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Advances in vapor compression air source heat pump system in cold regions: A review

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ABSTRACT

Vapor compression air source heat pump (VCASHP) system has been widely applied due to its simple structure and low initial cost. However, there are a series of problems when the system is operated for space or water heating in cold regions, and a number of research groups have done much work to improve VCASHP systems for solving these problems over the last two decades. This review presents an update on the recent advances in VCASHP systems applied in cold regions. In this paper, the advanced systems are classified into three major types: single-stage, dual-stage and multi-stage compression systems. In addition, the dual-stage compression system is divided according to the number of compressors and separate loops into quasi-two-stage, two-stage and cascade compression systems. The heating performances and characteristics of each type of compression systems with different working fluids and intermediate configurations have been analyzed and summarized. Meanwhile, several issues of these advanced systems that impede their widespread applications in cold regions are proposed. It is hoped that both the reviewed contents and proposed issues may be useful to the research fellows working in this field.

1. Introduction

A number of research groups and energy organizations have reported that stubbornly high building energy consumption (BEC) is one of the major global challenges for human sustainable development [1,2]. In 2010, about 32% of the total energy consumption was related to buildings [3], accounting for 30% of the homologous CO_2 emissions [4]. Meanwhile, about half of the BEC was utilized for space and water heating [3]. Therefore, improving the energy efficiency of such heating systems can play a pivotal role in addressing the issues of energy and environment, such as global warming and energy crisis. One recognized approach to solving these issues is to replace fossil fuel heating systems with heat pump systems. A large number of technologies on vapor compression heat pump systems with respect to air, solar, ground and coupled sources were investigated [5–10]. Particularly, over the last two decades, vapor compression air source heat pump (VCASHP) system has been widely applied due to its simple structure and low initial cost. However, there are a series of problems when a VCASHP system is operated for space or water heating in cold regions. For example, with a decline of ambient temperature, a decreased heating capacity of VCASHP system may be insufficient with respect to the consumer's requirement. Furthermore, its rising compression ratio may lead to an extremely high discharge temperature and its shut down [11]. Therefore, a great deal of previous research into VCASHP system has been carried out to address such problems.

To the best of authors' knowledge, the latest comprehensive review on VCASHP system in cold regions was published by Bertsch and Groll in 2005 [12]. Recently, although there are several reviews relating to the development of VCASHP system in cold regions, they all have their limitations. For example, Chua et al. [13] and Ni et al. [14] published reviews on heat pump systems, both of them only contained part of advances in VCASHP system in cold regions and some of the advances were not detailed. Sarkar [15] focused on ejector enhanced vapor compression refrigeration and heat pump systems while Aikins et al. [16] on dual-stage vapor compression heat pump systems. The aim of this paper is to provide a comprehensive and state-of-the-art review of existing literatures on the advances in VCASHP systems applied in cold regions. In order to achieve a better understanding of these advances, they are classified into different sections based on the structural characteristics of VCASHP systems: which are single-stage, dual-stage and multi-stage compression systems. Both the heating performances and characteristics of each type of compression systems are analyzed and summarized. Meanwhile, several issues of these advanced systems that impede their widespread applications in cold regions are also proposed. It is hoped that both the reviewed contents and proposed issues may be useful to the research fellows working in this field.

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Nomenclature

BIC	basic intermediate configuration
BEC	building energy consumption
COP	coefficient of performance
CVR	cylinder volume ratio
DEQCSS	double expansion quasi-two-stage compression system with subcooler
DSCS	double stage coupled system
HS	high stage
HSPF	heating seasonal performance factor
IIC	improved intermediate configuration
IHX	internal heat exchanger
INT	intermediate temperature
LS	low stage
P-h	pressure-enthalpy
P_g	pressure of gas cooler (MPa)
QCSS	quasi-two-stage compression system with subcooler
QCSFT	quasi-two-stage compression system with flash tank
QCSSFT	quasi-two-stage compression system with subcooler and flash tank
RIP	relative injection pressure
T_c	condensing temperature (°C)
T_e	evaporating temperature (°C)
T_i	indoor air temperature (°C)
T_o	outdoor air temperature (°C)
$T_{w,in}$	condenser water inlet temperature (°C)
TCSFT	two-stage compression system with flash tank
TCSS	two-stage compression system with subcooler
TEHX	thermoelectric heat exchanger
VCASHP	vapor compression air source heat pump
ZRM	zeotropic refrigerant mixture

2. Advances in single-stage compression system

Single-stage compression system means a VCASHP system in which the refrigerant is compressed once. The related research projects for improving the system performances in cold regions have been mainly concentrated in employing the following components: ejector, new refrigerant and oil injected compressor.

2.1. Ejector

A typical ejector is made up of four different sections, which are: a motive nozzle (named as primary nozzle in some literature), a suction chamber, a mixing chamber (including a convergent chamber and a constant-area throat tube) and a diffuser. In an ejector, the pressure drop of the primary flow can be used to drive the secondary flow as shown in Fig. 1 [15].

To the best of the authors' knowledge, there are two main patterns for the application of ejector to the single-stage compression system. The first is the utilization of ejector as a throttling device with the intention of reducing the throttling loss between the evaporator and condenser. This novel system was first proposed by Gay in 1931 [17]. Its schematic and pressure-enthalpy (P-h) diagram are shown in Fig. 2. Thereafter, a great deal of research focusing on the improvements in system performances, including heating/cooling capacity, energy efficiency ratio and exergy efficiency has been carried out. In general, the improvements would become more and more significant with an increase in the pressure difference between the condenser and evaporator [15,18–25]. However, most of the research objects were focused on the cooling performances of the single-stage compression systems under low temperature conditions. In view of the facts that the low temperature refrigeration conditions are similar to the low temperature heating conditions (they have the same evaporating temperature), and there are no devices to exchange heat with external environment in both conditions with the exception of condenser and evaporator, it can be concluded that the utilization of ejector as throttling device could improve the heating performances of the single-stage compression system in cold regions.

The second one is the utilization of ejector between the compressor and condenser. Chen et al. [26] put forward a novel single-stage compression system with an ejector and a subcooler, as shown in Fig. 3. The heating performances of the system were investigated theoretically and compared with those of a conventional system under specific conditions, with evaporating and condensing temperatures ranging from −15.0 to 10.0 °C and 55.0–60.0 °C, respectively. In addition, a ternary zeotropic refrigerant mixture (ZRM) R417A, which had similar physical properties and better environmental acceptability in comparison to R22, was selected as working fluid. The results showed that the improvements in heating capacity and COP were 15.2–37.3% and 1.6–6.9%, respectively. It was also reported that the design, operation and cost problems of the system should be studied and addressed with more additional theoretical and experimental work.

Besides the aforementioned systems, Zhu and Yu [27] came up with a single-stage compression system with an ejector and a thermoelectric heat exchanger (TEHX). As shown in Fig. 4, the TEHX could transfer heat from cold side to hot side on the basis of the principle of Peltier effect. The simulation results presented that the intermediate temperature (the refrigerant temperature at state point 5) significantly influenced the heating capacity and COP. The higher the intermediate temperature was, the lower the heating capacity was, while the higher the heating COP was. Provided that both the conventional system and the novel system had the same COP, the latter could improve the heating capacity of up to 13% with an appropriate intermediate temperature. In general, the novel system could achieve 16.4–21.7% improvements in both the heating capacity and COP in comparison to the conventional system which employed an auxiliary electric heater, as long as the power inputs of the electric heater and TEHX were equal.

In conclusion, employing an ejector as throttling or jetting device is one of the alternative ways to improve the heating performances of single-stage compression system in cold regions. However, to achieve the optimal system performances under variable conditions, exhaustive studies of the characteristics of the ejector are still required.

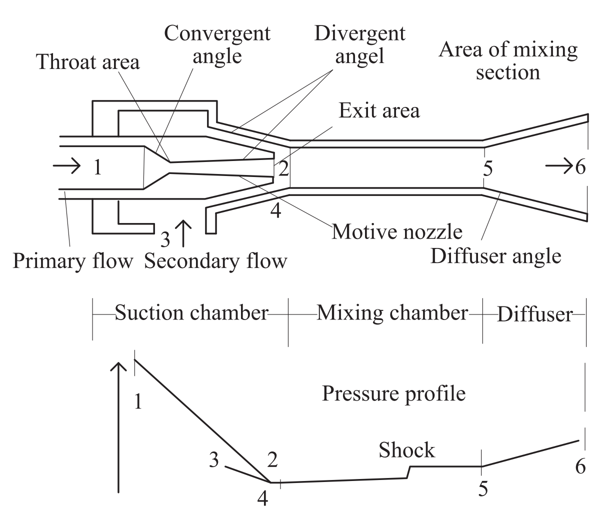

Fig. 1. Ejector geometry and pressure distribution [15].