PERGAMON

Energy Conversion and Management 43 (2002) 2033–2040

ENERGY CONVERSION & MANAGEMENT

www.elsevier.com/locate/enconman

High temperature hot water heat pump with non-azeotropic refrigerant mixture HCFC-22/HCFC-141b

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Received 27 March 2001; accepted 14 August 2001

Abstract

A water-to-water high temperature heat pump was studied experimentally. The performance of the system was characterized by refrigerant compositions, compressor RPM and water temperature change. For the experimental conditions of the inlet water temperature of evaporator of 40 °C and the inlet and outlet water temperatures of the condenser of 70 and 80 °C, respectively, the experiment shows that the coefficient of performance is maximum when the molar component of R22 is about 75%. It is shown that the maximum pressure of the system is under 2.5 MPa after taking R22/R141b as working fluids, even though the highest cooling water temperatures is about 80 °C.

Keywords: Mixtures; Heat pump; Non-azeotropic refrigerants

1. Introduction

A lot of low grade thermal energy, like solar energy and low temperature geothermal energy, has been neglected for possible application. Such energy as industrial waste heat (discharged by chemical factories, electric power plants and various types of engines) will cause thermal pollution if it is discharged directly to the surroundings. Thermal energy with temperatures between 50 and 80 °C can be used for heating, drying and even as the heat source for absorption or adsorption refrigeration, but there are still no perfect methods to make good use of heat with a temperature

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0196-8904/02/$ - see front matter
PII: S0196-8904(01)00150-9

Nomenclature

COP	coefficient of performance
F	frequency (Hz)
P	pressure (MPa)
Q_H	heating capacity (kW)
T	temperature of working fluid (°C)
X	molar composition
P_E	evaporating pressure (MPa)
P_C	condensing pressure (MPa)
P_{suc}	suction pressure (MPa)
P_{exh}	exhaust pressure (MPa)
$T_{C,in}$	temperature of working fluid at inlet of condenser (°C)
$T_{E,in}$	temperature of working fluid at inlet of evaporator (°C)
$TH_{C,in}$	water temperature at inlet of condenser
$TH_{C,out}$	water temperature at outlet of condenser
ΔT	temperature change of the heat transfer fluid (water) (°C)

Subscripts

C	condenser
E	evaporator
exh	exhaust
suc	suction
H	heating
in	inlet
out	outlet

between 30 and 50 °C. A high temperature heat pump might be a good means to use such heat properly. High temperature heat pumps have received attention and research for a long period. For example, Akio Migara tested a heat pump with R22/R114 in 1993 (the inlet and outlet temperatures of the condenser are, respectively, 40 and 60 °C, and those temperatures of the evaporator are, respectively, 30 and 10 °C) [1]. Leon Liebenberg took R22/R142b as working fluids of a high temperature heat pump to provide 60 °C hot water in 1996 [2]. Kazo Nakatani et al. compared the performances of heat pumps filled with R22/134a, R22/R152a, R22/R142b, R22/R123 at the condensing temperature of about 60 °C [3]. Vance Payne also measured the refrigerating and heating capacity and also the performance of a heat pump with different fluids R32/R290, R32/R152a, R290/R600a in 1996 [4]. It is critical that the working fluid is one of the most important aspects in the practical application of high temperature heat pumps because common refrigerants, such as R22, are no longer proper for a high temperature condition. Generally, mixtures are thought to be more suitable for high temperature heat pumps, since mixtures may improve the performance of heat pumps because of their special low pressure character at high temperature and may increase the system's COP for their unique temperature gliding in equilibrium. The main technological difficulties are how to deal with the mixtures' leakages and how to improve the mixtures' heat transfers [5].

In order to make good use of the low grade heat (30–50 °C) and to provide centralized heat for industry or buildings, a high temperature hot water heat pump with non-azeotropic refrigerant mixtures R22/R141b as working fluid was tested in this study. This paper shows the experimental results of such a heat pump with a heat output at about 80 °C. The typical experimental conditions are the inlet temperature of the evaporator is 40 °C and the inlet and outlet temperatures of the condenser are 70 and 80 °C, respectively. In the same conditions, the compression ratio will be less than 8 and the maximum pressure will be over 2.5 MPa if R22 is used for comparison.

2. Experimental equipment

The hot water heat pump system was designed as shown in Fig. 1, in which a hermetic compressor for R22 produced by TACHON Company (TACHON AE5031, France), was used. Since there is a big difference between the normal boiling temperature of R22 and R141b (shown in Table 1), a vapor–liquid separator is used to prevent the compressor being hit by liquid. On the other side, the separator may make it more difficult to bring oil back to the compressor, therefore, an additional tube is added at the bottom of the separator.

In order to compensate the decrease of heat transfer effect of the mixture, the evaporator and condenser are both of copper double pipes, and forced convective heat transfer is taken. The inside tube is spirally grooved, of which the inner and outer diameters are 16 and 19 mm, respectively. R22/R141b flows inside the tube, while the annular area around the tubes is filled with water. Five pairs of thermocouples plus two pressure sensors are fixed on the condenser to

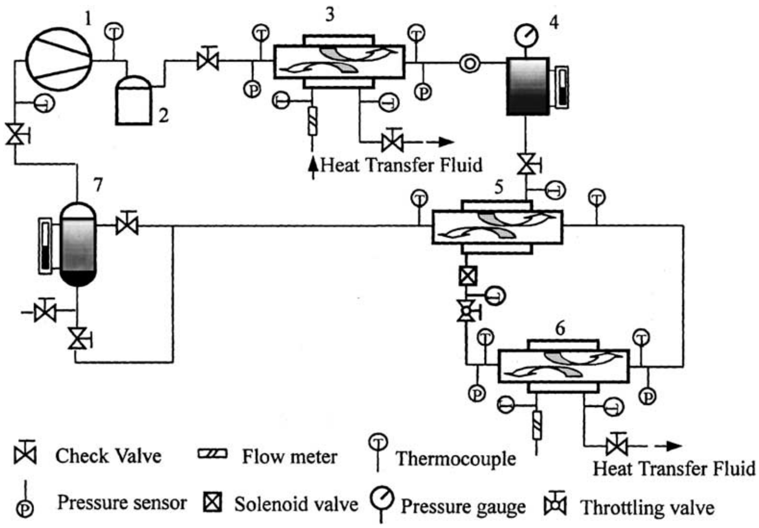

Fig. 1. Schematic of the experimental system. 1—compressor, 2—oil separator, 3—condenser, 4—liquid container, 5—heat exchanger, 6—evaporator, 7—vapor–liquid separator.

Table 1
Properties of R22 and R141b

	Properties				
	Normal boiling point (°C)	Critical temperature (°C)	Molecule weight (kg/kmol)	Saturation pressure, 15 °C (MPa)	Flammability
R22[a]	−40.84	96.00	86.48	0.791	No
R141b[b]	32.05	204.17	116.94	0.054	No

[a] Data from Ref. [6].
[b] Data from Ref. [7].

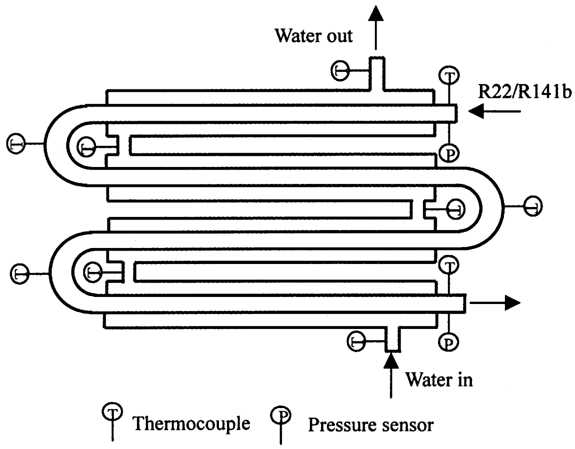

Fig. 2. The configuration of the condenser and also the arrangement of the various sensors.

Table 2
Properties of the sensors

	Variables						
	Temperature	Pressure	Flow rate	Power	Frequency	Composition	Data logger
Device	Thermocouple (USA)	Pressure transducer (China)	Turbine flowmeter and cymometer (China)	Electric variables measuring device (China)	Transducer (Japan)	Gas chromatograph (USA)	Data logger (USA)
Type	T (copper–constantan)	1151 (capacitive)	Lw-10Y	8831E	VS616P5 (YASKAWA)	HP6890A	HP 3054A
Accuracy	<1%	±0.25% of calibrated range	±0.5% of calibrated range	±1 W	±0.1 Hz	$\pm 10^4$ mV ml/mg	<±0.1%

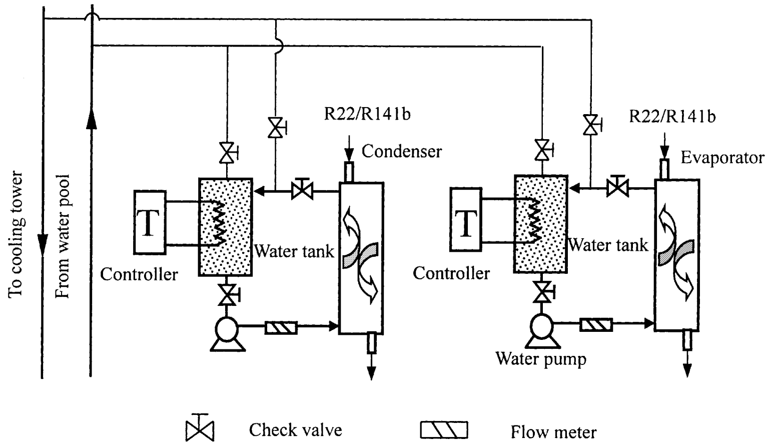

Fig. 3. The arrangement of water system.

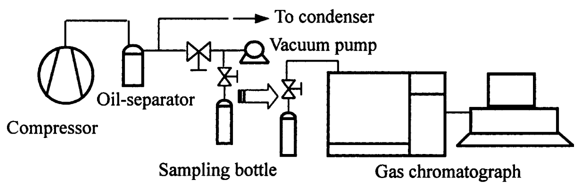

Fig. 4. Sampling and analyzing system.

examine the heat transfer, as shown in Fig. 2. Not only temperature and pressure but also water flow rate, power of the compressor, frequency and composition of the mixture are measured in the experiments. The sensors' properties are listed in Table 2.

The water system is designed as shown in Fig. 3, which has temperature controllers to ensure that the inlet water temperatures of the evaporator and condenser are, respectively, 40 and 70 °C.

When the state of the heat pump gets steady, the data logger is then started to get and save data from the sensors. In order to analyze the compositions, two bottles of working fluid are sampled from the system at the same sampling point after the bottles and all tubes are well evacuated. The discrepancy between the two samples when analyzed by a gas chromatograph should be no more than 1%. In order to prevent mixtures condensing when it is sampled and analyzed, the valves, bottles and tubes have to be heated. The scheme of sampling and analyzing of the mixture is shown in Fig. 4.

3. Experimental results

The performance of the heat pump was tested with different contents of R22, while the inlet water temperature of the evaporator and the inlet and outlet water temperatures of the condenser are controlled at fixed temperatures. The results are shown in Table 3.

Table 3
Experimental results with different compositions

	F (Hz)	X_{R22}	P_E (MPa)	P_C (MPa)	$T_{C,in}$ (°C)	$T_{E,in}$ (°C)	$TH_{E,in}$ (°C)	$TH_{C,in}$ (°C)	$TH_{C,out}$ (°C)	Q_H (kW)	COP
S9051	60	0.29	0.2174	0.7654	101.69	21.95	41.51	70.67	79.66	2.317	1.67
S8142	60	0.41	0.2458	0.8283	99.85	22.33	41.81	70.46	80.08	2.119	1.37
S8222	60	0.58	0.3956	1.3746	112.24	22.10	40.10	69.54	80.36	4.263	1.99
S8312	60	0.73	0.4297	1.5258	111.09	21.16	41.87	69.15	80.06	5.155	2.21
S9013	60	0.75	0.4732	1.8199	118.09	20.43	41.21	69.56	80.81	6.758	2.57
S9042	60	0.78	0.6304	2.0257	113.19	21.23	40.67	70.11	80.52	5.832	2.12

Table 4
Experimental results of Ref. [3]

	F (Hz)	X_{R22}	Q_H (kW)	P_{suc} (MPa)	P_{exh} (MPa)	COP
R22/R134a	93	50/50	2.41	0.42	2.55	2.13
R22/152a	101	62/38	2.40	0.37	2.31	2.14
R22/R142b	95	75/25	2.41	0.40	2.45	2.13
R22/R123	95	87/13	2.39	0.42	2.55	2.03
R22/R114	95	70/30	2.39	0.41	2.47	2.01
R22	79	100	2.39	0.53	2.94	2.03

It is obvious that the heat pump has a maximum heating COP of 2.57 when the mole fraction of R22 is about 75%. It is also found that a smaller fraction of R22 generally results in less heating capacity, which may be a result of R141b having less specific volume heating capacity than R22, but the compressor was currently designed for R22. Some other mixtures were charged into the heat pump system in Ref. [3] and those experimental results are listed in Table 4, where the condensing temperature was about 70 °C but the evaporating temperature was not indicated. Compared with this work, the COP is similar, while Ref. [3] has a relative high exhaust pressure.

In order to analyze the influence of frequency on the performance of the heat pump, experiments with three different frequencies, 40, 50 and 60 Hz, have been done when the compositions of the mixture are fixed. The results are listed in Table 5. It is found that frequency has

Table 5
Experimental results with different frequency

	No	F (Hz)	X_{R22}	P_E (MPa)	P_C (MPa)	$T_{C,in}$ (°C)	$T_{E,in}$ (°C)	$TH_{E,in}$ (°C)	$TH_{C,in}$ (°C)	$TH_{C,out}$ (°C)	Q_H (kW)	COP
S816	1	40	0.61	0.3988	1.1591	94.75	21.44	41.21	69.85	79.65	1.683	1.78
	2	50	0.60	0.3833	1.1781	99.25	22.12	38.23	69.06	79.51	2.943	1.81
	3	60	0.59	0.3588	1.1668	102.56	21.72	37.86	69.71	79.96	4.038	1.89
S831	1	40	0.74	0.5128	1.5627	108.22	22.61	42.62	69.73	79.86	5.012	2.21
	2	50	0.74	0.5504	1.5629	111.68	20.17	40.28	70.31	79.65	5.134	2.04
	3	60	0.73	0.5506	1.5258	111.09	21.17	41.87	69.15	80.06	5.155	2.21
S901	1	40	0.75	0.5608	1.8477	108.42	20.02	41.15	70.43	80.25	4.289	2.13
	2	50	0.75	0.6194	1.9580	114.50	20.91	39.48	70.02	79.35	5.751	2.42
	3	60	0.75	0.4988	1.8199	118.09	20.43	41.21	69.56	80.81	6.758	2.57

Table 6
Experimental results with different heat fluent (water) temperature difference (ΔT)

	F (Hz)	X_{R22}	P_E (MPa)	P_C (MPa)	$T_{C,in}$ (°C)	$T_{E,in}$ (°C)	$TH_{E,in}$ (°C)	ΔT_E (°C)	$TH_{C,in}$ (°C)	ΔT_C (°C)	Q_H (kW)	COP
S9044	50	0.79	0.6124	1.9279	112.97	20.75	40.54	14.59	69.56	10.10	5.011	1.87
S9043	50	0.78	0.6303	2.0257	113.19	21.24	39.38	9.52	70.61	9.91	5.282	1.92
S9041	50	0.74	0.5602	1.9829	116.20	20.47	39.88	6.05	69.99	9.84	5.356	2.17
S9042	50	0.78	0.6038	1.9194	113.63	20.26	39.78	6.32	65.79	14.15	6.369	2.38

a little influence on the compositions, and the COP increases very unclearly when frequency increases.

Although mixtures have worse heat transfer effects compared with pure refrigerants [5], refrigerant mixtures can improve the performance of heat pumps due to their temperature gliding characteristic, which will decrease the heat transfer temperature difference. The performance of the heat pump was tested when the compositions were fixed but the heat transfer fluid's temperature glide is different. The outlet water temperature of the condenser is 80 °C, and the inlet water temperature of the evaporator is 40 °C. The experimental results are shown in Table 6.

Therefore, if only the water temperature difference in the evaporator (ΔT_e) increases while the other variables are kept unchanged, the heating capacity will decrease. However, if the outlet water temperature of the condenser is kept at 80 °C, the heating capacity increases with the water temperature difference ΔT_c in the condenser.

4. Conclusions

The above experimental research has shown that: The pressure character of the high temperature heat pump is improved after taking R22/R141b as working fluid. The maximum pressure is less than 2.5 MPa, and the compression ratio is less than 8, even in high temperature working conditions that can satisfy the compressor's limits. The mixture is applied in a heat pump, and the system has been operated steadily over a long time. If the inlet and outlet water temperature of the condenser are, respectively, 70 and 80 °C and the inlet water temperature of the evaporator is 40 °C, the heat pump has the maximum COP of 2.57 when the mole fraction of R22 is about 75%. In conclusion, this type of heat pump has a great potential for application if geothermal heat or waste heat is used as a heat source.

On this working condition, it seems that the frequency of the compressor has little influence on the COP of the heat pump, and so do the compositions of the working fluid (R22/R141b). If only the water temperature difference in the evaporator ΔT_e increases, the heating capacity will decrease. However, the heating capacity increases with the water temperature difference ΔT_c in the condenser if the outlet water temperature of the condenser is fixed.

Acknowledgements

This work was supported by the State Key Fundamental Research Program of China under the contract no. G2000026309.

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