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Energy and exergy efficiency analysis of solar driven ejector–compressor heat pump cycle

Gang Yan, Tao Bai, Jianlin Yu*

Department of Refrigeration & Cryogenic Engineering, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

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Abstract

This study presents a solar driven ejector compression heat pump cycle (SEHPC) for air-source heat pump water heater application. The proposed cycle utilizing solar radiation to drive an ejector could effectively lift the suction pressure of the compressor and enhance the system heating performance. The thermodynamic investigations on the performance characteristics of the SEHPC using R134a and R1234yf as the refrigerant are performed with energetic and exegetic methods, and the comparative analyses with the conventional compression heat pump cycle (CHPC) are conducted. The simulation results show that SEHPC system yields a remarkable improvement of heating performance over the CHPC system. It is found that under the operating conditions considered, the system COP, heating capacity and heating exergy output could be improved by 15.3%, 38.1% and 52.8% over the conventional heat pump system, respectively. The largest exergy destruction is generated in the ejector, which could amount to 25.7% of the total system exergy input, followed by condenser and evaporator. The performance characteristics of the proposed cycle show its application potential in air-source heat pump water heater.

Keywords: Thermodynamic analysis; Air-source heat pump water heater; Ejector; Exergy

1. Introduction

Nowadays, the rapid economic development and population growth have led to the increasing energy demand. In this situation, energy saving becomes an important issue and attracts much attention around the world. Air source heat pump water heaters (ASHPWHs) become popular for both residential and commercial hot water applications due to higher energy efficiency compared to a traditional boiler using fossil fuels or an electric water heater (Omer, 2008). However, the performance degradation of the ASHPWHs at low ambient temperature has been the principal issue in practical operations. When the ambient temperature decreases, the system heating capacity and COP would degrade rapidly, and moreover the discharge temperature could reach an unacceptable value which can affect the compressor reliability. And this seriously limits the application of ASHPWHs at cold regions. Therefore, the performance and reliability of the ASHPWHs need to be improved to achieve appropriate heating performances under cold ambient conditions.

Recently, much work has been carried out to resolve the heating performance reduction for the air-source heat pumps (including ASHPWHs) at low ambient temperature, and various methods and techniques have been developed, which involve the two-stage compression (Baek et al., 2014; Agrawal et al., 2007), cascade cycles (Lv et al., 2015;

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* Corresponding author. Tel.: +86 29 82668738; fax: +86 29 82668725.
E-mail address: yujl@mail.xjtu.edu.cn (J. Yu).

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Nomenclature

A_P	area of the solar collector (m^2)
COP	coefficient of performance
c_p	specific heat of water ($kJ\ kg^{-1}\ K^{-1}$)
$\dot{E}x$	exergy flow rate (kW)
F_R	collector heat removal factor
h	specific enthalpy ($kJ\ kg^{-1}$)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
P	pressure (MPa)
Q_h	system heating capacity (kW)
Q_{rad}	solar radiation on the collector/generator (kW)
Q_u	useful energy gain at the solar collector (kW)
Q_{Ev}	refrigeration capacity at evaporator (kW)
q_v	volumetric heating capacity ($kJ\ m^{-3}$)
r_P	pressure lift ratio of ejector
s	specific entropy ($kJ\ kg^{-1}\ K^{-1}$)
G	solar radiation intensity ($W\ m^{-2}$)
T	temperature (°C)
T_a	ambient temperature
u	fluid velocity ($m\ s^{-1}$)
U_L	heat loss coefficient ($W\ m^{-2}\ K^{-1}$)
v	specific volume ($m^3\ kg^{-1}$)
W	motor power (kW)

Greek symbols

φ	exergy destruction ratio
η_{sys}	system exergy efficiency
η_{opt}	optical efficiency
μ	entrainment ratio

Subscripts

Cm	compressor
Cn	condenser
des	exergy destruction
d	diffsuer
Eje	ejector
Ev	evaporator
F	fueled exergy of heat source
Ge	generator
i	inlet
is	isentropic process
m	mixing chamber
n	nozzle
o	outlet
P	produced exergy of heat sink
p	plate collector
pi	pinch point
Tv	throttle valve
tot	total
s	sun, suction chamber
1–10	state points

Jung et al., 2014; Kim et al., 2013), vapor injection technique (Baek et al., 2014; Wang et al., 2015; Xu et al., 2013), ejector cycle (Sarkar, 2012) and solar-assisted heat pump cycle (Kara et al., 2008; Omojaro and Breitkopf, 2013; Ozgener and Hepbasli, 2007). Among these methods, the solar-assisted heat pumps (SAHPs) which combine the solar energy technology and heat pumps technology could effectively improve the heating performance and achieve excellent energy saving effect. And various solar-assisted heat pump systems coupling of solar field and heat pumps have been developed in the past years (Omojaro and Breitkopf, 2013), which could be basically classified into two types. One type is the indirect system (Lerch et al., 2015), such as the conventional solar-assisted heat pumps, in which the solar collector heating loop and a heat pump are separated units and the energy gained in solar collector is transferred to the evaporator by the secondary fluids flowing from solar loop to the refrigerant in the evaporator. Another typical system directly utilizes the solar radiation, such as the direct expansion solar-assisted heat pumps proposed by Sporn and Ambrose first at 1955 (Sporn and Ambrose, 1955), which directly use the solar collector as the evaporator and absorbs the heat transformed from solar radiation to improve the evaporation temperature and the system performance consequently. In the past decades, much work has been devoted to the direct utilization of solar collector as evaporator in heat pump systems due to its large energy saving potential (Kara et al., 2008; Chaturvedi et al., 2014; Torres-Reyes et al., 1998; Chow et al., 2010; Sun et al., 2014). From the open literature, it could be found that the energy saving effect of the solar-assisted air-source heat pumps is mainly resulting from the evaporation temperature improvement and the compression ratio reduction with the assistance from the solar radiation utilization.

Additionally, it should be pointed out that employing ejectors is also a proposing method to improve system performance of vapor compression heat pump cycles (Sarkar, 2012). In the past decades, a great effort has been devoted to theoretical and experimental evaluation of the ejector cycle performance (Chen et al., 2011, 2014; Huang et al., 2014; Li and Groll, 2005; Li et al., 2014; Manjili and Yavari, 2012; Pridasawas and Lundqvist, 2004; Sarkar, 2008; Shuxue and Guoyuan, 2011). An ejector can effectively utilize the expansion energy in the throttling process to lift the compressor suction pressure and thus enables to lower the power input of a compressor. Therefore, the performance of the vapor compression system can be improved with assist of an ejector. For the air-source heat pumps used at low ambient temperatures, the compression