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Theoretical analysis on a new direct expansion solar assisted ejector-compression heat pump cycle for water heater

Jiaheng Chen, Jianlin Yu *

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

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ABSTRACT

This paper proposes a new direct expansion solar assisted ejector-compression heat pump cycle for water heater which can efficiently utilize the solar energy and air energy. The new cycle has two operation modes to be chosen according to the solar radiation intensity. The energetic and exergetic performance of the new cycle is analyzed based on the built simulation model. Under the given conditions, the new cycle outperforms the basic ejector enhanced cycle in the heating coefficient of performance (COP) and heating capacity aspects by up to an average of 13.78% and 20.41%, respectively. The simulation results indicate that the operation mode A is more suitable for the low/zero solar radiation condition, while it's preferable to choose the operation mode B for the high solar radiation condition. The increase of the solar radiation intensity significantly benefits the performance of the new cycle, but decreases the system exergy efficiency. The exergy analysis also reveals that although the exergy destruction percentage of the solar collector increases with increasing the solar radiation intensity, the total exergy destruction percentage of other components decreases. The increase of the solar collector area always contributes to the performance improvement of the new cycle, but it should be kept in a proper range to guarantee the excellent performance and normal operation of the system.

1. Introduction

Heat pump technology is a high efficient and environmental heating technology based on Reverse Carnot cycle theory, which can extract heat from different heat sources, such as air, ground or water source (Chua et al., 2010; Esen et al., 2007). The heat pump system can offer environmentally friendly heating in applications ranging from domestic and commercial buildings to process industries, and thus it has obtained extensive application in recent years. With the demand of energy conservation and emission reduction, continuous efforts have been made to improve the performance of the heat pump, including modifying the heat pump cycle, optimizing system components and utilizing solar energy, etc. (Wang et al., 2017; Zhao et al., 2014; Esen, 2000). Practical studies have proved the potential of heat pumps to drastically reduce the energy consumption and greenhouse gases emission (Berntsson, 2002).

The water heating has been the third major energy consumer in the residential energy consumption (Hepbasli and Kalinci, 2009), and at present most of this demand is met by the natural gas water heater or electric water heater. These conventional water heaters generate heat by directly or indirectly consuming the fossil fuels or electricity, and thus the thermal efficiency is quite low. As an alternative, applying the heat pump technology in the water heater should be a feasible method to save energy consumption and improve the overall energy efficiency of water heater. Actually, since the 1950s, various researches have been performed on the heat pump water heaters. Saikawa and Koyama (2016) theoretically studied the ideal vapor compression cycle for tap water heating and developed the prototype of CO_2 heat pump water heater for residential use. Guo et al. (2011) presented a new approach to predict the energy consumption of a domestic air source heat pump water heater based on grey system theory and obtained satisfactory prediction accuracy. Continuous efforts also were made by researchers to improve the performance of the heat pump water heater. Peng et al. (2016) developed a quasi-steady-state system model of an air source heat pump water heater and indicated that the system using electronic expansion valve achieved the best performance. A dynamic simulation program was developed by Ibrahim et al. (2014) to study the transient characteristics of an air source heat pump water heater and the simulation results revealed that mini-tubes condensers improved the performance.

Recently, the ejector enhanced heat pump cycle (EHPC) also has been a promising way to improve the performance of the water

* Corresponding author.
E-mail address: yujl@mail.xjtu.edu.cn (J. Yu).

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Nomenclature

A	area (m^2)
COP	coefficient of performance
Ex	exergy rate of fluid (W)
F_R	heat removal factor
G	solar radiation intensity ($W \cdot m^{-2}$)
h	specific enthalpy ($kJ \cdot kg^{-1}$)
I	exergy destruction (W)
m	mass flow rate ($kg \cdot s^{-1}$)
n	rotate speed ($r \cdot min^{-1}$)
P	pressure (kPa)
q	vapor quality
Q_h	heating capacity (W)
r_{pj}	pressure lift ratio
s	specific entropy ($kJ\ kg^{-1}\ K^{-1}$)
t	Celsius temperature (°C)
T	Kelvin temperature (K)
U_L	heat loss coefficient
w	velocity ($m\ s^{-1}$)
W	power (W)

Greeks symbol

η	efficiency
φ	percentage
μ	entrainment ratio

Subscripts

0	reference state
1*ndash*8	state points of refrigerant
a	air
c	condensing
com	compressor
con	condenser
d	diffuser
dis	displacement
e	evaporating
ej	ejector
ev	expansion value
eva	evaporator
exh	heat exergy
f	refrigerant in the solar collector
h	heating
i	inlet
id	identical
is	isentropic
m	mixing process
n	nozzle
o	outlet
p	primary flow
pl	plate
rad	radiation
s	secondary flow
sc	solar collector
sys	system
v	volumetric

heater (Sarkar, 2012). The ejector in the EHPC can help recover the expansion work normally wasted in the throttling processes and further improves the cycle performance. Xu et al. (2012) conducted an experimental investigation on a transcritical CO_2 heat pump cycle with an adjustable ejector and indicated that about 20–30% of the maximum possible work rate recovery potential could be recovered by the ejector. Meanwhile, except for using the ejector to recover the expansion work, the performance of the heat pump can be further improved by utilizing the renewable and clean solar resource. Actually, various solar-assisted heat pump water heaters (SHPWHs) have been studied by researchers, which can be mainly classified as two types: the indirect expansion SHPWH (IDX-SHPWH) and the direct expansion SHPWH (DX-SHPWH). With the advantage of less system units and lower initial investment, the DX-SHPWH system attracts more and more attention in recent years (Facão and Carvalho, 2014; Omojaro and Breitkopf, 2013). Nevertheless, the DX-SHPWH also has a significant drawback that the solar collector-evaporator is mainly designed to absorb the solar radiation as a solar collector but not extract heat from the air resource as an evaporator. And thus, under the low/zero solar radiation condition, the DX-SHPWH may not absorb enough heat from the air resource as the complement to the solar energy, and then the performance will deteriorate seriously. The experiment conducted by Sun et al. (2015) indicated that the DX-SHPWH showed poorer performance compared with the conventional air source heat pump water heater in night conditions because of the poor convectional heat exchanging performance of the solar collector/evaporator and the radiative heat loss to the night sky. Aimed to efficiently utilizing both the solar energy and air energy, a new direct expansion solar assisted ejector-compression heat pump cycle (DX-SEHPC) for water heater is presented in this study. In the DX-SEHPC, individual evaporator and solar collector are adopted and connected by an ejector. Under the high solar radiation condition, the solar energy will be the major energy resource and help the system achieve higher efficiency compared with the basic EHPC. Under the low/zero solar radiation condition, the air energy will be the major energy resource, which can help the DX-SEHPC still obtain relatively high performance. In a word, with the help of the individual evaporator and solar collector, the DX-SHPWH can dramatically improve the water heater performance by fully utilizing the solar energy, and avoid the drawback of the convenient DX-SHPWH mentioned above. And thus, the DX-SEHPC can always maintain relatively high performance under all the operation conditions and significantly decrease the energy consumption on water heating. The energetic and exergetic characteristics of the DX-SEHPC will be investigated by simulation method, and its potential performance enhancement will be also evaluated by comparing to the EHPC and basic heat pump cycle. Furthermore, the effect of the key operation parameters of the DX-SEHPC on its performance will be also evaluated and it will provide a guide for the application of the DX-SEHPC. The purpose of the present study is to explore the possibility of adopting the DX-SEHPC to improve the efficiency of the water heater and save the electricity consumption.

2. Cycle description

A schematic diagram of a basic ejector enhanced heat pump cycle (EHPC) for water heater is illustrated in Fig. 1. The EHPC mainly consists of six basic components, i.e. a compressor, a condenser, an ejector, a phase separator, an electronic expansion valve (EEV), and an evaporator. The ejector can help the EHPC lift the compressor suction pressure by recovering part of the expansion work and achieve better performance. To further utilize the solar energy, a new direct expansion solar assisted ejector-