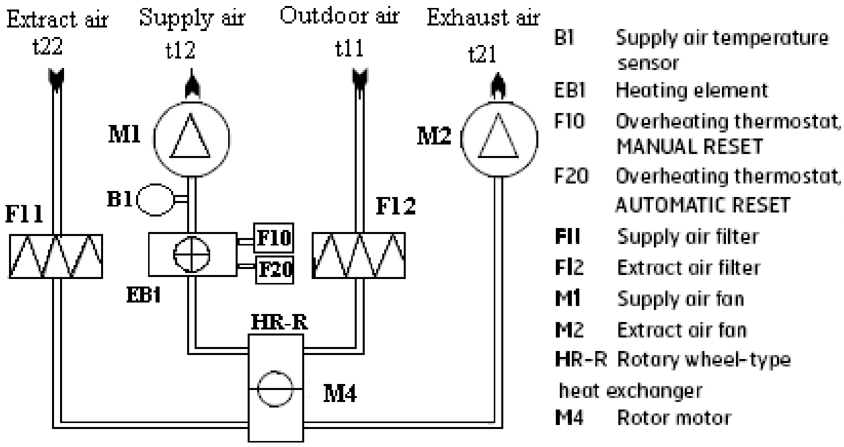

Fig.2. Schematic diagram of the rotary heat exchanger installed in the building, taken from FLEXIT Company [12]

The operating points of the unit can be determined from the diagram shown in Fig.3.The operating points at 0.5 and 1.0 Ach are shown with the orange dashed and continuous lines respectively in Fig.3.

Given the ventilation rates and Fig.3, it is possible to find the operating rates such as pressure, noise, and fan(s) electrical energy consumption. The unit efficiency was derived from equation (1) as shown below, and the determined values are shown in Table 1.

Temperature efficiency η [13]:

$$\eta = (t_{12} - t_{11})/t_{21} - t_{11}) \quad (1)$$

Table 1.The operating rates of the unit

Specifications	Operating rates
2 Fans power (max. 2 x 165 W)	70 W
Temperature efficiency	74.5%
Ventilation rate	0.5 ach (35 l.s^{-1})
Noise	50 dBA

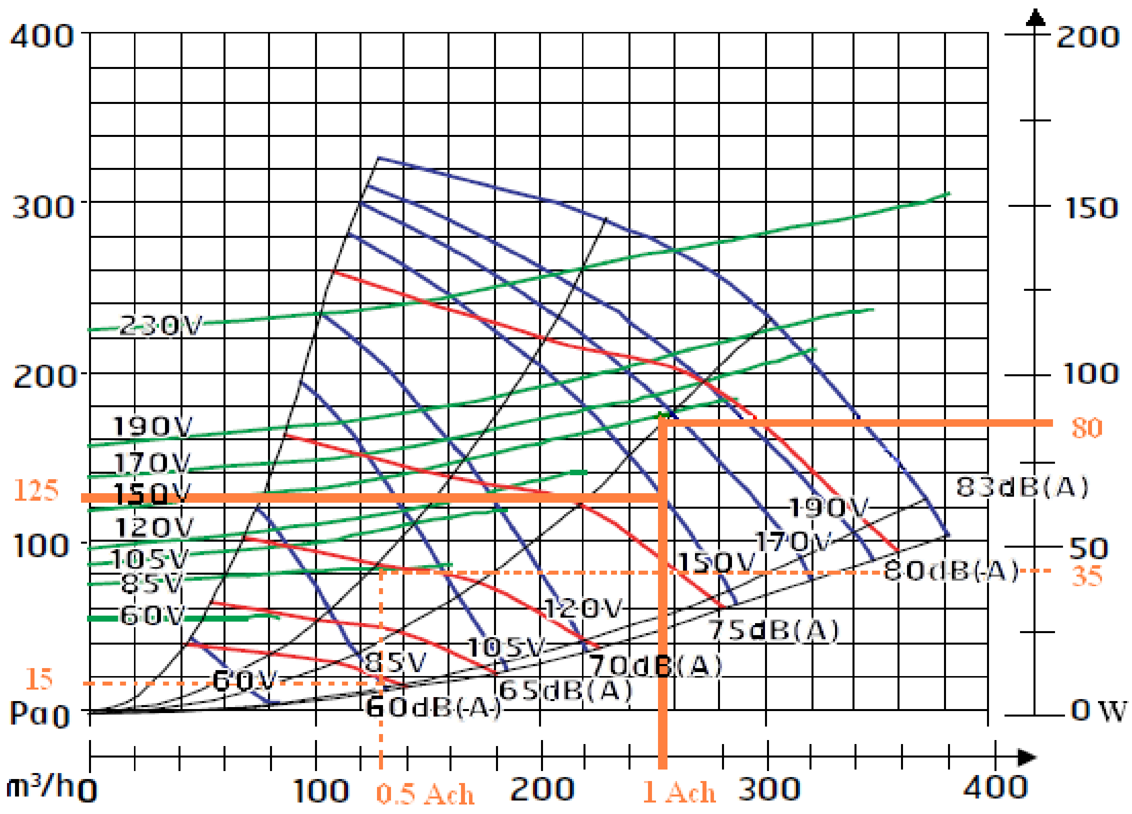

Fig.3. Characteristics curves of air supply AC fan 1. Capacity curves (blue), 2. Operation curves (black), 3. Power consumption curves (green) 4. Sound curves (red) 5. Operation points (orange), (from FLEXIT Company [12]).

This unit provides the outdoor air at three levels, i.e. 0.25, 0.5 and 1 ach. At a particular instance, the outdoor and the indoor conditions (t_{11},t_{21},$RH_{Outdoor}$,RH_{Indoor})were measured and the other variables were calculated through equations (1).

According to the manufacturer, the maximum temperature and humidity efficiencies of this rotary heat exchanger unit are 80% [13]. These values are not always reached, as demonstrated below:

$\eta_t = (14.5+7.4)/(22+7.4) = 74.5\%$

This unit can use two types of fans, AC and DC. The fans mechanical efficiency for AC and DC fans are calculated 9.7 and 5.5 kW per cubic meter per second at 0.5 Ach respectively. This means that mechanical efficiency of an AC fan is about 0.56% lower than of a DC fan.

As shown in Fig. 3, the AC fan power at 0.5 Ach is about 35 W and the annual energy use of 2 fans (supply and exhaust fans) would be 613 and 350 kWh for AC fans and DC fans respectively.

4 Heat losses of the house

Thermal losses in buildings are generally attributable to ventilation losses, transmission losses of the envelope and losses of domestic hot water. Ventilation losses are increasing due to the new indoor air quality standards and the focus on reducing indoor radon concentration in cold climates. Reducing losses due to ventilation are therefore expected to have a large impact on energy use. Calculations of the ventilation losses for this case study are as the following:

Ventilation losses are investigated using exhaust fan and heat recovery as a ventilation system.

a. Using exhaust fan:

It is assumed that the fan-driven supply air flow represents 90 % of the fan-driven exhaust air flow (a normal ratio leading to a low negative pressure indoors on average, which is an advantage when humidity is taken into account), temperature efficiency for the heat exchanger 74 % and air leakage in addition to fan-driven ventilation equal to 0.05 Ach.

0.9×0.5 Ach$\times$ 259 m^3 = 116.55 $m^3.h^{-1}$ = 0.04 $kg.s^{-1}$ = 32.4 $l.s^{-1}$

Total infiltration (air leakage) not affected by the heat exchanger is the sum of fan-driven infiltration (10 % of the exhaust air flow) [14], and the air leakage 0.05 ach corresponding to air leakage both in and out in addition to fan-driven ventilation:

0.1×0.5 Ach$\times$ 259 m^3 + 0.05 Ach$\times$ 259 m^3 = 25.9 $m^3.h^{-1}$ = 7.2 $l.s^{-1}$

Specific ventilation loss (Q_v) is the sum of fan-driven supply air loss (Q_s), and the total infiltration loss (Q_l):

$$Q_v = Q_s + Q_l = \Sigma \dot{m}\, C_p \qquad (2)$$

Where: C_p = air heat capacity (1.01 $KJ.kg^{-1}°C^{-1}$) and $\dot{m}$ = mass flow ($kg.s^{-1}$)

Q_v = 39.4+ 8.7 = 48 $W.°C^{-1}$

Based on monthly long mean temperature in Stockholm [15] and fixing room temperature at 20 ℃, the heating degree days give 4500 degree days corresponding to 108000 heat degree hours per year.

$$E_v = Q_v \times G_t \qquad (3)$$

Where: G_t = heat degree hours per year.

E_v = 4254 + 938.5= 5192 kWh per year

b. Using heat recovery system:

The heat exchanger reduces the heat demand by a factor ($1 - \eta_t$). However, the heat exchanger only affects the fan-driven supply air (90 % of the exhaust air).

Equation (4) shows the energy demand of heating using heat exchanger:

$$Q_{Hex} = Q_s\,(1 - \eta_t) \qquad (4)$$

Q_{Hex} = 10.24 $W.°C^{-1}$

E_{Hex} = 1106 kWh per year and $E_{rec} = E_s - E_{Hex}$ = 3148 kWh per year

If it is considered, $0.25 \le \lambda_v \le 1$, $2000 \le HDD \le 6000$ and $0.7 \le \eta_t \le 0.85$, annual energy recovery is in the following ranges:

$6 \le E_{rec} \le 90$ $kwh.m^{-2}$, and for this case study E_{rec} = 30 $kwh.m^{-2}$.

Ventilation losses of the house are summarized in Table 2. Normal condition is defined as in which ventilation rate and infiltration rate are 0.5 and 0.05 Ach respectively.

Table 2. Ventilation losses of the house at normal condition

Heat loss Types	Specific heat loss W/°C	Energy kWh/year	Recovered energy kWh/year
Exhaust fan(0.5 Ach)	39.4	4254	--
HRV(0.5 Ach)	10.2	1106	3148
Air leakage (0.05 Ach)	8.7	938.5	--

The other heat losses in the house are transmission loss and domestic hot water loss. The calculation results of transmission and domestic hot water losses are 8240 and 3186 kWh per year respectively. This means that total heat loss for this house is about 10284 kWh per year.

5 Results

5.1 Radon measurements

Radon concentrations were measured constantly during the winter. The measurement tools included a continuous radon meter (CRM) and alpha track detectors (ATD). Table 3 shows the results of these measurements.

Table 3.Radon measurements results

Date and period	ATD ($Bq.m^{-3}$)	CRM ($Bq.m^{-3}$)	Air change rate (h^{-1})	Ventilation type	Remedial action
2008-2 (2 weeks)	3580±380	------	0.25	Exhaust fan	No action
2010-2-10 (1 week)	------	150±15	0.25	HRV	3connected sumps
2010-3-18 (12 days)	------	65±6	0.5	HRV	3connected sumps
2010-4-22 (12 days)	------	36±4	1	HRV	3connected sumps

There are usually some errors in radon measurement, such as place of detectors, measuring period and electromagnetic fields for electronic radon meter. These factors can affect on measurement results.

5.2 Analytical analysis

If it is assumed that the rate of the radon generation (G) is constant, then the radon content of the indoor radon can be calculated as:

$$C= EA/V(\lambda + \lambda_v) \quad (5)$$

Where C($Bq.m^{-3}$) accounts for the indoor radon at the steady state, E($Bq.m^{-3}.h^{-1}$) is the rate of radon exhalation, A(m^2) is the area of the radon exhalation surface (the floor area in this case), V(m^3) is the volume of the house, and λ_v (h^{-1}) is the ventilation rate of the house.

Using Equation (5) indoor radon can easily be calculated with E=65 $Bq.m^{-3}.h^{-1}$ [17], and the given data from the case study of the house for different ventilation rates. The results are as shown in the following table.

Table 4. Analytical results of indoor radon

Ventilation rate (Ach)	Indoor radon ($Bq.m^{-3}$)
0.0	3582
0.25	108
0.5	54
1.0	27

It can be seen that measured data from Table 3 are comparable with the analytical results. The error between analytical analysis and measurement data is less than 14% at 0.5 Ach.

In order to show the impact of the ventilation rate on the radon level, and to have a qualitative comparison, the radon concentrations were measured by means of a continuous radon monitor (CRM) instrument at three different ventilation rates (Fig.4). However, this figure is not suitable for a quantitative comparison due to the short measurement time.

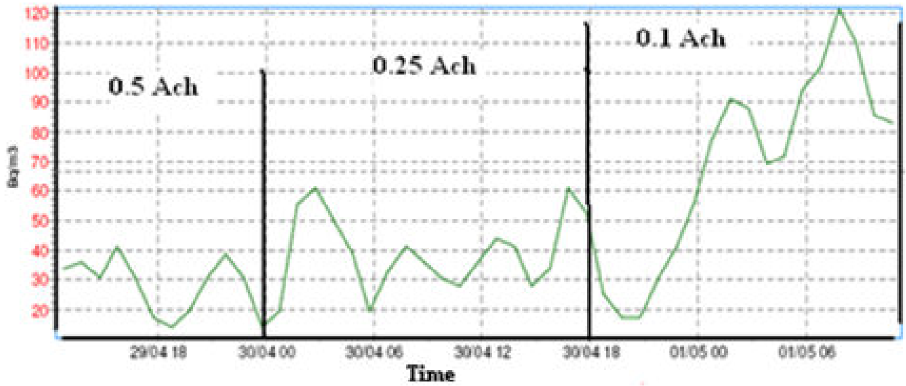

Fig.4. Continuous radon concentration levels measured with CRM.

5.3 Dynamic simulation results

For a long-term assessment of the heat recovery ventilation efficiency it is necessary to consider the complete time series of outdoor temperature temperature and humidity efficiencies. All these time-dependent effects were taken into account through using dynamic thermal simulation programs. These results are explained in this section.

Table 5 shows delivered energy overview of the simulation results. In this table, delivered energy for ventilation is related to electrical energy for supply and exhaust fans and heating refers to thermal losses of the house.

These values are comparatively close with the calculation results as seen in section 4.

and all the losses and gains of the building during the heating period.

The variations in outdoor temperature and ventilation rate may change the heat recovery

Table 5. Delivered energy overview

	kWh	$kWh.m^{-2}$
Domestic hot water	3386	31
Ventilation@0.5 Ach	616	8
Heating @0.5 Ach	9977	93

The annual results of the IDA dynamic simulation are shown in Table 6. This table compares the heat recovery ventilation system with an exhaust (traditional) fan ventilation system. Also using DC fan instead of AC fan can reduce electrical energy more than 50%.

Table 6.Simulation results of energy savings with different ventilation rates

Ventilation system	Air change rate (h^{-1})	Heat recovery (kWh)	AC Fans energy use (kWh)	DC Fans energy use (kWh)
Heat recovery ventilation	1.0	7163	1227	514
	0.5	3506	616	352
	0.25	1799	307	129
Exhaust fan	0.5	0	4368	-------

The whole-year predicted result of the dynamic simulation is shown that the heat exchanger ventilation system can damp wide variations in the outdoor conditions and maintain the indoor air at a set point temperature with a small variation throughout the year.

The results of measurement and simulation showed that increasing ventilation rates decrease indoor radon levels (inversely proportional) but raise ventilation energy use (direct proportional). Table 7 compares different ventilation rates, indoor radon levels and total ventilation losses quantitatively.

Table 7: Comparison between energy use and radon level

Ventilation rate (Ach)	Fans energy use(kWh)	Ventilation thermal energy use (kWh)	Radon level ($Bq.m^{-3}$)
0.25	350	2630	150
0.5	616	5192	65
1	1400	10384	36

5.4 Economic analysis

5.4.1 Energy analysis

In order to install a radon mitigation system, the following aspects should be considered: ventilation loss, cost of the operational energy and the future energy price, climate, fan(s) energy consumption, heat energy cost, indoor air temperature and ventilation rate (dependent on the life style of the occupants), and the initial and installation costs of the unit.

The heating and cooling degree day is a useful method which has been used in industry and academia for many years [18].

In cold climates, high heating degree days are very important from the viewpoint of the energy recovery when proposing the ventilation system for radon mitigation. The energy loss and the initial costs of a ventilation system to reduce radon levels are usually the main concerns of the home owners.

In order to install a radon mitigation system, some costs and key factors such as the direct electrical energy cost, efficiency, noise and service life time of the ventilation unit should be considered:
Since the ventilation system is installed indoors, the size of the system is also a concern for the homeowners.

A general and accepted approach to calculate the recovered energy is the outside temperature cumulative curve during the heating and cooling period. The seasonal recoverable energy at constant room temperature (20°C) was calculated.

5.4.2. Energy life cycle cost analysis

The net present value (NPV) method was used to evaluate the cost-effectiveness of an investment in the future.

Life cycle costs consist of the initial capital investment, the installation costs of the rotary heat exchanger unit, which is about 4000 USD for this unit, and the energy and maintenance costs. The annual electrical consumption of the unit is 616 kWh. The annual cost of replacing two of the unit's filters is about 80 USD.

For the NPV analysis, the following assumptions were considered:

i = 4%, q= 2%, n = 25 years and Energy cost in Sweden is roughly about 0.16 USD per kWh including all taxes.

In this method if the net present value of all the savings is larger than the initial capital cost, an investment is profitable [19].

Based on analytical relations, the NPV of this heat recovery was calculated and the results of the life cycle cost are shown in Table 8. The life cycle cost analysis shows that the use of a HRV system is cost-effective, and with regard to the annual increase of the energy cost, in this case the investment will have a payback period of about 12 years.

Table 8.Ventilation systems life cycle cost analysis.

Ventilation system	Capital cost (USD)	Annual costs (USD) Energy	Maintenance	life-cycle costs (USD)
Traditional fan	100	702	-----	13605
HRV with AC fan	4000	98	80	7488
HRV with DC fan	4000	56	80	6655

The annual energy saving varies with the ventilation rate; the amount of ventilation loss with and without the heat exchanger unit is shown in Figure 5. The two key factors which potentially add to the utility costs of a residential radon mitigation system are the outside environmental conditions and the house air exchange rate (Ach). Considering that there may be a 30-60% increase in energy consumption due to buildings ventilation [4] and radon mitigation system, it is apparent that a huge amount of energy can be saved through a heat recovery ventilation system. Therefore, employing this type of radon mitigation system is quite cost-effective.

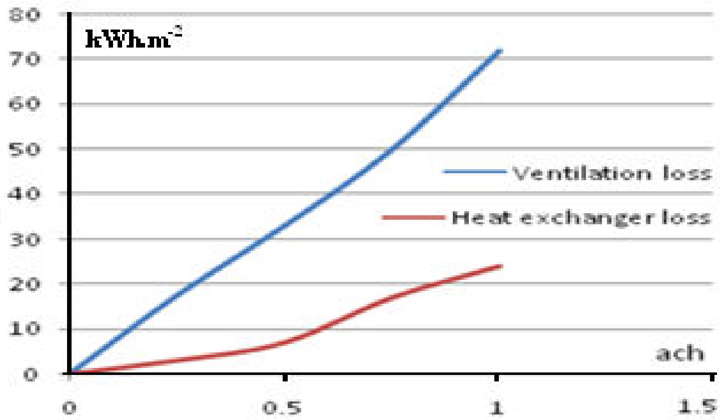

Fig.5. Ventilation and heat exchanger ventilation system losses

6 Discussion

Heat recovery units are manufactured in Europe and small size units suitable for single family buildings cost in the range 2700-4800 USD [12].

This study showed that balanced ventilation with heat recovery provides better indoor air quality (lower radon level) due to balanced supply/exhaust airflows and in same time saves energy due to heat recovery. While results with "business as usual" solution i.e. exhaust ventilation without heat recovery makes higher depressure (potential for radon inflow) and does not recover the heat of exhaust air.

The reduction in purchased energy after using heat exchanger unit is a clearly obvious. This is amounted to 2940 kWh per year which is almost near to calculation result. Also data concerning the energy use in Swedish Single-family houses has reported 102 kWh.m^{-2} for net heating [20], which is close to 93 kWh.m^{-2}, resulted from the simulation of this case study.

The analytical and dynamic simulation results indicate that by using this type of ventilation system to mitigate the radon level, Swedish buildings can save between 30-42 kWh.m^{-2} of energy per year for between 4000 and 6000 heating degree days. If it is considered that each of the 500,000 buildings has at least 50 m^2 of floor area, the annual energy savings would be roughly 1000 GWh. These figures are rough estimates, and can vary widely due to a great number of factors. In practice, the energy saving through the heat recovery between the exhaust and the supply air “competes” to save energy with many other measures.

The economic evaluation of the heat exchanger from the exhaust air depends on the volume and duration of the ventilation. The payback increases with increasing annual utilization hours. This means that heat recovery ventilation systems are more advantageous for long and severe winters such as those in Sweden.

6 Conclusion

Nowadays HRV systems are a well-known technology in Sweden as most energy efficient systems. But his study focused on another aspect of this technology and showed that it could be applicable in order to reduce the indoor radon problem.

Contrastingly, an extractor fan ventilation system with a negative pressure draws outdoor air from all possible sources. Unfortunately using extract fan is a common method to mitigate indoor radon level in Sweden.

A Heat recovery ventilation system has strong effects on radon mitigation and energy saving in residential buildings. This technology enables improvement of both indoor air quality and energy efficiency without sacrificing either. A heat recovery ventilation system can give substantial final energy reduction, which it depends strongly on the initial cost, the annual costs of maintenance and electricity used for unit and the air tightness of buildings.

The first set of conclusions derived from using the balanced heat exchanger ventilation system relates to the indoor air quality and the radon concentration; the balance between the air supply and the exhaust air prevents radon from being sucked out of the ground and into buildings. Regarding the effects of air pressure condition due to air tightness and supply/exhaust airflow ratio, simulation results show that reducing air tightness of the house leads to reducing indoor radon and with increasing supply/exhaust airflow ratio at constant exhaust air flow rate, indoor radon is increased.

The second set of conclusions regarding the advantages of a heat exchanger relates to the energy savings. This study shows that in comparison to exhaust fan ventilation, a heat exchanger ventilation system could save 74% of the energy lost through ventilation and about 30 $kwh.m^{-2}$ can be saved per year. This means that the recovered energy for this case study is about 3000 kWh per year based on analytical and simulation results.

The colder the climate is, the more energy can be saved and recovered. The economic calculations of the NPV method and the energy life cycle cost shows that the capital investment is cost-effective even if the energy price remains unchanged in future years.

From an indoor air quality point of view, a higher radon level requires a higher ventilation rate. Under these circumstances a heat recovery ventilation system can recover more energy and the investment payback time would be shorter. Where there is both a cold climate and high radon levels, the investment cost of installing a heat recovery ventilation system can indeed be balanced by the energy savings, since more heat degree days (more energy demand) and higher radon levels lead to more energy savings.

In Sweden, due to the long winters, the large number of heating degree days and the elevated radon levels in residential buildings, using heat exchanger ventilation systems can be a quite cost-effective strategy for both energy saving and indoor radon active remedy.

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