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Exergy–economic evaluation of heat recovery device in mechanical ventilation system

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ABSTRACT

The paper presents new approach in evaluation of heat recovery devices in mechanical ventilation system. The evaluation is based on exergy balance equation and economic analysis, what requires application of one of multicriteria decision aid methods—weighted sum method. The proposed set of evaluation criteria consists of: driving exergy, simple payback time and investment cost. The proposed method is applied to compare the four variants of heat recovery device in inlet-exhaust mechanical ventilation system of the capacity of 10,000 m^3/h installed in residential part of hotel. The analysis is performed for four preference models. The results of the multicriteria evaluation indicate that counter flow plate heat exchanger and the rotating heat/mass regenerator are better solutions comparing with water loop heat exchanger and heat pipe heat exchanger. Counter flow plate heat exchanger is the most compromise solution for the two preference models PREF_00 (based on statistic approach) and PREF_03 (investment cost priority preference model). Rotating heat/mass regenerator is the most compromise solution for the preference model 01 (driving exergy priority preference model). The proposed method can be helpful in the choice of the most compromise solution of the heat recovery device in pre-design phase.

1. Introduction

The key function of mechanical ventilation is to provide required indoor air quality (IAQ), which is related to the reduction of the content of air contaminants in the air of physical, chemical and biological nature. Energy needs of ventilation in new buildings—low energy buildings, which are characterized by very limited energy dissipation by heat transmission, are of greatest importance. The use of heat recovery in mechanical ventilation systems is obligatory bearing in mind the energy performance directive of buildings (EPBD) [1]. Directive defines the technical building system as the technical equipment for the heating, cooling, ventilation, hot water and lighting or for a combination thereof, of a building or building unit [1]. In majority of cases the choice of heat recovery device is based on its energy efficiency only, sometimes supported by investment cost analysis.

The energy balance analysis based on the first law of thermodynamics allows for the quantitative evaluation of energy flows in thermodynamically open systems, but it is impossible to distinguish the quality of different energy forms. The same amount of energy in the form of low temperature heat is less "worth" than high temperature heat or electricity. In order to take those differences into account exergy analysis approach has been proposed.

The exergy approach is based on a simultaneous application of the first and the second law of thermodynamics. These laws can be paraphrased into: "Nothing disappears but everything dissipates" [2–5]. On the other hand the use of exergy as the only one evaluation criteria may lead to ineffective solutions from economic point of view. For instance one can reduce internal exergy losses by increasing the heat recovery device exchange surface, which leads to the decrease of average temperature of heat exchange, but it increases the investment cost of such a solution. More information about the principles of exergy analysis can be found [5–7], Thus, new approach in evaluation of heat recovery devices in mechanical ventilation system based on exergy balance equation and economic analysis is required. That new approach becomes the multicriteria problem, which can be solved using one of the multicriteria decision aid methods—modified weighted sum method.

A review of typically used methods for heat recovery is given in [8]. There are many papers focused on the topic of heat recovery device in mechanical ventilation systems in buildings. Those papers are mainly focused on energy efficiency and energy balance analysis based on the first law of thermodynamics is used as evaluation tool.

Exergy analysis of building services, including mechanical ventilation systems is used less often. Some applications of that approach based of simultaneous use of first and second

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Nomenclature

$b_{ch,F,i}$	specific chemical exergy of the "i-th" fossil fuel ((kW h) kg^{-1})
$\dot{B}_{in}$	flux of exergy entering the control volume of a thermodynamically open system (W)
$\dot{B}_{out}^{use}$	flux of useable exergy leaving the control volume of a thermodynamically open system (W)
Cf_i	cash flow of the project in its "i-th" year of operation (zł a^{-1})
$C_{FIX,i}$	fixed cost of the system operation in the "i-th" year (zł a^{-1})
C_{OP}	total operating costs of the system (zł)
cr_{DrEx}	driving exergy criterion
cr_{INV}	investment cost criterion
cr_{SPBT}	simple payback time criterion
$C_{VAR,i}$	variable cost of the system operation in the "i-th" year (zł a^{-1})
E_F	annual inlet and exhaust fans electricity consumption ((kW h) a^{-1})
f_j	weighted sum factor for variant "j"
I_0	initial investment cost (zł)
$I_{0,i}$	delivery cost of heat recovery device i-th item ((kW h) a^{-1})
INC_i	income related to the system operation in the "i-th" year (zł a^{-1})
$m_{F,i}$	annual consumption of the "i-th" fossil fuel used for the operation of the air handling unit (kg a^{-1})
$\max(x_{i,j})$	maximum value of criterion x_i, $\min(x_{i,j})$ minimum value of criterion x_i.
NPV	net present value (zł)
P_{EL}	unit price of electricity (zł (kW h)$^{-1}$)
P_H	unit price of heat (zł (kW h)$^{-1}$)
Q_{AH}	annual air heater heat consumption ((kW h) a^{-1})
R	effective rate of return for the considered market
$\dot{S}_{gen}$	flux of total increase of entropy of a thermodynamic system in an infinitely short time $d\tau$ (W K^{-1})
SPBT	simple payback time (a)
t	number of years of the economic analysis (a)
T_D	number of hours of daily operation (h d^{-1})
T_{ex}	average seasonal temperature of ambient air (K)
T_{in}	supply temperature of the inlet air (K)
$t_{INC,i}$	annual income tax rate in the "i-th" year
w_i	weight of criterion "i"
$X_{i,j}$	normalized value of criterion x_i, for variant "j"
Z_{AH}	number of days of the air heater operation (h d^{-1})
Z_{MV}	number of days of annual operation (h d^{-1})
zl	Polish zloty (currency)
$\delta\dot{B}_{ext}$	flux of external exergy losses of a thermodynamically open system (W)
$\delta\dot{B}_i$	flux of internal exergy loss in i-th element of mechanical ventilation system (W)
$\delta\dot{B}$	flux of the internal exergy loss of a thermodynamic system in an infinitely short time $d\tau$ (W)
$\Delta\dot{B}_{HS}$	flux of change of exergy of an external heat source being in contact with a thermodynamically open system (W)
ΔC_{ex}	annual reduction of system operating cost referred to the basic solution (zł a^{-1})
ΔE_F	seasonal additional electricity use of the inlet and exhaust fans
Δp_{ex}	additional pressure drop in the exhaust installation (Pa)
$\Delta p_{ex,tot}$	total pressure drop in the exhaust installation (Pa)
Δp_{in}	additional pressure drop in the inlet installation (Pa)
$\Delta p_{in,tot}$	total pressure drop in the inlet installation (Pa)
ΔQ_{HR}	seasonal heat recovery in the system ((kW h) a^{-1})
ΔX_i^{pref}	value of the preference threshold for criterion X_i.
$\eta_{F,ex}$	total efficiency of the exhaust fan
$\eta_{F,in}$	total efficiency of the inlet fan
η_{HR}	seasonal efficiency of the heat recovery

laws of thermodynamics are presented in this paper. Hepbasli [9] showed review of the studies conducted on low exergy heating and cooling systems for the sustainable buildings. The comparison of various low exergy heating and cooling systems has been presented in this study. Zmeureanu and Yu Wu [10] presented nine design alternatives of HVAC systems in residential house in Montreal. They employed exergy analysis to calculate the exergy destruction and exergy supply in each of evaluated systems. The study by Dovjak et al. [11] concerned exergy and energy analysis of the whole heating system in Slovenian buildings. Sakulpipatsin et al. [12] presented an extended method for exergy analysis of buildings and HVAC systems. The exergy analysis of an air heating system was published in [13]. A mathematical model was proposed consisting of three items of energy chain: air handling unit, air distribution system and heated room. Some researches applied the exergy approach in order to analyze heating systems [14], thermal energy storage [15], solar water heating systems [16] and geothermal district heating system [17].

A modified trend in exergy analysis was named advanced exergy analysis. The theory and application of the conventional and advanced exergy analysis were given in [18]. Hepbasil and Kecebas [19] applied an advanced and conventional exergy analysis method to identify the potential for improvement and the interactions between the components in geothermal district heating system.

The International Energy Agency (IEA) Annex 49 applied the exergy analysis as evaluation tool for high performance buildings and communities. The results of research were published in [20]. The objective of Annex 49 was to identify the measures allowing for the reduction of the driving exergy demand of buildings, carbon dioxide (CO_2) emissions of the building stock and to support development of sustainable and reliable energy systems in the building sector. One section of Annex 49 report was devoted to adjustment of ventilation rates based on actual needs. Authors compared mechanical ventilation system and hybrid ventilation system (combining natural and mechanical ventilation systems). Studies were carried out for the medical building. Simulations showed that it was possible to combine a sustainable low-exergy building and at the same time to ensure a comfortable and healthy indoor environment [20].

Sometimes the exergy analysis is supported by cost analysis. A detailed overview of economic evaluation of built environment mechanical systems can be found in [21]. The simultaneous exergy–economic analysis was applied to the specific energy solutions by relatively few researchers. For example Ozgener and Hepbasil [22] investigated capital costs and thermodynamic losses for devices in solar assisted ground-sources heat pump with a ground heat exchanger. They found that systematic correlation between the capital cost and exergy loss (total or internal) for components and the overall system exist but not between external exergy loss or capital cost and energy. Exergoeconomic analysis for a novel air cooler was described in [23]. The results showed that the exergetic cost refers to the correlation, which exists among exergy loss, destruction rates, yearly working hours and capital cost. Alkan et al. [24] focused on exergoeconomic analysis for geothermal