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A simplified economic model and case study for recovery ventilation based on SPECO method

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\textbf{ABSTRACT}

Covid-19 further revealed the significance of ventilation by air conditioning systems. Most common split heaters and resistance heaters recirculate the indoor air without ventilation process. Ventilation wastes energy consumption by the building. However, adding an air-to-air heat recovery unit seems a quick solution to reduce the wasted heat of the ventilation process. Nonetheless, recovery unit means further pumping power (pressure drop through the air-to-air heat exchanger), capital cost, additional fans and their electricity consumption, exergy costs and so on. Hence, the profitability of the recovery unit depends on outdoor temperature, desired indoor temperature, electricity price of the region, exergy loss and also the aforementioned factors. In this research the general standard Specific Exergy Costing theory is employed and simplified as an economic strategy for recovery ventilation. The model not only is able to predict the profitability of the ventilation process using air-to-air heat exchanger, but also it is an optimization tool for air-to-air heat recovery units as provided as a case study in this paper.

\textbf{Nomenclature}

\begin{itemize}
\item \(c\) Cost per unit of exergy stream ($/J)
\item \(c_{p}\) Specific heat of the fluid (J/kg k)
\item \(c_{p,c}\) Specific heat of the cold fluid (J/kg k)
\item \(c_{p,h}\) Specific heat of the hot fluid (J/kg k)
\item \(c_{q,\text{heating}}\) Cost per unit of heating ($/J$ or $$/kWh$
\item CRF Capital recovery factor\(\dot{C}_{p,k}\) Capital recovery factor\(\dot{C}_{p,k}\) Cost rate of power or work for \(k\)th component ($$/s$
\item \(\dot{C}\) Cost rate associated with entering exergy stream of mass transfer ($$/s$
\item \(\dot{C}_{q}\) Cost rate associated with exiting exergy stream of mass transfer ($$/s$)
\end{itemize}
1. Introduction

Ventilation is a key required factor of air conditioning systems in buildings to keep the indoor environment fresh and healthy. However, ventilation process always increases the required heating/cooling energy to reach the desired indoor temperature. That is why air-to-air heat exchanger is sometimes recommended to recover the wasted energy due to the ventilation process. However, installation of any heat recovery unit in ventilation lines requires further costs due to capital, running, exergy stream, electricity, pumping power cost etc. Indeed, the profitability of recovery ventilation depends on many factors such as outside air temperature, desired indoor air temperature, pressure drop through the heat recovery unit, required fans to overcome the mentioned pressure drop, capital/investment costs of all equipment, exergy costs, electricity price of the region, type of heater (electrical heater or heat pump etc.), required air flow rate. Hence, it is remarkable to evaluate the realistic cost of heat recovering ventilation to make the best decision based on all mentioned factors. Economic consideration is also essential for optimal design of heat recovery systems.
As a result, the required cost rate of heat recovery unit should be compared with the energy saving due to the heat recovery unit to provide a logical decision whether the heat recovery unit is profitable to be installed or not. It is noted that, the cost-profit viewpoint depends also on country’s energy policy and infrastructures as well. Sometimes, the limitation of supplied energy (depending on natural oil sources etc. in a country) justifies the application of such energy saving techniques irrespective of their side costs. Moreover, the type of energy source (electricity, gas, oil etc.) to heat/cool the building indoor air is another effective factor in this regard. The selected previous investigations on energy/economic analysis of ventilation process are summarized in the following.

Blocken et al. [1] worked on ventilation and aerosol particle concentration in a gym during the Corona Virus pandemic. Wang et al. [2] experimentally studied the economic aspects and flow behaviour of parallel push-pull ventilation system. They tried to reduce the outlet exhaust flow rate by reducing the size of the exhaust hood and three different range of fluid flow conditions were compared. Dadoo [3] evaluated the energy and economic characteristics of ventilation heat recovery for a multi-family building in a Nordic climate condition. The efficiency of the recovery unit was evaluated taking into account frost condition, energy tariffs and heat supply options. Based on their results, the frost condition occurred in the recovery unit can significantly reduce the performance of air handling unit in cold climates. Jongbeak et al. [4] proposed a multi-function window combined with photovoltaic module and a ventilation system and tried to optimize the system from environmental and economic point of views. According to their findings, the most efficient size for ventilation system of the proposed window is 3–5% of the window’s size. Morz and Dutka [5] worked on exergy-economic parameters of heat recovery in mechanical ventilation systems. They modelled four different types of recovery device in mechanical ventilation in the hotel. Based on their findings, counter flow plate heat exchanger is the most compromise solution. Dutton et al. [6] studied the natural ventilation process for California offices from health and economic viewpoints. Ozyogurtcu et al. [7] investigated the economic characteristics of a ventilation system including an exhaust heat recovery, electrical heater and solar energy. Indeed, the system is able to store the solar energy and use it during the solar-off period. They proposed system reduces around 86% the energy consumption compared to the conventional systems. Payback period was estimated around 5 years for Izmir city in Turkey. Picallo-Peres et al. [8] worked on energy and exergy characteristics of ventilation process of a building which includes a heat recovery system. Based on their results, the recovery unit can significantly reduce the energy consumption of the building. The energy efficiency of the recovery ventilation was found around 90% in their study. Cao et al. [9] proposed a hybrid system including solar chimney ventilator, photovoltaic panel and phase change material. They tried to evaluate the heat recovery system for this hybrid system which is able to produce simultaneous power and ventilation. Li et al. [10] proposed a new ventilation system in which solar air collector is employed to save the required energy of ventilation process through the winter season. They concluded that, although the proposed system is not the best, it can be considered a significant progress from energy saving and environmental protection viewpoints. Lapertot et al. [11] optimized hybrid earth-air heat exchanger and heat recovery ventilation for residential buildings based on French climate conditions. Similar system was considered and evaluated for China by Peng et al. [12]. Chen et al. [13] performed an energy analysis for three ventilation systems applicable for large machining plant. They indicated that the energy used for ventilation process of improved displacement system is around 17% and 20% lower compared to the mixing ventilation and existing ventilation systems. Pekdoğan et al. [14] experimentally investigated a decentralized heat recovery ventilation system. They focused on the impact of running period of the system and fab characteristics on the ventilation energetic performance. Khadrs et al. [15] compared the economic characteristics of three renovated multi-family buildings with different ventilation strategies. Filis et al. [16] tried to clarify the impacts of wind pressure and stack effect of the efficiency of the ventilation process including heat recovery. They showed that units with axial fans are more sensitive in comparison with the units working with centrifugal fans. Dingyi et al. [17] carried out an investigation to analyse the ventilation of deep excavation roadway. Zhang et al. [18], Wiriyasart et al. [19] and Cherrier et al. [20] worked on impact of thermal insulation of ventilation performance, ventilation analysis of workshop room with multiple heat source and natural ventilation for Ghardaia respectively. Dizaji et al. [21] employed specific exergy costing theory for economic evaluation of any passive heat transfer enhancement techniques of heat exchangers. Fernández-Zayas et al. [22] evaluated the possibility of natural ventilation for office building in Mexico. William et al. [23] tried to investigate the relevance of Covid transmission risk with HVAC solutions for indoor environments.

In this paper attempts are made to apply and simplify the general Specific Exergy Costing theory proposed by Ref. [24] for heat recovery ventilation as an economic strategy for any case study in this area which has not been carried out before. All effective
parameters including outside temperature, expected indoor air temperature, pressure drop through the heat recovery unit, required fans to overcome the mentioned pressure drop, capital/investment costs of all equipment, exergy costs, electricity price of the region, type of heater (resistance heater or heat pump), required air flow rate and so on. The application of this strategy is to clarify whether the application of heat recovery unit in ventilation process is recommended or not from both economic and energy criteria (compared to the simple ventilation without recovery unit).

2. Formulation

Fig. 1 shows a general form of air-to-air heat recovery unit applicable in ventilation process. Four general components i.e. hot side channel(s), cold side channel(s), hot side fan and cold side fan are considered for any type of air-to-air energy recovery unit. The fans are representative of the costs associated with required pumping power to overcome the pressure drop through the heat exchanger [21].

Specific Exergy Costing (SPECO) theory [24] is employed here for economic formulation of the air-to-air heat exchanger. The required general steps to apply the SPECO theory for any thermodynamic system is as below [21,24].

- Identifying control volume (C.V)
- Identifying the number of components of C.V
- Definition of fuel and product for any component
- Applying the cost balance equation for each component
- Defining auxiliary equations (F principle and P principle) if required
- Simultaneous solving of all cost and auxiliary equations to find the required cost parameters

For an air-to-air heat recovery unit, the whole heat exchanger and related fans are considered as the control volume as shown in Fig. 1. The whole control volume can be considered as four separate components including hot side channel(s), cold side channel(s), hot side fan and cold side fan. As explained in Refs. [21,22], the desired exergetic output from a component is product while the fuel and products are presented in Table 1. The mathematical concept of cost balance equations is provided in Eq. (1). The left side of equations are associated with entering exergies while the right-hand parameters are associated with exiting exergies.

\[
\begin{align*}
\text{Cold channel: } & \dot{C}_2 + \dot{C}_3 + \dot{Z}_c = \dot{C}_1 & (1.1) \\
\text{Hot channel: } & \dot{C}_2^h + \dot{Z}_h = \dot{C}_1^h + \dot{C}_3^h & (1.2) \\
\text{Cold side fan: } & \dot{C}_1 + \dot{C}_{1c} + \dot{Z}_{1c} = \dot{C}_2 & (1.3) \\
\text{Hot side fan: } & \dot{C}_1^h + \dot{C}_{1h} + \dot{Z}_{1h} = \dot{C}_2^h & (1.4)
\end{align*}
\]

The unit of all parameters in Eq. (1) is dollar per second ($/s). Zero-unit cost is assumed for entering air fluid to the fans i.e. $\dot{C}_1$ and $\dot{C}_1^h$ (one of them is supplied from the outside ambient air). Thus, Eq. (1) is rewritten as Eq. (2) by consideration of mentioned zero costs and also removing $\dot{C}_q$ between Eq. (1.1) and Eq. (1.2).

\[
\begin{align*}
\begin{cases}
\dot{C}_2 + \dot{C}_3 + \dot{Z}_c + \dot{Z}_c = \dot{C}_1 + \dot{C}_y \\
\dot{C}_{1c} + \dot{Z}_{1c} = \dot{C}_2 \\
\dot{C}_{1h} + \dot{Z}_{1h} = \dot{C}_2^h
\end{cases} & (2)
\end{align*}
\]

It is noted that, the aim of heat recovery unit is generating pre-heated air. Hence, the first desired cost rate is $\dot{C}_3$. However, all parameters at the right-hand side of Eq. (2) are unknown. Indeed, there are four unknown parameters with only three equations. Hence, another auxiliary equation is needed which can be derived using F principle. It is noted that the specific exergy increases for one stream (cold air) and decreases for the other material stream (hot air) through the heat exchanger of the recovery unit. As described by Ref. [24], as a decrement of specific exergy belongs always to the fuel and also as the specific exergy increase of cold stream (hot air) is desired with the purpose of the component (heat recovery unit), the F principle will be as Eq. (3).

\[
c_{2y} = c_{3y} & (3)
\]

Now, Eq. (2) and Eq. (3) are combined as a new set of equations as shown in Eq. (4) in which “$\dot{Z}_h + \dot{Z}_c$” is shown with $\dot{Z}_{\text{HEX}}$ (cost rate of capital cost of heat exchanger).

\[
\begin{align*}
\begin{cases}
\dot{C}_2 + \dot{C}_3 + \dot{Z}_c + \dot{Z}_c = \dot{C}_1 + \dot{C}_y \\
\dot{C}_{1c} + \dot{Z}_{1c} = \dot{C}_2 \\
\dot{C}_{1h} + \dot{Z}_{1h} = \dot{C}_2^h
\end{cases} & (4)
\end{align*}
\]
\[
\begin{align*}
\dot{C}_2 + \dot{C}_3 + \dot{Z}_{\text{HEX}} &= \dot{C}_1 + \dot{C}_4 \quad (4.1) \\
\dot{C}_{1e} + \dot{Z}_{1e} &= \dot{C}_2 \quad (4.2) \\
\dot{C}_{1h} + \dot{Z}_{1h} &= \dot{C}_3 \quad (4.3) \\
\dot{C}_4 &= \dot{C}_4 \quad (4.4)
\end{align*}
\]

Cost rates associated with exergy streams (i.e. \(\dot{C}_2, \dot{C}_3, \dot{C}_2\)' and \(\dot{C}_3\)') are defined as Eq. (3) in which “c” is cost per unit of exergy stream.

\[
\begin{align*}
\dot{C}_2 &= c_2 X_2 \\
\dot{C}_3 &= c_3 X_3 \\
\dot{C}_2' &= c_2 X_2' \\
\dot{C}_3' &= c_3 X_3'
\end{align*}
\]

By replacing Eq. (5) in Eq. (4) the below equation is obtained.

\[
\begin{align*}
\dot{C}_{1e} + \dot{Z}_{1e} &= c_2 \dot{m}_e x_2 + c_3 \dot{m}_e x_3 + \dot{Z}_{\text{HEX}} = c_2 \dot{m}_e x_2 + c_3 \dot{m}_e x_3 \\
\dot{C}_{1h} + \dot{Z}_{1h} &= c_2 \dot{m}_h x_2' + \dot{Z}_{\text{HEX}} = c_2 \dot{m}_h x_2'
\end{align*}
\]

Eq. (6) contains four independent equations and four unknown parameters i.e. \(c_2, c_2', c_3\) and \(c_3\). By solving Eq. (6), the cost per unit of pre-heated air \((\dot{C}_3)\) and consequently cost rate associated with pre-heated air \((\dot{C}_3, \dot{C}_3, \text{final desired aim of the heat recovery unit})\) is obtained as Eq. (7) (it is mentioned that \(C_3 = c_3 m_3 x_3\)) [24–27].

\[
\dot{C}_3 = (\dot{C}_{1a} + \dot{Z}_{1a}) \left( \frac{x'_2 - x'_3}{x'_2} \right) + \dot{C}_{1e} + \dot{Z}_{1e} + \dot{Z}_{\text{HEX}}
\]

A strategy is still required to evaluate the cost rates of capital costs \((\dot{C}_{1a}, \dot{Z}_{1a} \text{ and } \dot{Z}_{\text{HEX}})\), cost rate of power consumption by the fans \((\dot{C}_{1e} \text{ and } \dot{C}_{1h})\) and also specific exergy of the fluids \((x'_2 \text{ and } x'_3)\). The capital cost of any device is available online in the form of $ (not \$/s). However, the capital costs in term of $ can be converted to the rate of capital cost rate \((\dot{Z})\) by Eq. (8) [24–27].

\[
\dot{Z}_4 = 4 \times 3600 \times \frac{\phi}{3600 N} = 4 \times 75 \times 10^{-10} \text{(s)}
\]

Cost rate associated with power consumption by the cold side fan and hot side fan \((\dot{C}_{1e} \text{ and } \dot{C}_{1h})\) can be evaluated by Eq. (9). However, \(P_6\) in Eq. (9) depends on air flow rate and total pressure drop calculated via Eq. (10). Replacing Eq. (10) in Eq. (9) yields Eq. (11).

\[
\begin{align*}
\dot{C}_{1e} &= 3600 \times \frac{P_6}{1000 \times \eta} \\
\dot{C}_{1h} &= \frac{\Delta P_h \times Q_h \times Y}{\eta_h \times 36 \times 10^5} \\
\dot{C}_{1a} &= \frac{\Delta P_a \times Q_a \times Y}{\eta_a \times 36 \times 10^5}
\end{align*}
\]

Based on the definition of exergy, the terms \(x_2\) and “\(x'_2 - x'_3\)” are defined by Eq. (12) with consideration of air fluid as an ideal gas assumption.

\[
\begin{align*}
x'_2 &= c_{ph}(T'_2 - T_0) - T_0 \left[ c_{ph} \ln \left( \frac{T'_2}{T_0} \right) - R \ln \left( \frac{P'_2}{P_0} \right) \right] \\
x'_2 - x_3 &= c_{ph}(T'_2 - T_0) - T_0 \left[ c_{ph} \ln \left( \frac{T'_2}{T'_0} \right) - R \ln \left( \frac{P'_2}{P'_0} \right) \right] \quad (12)
\end{align*}
\]

The employment of Eqs. (8), (11) and (12), Eq. (7) can be written as Eq. (13).

\[
\dot{C}_3 = \left( \frac{\Delta P_h \times Q_h \times Y}{\eta_h \times 36 \times 10^5} + \dot{Z}_{1a} \right) \left( c_{ph}(T'_2 - T_0) - T_0 \left[ c_{ph} \ln \left( \frac{T'_2}{T_0} \right) - R \ln \left( \frac{P'_2}{P_0} \right) \right] \right) + \left( \frac{\Delta P_a \times Q_a \times Y}{\eta_a \times 36 \times 10^5} + \dot{Z}_{1a} + \dot{Z}_{\text{HEX}} \right) \quad (13)
\]

The unit of \(\dot{C}_3\) obtained by Eq. (14) is $/s which provides a good sense of required money (per time) to run the given heat recovery.
and produce pre-heated air. As can be seen, the cost rate is exactly determined by giving the inlet/outlet temperatures, pressure drop, air flow rates and cost of electricity of the region with consideration of all associated costs i.e. exergy cost (environment temperature), pumping power, electricity, capital cost etc. That means this criterion even can be employed in designing and optimization process of heat recovery units. Finally, the profitability can be calculated using Eq. (14).

\[
\text{Profitability} = \frac{\dot{C}_{\text{save}}}{\dot{C}_3} \quad (14)
\]

\[
\begin{align*}
\text{For resistance heater:} & \quad \dot{C}_{\text{save}} = \frac{\dot{m}_c c_p (T_3 - T_2) \times Y}{3600000} \\
\text{For heat pump:} & \quad \dot{C}_{\text{save}} = \frac{\dot{m}_c c_p (T_3 - T_2) \times Y}{3600000 \times COP}
\end{align*}
\]

3. Case study

Table 2 presents the characteristics of a given heat recovery unit. Decision making process for the application of this unit depends on the pre-heated air production cost rate \( \dot{C}_3 \) and profitability of the unit. \( \dot{C}_3 \) and profitability of this unit is calculated for different outside air temperatures (desired indoor temperature is 298 K) using the model. Fig. 2 shows the results of the model while the electricity price is 0.4 $/kWh for both electric heater and heat pump. Fig. 3 presents the same results while the electricity price is 0.1 $/kWh.

According to Figs. 2 and 3 the cost rate of pre-heated air production \( \dot{C}_3 \) varies between around 0.1 and 0.14 $/h depending on ambient temperature and price of electricity. The cost rate of preheated air production \( \dot{C}_3 \) is increased with increment of outside air temperature. Nonetheless, the profitability of the application of heat recovery unit is positive for both electrical heater and heat pump in Fig. 2 in which the price of electricity is 0.4 $/kWh. It means the application of recovery unit in ventilation process is economical to obtain the desired temperature (298 K) with consideration of all costs (compared to the pure simple ventilation without recovery unit to reach the same indoor temperature with stronger heater). Based on Fig. 2, the profitability of the recovery unit while the heating unit is electric heater is higher. Depending on the ambient temperature, recovery ventilation can save around 0.7 $ per hour which is
considerable. The profitability of recovery ventilation for heat pump is less than the electrical heater. Moreover, with increment of coefficient of performance of the heat pump (COP) the profitability of the recovery unit is reduced. It means for highly efficient heat pumps adding recovery is less economic.

Fig. 3. Variation of $C_3$ and profitability against outside temperature (electricity price is 0.1 $/\text{kWh}$ and desired indoor temperature is 298 K).

Fig. 4. a) Preheating cost against pressure drop of the recovery unit (electricity price is 0.1 $/\text{kWh}$) and b) Preheating cost against pressure drop of the recovery unit (electricity price is 0.4 $/\text{kWh}$).
However, for the regions with cheaper electricity price the profitability of the recovery unit is negative for the heat pump with COP >1.5 which is provided in Fig. 3 in which the electricity price is 0.1 $/kWh. Negative profitability means recovery ventilation is not economical. In other words, simple ventilation is cheaper than the recovery ventilation. It is mentioned that, in simple ventilation the air is simply ventilated without recovery unit. In simple ventilation, the heating unit should work with higher capacity to obtain the same desired indoor air temperature. Even when the price of electricity is low, the profitability of recovery ventilation is positive when the heating unit is electrical heater. Hence, the ventilation process can be recommended for electrical heater for a wide range of electricity price.

As described before, the other application of the present strategy is designing/optimization tool of heat recovery units. As a sample, the pressure drop through the heat exchanger is considered as a designing criterion [28–30]. For the given outside and indoor temperature (273 K and 298 K respectively) the impact of pressure drop through the recovery unit (which is a designing parameter [31–33]) on pre-heating cost is presented in Fig. 4 (a) (other characteristics of the recovery unit is assumed as Table 2) for electricity price of 0.4 $/kWh. Fig. 4 (b) shows the same results for the electricity price of 0.1 $/kWh. The impact of all other designing parameters can be evaluated similarly which is beyond of the main aim of this study. However, the future researchers may be interested to work further of the designing application of the model for heat recovery unit [34,35]. According to Fig. 4, higher pressure drop through the heat recovery unit increases the cost rate of air fluid pre-heating which is predictable. Nonetheless, the model can be employed to provide a multi optimization process with consideration of all effective parameters and factors to design and fabricate the most effective heat recovery unit.

4. Conclusion

In this research, attempts were made to provide an economic criterion for recovery ventilation using SPECO method. The strategy is able to explicitly identify whether adding a heat recovery unit in ventilation process is economical or not compared to the simple ventilation (without recovery unit) with consideration of all effective parameters including outside air temperature, expected indoor air temperature, pressure drop through the heat recovery unit, required fans to overcome the pressure drop through the recovery unit, capital/investment costs of all equipment, exergy costs, electricity price of the region, type of heater (electrical heater or heat pump), required air flow rate and so on. The provided model not only is able to act as decision making criteria, but also it is able to act as a designing/optimization tool for any air-to-air heat recovery unit. Case study was provided for both mentioned applications. Besides, the model was successfully able to predict the impact of any designing parameter of economic aspect of the recovery unit. Multi-optimization of heat recovery unit is proposed for the next interested researchers in this area.

Author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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