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Experimental study on the characteristics of triplex loop heat pump for exhaust air heat recovery in winter

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ABSTRACT

Ventilation heat recovery is an important means of effectively reducing the energy consumption of buildings. To improve the performance of a heat pump heat recovery system under large temperature difference conditions in winter, a triplex loop heat pump system, which contains three independent heat pump cycles, is proposed in place of its single loop counterpart. Operating characteristics and system performance were analyzed while indoor temperature was constant at 20 °C and as outdoor temperature dropped from 15 °C to −20 °C. Results showed that with the decrease of the outdoor temperature, the mass flow rate and temperature effectiveness of the triplex loop heat recovery system decreased whereas the heating capacity and the coefficient of performance (COP) increased. Under the experimental conditions, the COP of the triplex loop system had an advantage over the traditional heat pump system when the outdoor temperature was below 2.5 °C. When the outdoor temperature was −20 °C, the COP of the triplex system could reach 9.33, which was 23.1% higher than that of the traditional system.

1. Introduction

Ventilation system design is particularly necessary for buildings. It can maintain the quality of indoor air and reduce the concentration of bacteria and viruses. However, a ventilation system can cause excessive energy consumption through the air conditioning system of buildings [1]. In cold regions, heating energy consumption accounts for a large proportion of the total energy consumption of buildings [2–4]. Furthermore, fossil fuels such as coal are still used as the primary source of heating energy in some developing countries. This heating method not only has poor utilization of energy but also releases substantial greenhouse gases and harmful substances into the environment [5]. Indoor exhaust air has a higher temperature in winter, it can be recovered by a ventilation heat recovery system to reduce the energy consumption of heating systems [6,7]. Under new building standards, all newly built buildings in some European countries must have a ventilation system with heat recovery [8].

Heat recovery from the exhaust air can be performed in many ways. At present, the main types of heat recovery devices in ventilation systems include rotary thermal wheels, plate exchangers, heat pipes, run-around systems and heat pumps. The rotary thermal wheel is a heat recovery device that realizes heat exchange between two air flows through the heat storage and heat release effect of the material during the rotation of the wheel body. The plate heat exchanger consists of thin metal plates separated by small spaces through which two adjacent and different airstreams pass. Heat recovery occurs as the heat transfers through a plate from one airstream to the other. The heat pipe can be divided into the evaporation, adiabatic and condensing sections. The refrigerant absorbs the heat from exhaust air and vaporizes. Afterward, the refrigerant steam flows into the condensing section under the effect of the small pressure difference and then condenses after releasing heat to fresh air. The run-around system has gas–liquid heat exchangers on the fresh and exhaust air sides. The liquid in the system circulates between the high- and low-temperature sides to achieve the heat recovery effect. Heat pump heat recovery system consists of a series of equipment, such as compressors, condensers and evaporators. Its structure is similar to that of an ordinary air source heat pump air conditioning system. Exhaust and fresh air flow through the evaporators and condensers, respectively. Compared with other types of heat recovery methods, the heat pump heat recovery system can avoid cross contamination between fresh and exhaust air. Moreover, it can provide the room with fresh air with higher temperature and has higher recovery efficiency [9–13]. Under certain working conditions, the temperature effectiveness of the heat pump heat recovery system can exceed 100%, so the fresh air does not need to be reheated. Chen et al. found that the heat pump heat recovery system has better energy saving potential than

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Nomenclature

$\dot{m}_A$	refrigerant mass flow rate of Loop A, kg/s
$\dot{m}_B$	refrigerant mass flow rate of Loop B, kg/s
$\dot{m}_C$	refrigerant mass flow rate of Loop C, kg/s
$\dot{m}_D$	refrigerant mass flow rate of Loop D, kg/s
V_A	displacement of Compressor A, m^3/s
V_B	displacement of Compressor B, m^3/s
V_C	displacement of Compressor C, m^3/s
V_D	displacement of traditional system, m^3/s
v_{A1}	specific volume of refrigerant at Point A1, m^3/kg
v_{B1}	specific volume of refrigerant at Point B1, m^3/kg
v_{C1}	specific volume of refrigerant at Point C1, m^3/kg
v_{D1}	specific volume of refrigerant at Point D1, m^3/kg
$\dot{m}_{total}$	refrigerant mass flow rate of Loop A, kg/s
Q_{total}	total absorbed heat of the triplex loop system, kW
Q_D	total absorbed heat of the traditional system, kW
h_{A1}	enthalpy at Point A1, kJ/kg
h_{A4}	enthalpy at Point A4, kJ/kg
h_{B1}	enthalpy at Point B1, kJ/kg
h_{B4}	enthalpy at Point B4, kJ/kg
h_{C1}	enthalpy at Point C1, kJ/kg
h_{C4}	enthalpy at Point C4, kJ/kg
h_{D1}	enthalpy at Point D1, kJ/kg
h_{D4}	enthalpy at Point D4, kJ/kg
Q	total heating capacity, W
q_{vi}	air volume flow rate of fresh air duct, m^3/s
C_{pa}	specific heat capacity of air, J/kg °C
t_{f2}	temperature of air leaving the fresh air duct, °C
t_{f1}	temperature of air entering the fresh air duct, °C
v_n'	specific volume of air, m^3/kg
W_n	absolute humidity of air, kg/kg
t_{e1}	temperature of air entering the exhaust air duct, °C
W_A	input power of Compressor A, W
W_B	input power of Compressor B, W
W_C	input power of Compressor C, W
W_F	input power of fans, W
η	temperature effectiveness, %
COP	coefficient of performance

the rotary wheel and the plate heat recovery system [14]. Fracastoro et al. verified that the efficiency of a heat pump system using building exhaust air as the heat source is higher than that which uses a ground source; moreover, the system installation cost of the former is smaller than that of the latter [15]. The above research results indicate that ventilation heat recovery systems with heat pump have broad application prospects. Currently, the global energy solution represents a tense situation and research on nearly zero-energy buildings is in full swing. Given the advantages of the ventilation heat pump heat recovery system over other systems, many scholars have applied heat pumps for exhaust air heat recovery in nearly zero-energy buildings [16–19]. Therefore, the working properties of heat pump systems in ventilation heat recovery applications must be studied and system performance is necessary to be improved.

The ventilation heat recovery system with a heat pump also presents some problems. The ventilation heat recovery system is essentially an air source heat pump system. With the reduction of outdoor temperature in cold climate conditions, the heat pump system will encounter many issues, such as high pressure ratios, deterioration of mechanical lubrication and reduced mass flow and heat production [20–22]. However, in the heat recovery system, the air temperature entering the condenser in winter is the outdoor ambient temperature, which is lower than the indoor air temperature that enters the evaporator. Therefore, the problem wherein the pressure ratio of the system increases when the outdoor temperature drops will be eliminated. In [15], the supply air temperature to the room decreased gradually with the decreasing outdoor temperature in winter. By the calculation formula of temperature effectiveness [10] that temperature effectiveness decreases with the decrease in outdoor temperature. Accordingly, the evaporation temperature decreases and the heat recovery system mass flow is reduced.

In the traditional heat pump system, the working volume of the compressor and vapor injection is increased to solve the problem of mass flow reduction given large differences between indoor and outdoor temperatures [23–27]. However, these methods are based on the premise that the pressure ratio of the compressor increases gradually with the increase of the temperature difference indoors and outdoors and they do not fully comply with the actual operating characteristics of the heat pump heat recovery system. In addition, no related research is found on the mass flow rate increase of the ventilation heat pump heat recovery system given a large-temperature-difference environment between indoor and outdoor. Increasing the mass flow rate of the heat recovery system under the same operating conditions is critical to improving system performance. The mass flow of the system is most directly related to the evaporation temperature. Hence, a complete system can be decomposed into small systems that work in different pressure ranges. All small systems must complete the cycle within the existing system pressure interval in the form of a ladder and then only one small system will have the same evaporation pressure as the original system while the evaporation pressure of the other systems increases gradually. This approach can substantially mitigate the problem of mass flow rate attenuation when the evaporation pressure drops.

Therefore, to improve the mass flow rate of the heat pump ventilation heat recovery system given a large temperature difference indoors and outdoors and enhance system heat recovery performance, a ventilation heat recovery system with three independent heat pump loops is proposed in this work. The principle and structure of the system are introduced and an experimental bench is established to analyze the operating characteristics of the triplex loop heat pump ventilation heat recovery system under different experimental conditions.

2. System principle and experimental method

2.1. System principle

A P-h diagram of the triplex loop heat pump system is illustrated in Fig. 1. The theoretical heat pump circulations and corresponding pressure intervals are as follows: Cycle A1-A2-A3-A4-A1 for the low-pressure interval, Cycle B1-B2-B3-B4-B1 for the middle-pressure interval and Cycle C1-C2-C3-C4-C1 for the high-pressure interval. Cycle D1-D2-D3-D4-D1 shows a traditional heat pump circulation, for which the condensing pressure is at the highest pressure, the evaporation pressure is at the lowest pressure and the pressure ratio of the compressor is relatively large compared with those of the triplex loop system. Relative to the traditional single loop heat pump cycle, the triplex loop system can be regarded as a stepped compression cycle from the enthalpy diagram. This step compression cycle can be used as a method of approaching the Lorenz cycle [22].

For the triplex loop system, the refrigerant mass flow rate of Loop A is

$$\dot{m}_A = \frac{V_A}{v_{A1}}. \tag{1}$$

The cooling capacity of Loop A is

$$Q_A = \dot{m}_A (h_{A1} - h_{A4}). \tag{2}$$