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Experimental performance of high temperature heat pump with near-azeotropic refrigerant mixture

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ABSTRACT

A near-azeotropic refrigerant mixture named BY-4 was developed for a high temperature heat pump in the paper. The study tested the experimental performance of single-stage high temperature heat pump with BY-4 as work fluid. Under the experimental conditions of the inlet water temperature of evaporator at 50–70 °C, the outlet water temperature of condenser could reach 80–110 °C. The maximum pressure of the system was only 1.73 MPa even when the output temperature rose up to 110 °C. The experimental results showed that the COP (coefficient of performance) of heat pump was higher than 3.5 when the temperature difference between the condenser outlet water and the evaporator inlet water was less than 30 °C. Thus, BY-4 was recommended as working fluid for high temperature heat pump with a single-stage cycle due to its good comprehensive properties and excellent cycle performance.

1. Introduction

In various industrial production processes, a large quantity of waste heat is discharged into the environment. The emission of industrial waste heat with relatively high grade energy (30–85 °C) is relatively concentrated. However there is short of appropriate technology to recover and utilize them, which results in energy waste and thermal pollution [1]. Fossil fuel as traditional energy resource is commonly used in the thermal process, such as the building heating, food drying, rubber production and so on. The combustion temperature of fossil fuel is above 1000 °C, so they should be mainly used as high grade energy. But actually, they are often used as low grade energy about 60–150 °C [2,3]. It means that the use of conventional energy sources is irrational in many cases, and a large amount of harmful gas and dust is emitted into air. The high temperature heat pump has been shown to be a higher energy efficiency and environmentally friendly in space heating, industrial heating and utilization of waste heat. Thus, it is gaining increasing popularity in the last few years in industrial heating and heat recovery.

A suitable high-temperature working fluid with good performance is the key in the practical high temperature heat pump technology. Many studies have been conducted on the performance of the working fluid to give the output temperature in the range of 70–120 °C. Devotta et al. [4] carried out the theoretical cycle analysis on the performances of pure refrigerants in the condensing temperature range from 80 °C to 120 °C. The result showed that the HFC143 offered the best COP values. Li et al. [5] took the R22/R141b as work fluid and the heat output temperature reached 80 °C. Liu Nanxi et al. [6] tested the performance of a heat pump with R124/R142b/R600a and provided the condenser outlet water of 90 °C with a high COP. Zhang et al. [7] compared the cycle performance of R245fa/R152a with different composition. Under the experimental conditions of the condenser outlet water temperatures of 90 °C and the evaporator inlet water temperature of 45 °C, the COP of M1B (mass fraction of 37% R152a and 63% R245fa) was above 3.4. However, little research on the experimental performance of the high temperature heat pump in the heat output temperature above 100 °C has been done before.

The present study was motivated by a desire to explore a single-stage high temperature heat pump, which could give a heat output temperature above 100 °C. A high temperature heat pump with BY-4 as working fluid was built and tested in different operating condition. Experimental results showed that the high temperature heat pump could provide a heat output temperature at about 80–110 °C when the inlet water temperature of evaporator was

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Nomenclature

COP	coefficient of performance
p	pressure (MPa)
P_c	critical pressure
P_{in}	input power (kW)
Q	heat capacity (kW)
Q_v	heating capacity per unit volume (kJ/m^3)
m_w	water flow (m^3/h)
t	temperature (°C)
T_c	critical temperature (K)
T_b	normal boiling (K)
T_k	condensing temperature (K)
T_0	evaporating temperature (K)
S	Entropy (kJ/K)

Greek symbols

μ	heating efficiency

Subscripts

c	condense; condenser
disch	discharge
e	evaporate; evaporator
in	inlet
out	outlet
w	water

Superscripts

′	first derivative
″	second derivative

50–70 °C. The maximum pressure of the system was under 1.8 MPa and COP was above 3.5, even though the heat output temperature reached and held on 110 °C.

2. Properties of working fluid

2.1. Selection criteria

Refrigerant performance has been a hot topic since the development of the heat pump technology. Previous studies focus on the balanced development of thermodynamic properties, safety, economy and friendly environment [8,9]. A desired refrigerant applied to the high temperature heat pump mainly includes some aspects as follows.

(1) Proper working pressure: the condensation pressure under high temperature condition is lower than 2.4 MPa [10]; the compression ratio is less than 8 with a single-stage cycle;
(2) Environment-friendly, nontoxic and nonflammable [11];
(3) A high COP under a high heat output temperature;
(4) Good miscibility of lubricants.

2.2. Analysis of thermo-physical properties

A near-azeotropic mixture (BY-4) was proposed for the high temperature heat pump. Our study investigated the performance of BY-4 and other seven kinds of working fluids under typical operating conditions of high temperature heat pump. Table 1 lists the basic thermo-physical and environmental properties of these considered working fluids. The REFPROP 8.0-NIST Reference Fluid Properties Database was applied to calculate the basic thermo-physical properties [12]. The selection of BY-4 was based on a profound study of the thermo-physical and physicochemical properties of the possible pure working fluids. It is a binary near-azeotropic mixture, which is environmentally friendly, non-toxic and non-flammable.

A comprehensive investigation was made to analyze working fluids used to the high temperature heat pump by studying the thermo-physical and physicochemical properties of the possible high temperature working fluids. The typical operating conditions of high temperature heat pump used to compare and analyze the theoretic performance of investigated working fluids are: evaporating temperature of 60 °C, condensing temperature of 90–110 °C, superheating of 5 °C and subcooling of 5 °C. The compress process is isentropic, evaporation and condensation processes are isobaric and adiabatic, throttling process is isoenthalpic. Since the non-azeotropic refrigerant mixture has a glide temperature, the mean values of bubble point and dew point at condensing pressure and evaporating pressure are specified as the condensing temperature and evaporating temperature, respectively.

COP and power consumption of compressor variation with condensing temperature at evaporating temperature of 60 °C are shown in Fig. 1a and b. The COP decreases with condensing temperature increases, but the tendency is opposite to power consumption of compressor. HCFC123, BY-4, HFC245ca and HFC245fa have the higher COP and power consumption values. HFC236fa gives lower COP and power consumption values. The power consumption value of CFC114 is the lowest among all working fluids. Other working fluids have moderate performance.

Fig. 1c shows condensing pressure variations with condensing temperature. Condensing pressure is a critical performance parameter, because it impacts on system cycle performance remarkably and compressor performance and efficiency especially to condensing temperature above100 °C. As shown in Fig. 1c, when condensing temperature is 110 °C, the condensing pressures of HCFC123 and HFC245ca are only about 1 MPa. The condensing pressure of HCFC124 is higher than 2.4 MPa in condensing temperature above 100 °C. Furthermore, HFC236fa has the higher condensing pressure (about 2.4 MPa) in condensing temperature of 100 °C. Therefore, they are unsuitable to been applied in the high temperature heat pump.

Fig. 1d and e shows latent heat and heating capacity per unit volume variation with temperature. Latent heat and heating capacity per unit volume has an influence on heat pump unit size, compressor power consumption and so on. BY-4 has the higher values of latent heat and heating capacity per unit volume. It is useful to equipment selection and is also contributes to better performance.

Table 1
The basic thermal properties and environmental properties [13].

Substance	Molar mass (kg/kmol)	T_b (°C)	T_c (°C)	P_c (MPa)	ODP	GWP(100 yr)
HFC236ea	152.04	6.19	139.29	3.502	0	710
HFC236fa	152.04	−1.4	124.9	3.2	0	9400
HFC245ca	134.05	25.13	174.42	3.925	0	560
HFC245fa	134.05	15.14	154.01	3.65	0	950
HCFC123	152.93	27.823	183.68	3.66	0.012	120
HCFC124	136.48	−11.963	122.28	3.62	0.026	620
CFC114	170.92	3.6	145.7	3.26	0.85	9800
BY-4	124.5	11.9	150.2	4.44	0	755