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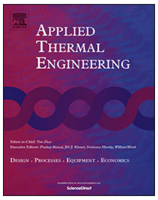

Research Paper

Theoretical analysis on optimal configurations of heat exchanger and compressor in a two-stage compression air source heat pump system

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HIGHLIGHTS

- Optimization of a flash tank cycle based heat pump system is conducted.
- The optimal thermal conductance allocations are obtained under given conditions.
- The system heating capacities are affected by thermal conductance allocation.
- There exists an optimal compressor displacement ratio for optimum system COP.

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ABSTRACT

This paper presents an optimum system configuration analysis for a flash tank cycle (FTC) based two-stage compression air source heat pump system using a developed theoretical model with lumped parameter method. The analysis is carried out with respect to the thermal conductance allocation of total heat-exchanger inventory (condenser and evaporator) as well as the volume ratio of low-pressure compressor to high-pressure compressor in the system. The analysis results indicate that the heating coefficient of performance (COP) of the heat pump system can be maximized by optimally allocating the thermal conductance inventory of the two heat exchangers. Moreover, there also exists an optimal compressor volumetric displacement ratio, corresponding to the optimum system COP, when the cooling capacity of system is specified. The effects of main operation parameters on the configuration parameters and optimal performances have been discussed. The obtained results may provide some guide for the FTC based air source heat pump system optimization.

1. Introduction

Over the past years, air source heat pumps have attracted a great deal of attention for their merits of energy-saving and environmental protection [1,2]. But when they operate at low ambient temperatures, several problems, such as the reduction in the heating capacity and heating coefficient of performance (COP), high compressor discharge temperature, etc., cause some application limitations. In this case, the development of air source heat pumps with higher performances and wider operating temperature range has become a major challenge. For the issues regarding performance degradation of air source heat pumps, some solutions to enhance the heating performance and reliability of the heat pump have been studied, including refrigerant injection technique, two-stage compression systems and cascade system [3–9]. The use of those methods provides more opportunities to apply air source heat pumps in cold regions.

Traditionally, two-stage compression systems consisting of two individual compressors have received much attention for refrigeration applications [10–13]. However, they have also been well justified to improve the heating performance of systems for air source heat pump applications in cold climates. Agrawal et al. [14] carried out optimization studies of two-stage transcritical carbon dioxide heat pump cycles, and indicated that the flash gas bypass system yields the best performance among the three two stage cycles analyzed. Özgür and Bayrakçi [15] also conducted the second law analysis for a two-stage compression transcritical CO_2 heat pump cycle, and identified the main factors that affect the two-stage compression transcritical CO_2 system efficiency. Bertsch and Groll [16] investigated an air-source two-stage heat pump using R410A as the refrigerant, and experimentally verified that the heat pump is able to operate at ambient temperatures between −30 °C and 10 °C with supply water temperatures of up to 50 °C. Kwon et al. [17] evaluated a two-stage compression heat pump system for district heating utilizing waste energy, and obtained the system performance characteristics under various operating conditions. Cao et al. [18] analyzed different high-temperature two-stage heat pump systems for low-grade waste heat recovery, and showed that the two-stage heat pump

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system with flash tank was preferred. Overall, two-stage compression systems could be a good alternative to avoid the performance deterioration of air source heat pumps in cold climates, and relevant research can drive their development in low temperature ambient application.

For two-stage compression heat pump systems, there are two typical cycle configurations, i.e. flash tank cycle (FTC), and internal heat exchanger cycle (IHXC) [19]. Between these two cycles, the FTC has received more attention in recent years. Basically, previous research on the FTC is mainly focused on the cycle performance improvement, component optimization or cycle control strategies. In fact, these issues are closely related to the system configurations of FTC. As is well known, the FTC system mainly consists of a flash tank, two compressors, an evaporator and a condenser. The configuration for the FTC systems is particularly involved in the parameters of compressor and heat exchangers, such as the heat exchange area or thermal conductance of heat exchangers and compressor displacement volume [19,20], which play a key influence on overall system performance. To make effective use of the FTC, it is necessary to explore the relationship between the configuration parameters and the main performance parameters.

In this paper, we present an analytical model with lumped parameter method for a FTC based air source heat pump air conditioner. In the model, heat exchanger thermal conductance inventory is considered as a constraint condition for configuring the FTC system [21]. Based on the developed model, the performance and optimum design conditions of the FTC system are analyzed in detail for different configuration parameters and operating conditions. Furthermore we analyzed the relationship of the optimal compressor volumetric displacement ratio and the optimal thermal conductance allocation at a different heat exchanger thermal conductance inventory. The influence of the different refrigerant on system optimal compressor volumetric displacement ratio is investigated. The objective of this work is to provide some theoretical guidance for the optimal design and operation of air source heat pump using the FTC systems.

2. Analytical model of the FTC system

The schematic diagram of the FTC system is shown in Fig. 1(a), where the system consists of two compressors, a condenser, a flash tank, two expansion valves and an evaporator. The cycle system includes two circuits: a main refrigerant circuit and a bypass refrigerant circuit. The main circuit refrigerant flow is circulated by the low-pressure compressor through the high-pressure compressor, the condenser, the high pressure expansion valve, the flash tank, the low pressure expansion valve and the evaporator, whereas the bypass circuit flow is circulated by the flash tank through the high-pressure compressor, the condenser, and the high pressure expansion valve. Fig. 1(b) shows the detailed working process of the FTC system on pressure-enthalpy diagram. In the condenser, high pressure superheated refrigerant vapor from the high-pressure compressor (state 4) is cooled to the saturated or subcooled liquid (state 5) by secondary fluid (indoor air). The refrigerant liquid is expanded through the high pressure expansion valve, and then the two-phase refrigerant at an intermediate pressure (state 6) enters into the flash tank, in which it is separated into the two phase refrigerant, including the saturated liquid (state 7) and saturated vapor (state 8). On the one hand, after the saturated liquid passes through the low pressure expansion valve, it is heated by outdoor air in the evaporator to be a saturated or superheated vapor (state 1) and then flows into the low-pressure compressor. On the other hand, after the saturated vapor from the flash tank mixes with the superheating refrigerant vapor (state 2) at the outlet of the low-pressure compressor, the vapor mixture (state 3) is compressed by the high-pressure compressor and then enters to the condenser.

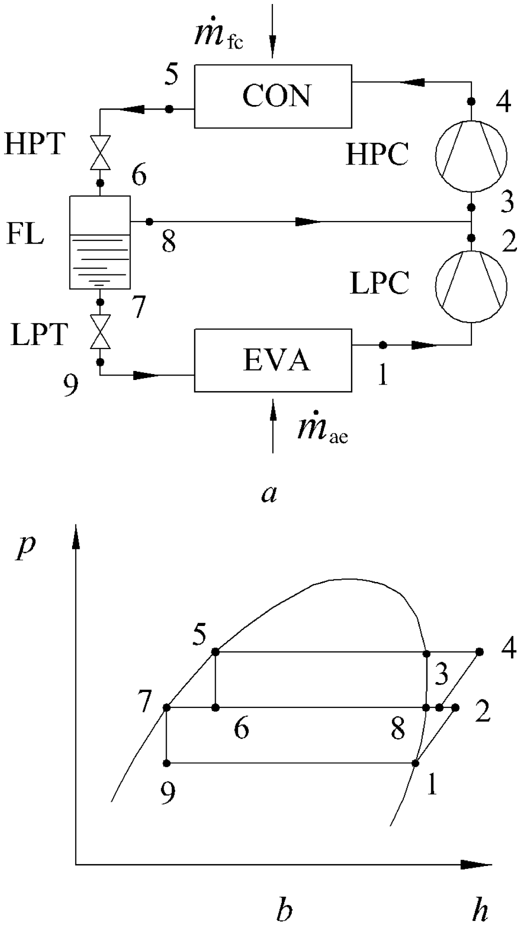

Fig. 1. (a) Schematic diagram of air source heat pump system (b) *p-h* diagram of the cycle. LC – low-pressure compressor; HC – high-pressure compressor; CON – condenser; EVA – evaporator; FL – flash tank; HPT – high pressure throttle; LPT – low pressure throttle.

For modeling the FTC based air source heat pump system, the condenser and the evaporator were modeled by using the ε-NTU method, and two compressors were modeled based on the efficiency of the method, for simulations. Furthermore the following assumptions are made:

1. Refrigerant pressure drops are neglected in the evaporator, the condenser and inlet or outlet of the compressors;
2. Mixing process of refrigerant at the outlet of the low-pressure compressor occurs at a constant intermediate pressure;
3. Refrigerant leaving from the condenser and the evaporator is saturated liquid and saturated vapor, respectively;
4. No heat losses to the environment from the system;
5. The throttling processes in the expansion valves are isenthalpic.

Based on the assumptions above, the heating capacity of the condenser can be obtained as

$$\dot{Q}_c = \varepsilon_c \dot{m}_{fc} c_{pfc} (t_c - t_{fci}) \tag{1}$$

where $\dot{m}_{fc}$ and c_{pfc} are the mass flow rate and specific heat of the heated fluid in the condenser; t_c is the condensing temperature, and t_{fci} is the temperature of the fluid heated, at the inlet of the condenser; ε_c is the heat exchanger effectiveness of the condenser, which can be given by Eqs. (2) and (3),

$$\varepsilon_c = 1 - \exp(-U_c A_c / \dot{m}_{fc} c_{pfc}) \tag{2}$$