Exergy-based Control of a Dwelling Ventilation System with Heat Recovery

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Abstract— **On the base of exergy-based approach it is shown that for the ventilation systems there are operating modes for which heat recovery increases exergy of fuel expended to provide the ventilation air compared to cases without bringing any recovery of heat and additional power consumption to drive the air flow by the fans. For the specified system, in case of switching ventilation unit to the operation mode of lower values of spent fuel exergy it is possible to provide annual saving from 5 to 15 % of the primary energy sources.**

Keywords— ventilation system; exergy analysis; control; heat recovery; exergy saving.

I. Introduction

Heat/energy recovery from exhaust air in dwelling ventilation systems provides a possibility to reduce energy consumption [1]. From viewpoint of the energy conservation statement which is based on the first law of thermodynamics such systems are effective. To drive fans for air distribution electricity is consumed. The quality of electrical energy is much higher compared with the same amount of recovered thermal energy. Exergy-based approach which is based on the second law of thermodynamics provides a possibility to evaluate the level of energy quality and improve control of dwelling ventilation system by decreasing consumption of the most valuable types of energy.

The paper [2] presents steady-state energy and exergy analyses for dwelling ventilation with and without air-to-air heat recovery and discusses the relative influence of heat and electricity on the exergy demand by ventilation airflows in winter conditions of Netherlands. It has been shown that from an exergy viewpoint, it could make sense to use the heat recovery unit only when environmental air temperature is low enough to compensate the additional need for electricity. When the air temperature is not too low, electricity input could be decreased by letting ventilation air bypass the heat recovery unit or by operating the heat recovery unit at low ventilation airflow rate, depending on outdoor temperatures and indoor occupancy conditions.

The authors [3] in contrast to traditional performance parameters also applied exergy analysis and nonequilibrium thermodynamics to characterize the performance of heat recovery ventilator and a structurally similar membrane energy recovery one. They showed that the exergy efficiency can be used to identify the range of operating conditions for which the recovered heat and moisture are not enough to compensate power consumed by ventilation fans, and for which it is more beneficial to bypass the energy recovery unit.

The work [4] addresses the trade-off of heat recovery and fan power consumption in the ventilation system based on primary energy, carbon dioxide emission, household consumer energy price and exergy frameworks for a broad range of operating conditions in the different climates in Europe. The paper shows that the profitability concerning operating energy recovery ventilation as opposed to simple mechanical exhaust or natural ventilation strongly depends on the type of conversion coefficient between electrical energy and fuel combustion for heating, building performance, climatic conditions of a region, investment and maintenance cost.

On the annual energy and exergy performance the paper [5] shows that addition of a mechanical ventilation system with heat recovery increases the energy efficiency, however, it decreases the exergy efficiency. The authors conclude that the use of a separate mechanical ventilation system in a house should be considered with caution, and recommended only when other means for controlling the indoor air quality cannot be applied.

The results presented in considered papers are based on the exergy values at room or primary energy levels without focusing on the efficiency of energy conversion and delivery processes (electricity, heating system). The conclusions may be more sophisticated if the exergy-based parameters are considered in all subsystems of energy conversion system.

The scope of the paper is to demonstrate benefits of application of exergy-based approach for better control strategy in a dwelling ventilation system taking into account all intermediate steps from primary energy transformation to final energy consumption in climate conditions of Ukraine.

II. Methodology

The Figure 1 provides a schematic illustration of the analyzed system from primary energy conversion to the building envelope. The dwelling ventilation system consists of a heat recovery unit, two fans and two additional heaters. In case of heat recovery from the exhausted air stream the system increases the electricity consumption by ventilation fans to compensate additional pressure drops in the air-to-air heat exchanger. If the outdoor air temperature is too low the ventilation air is first preheated with the additional hot water preheater. The second hot water heater is used only if the temperature of ventilation air, after the heat recovery, is lower than the indoor air temperature. If streams bypass the recovery unit the outdoor air is heated in the both hot water heaters and fan power required to drive the air flow is decreased.

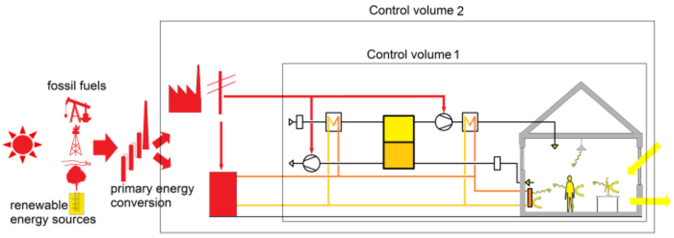

Figure 1. Energy supply chain for space heating in a buildings from primary energy transformation to final energy, including all intermediate steps up to the supply of the heating demand

Two control volumes are considered to analyze the amount of fuel exergy (representing the resources in terms of exergy) expended to provide the product exergy (representing the desired result, ventilation air, in terms of exergy) [6] (see Figure 1).

For investigation of variable operational modes of the system due to fluctuating in outdoor conditions a mathematical model for energy and exergy assesment has been developed using 24-hour time step quasi-stationary approach. The model is based on mass, energy and exergy balances for the specified dwelling, ventilation and heating system.

The analysis is performed for a typical Ukrainian individual house. The dwelling has one floor with a gross floor area of 90 m² and a volume of 225 m³. For the reference case weighted average insulation value of non-glazed external surfaces is 0.5 W/(m^2·K). U-value of windows including frames is 2 W/(m^2·K). Infiltration rate is regarded as 1 h^{-1}. Internal heat gains are defined with a constant value of 10 W/m^2. Setpoint for the indoor temperature is 18 °C. The fraction of east and west oriented glazing is 30%, of the south one – 50%, of the north one – 20%. Heat recovery efficiency of the ventilation system is equal 55 %. Heating needs in the both hot water heaters are covered by a heat pump system.

For the control volume 1 the exergy of fuel was calculated using the formula

$$E_{F,1}(\tau)=E_{F,PH}(\tau)+E_{F,H}(\tau)+E_{F,fun}(\tau), \qquad (1)$$

where

$$E_{F,PH}(\tau)=En_{PH}(\tau)\cdot\{1-T_0(\tau)/[T_{in}(\tau)-T_{out}(\tau)]\cdot\ln[T_{in}(\tau)/T_{out}(\tau)]\}; \qquad (2)$$

$$E_{F,H}(\tau)=En_{H}(\tau)\cdot\{1-T_0(\tau)/[T_{in}(\tau)-T_{out}(\tau)]\cdot\ln[T_{in}(\tau)/T_{out}(\tau)]\}; \qquad (3)$$

τ – time step, τ=24 hr; En_{PH}, En_H – daily energy consumed in the hot water preheater and heater of the ventilation air, kW·hr; T_0 – temperature of outside air, K; T_{in} – heater and preheater inlet temperature of water, K; T_{out} – heater and preheater outlet temperature of water, K; $E_{F,fun}$ – electricity consumed by the fans, kW·hr.

For the control volume 2 the exergy of fuel was calculated using the formula

$$E_{F,2}(\tau)=[E_{F,HP}(\tau)+E_{F,fun}(\tau)]/\varepsilon, \qquad (1)$$

where

$$E_{F,HP}(\tau)=[En_{preheater}(\tau)+En_{heater}(\tau)]/COP(\tau), \qquad (1)$$

ε – exergy efficiency of electricity generation on thermal power plant, ε=0.37 [7]; COP(τ) – coefficient of performance of the heat pump system, calculated on the base of [8].

Figure 2 illustrates values of the exergy of fuel expended to provide the ventilation air for the control volume 1 as a function of outside temperature. The line 1 represents the mode of using heat recovery system. The line 2 belongs to the mode when the air streams bypass the recovery unit. It can be observed that the lines 1 and 2 intersect at the environmental air temperature equal to -6 °C. For this temperature the values of exergy of fuel for the two different modes are equal. So, at the environmental air temperatures lower than -6 °C the exergy of fuel expended to provide the ventilation air is lower for the mode 1 (heat recovery application). If the outside air temperatures are higher than -6 °C it is more beneficial to bypass the recovery unit.

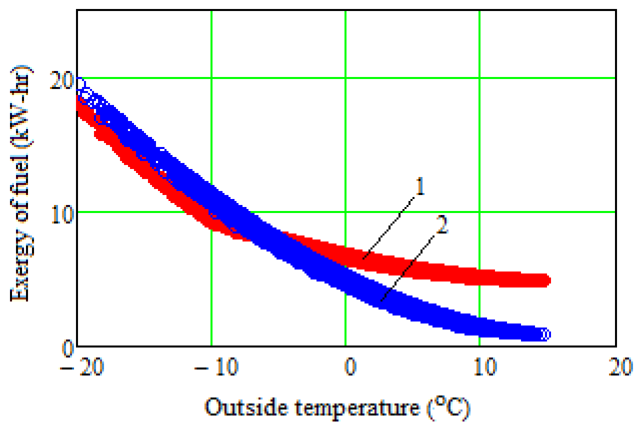

Figure 2. Exergy of fuel expended to provide the ventilation air versus outside temperature for the control volume 1: 1 - with heat recovery; 2 - without heat recovery

Figure 3 presents results of calculating values of the exergy of fuel spent in the ventilation system for the control volume 2 as a function of outside air temperature. The line 1 belongs to the mode of heat recovery and the line 2 – to the mode of bypassing the recovery unit. For the control volume 2, if the outside air temperatures are lower than 0 °C the exergy associated with fuel is lower for the mode 1 (heat recovery application). On the contrary, if the outside temperatures are higher than 0 °C it is makes sense to bypass the recovery unit because the exergy of fuel for this mode is lower than for the mode of heat recovery.

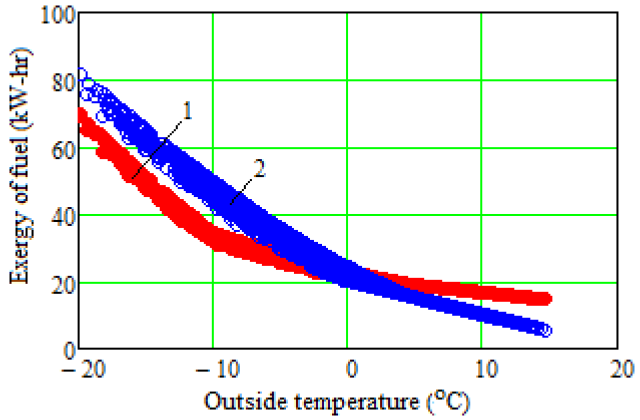

Figure 3. Exergy of fuel expended to provide the ventilation air versus outside temperature for the control volume 2: 1 - with heat recovery; 2 - without heat recovery

The results presented above reveal a potential to improve the efficiency of the dwelling ventilation system through the implementation of an exergy-based control strategy, which tries to fulfill the demand of the ventilation system with low-quality energy sources involving the bypassing mode of heat recovery unit.

Figure 4 demonstrates the values of annual fuel exergy saving over 27-year period for the control volume 2 of the reference system in case of applying the proposed exergy-based control approach.

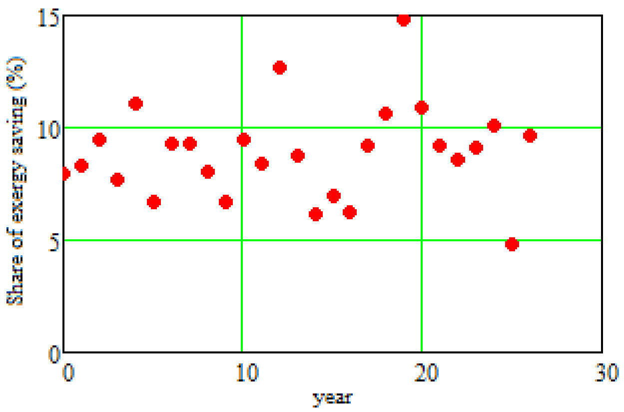

Figure 4. Annual values of saving exergy associated with fuel for the control volume 2

It can be observed from the Figure 4 that in comparison to the conventional operating the dwelling ventilation system with heat recovery (recovering energy from the exhausted air stream for the all range of operating modes) it is possible to save annually from 5 to 15 % of the primary high quality energy bypassing the recovery unit in cases when the recovered exergy of heat is not enough to compensate the fan power consumed to drive the air flow through the recovery unit.

Conclusions

For the climate conditions of Ukraine it has been shown that the exergy-based approach can be used to identify the range of operating conditions for which the dwelling ventilation system with heat recovery is responsible for increasing the high-quality energy sources need and for which it is more beneficial to bypass the recovery unit. Such phenomenon cannot trivially be predicted by traditional energy-based performance parameters.

Implementation of the proposed exergy-based control strategy provides a possibility of saving annually from 5 to 15 % of the primary high quality energy sources.

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