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Research Paper

Thermodynamic analysis and parameter estimation of a high-temperature industrial heat pump using a new binary mixture

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HIGHLIGHTS

- An optimized high-temperature heat pump using MF-1 was designed and built.
- A function for MF-1 was defined to achieve accurate control of superheat.
- Experimental investigations of the HTHP were carried out at high temperature level.
- Energy and exergy analyses were conducted to evaluate the performance of the HTHP system.
- A parameter estimation method was developed to predict the performance of the HTHP system.

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ABSTRACT

An optimized high-temperature heat pump (HTHP) adopting a new binary mixture named MF-1 as working fluid was designed and built for industrial waste heat recovery. A new function for MF-1 was defined to achieve accurate control of superheat in the expansion valve. Experimental investigations of this heat pump were carried out at high temperature level of 40–60 °C on evaporation unit and 70–110 °C on condensing unit. Energy and exergy analyses provided insight on the quantity and quality of energy conversion of the HTHP system in different running conditions. Based on the energy and exergy analyses, this study investigated how the heat-source temperature and heat-sink temperature have effect on the performance of each component and the HTHP system. Additionally, a parameter estimation method based on the regression analysis was developed to evaluate the performance of the HTHP system. A comparison of the experimental and simulated results was made to demonstrate the reliability of the presented method. The simulated results indicated that the HTHP system using MF-1 can produce heat at the temperature of 120 °C with good performance.

1. Introduction

The ever-increasing global energy demands, together with the negative environmental impact, have reinforced the efforts to improve energy efficiency for all energy systems [1,2]. A solution to improve energy efficiency involves a reduction of energy consumption of industrial processes by utilizing heat recovery technologies.

Many industrial processes release a large amount of waste heat at below 100 °C and the substantial quantities of waste heat energy remain unrecovered due to technical and economic barriers [3]. In addition, some industrial processes requires at higher range of temperature, especially 100–130 °C [4,5]. Therefore, attempts to introduce high-temperature heat pumps have attracted significant attention to recover the waste heat in industrial processes, especially at high temperature level [6,7].

Many studies have developed high-temperature heat pumps to increase the temperature of the heat source to a higher and more useful temperature. Boblin et al. experimentally validated the feasibility and reliability of heat pumps adopted ECO3 (GWP 980/100 yr) providing heat up to 120 °C [8]. Sho et al. experimentally and numerically investigated the heat pump performance using R1234ze(E) and R1234ze(Z), the simulation results indicated the heat pump adopting R1234ze(Z) as refrigerant has high COP (coefficient of performance) at a condensation temperature of 105 and 125 °C [9]. Marwan et al. developed an industrial high-temperature heat pump using R718 for waste heat recovery to produce heat at the temperature above 100 °C [10,11]. Yu et al. evaluated the performance of a HTHP using scroll compressors with a near-azeotropic refrigerant mixture named BY-4. The system with high COP can produce heat

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Nomenclature

$c_{p,w}$	water specific heat (J kg^{-1} K^{-1})
Diff	relative difference
$Ex_{des.eva}$	exergy destruction in the evaporator (kW)
$Ex_{des.com}$	exergy destruction in the compressor (kW)
$Ex_{des.con}$	exergy destruction in the condenser (kW)
$Ex_{des.exp}$	exergy destruction in the expansion valve (kW)
$Ex_{des.sys}$	exergy destruction in the high-temperature heat pump system (kW)
ex	specific exergy (kJ kg^{-1})
$ex_{e,w,in}$	specific exergy of the inlet water in the evaporator (kJ kg^{-1})
$ex_{e,w,out}$	specific exergy of the outlet water in the evaporator (kJ kg^{-1})
ex_f	specific exergy of working fluid (kJ kg^{-1})
$ex_{c,w,in}$	specific exergy of the inlet water in the condenser (kJ kg^{-1})
$ex_{c,w,out}$	specific exergy of the outlet water in the condenser (kJ kg^{-1})
h	specific enthalpy (kJ kg^{-1})
I_{eva}	exergy destruction rate in the evaporator (%)
I_{com}	exergy destructionrate in the compressor (%)
I_{con}	exergy destructionrate in the condenser (%)
I_{exp}	exergy destructionrate in the expansion valve (%)
$m_{e,w}$	water mass flow rate in the heat source (kg s^{-1})
m_f	mass flow rate of working fluid (kg s^{-1})
p	pressure (MPa)
p_c	critical pressure (MPa)
p_{dis}	discharge pressure (MPa)
p_{ra}	compression ratio (MPa/MPa)
p_{suc}	suction pressure (MPa)
P_{in}	power input (kW)
P_{th}	theoretical power input (kW)
Q_{evp}	heat transfer rate in the evaporator (kW)
Q_{con}	heat transfer rate in the condenser (kW)
R^2	coefficient of determination
s	entropy (kJ kg^{-1} K^{-1})
T	temperature (°C)
T_b	boiling temperature (°C)
T_c	critical temperature (°C)
t_{dis}	discharge temperature (°C)
$t_{e,w,in}$	inlet water temperature of evaporator (°C)
$t_{e,w,out}$	outlet water temperature of evaporator (°C)
t_e	evaporation temperature (°C)
$t_{c,w,in}$	inlet water temperature of condenser (°C)
$t_{c,w,out}$	outlet water temperature of condenser (°C)
t_c	condensing temperature (°C)
t_{sup}	superheat degree (°C)
Greek	
η_{eva}	exergy efficiency in the evaporator (%)
η_{com}	exergy efficiency in the compressor (%)
η_{con}	exergy efficiency in the condenser (%)
η_{sys}	exergy efficiency in the high-temperature heat pump system (%)
Abbreviations	
COP	coefficient of performance
GWP	global warming potential
HTHP	high-temperature heat pump
ODP	ozone depleting potential
Numbers	
0	reference point
1–4	state point

at the temperature of 110 °C [12]. However, high-temperature heat pumps applied in different industries are often limited to the heat production at a temperature of 100 °C because of immature technology and economic barriers caused by poor performance. Therefore, further research should pay more attention to make the HTHP more reliable and improve heat pump performance that is helpful to cover the economic barriers.

The objective of the present work is to develop a high-temperature industrial heat pump system by using a new binary mixture named MF-1 as working fluid. The function of the saturation temperature and saturation pressure for MF-1 was defined to achieve an accurate control of superheat in connection with MF-1. The energy and exergy performance of the HTHP system using MF-1 was investigated and evaluated to analyse the quantity and quality of energy conversion. Additionally, a parameter estimation method based on the regression analysis was developed to evaluate the performance of the HTHP system. A comparison of the calculated result based on the experimental data and simulated result was made to demonstrate the reliability of the presented method. The potential of the HTHP system using MF-1 to produce higher output temperature was also assessed by the proposed method.

2. Experimental system of an optimized HTHP

2.1. Experimental system description

An experimental system was designed and built for testing the performance of a HTHP system on a national heat-pump test bench which was located in Weifang, Shandong province, China. A binary mixture named MF-1 was used as the working fluid in the HTHP system. It is environment-friendly, non-toxic and non-flammable. Table 1 lists some properties of MF-1 [13]. Fig. 1 shows the schematic diagram of this experimental system. As shown in Fig. 1, the experimental system included two loops: the refrigerant loop and the water loop.

The refrigerant loop mainly includes an evaporator, a condenser, a semi-hermetic screw compressor with lubricating oil of B320SH, an electronic expansion valve. The component parameters of the refrigerant loop are listed in Table 2. The evaporator is the dry-type tube-shell heat exchanger considering the return oil problem of the compressor. Each heat pipe unit with internal thread was made of red copper with an outside diameter of 12 mm, length of 2400 mm and thickness of 0.75 mm. A screw compressor was designed to solve the problem in the HTHP where a large capacity was demanded. The screw clearance of the compressor was increased taking the high-temperature running condition into account. The condenser is the full-liquid tube-shell heat exchanger. Each heat pipe unit with internal and external threads was made of red copper with an outside diameter of 16 mm, length of 2400 mm and thickness of 1.2 mm. The electronic expansion valve is ETS250 with an electronic superheat controller EKC312. Before heat pump system can be started, refrigerant setting must be done. 28 traditional refrigerants can be selected in EKC312 that has defined the functions of saturation temperature and saturation pressure of refrigerant, but the function of MF-1 as a new high-temperature mixture refrigerant was not defined in the EKC312. Therefore, some optimizations of the electronic expansion valve