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A thermodynamic analysis of an auto-cascade heat pump cycle for heating application in cold regions

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ABSTRACT

The coefficient of performance (COP) of air-source heat pumps (ASHP) decreases toward low outdoor temperatures. This paper presents an auto-cascade heat pump system (ACHPS) with the objective to improve the heating performance of ASHP in cold climate. The auto-cascade process is achieved based on the separation of binary zeotropic refrigerant mixture consisting of pure refrigerants with different boiling points. Fluid selection for the ACHPS is carried out to validate the feasibility for potential application. Based on the performance analysis on COP, 15 qualified binary mixtures are obtained. R143a/R600 (0.8/0.2) tops the potential working fluid with a COP of 2.15. The effects of system parameters, such as circulation composition, heat transfer fluid (HTF) temperature glide and temperatures of heat source and sink on COP and exergy efficiency of ACHPS are thereafter investigated. The simulation results show that there exist a maximum COP of 2.15 and a maximum of exergy efficiency of 37.2% at the R143a mass fraction of 0.8 when the ambient temperature and heating temperature are −10 °C and 50 °C, respectively. Finally, by comparison with the single-stage heat pump operating with commercially available refrigerants, the proposed ACHPS shows an advantage of compressor isentropic efficiency. The compression isentropic efficiency of ACHPS could be increased by 25.5% compared to the single stage cycle working with R407c when the ambient temperature is −10 °C.

1. Introduction

Since the last century, primary heating sources for residential buildings in northern China are either the coal-fired stoves or the urban central heating with coal-fired power plants. These heating options, which are the main contributors of $PM_{2.5}$ [1], emitted a large amount of black carbon and will aggravate the air pollution during the heating season. Seeking alternative heating that could meet the requirements of sustainable development becomes significant with an increasing pressure from public. Air-source heat pumps (ASHP) based on the vapor compression cycle would perhaps be the most promising technology to solve this problem. Due to its outstanding energy-saving performance, ASHP has been widely used for residential and commercial heating systems [2,3]. However, as the outdoor air temperature drops, performance of ASHP unit will drastically deteriorate. Such characteristic under cold climates, for example, poor compression condition, unreliable heating capacity and deterioration of coefficient of performance (COP), limits the popularization of ASHP [4].

Considerable attention has been paid to improve the applicability of ASHP in cold regions. Bertsch et al. [5] simulated and tested an air-source two-stage heat pump using R410a as refrigerant at ambient temperature of −30 °C and supply water temperature of 50 °C. Results showed that a COP of 2.1 and second law efficiency of 45% could be achieved. Wang et al. [6] proposed a double-stage coupled heat pumps coupling ASHP and water source heat pump together to improve the heating performance of the heat pump system under cold environment. Field test results indicated that when the ambient temperature and supply water temperature were −6.3 °C and about 43 °C, respectively, the compression ratio of the double stage system decreased 50% and the energy efficiency ratio (EER) was improved by 130% compared to the single stage system. Wu et al. [7] carried out dynamic experiments with a cascade ASHP water heater with phase change material under various operating conditions. The heating COP values in cascade mode ranged from 1.74 to 2.55 when the air temperature was −7 °C. Ma et al. [8,9] proposed an improved heat pump system with a scroll-compressor economizer to increase the heating capacity in severe winter temperatures. Compared with a conventional ASHP system, the energy efficiency of the improved system increased 6.0% when the condensing temperature and evaporating temperature were 45 °C and −15 °C, respectively. Besides, injecting refrigerant in compressors

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Nomenclature

Abbreviation

ACHPS	auto-cascade heat pump system
ASHP	air source heat pump
COM	compressor
CON	condenser
COP_h	coefficient of performance of heating
EER	energy efficiency ratio
EVA	evaporator
GTD	clide temperature difference
HTF	heat transfer fluid
HC	hydrocarbon
HFC	hydrofluorocarbon
MIX	mixer
PFC	perfluorocarbon
$PM_{2.5}$	particle matter with aerodynamic diameter less than 2.5 microns
REC	recuperator
SEP	separator
VAL	throttle valve

Symbols

h	specific enthalpy (kJ/kg)
s	specific entropy (kJ/kg K)
m	mass flow rate (kg/s)
I	irreversibility loss (kW)
P	pressure (kPa)
P_r	pressure ratio
ΔCOP_h	improvement in COP_h (%)
ΔP_r	change in pressure ratio (%)
Q_c	heating capacity (kW)
T	temperature (°C)
W	power consumption (kW)
X	vapor quality
Z_{143a}	mass fraction of R143a
η	efficiency

Subscript

1,2,3 et al.	the state points of the ACHPS system
a	ambient
cond	condenser
evap	evaporator
basic	basic circuit
I	circuit I
II	circuit II
max	maximum
s	isentropic
sw	supply water

to compose a quasi two-stage compression heat pump system has also been recognized as an approach with good prospects. Heo et al. [10] studied the heating performance of a flash tank vapor injection cycle using R410a at various ambient temperatures. The COP and heating capacity of the proposed cycle were enhanced by 10% and 25%, respectively, at the ambient temperature of −15 °C. Xu et al. [11] designed and constructed an ASHP prototype coupled with economized vapor injection scroll compressor and ejector under the condition of the evaporation temperature of −20 °C. The experimental results demonstrated that a heating EER of 2.15 was obtained for the ASHP prototype, which was about 4% higher than that of the system without an ejector. Two-stage heat pumps operate with two compressors, which not only leads to higher installation cost, but also brings troubles in oil management. Furthermore, for both two-stage system and quasi two-stage system, it is difficult to control the intermediate pressure, which is however an important factor determining the cycle performance.

Single stage ASHP water heaters with special design are also proposed by some researches. Chen et al. [12] investigated theoretically the performance of a novel ejector enhanced vapor compression heat pump cycle, for the ranges of evaporating temperature (−15 to 10 °C) and condensing temperature (55–60 °C). It was found that the maximum COP and volumetric heating capacity could be improved by up to 1.6–6.9% and 15.2–37.3% over the conventional heat pump cycle, respectively. Neksa et al. [13] performed an experimental study on transcritical CO_2 heat pump water heaters. It was reported that the prototype system operated with a COP of 3.00 while heating water from 8 °C to 60 °C when the evaporator temperature was reduced to −20 °C. White et al. [14] reported that a maximum COP of about 3.00 was obtained for water output temperature of 90 °C at evaporating temperature of −6.4 °C using a transcritical CO_2 heat pump. CO_2 has proven its potential as an appropriate working fluid for heating in research setting. However, to make effective use of the transcritical cycle, the large pressure difference and uniqueness of gas cooling process must be addressed [15].

In summary, for the development of cold climate ASHP, the two stage compression cycle is a near term technology, while the transcritical CO_2 cycle is a long term technology; ejector as a performance enhancing device could be applied in both the two types of technology. To fill the gap between the near term technology and the long term technology, a media term technology named as auto-cascade heat pump system (ACHPS) is proposed in this paper. This idea originates from auto-cascade refrigerator (ACR) which could produce cryogenic and ultralow cooling over a wide span of temperatures using only one compressor [16]. However, very few reports about ACHPS could be found in the open literature; hence, validating the feasibility of applying ACHPS becomes the primary purpose of the present study. Similar to the ACR system, the ACHPS performance depends markedly on the properties of the working fluid; as a result, screening proper refrigerant mixtures for the ACHPS based on the standard working condition is the first step of the present research. The influences of system parameters on the cycle performance are thereafter investigated. Finally, a performance comparison between the conventional single stage heat pump and the ACHPS is conducted.

2. Thermodynamic analysis on ACHPS

2.1. Cycle description

The ACHPS is comprised of compression, condensation, gas–liquid separation, throttling, evaporation and mixing process. Fig. 1 shows the flow chart of an ACHPS operating with single phase separator. The high temperature and high pressure vapor zeotropic mixture discharged from the compressor (A) partially condenses in the condenser (B). Then it flows into the phase separator (C) where the vapor and liquid phases of the refrigerant mixture are separated; note that the liquid and vapor phases have different compositions according to the lever rule. The vapor being rich in the more volatile component flows out from the top of the separator (C) at point 4, named as circuit I and the liquid which is rich in the less volatile component flows out from the bottom of the separator (C) at point 5, named as circuit II. The vapor refrigerant in circuit I flows into the recuperator (D) and completely condenses before it reaches the throttle valve (E). After pressure dropped in the throttle valve (E), the refrigerant evaporates in the evaporator (F). Meanwhile, the liquid phase refrigerant mixture flows out from the bottom of the phase separator (C). After pressure dropped