Exergy Analysis as an Assessment Tool of Heat Recovery of Dwelling Ventilation Systems

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ABSTRACT

In cold and moderate climates, improvements in building shell insulation and air-tightness imply a shift in heating loads from transmission and infiltration towards ventilation. Heat recovery from the ventilation airflow plays an increasingly important role in minimising energy needs. Such heat recovery systems rely on the input of electric power (to drive fans, heat pumps, etc.) in order to recover thermal energy. Since electricity input is relatively small compared to the amounts of thermal energy recovered, such systems are efficient from an energy viewpoint. One important yet often overlooked aspect, however, is the difference in 'quality' between the high-grade electricity input and the lower grade thermal energy recovered. This paper analyzes the effectiveness of heat recovery from ventilation airflows from the viewpoint of exergy. The results provide a common basis for evaluating different forms of energy (e.g. thermal and electric), considering their different abilities to produce work in relation to a given environment.

KEYWORDS

exergy, heat recovery, ventilation, winter, buildings

INTRODUCTION

Heat recovery systems are efficient from an energy viewpoint, since the input of electricity to drive fans, pumps, etc. is relatively small compared to the amounts of thermal energy recovered. However, there is a difference in 'quality' between the high-grade electricity input and the lower grade thermal energy recovered.

Exergy analysis provides a common basis for evaluating heat and electricity, considering their different abilities to produce work in relation to a given environment [Boelman, E. C., 2002; Wall, G., 1990; Rosen, M. A. and Dincer, I., 2001; Ala-Juusela M. (ed.), 2004]. Unlike energy, exergy is not subject to a conservation law.

This paper presents steady-state energy and exergy analyses for dwelling ventilation with and without heat recovery from ventilation airflow, and discusses the relative influence of heat and electricity on the exergy demand by the ventilation airflow.

APPROACH

Energy and exergy analyses are performed for dwelling ventilation, using mechanical exhaust with natural air supply (without heat recovery) and balanced ventilation with heat recovery. The aim of the developed calculation method is to assess different systems of heat recovery from the exhaust air in term of exergy. The mechanical exhaust ventilation utilises a fan (DC or AC fan), and the balanced ventilation utilises a heat recovery unit (HRU) containing a heat exchanger plus supply and exhaust fans. The dwelling ventilation details are shown in Figure 1.

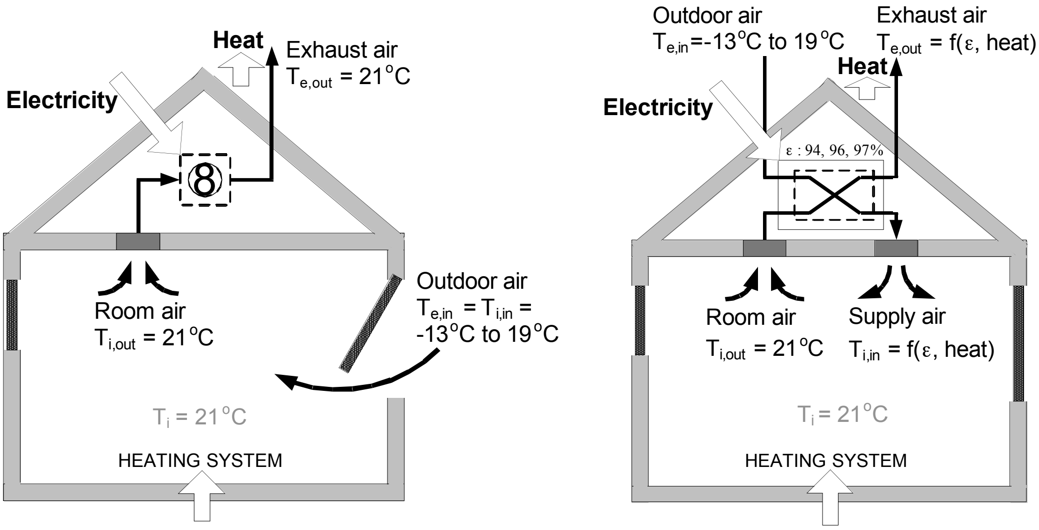

Figure 1: Dwelling ventilation: mechanical exhaust ventilation with natural air supply (a, left, reference case); balanced ventilation with heat recovery (b, right)

The analysis assumes steady state operation and considers only dry air, thus neglecting latent heat exchange between ventilation air flows.

The mechanical exhaust ventilation with natural air supply (hereunder "mechanical exhaust ventilation") uses an AC fan (Model: CVE 166 [Itho bv., 2005a]) or a DC fan (Model: CVE ECO-fan 2 [Itho bv., 2005b]). Outdoor air enters the dwelling at temperature ($T_{i,in}$) and goes through the exhaust fans at room temperature ($T_{i,out}$), as shown in Figure 1a and Table 1. Pressure difference between air entering and leaving the dwelling is neglected.

TABLE 1 (left) General calculation values [CEN, 2000, 2005; Climate data, 1965]
TABLE 2 (right) Thermal effectiveness (ε) versus airflow rates (Q)

Parameters	Values
Air density (ρ)	1.23 kg m^{-3}
Spec. heat capacity of air ($C_{p,air}$)	1.008 kJ kg^{-1}K^{-1}
Outdoor air temperature (T_e)	from -13°C to 19°C
Room air temperature (T_i)	21°C
Airflow rates (Q)	0.028, 0.042, 0.063 m^3/s

Q [m3/s]	ε [−]
0.063	0.94
0.042	0.96
0.028	0.97

The balanced ventilation with heat recovery case (Figure 1b) assumes a DC Heat Recovery Unit (HRU ECO-fan 3 S B [Itho bv., 2005c]), containing two DC fans and a heat exchanger with high thermal effectiveness (ε). The effectiveness and fan electricity input are calculated by interpolating from manufacturer's data [Itho bv., 2005c] in relation to airflow rates (see Table 2). Outdoor air gains heat from exhaust air entering the heat exchanger in the HRU at room air temperature ($T_{i,out}$) and leaving the dwelling at temperature ($T_{e,out}$).

EXERGY ANALYSIS OF DWELLING VENTILATION

The comparison between the different ventilation systems is based on the following method to calculate thermal energy and thermal exergy demands by ventilation airflows in relation to outdoor temperature, and electricity input to ventilation unit. The exergy analysis is carried out for the heating period. The calculations steps from Eqn. 1 to Eqn. 6 apply to both mechanical exhaust ventilation and balanced ventilation. Eqn. 7 is used to calculate air temperatures at the HRU.

Electricity input to ventilation unit

The system line is constructed according to Eqn. 1, where *P* is the pressure drop of the system, *C* is a coefficient, and *Q* is the airflow rate. Average *C* values can be calculated from manufacturers' data (used CVE ECO-fan [Itho bv., 2005b] and HRU ECO-fan 3 S B [Itho bv., 2005c]).

$$P = P_{\text{f,st}} = CQ^2 \qquad \text{Eqn. 1}$$

$$P_{\text{f,tot}} = P_{\text{f,st}} + P_{\text{f,ke}} \qquad \text{Eqn. 3}$$

$$P_{\text{f,ke}} = \frac{1}{2}\rho\left(\frac{Q}{A_{\text{duct}}}\right)^2 \qquad \text{Eqn. 2}$$

$$Pe_1 = Pe_2\left(\frac{D_2}{D_1}\right)^4\left(\frac{Q_1}{Q_2}\right)^3\left(\frac{\tilde{n}_1}{\tilde{n}_2}\right) \qquad \text{Eqn. 4}$$

The fan total pressures ($P_{\text{f,tot}}$) for the AC and DC fans are calculated using equations 1 to 3, where $P_{\text{f,st}}$ is the fan static pressure, $P_{\text{f,ke}}$ is fan kinetic pressure, ρ is air density (assumed constant over the temperature range), A_{duct} is an inner duct cross-section area and *Q* is airflow rate, Table 1.

The electricity (*Pe*) input to the AC and DC fans is calculated using the fan law Eqn. 4 [ASHRAE, 2000], where D is the fan impeller diameter. The fan law is used to predict performance of the fan when test data are available (data with index 2 in Eqn. 4). Test data for Eqn. 4 come from data at the intersection points where the system line intercepts the working line of the fans, in the graph of fan static pressure versus airflow rate given by the fan producer (used [Itho bv., 2005a, 2005b]).

Thermal energy and exergy demand by ventilation airflow

Thermal energy demand (En_{th}) and thermal exergy demand (Ex_{th}) by the ventilation airflow are calculated by using Eqn. 5 and Eqn. 6, where $T_{\text{i,out}}$ is room air temperature (21°C) and $T_{\text{i,in}}$ is outdoor air temperature (between -13°C and 19°C).

$$En_{\text{th}} = \rho_{\text{air}} Q C_{\text{p,air}} (T_{\text{i,out}} - T_{\text{i,in}}) \qquad \text{Eqn. 5}$$

$$Ex_{\text{th}} = \rho_{\text{air}} Q C_{\text{p,air}} \left(T_{\text{i,out}} - T_{\text{i,in}} - T_{\text{e}} \ln\left(\frac{T_{\text{i,out}}}{T_{\text{i,in}}}\right)\right) \qquad \text{Eqn. 6}$$

Total exergy demand by ventilation airflow

The total exergy demand by ventilation airflow, *Ex,* is determined by adding the thermal exergy demand by the ventilation airflow (Ex_{th}, Eqn 6) and the electricity input to the fan (*Pe*, Eqn. 4). The total exergy demand is different from total exergy consumption (considered an energy flow: from primary energy transformation to energy delivery process). This is because heat and electricity production could have different configurations of their energy flows. The forms of energy could thus cost different amounts of the whole flows' irreversibilities.

Exergy of the electricity input is equal to energy of the electricity input, because the electric energy can be completely converted to mechanical work. The electricity input depends on the airflow rate and pressure loss, but is not directly affected by ambient temperature. Table 3 shows electricity inputs and airflow rates of the applied fans and HRU, calculated according to equations 1 to 4.

TABLE 3 Electricity inputs (*Pe*) versus the airflow rates (*Q*)

	AC fan			DC fan			DC HRU		
Q [m^3/s]	0.028	0.042	0.063	0.028	0.042	0.063	0.028	0.042	0.063
Pe [W]	14	35	45	6	8	22	28	47	110

Temperatures at heat recovery in balanced ventilation

Supply air temperatures ($T_{i,in}$) are calculated using heat exchanger thermal effectiveness (ε) and heat balance equations, assuming the same airflow rates though the HRU for supply and exhaust air.

$$T_{i,in} = T_{e,in} + \varepsilon (T_{i,out} - T_{e,in}) \qquad \text{Eqn. 7}$$

where T_e is outdoor air temperature and T_i is room air temperature.

RESULTS AND DISCUSSION

This chapter presents analysis results for the applied fans and HRU in terms of heat and electricity, on an instantaneous basis.

Thermal energy and exergy demand by ventilation airflow

Figure 2 shows thermal energy (En_{th}) and thermal exergy (Ex_{th}) demand by the ventilation airflows, as a function of outdoor air temperatures. Using the applied AC fan or DC fan in the mechanical exhaust ventilation with natural air supply has no effect on the thermal energy or thermal exergy, because the fans have no effect on the air supply and exhaust temperatures. Ventilating at higher airflow rate requires more thermal energy and thermal exergy in all cases, because the ventilation heat demand depends on the airflow rate.

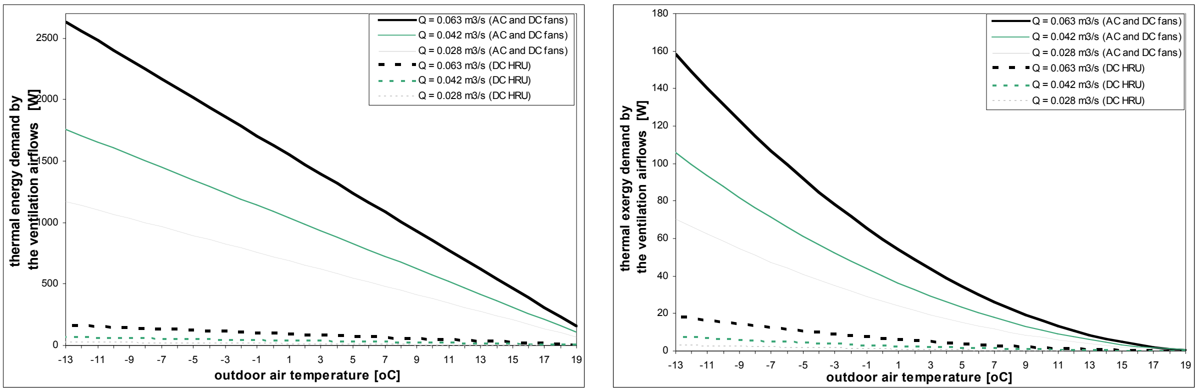

Figure 2: En_{th} (a, left) and Ex_{th} (b, right) versus T_e

In absolute terms, the thermal exergy demand is much lower than the thermal energy demand, because the temperature differences involved are relatively small. However, thermal energy demand varies linearly with outdoor air temperature, while thermal exergy demand does not. Hence, in relative terms the thermal exergy demand increases more strongly than the thermal energy demand for lower outdoor air temperatures.

Figure 3 illustrates total exergy demand by ventilation airflow (Ex) of the ventilation systems as a function of outdoor air temperature and airflow rate. The smooth lines represent the total exergy demand of the mechanical exhaust ventilation using the DC fan. The dashed lines represent the total exergy demand of the mechanical exhaust ventilation using the AC fan (Figure 3, left) and the total exergy demand of the balanced ventilation with heat recovery (Figure 3, right).

As outdoor air temperature T_e increases from -13°C to 19°C, total exergy demand decreases for a given airflow rate. The sharpest decrease is for the DC fan, followed by the AC fan and lastly by the DC HRU. The DC HRU lines in Figure 3 (right) are less sensitive to variations in T_e (from -13°C and 19°C) because the DC HRU requires mainly electricity, while the AC and DC fans require relatively more heat. The DC fan requires less exergy than the AC fan for the entire range of T_e. Compared to the DC HRU, the DC fan requires more exergy at lower T_e, and relatively more exergy as T_e increases towards the indoor air temperature.

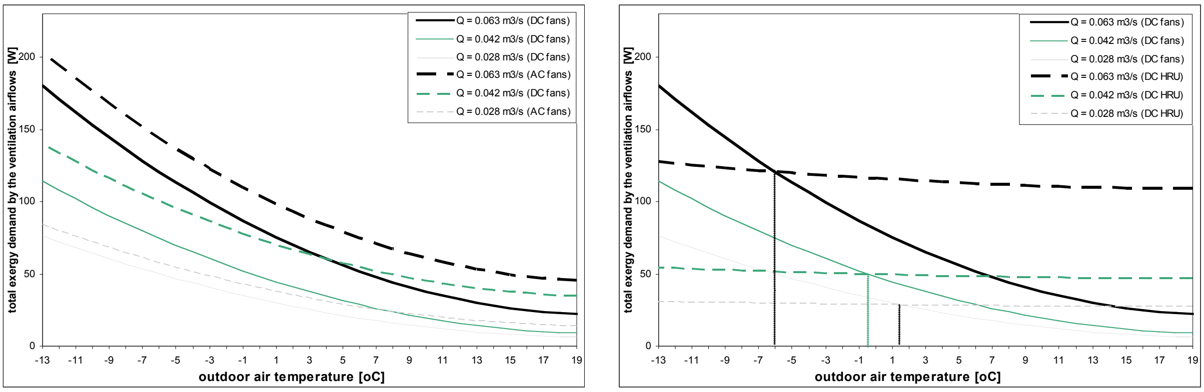

Figure 3: Total exergy *Ex* versus ambient temperature T_e

The total exergy demand lines (*Ex*) for DC fan and DC HRU intersect at a given outdoor temperature ($T_{e,intersect}$) for a given airflow rate (Figure 3, right). $T_{e,intersect}$ shows at which outdoor air temperature the total exergy demands of two different ventilation systems are equal. These *Ex* lines could be applied for evaluating the total exergy demands of different ventilation systems at different outdoor air temperatures. For example, at T_e = -10°C, the balanced ventilation with the DC HRU at 0.063 m^3/s airflow rate uses ca. 125 W, while the mechanical exhaust ventilation with the DC fan at the same airflow rate uses ca. 150 W. Nevertheless, at T_e = -3°C the balanced ventilation with the DC HRU at the same airflow rate uses ca. 120 W, while the mechanical exhaust ventilation with the DC fan uses ca. 100 W. At $T_e > T_{e,intersect}$, using the mechanical exhaust ventilation with the DC fan results in less total exergy demand than using the balanced ventilation with the DC HRU at the same airflow rate.

This conclusion changes if not the exergy demand but the exergy consumption is considered. The exergy efficiencies of the electricity and heat production then are important characteristics.

Ratio between total exergy and total energy demand by ventilation airflow

Figure 4 illustrates ratios between total exergy (*Ex*) and total energy (*En*) demands by ventilation airflow of the dwelling ventilation systems, when outdoor air temperature (T_e) changes from -13°C to 19°C.

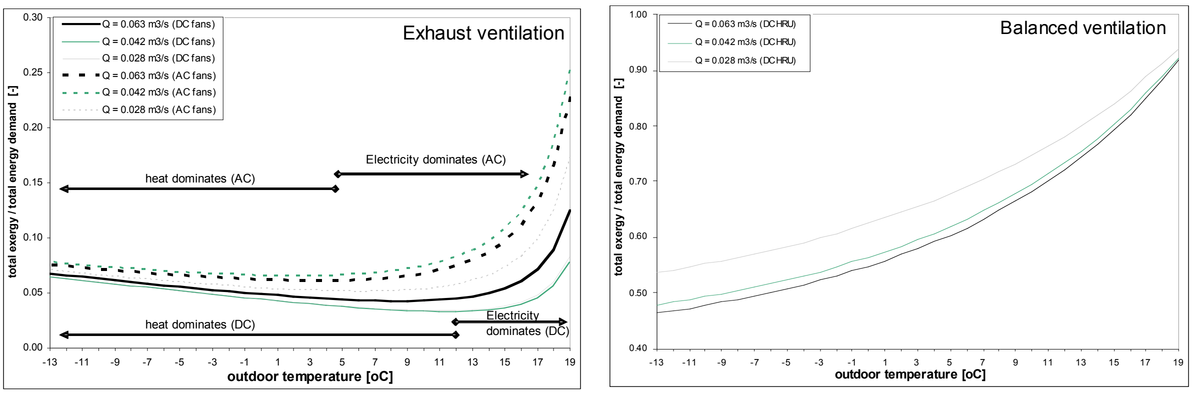

Figure 4: Ratio between *Ex* and *En* of the dwelling ventilation versus T_e

In Figure 4 (left), the *Ex*/*En* ratio decreases with increasing outdoor temperature (T_e), on the left part of the graph (heat dominated parts). This reflects the fact that exergy demand due to ventilation and heat exchange (Ex_{th}) decreases with rising T_e. On the right part of the graph, the *Ex*/*En* ratio increases steeply as T_e rises. This is because of a significant increase in the relative share of electricity input: although the thermal exergy demand (Ex_{th}) decreases sharply, as shown in Figure 2 (right), the electric power (*Pe*) required for driving the fans remains unchanged. Because exergy assigns a higher value to electricity than to low grade heat, when T_e increases, the total exergy demand decreases at a much slower rate than the total energy demand.

In Figure 4 (right), the electricity input to drive the balanced ventilation and heat recovery systems always exceeds the thermal exergy required in ventilation and heat transfer, for the entire range of outdoor temperatures between -13°C to 19°C. Moreover the *Ex*/*En* ratios in Figure 4 (right) are bigger than in Figure 4 (left), for the same outdoor air temperatures and airflow rates (note that the graphs have different scales). This is because the electricity input to the balanced ventilation is significantly bigger than the thermal exergy required in the balanced ventilation.

CONCLUSIONS

This paper presented steady-state energy and exergy analyses for dwelling ventilation with and without heat recovery from ventilation airflows, to compare different ventilation systems from the exergy point of view. Exergy analysis assigns values to thermal energy according to its temperature level: systems closer to ambient temperature have lower thermal exergy. Electricity has a high exergy value because it can directly be converted into work. In terms of exergy the amount of electricity input to fans and heat recovery unity (HRU) is much more significant than in terms of energy, because electricity has a higher exergy value than thermal energy.

At lower ambient temperatures (T_e), mechanical exhaust ventilation with natural air supply has higher total exergy demand than balanced ventilation with heat recovery. This trend reverses as T_e increases towards the indoor temperature. The ventilation with heat recovery is also less sensitive to T_e, since it requires mainly electric exergy.

From an exergy viewpoint, it could make sense to let ventilation air bypass the heat recovery unit when T_e is not too low, and use the HRU only when T_e is low enough to compensate the additional need for electricity.

For the next step, exergy analysis framework of energy conversion and delivery processes (electricity, heating system) will be developed and integrated to this analysis framework, to acquire the total exergy consumption of the whole energy supply system.

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