Economic analysis of condensing exhaust air heat recovery fresh air all-in-one unit in Hangzhou area

Zhiyi Wang¹*, Cui Xia¹ and Yunge Wu²

¹School of civil engineering and architecture, Zhejiang Sci-Tech University, Hangzhou, 310018, China
²Zhejiang Institute of Mechanical & Electrical Engineering Co., Ltd., Hangzhou, 310051, China

*Corresponding author’s e-mail: zywang-wf@163.com

Abstract. Condensing exhaust air heat recovery fresh air all-in-one unit deals fresh air with the heat of building exhaust air as cold or heat source and it has a high efficiency. In this paper, energy consumption of air source heat pump system which introduced condensing exhaust air heat recovery fresh air all-in-one unit is analysed, and equipment's static and dynamic payback period of investment is calculated in fixed number of year. In a similar system, condensing exhaust air heat recovery fresh air all-in-one unit has very good application prospects.

1. Introduction
Indoor air quality (IAQ) is the necessities of life at home and in public areas due to people spend most of their time indoors, and poor IAQ of lacking fresh air exchange may affect health. To maintain IAQ at a safe concentration level, room may be ventilated in a controlled manner to maintain thermal comfort and adequate temperature, but at the same time, the extensive use of fresh air increases the energy consumption of the air conditioning system. So how to reduce the energy consumption of fresh air has gradually become a research focus, and the exhaust heat recovery methods are proposed in the design of the air conditioning system.

The traditional fresh air conditioning unit generally adopts a large enthalpy difference cooler to handle the outdoor air directly, which needs an auxiliary cold and heat source. It consumes lots of energy and has poor heat and heat source efficiency [1]. If the residual heat in the exhaust can be fully utilized, the energy consumption of the fresh air treatment will be reduced and the capacity of the cold and heat source, the distribution system as well as the pipeline will be lessened, then the operation cost of air conditioning can be cut down, so that the efficiency of the entire system will be improved [2-3]. Due to the introduction of exhaust heat recovery technology, the exhaust heat recovery technology was divided into two different ways by researchers depending on the energy recovered, namely sensible heat recovery and total heat recovery, among which the commonly used ones include plate fin type, rotary type, heat pipe type and heat pump type [4-7]. But the heat recovery efficiency of the air-to-air heat exchanger exhaust heat recovery is about 70%, the fresh air and return air treated by the air-to-air heat exchanger exhaust heat recovery unit still need to be heated (or cooled) before supply to the room.

Lazzarin and Gasparella [8] analysed the heat recovery efficiency of building ventilation systems and found that the use of heat recovery technology had certain conditions. The heat recovery efficiency was closely related to temperature. When the temperature difference between exhaust and fresh air is smaller, the sensible heat or latent heat recovery efficiency of the heat recovery device will
be lower, especially when the temperature difference is less than 2 °C. Roult [9] et al. proposed two new energy evaluation methods for the question about whether the heat recovery device needs to be used, and analysed the factors affecting the recovery efficiency of the heat recovery device, as well as the operating performance of the fan when the unit is leaking, which could effectively guide the research of heat recovery technology in practical engineering. Exhaust air energy was used to pre-heat (cool) the fresh air in most investigation conducted on exhaust air energy recovery, thus changed the condition of fresh air on the evaporator side. Few studies are conducted to use the exhaust air energy to change the environment on the condenser side. In this article, a condensing exhaust heat recovery fresh air all-in-one unit is designed and its energy conservation is demonstrated.

2. Condensing exhaust heat recovery fresh air all-in-one unit

The condensing exhaust heat recovery fresh air all-in-one unit is an integrated new air conditioning unit that utilizes building exhaust as a condensing air of the unit. It combines the fresh air unit and the heat pump system by using a mixed air about fresh air and exhaust air as a heat source, which fully uses the exhaust energy of the building. The system of condensing exhaust heat recovery fresh air all-in-one unit is shown in figure 1.

During cooling, the unit uses the mixed air as the cold source of the unit. Because of the low temperature room exhaust, the unit's condensing temperature and the compressor power consumption be reduced, thus the unit's energy efficiency ratio can be improved. On a heating condition, the unit uses the mixed air as the heat source of the unit. Recycling the air in the room improve the unit's evaporation temperature, increases the unit's heating capacity, reduces the unit's frosting temperature, and expands the unit's operating range.

3. System analysis

The energy in the exhaust air is recovered by the system through heat pump technology, thereby reducing the fresh air load after the condensing exhaust heat recovery fresh air all-in-one unit be introduced in the air source heat pump unit system. Meanwhile, the cooling and heating load of the air conditioning system is reduced, thus the energy consumption of the air source heat pump chiller system is reduced, and however it also increases the energy consumption of the exhaust fan and the energy consumption of the compressor. The increase in energy consumption caused by the unit is divided into two parts: one is the increased resistance of the exhaust through the heat exchanger, and another is that the increase in the amount of air caused by the mixing of some fresh air. In addition, exhaust air also brings some energy consumption to the compressor. The equations related to the heat pump unit and compressor have been provided in this section.

The cold or heat recovered by the condensing exhaust heat recovery fresh air all-in-one unit is expressed as in equation (1).
\[ Q = G_{\text{Fresh, air}} (h_{\text{in}} + h_{\text{out}}) \]  

(1)

Where \( G_{\text{Fresh, air}} \) is the Fresh air volume (kg/s), \( h_{\text{in}} \) is the air enthaly into the unit (kJ/kg), \( h_{\text{out}} \) is the air enthaly at the exit of the unit (kJ/kg).

The increased in energy consumption of the exhaust fan is calculated as in equation (2).

\[ \Delta N_{\text{Fan}} = \left( \Delta P_{\text{Exhaust}} G_{\text{Exhaust}} + P_{\text{Mixture}} G_{\text{Mixture}} \right) \eta_{\text{Fan}}^{-1} \]  

(2)

Where \( \eta_{\text{Fan}} \) is the full pressure efficiency of the fan, \( G_{\text{Exhaust}} \) is the exhaust air volume of the air conditioning system (m\(^3\)/h), \( G_{\text{Mixture}} \) is the air volume mixed in outdoor (m\(^3\)/h), \( \Delta P_{\text{Exhaust}} \) is the increased resistance of the refrigerant heat exchanger (kPa), \( P_{\text{Mixture}} \) is the resistance that the mixture inlet needs to overcome by the fan (kPa).

The energy consumption reduction of the air source heat pump chiller unit is calculated as in equation (3). The energy saving of the cold water circulating water pump is calculated as in equation (4).

\[ \Delta N_{\text{Chiller}} = G_{\text{Fresh, air}} (h_{\text{in}} + h_{\text{out}}) \text{COP}^{-1} \]  

(3)

\[ \Delta N_{\text{Chw, pump}} = H_{\text{Chw, pump}} G_{\text{Fresh, air}} (h_{\text{in}} + h_{\text{out}}) \left( \eta_{\text{Chw, pump}} c_{\text{Chw}} \Delta t_{\text{Chw}} \right)^{-1} \]  

(4)

Where COP is the Coefficient of Performance, \( H_{\text{Chw, pump}} \) is the thermodynamic head of the chilled water pump (Pa), \( \Delta t_{\text{Chw}} \) is the temperature difference of chilled water supply and return (°C), \( c_{\text{Chw}} \) is the specific heat capacity of the chilled water (kJ/(kg·k)), \( \eta_{\text{Chw, pump}} \) is the full pressure efficiency of chilled water pump.

The energy saving of the hot water circulation pump is calculated as in equation (5).

\[ \Delta N_{\text{hw, pump}} = H_{\text{hw, pump}} G_{\text{Fresh, air}} (h_{\text{in}} + h_{\text{out}}) \left( \eta_{\text{hw, pump}} c_{\text{hw}} \Delta t_{\text{hw}} \right)^{-1} \]  

(5)

Where \( H_{\text{hw, pump}} \) is the thermodynamic head of the hot water pump (Pa), \( \Delta t_{\text{hw}} \) is the temperature difference of hot water supply and return (°C), \( c_{\text{hw}} \) is the specific heat capacity of the hot water (kJ/(kg·k)), \( \eta_{\text{hw, pump}} \) is the full pressure efficiency of chilled water pump.

4. Engineering analysis

4.1 Engineering overview

The paper takes a project in Hangzhou as an example, the office building in Hangzhou with a building area of 14,000 m\(^2\) and an air-conditioning area of 12,100 m\(^2\). The office's lighting power is 20 W/m\(^2\), the public area is 15 W/m\(^2\), the office equipment power is 20 W/m\(^2\), the personnel density is 0.1 m\(^2\) per person, and the public area is 0.022 per person. The fresh air volume is 30 m\(^3\)/h per person.

Hangzhou outdoor design calculation temperature in summer are dry-bulb temperature of 35.6 °C and wet-bulb temperature of 27.9 °C, the air conditioning outdoor calculation temperature is -2.4 °C and the relative humidity is 76% in winter. Indoor design calculation temperature are the temperature of 26 °C and relative humidity of 60% in summer, the indoor design calculation temperature is 20 °C and relative humidity is 40% in winter. The air conditioning is available from Monday to Friday from 8:00 to 20:00. The cooling time is from May to September, and the heating time is December, January and February. The air conditioning operation mode is starting to heat when the outdoor temperature is lower than 20 °C, and starting to cool when the outdoor temperature exceeds 26 °C.

It is calculated that the design cooling load of this office building is 1021 kW and the heating load is 590 kW, the calculated fresh air volume is 33,810 m\(^3\)/h. Therefore, five hot and cold water units of air source heat pump were selected for this project, and the performance parameters are shown in table 1. Moreover, five condensing exhaust heat recovery fresh air all-in-one unit were selected according to the fresh air volume of 33,810 m\(^3\)/h, its rated air volume is 7000 m\(^3\)/h.

| Project       | Capacity /kW | Power /kW | COP   |
|---------------|--------------|-----------|-------|
| Refrigeration | 205          | 73.2      | 2.8   |
| Heating       | 241          | 83        | 2.9   |

Table 1. Air source heat pump water chiller performance parameters.
During the operation, the measured inlet enthalpy of fresh air in summer was 89.31 kJ/kg, and the export enthalpy of fresh air in summer was 59.84 kJ/kg. The measured inlet enthalpy of fresh air in winter was 18.52 kJ/kg, and the export enthalpy of fresh air in winter was 41.92 kJ/kg. From the equation (1), the energy recovered from fresh air cooling in summer is 343.40 kW, and the energy recovered from fresh air heating in winter is 263.72 kW. The annual operating energy consumption of the air source heat pump system which introduced condensing exhaust air heat recovery fresh air all-in-one unit is calculated according to the equation (1)-(5), and the results are shown in table 2.

Table 2. Energy consumption change of air conditioning system after increasing condensing exhaust air heat recovery fresh air all-in-one unit.

| Project                        | Energy savings (kW) | Remarks                                      |
|--------------------------------|---------------------|----------------------------------------------|
| power changes in summer        | 122.64              | -                                            |
| power changes in winter        | 90.94               | -                                            |
| change of chilled water pump power | 13.05            | full pressure efficiency of pump: 0.75, Head: 650Pa |
| change of heat water pump power | 5.01                | full pressure efficiency of pump: 0.75, Head: 650Pa |
| change of all-in-one unit power in summer | -95.39          | running time in summer is 1266h               |
| change of all-in-one unit power in winter | -67.62          | running time in winter is 723h               |
| change of exhaust fan power    | -9.41               | full pressure efficiency of exhaust fan: 0.75 |
| Annual power saved            | 59.22               | -                                            |

4.2 Economic analysis
The economic value of the system can be judged by the investment recovery period which calculated by the economic analysis. The reduced value of the initial investment of air conditioning cold and heat source is expressed as in equation (6). The initial investment in the condensing exhaust air heat recovery fresh air all-in-one unit is expressed as in equation (7).

$$\Delta C_{primary} = C_{primary1} - C_{primary2} = \frac{Q \eta \lambda p_t}{10000}$$

$$C_e = \frac{G \eta p_s}{10000}$$

Where $C_{primary1}$ and $C_{primary2}$ are the initial investments of air conditioning cold and heat sources before and after the use of condensing exhaust heat recovery, $Q$ is the design heat and cold load of the air conditioning system (kW), $\eta$ is the ratio of the fresh air load of the air conditioning system to the design load of the air conditioning system (%), $p_t$ is the cost of air source heat pump hot and cold water unit (yuan), the current price is 700 yuan / kW. $P_s$ is the unit air volume price in the market (1000 yuan / (m$^3$ / h)).

The annual operating cost (10,000 yuan) of air-conditioning cold and heat source is calculated as in equation (8). The annual operating costs saved by cold and heat sources is calculated as in equation (9).

$$C_o = \frac{\sum N \eta T \lambda \lambda_p p_d}{10000}$$

$$\Delta C_o = C_{o1} - C_{o2} = \frac{\sum \Delta N \eta T \lambda \lambda_p p_d}{10000}$$

Where $N$ is the power consumption of air source heat pump unit (kW), $\eta$ is the ratio of the actual load to design load of air conditioning system (%), $T$ is the annual operating time of the air conditioning system (h), $\lambda$ is the proportion of the operating time under various air conditioning loads (%), $p_d$ is the price of electricity, this article takes 1 yuan / (kW · h). $C_{o1}$ and $C_{o2}$ are the annual operating cost of the air source heat pump of the air conditioning system before and after the fresh air unit is recovered by
using the condensing exhaust heat, $\Delta N_s$ is the reduced power of the air conditioning system equipment after using the condensing exhaust heat recovery fresh air all-in-one unit (kW).

Static and dynamic investment payback period for condensing exhaust air heat recovery fresh air all-in-one unit are calculated as in equation (10)-(11).

$$n = C_e \Delta C_e (\Delta C_o)^{-1}$$  \hspace{1cm} (10)

$$m = \ln \left( \frac{\Delta C_e}{\Delta C_o} \left[ \ln(1+i) \right]^{-1} \right)$$  \hspace{1cm} (11)

Substituting the data into equation (10)-(11), the static recovery period of the condensing exhaust air heat recovery fresh air all-in-one unit applied to the office building is 3.8 years, the dynamic investment payback period can be calculated as 4.7 years. Where $i$ is the discount rate, in this article it takes 8%.

5. Conclusion
The condensing exhaust heat recovery fresh air all-in-one unit recovers the exhaust energy by designing the condenser in the exhaust passage and using the mixed air as the condensed air. It is more efficient, more eco-friendly, and its application improves the device COP value. Taking a typical office building in Hangzhou as an example, this paper uses the equation of the payback period and related data to calculate the static investment payback period and the dynamic investment payback period. The static investment payback period is 3.8 years, and the dynamic investment payback period is 4.7 years, which shows this equipment has good return and value in similar areas.

Acknowledgments
The authors wish to thank the “Fault detection and diagnosis research of air conditioning and refrigeration system based on deep learning algorithms” for the financial support of Zhejiang Natural Science Foundation.

References
[1] Ma, L.S., Yang, J., Zhang, X. (2011) Plate-type Air-to-air Energy Recovery Heat Exchanger Applied in Shanghai. Building Energy Efficiency, 39: 16-18.
[2] Wu, Y.H., Liang, J. (2008) Analysis of exhaust air heat recovery in air conditioning system design. Heating Ventilating & Air Conditioning, 09: 60-63.
[3] Riffat, S.B., Gillott, C. (2002) Performance of a novel mechanical ventilation heat recovery heat pump system. Applied Thermal Engineering, 22: 839–845.
[4] Pan, J.M. (2010) Improvement of a Mechanical Ventilation Heat Recovery System (MVHR) with Its Transfer Process Particularly Based on Thermodynamic Cycle. Building Energy Efficiency, 38: 14-18.
[5] Li, S.H., Zhang, X.S., Du, K., Cai, L. (2005) Analysis and Research on New of Air Energy Recovery Device. Building Energy & Environment, 04: 49-51.
[6] Wen, X.H. (2011) Classification and Application of Air Heat Recovery Devices. Building Energy Efficiency, 01: 9-12.
[7] Alonso, M.J., Liu, P., Mathisen, H.M., Ge, G.M., Simonson, C. (2015) Review of heat/energy recovery exchangers for use in ZEBs in cold climate countries. Building and Environment, 84: 228-237.
[8] Lazzarin, R.M., Gasparella, A. (2008) Technical and economic analysis of heat recovery in building ventilation systems. Applied Thermal Engineering, 18: 47-67.
[9] Roult, C.A., Heidt, F.D., Foradini, F., Pibiri, M.C. (2001) Real heat recovery with air handing units. Energy and buildings, 33: 495-502.