ELSEVIER

Energy Conversion and Management 45 (2004) 1369–1378

ENERGY CONVERSION & MANAGEMENT

www.elsevier.com/locate/enconman

Experimental evaluation of a non-azeotropic working fluid for geothermal heat pump system

L. Zhao *

Department of Thermal Energy and Refrigeration Engineering, School of Mechanical Engineering, Tianjin University, No. 92 Weijin Road, Tianjin 300072, PR China

Received 27 May 2003; accepted 1 September 2003

Abstract

Geothermal energy resources are found in many countries. A reasonable and efficient utilization of these resources has been a worldwide concern. The application of geothermal heat pump systems (GHPS) can help increase the efficiency of using geothermal energy and reduce the thermal pollution to the earth surface. However, this is only possible with a proper working fluid. In this paper, a non-azeotropic working fluid (R290/R600a/R123) is presented for a GHPS where geothermal water at 40–45 °C and heating network water at 70–80 °C serve as the low and high temperature heat sources. Experimental results show that the coefficient of performance (COP) of a GHPS using the working fluid is above 3.5 with the condensation temperature above 80 °C and the condensation pressure below 18 bar, while the temperature of the geothermal water is reduced from 40–46 °C to 31–36 °C.

Keywords: GHPS; Non-azeotropic working fluid; Experimental study

1. Introduction

Geothermal energy resources are found in many countries, but most of them belong to the category of intermediate or low temperature below 100 °C that is often used in winter heating [1,2]. The application of heat with geothermal water helps reduce the use of coal and, thus, improves air quality. However, the geothermal water is usually discharged at 40–50 °C directly, since low enthalpy energy is relatively more difficult to extract. This is frequently observed, especially in

* Tel.: +86-22-2740-5049; fax: +86-22-2789-0050.
E-mail address: jons@tju.edu.cn (L. Zhao).

0196-8904/$ - see front matter © 2003 Published by Elsevier Ltd.
doi:10.1016/j.enconman.2003.09.004

developing countries [3]. This practice not only results in low efficiency of using geothermal energy resources but also causes pollution to the earth surface [4].

In order to solve the problem, a geothermal heat pump system (GHPS) is often used [1]. Among the many types of heat pump systems, the vapor compression heat pump system is more widely adopted for its mechanical simplicity and higher efficiency. It is also the type that is under study in this paper.

The vapor compression GHPS' low temperature source is geothermal water at 40–45 °C, and its high temperature source is clear water at 70–80 °C for the heating network. When the geothermal water flows through the evaporator, its heat is transferred to the working fluid in the GHPS, and its temperature is decreased. When the working fluid flows in the condenser, its heat is transferred to the heating network water, keeping the temperature of the water at a high level. Here, we can easily understand that working fluids are very important to the GHPS. Currently, R22 is used in most of the GHPS, most of which have a COP around 3 [5].

Despite its many good properties, there are many undesirable aspects about R22. Firstly, R22, as a member of the HCFC family, will not be adopted for its high ODP (ozone depletion potential, relative to R12) and GWP (greenhouse warming potential, relative to CO_2). Secondly, it has too high saturation pressure at a relatively high condensation temperature. For example, at a condensation temperature around 70 °C, its saturation pressure is over 30 bar, exceeding the limit of ordinary reciprocating compressors, say 25 bar. Thirdly, when the condensation temperature is close to the critical temperature, the COP decreases rapidly. Because these reasons, the condensation temperature of the GHPS using R22 can only be up to 60 °C. In other words, the heating network water can only reach around 52 °C [5]. The feed water temperature and return water temperature are generally designed at 70–95 °C in a heating network system, much higher than the GHPS outlet water temperature. Therefore, if the GHPS using R22 is used in a heating network system, extra cost has to be incurred to overcome the lower than desired outlet water temperature. A feasible alternative to the problem is a non-azeotropic working fluid for the GHPS. It should be compatible with environment conservation. Its saturation pressure should be lower than 25 bar when the condensation temperature is at 80–100 °C, ensuring that the feed water temperature can be at least 70 °C. Its heat capacities should be higher than 2.5 J/cm^3, ensuring that the working fluid does not overexpand and the boundary dimensions of the GHPS do not get too large.

Up to now, many substitutes for R22 have been proposed, such as R410A and R407C. However, their saturation pressures are still too high when the condensation temperature is at 80–100 °C. Usually used as working fluids at high operating temperatures, R114 and R123 are seldom used for GHPS with a reciprocating compressor due to their small heat capacities. They could be used for GHPS with a centrifugal compressor, but such a compressor has an undesirably large size. Some researchers have attempted to use mixtures of R12, R11 and R22, which again cause environmental issues [6]. To sum up, it is necessary to seek some working fluids that can be used in the GHPS.

2. The working fluids option

It may be challenging to find suitable working fluids among a lot of options. In this study, this was done in the following procedure.

Firstly, the NIST REFPROP 4.0 (a piece of software for calculating thermophysical properties) was used in order to seek some working fluids that might be suitable to be used in GHPS. As a result, seven mixture working fluids were found, such as (R142b and R290), (R152a and R123), (R124, R123 and R290), (R290, R600a and R123) etc.

Secondly, these seven mixture working fluids were tested in a small experimental GHPS with a 2 kW compressor. Many experiments were performed with the condensation temperature up to 80–100 °C. Data were collected by a computer when the system had reached a steady state. Through comparing the experimental data for the seven mixtures, our search was narrowed to three, (R290, R123 and R600a), (R290, R152a and R123) and (R290 and R123).

Thirdly, after analysis of the exergy losses of the three mixtures in the GHPS, the mixture (R290, R600a and R123) was found to be the best and was, therefore, recommended for the GHPS.

Lastly, the mixture was re-examined in consideration of environmental protection and other issues. R290 and R600a, as hydrocarbon substances, are environment friendly with zero ODP and GWP at the same level as CO_2. Other advantages of these two substances include low freezing points, easy availability, non-corrosiveness for metals and dissolvability with lubricants. However, they are combustible, so some flame retardants should be mixed with them. R123, the third substance in the recommended mixture, is a sort of nonflammable halohydrocarbon. Its ODP is only 0.02 and GWP 29, and it can only exist in the atmosphere for 1.53 years, which means that it will have little harmful effect on the environment. Therefore, R123 can be used as the flame retardant for the mixture working fluids.

Based on the above analyses, the authors proposed the non-azeotropic mixture working fluid, that is composed of R290 (propane, C_3H_8), R600a (isobutene, C_4H_{10}) and R123 (1,1 dichloro-2,2,2 trifluroethane, $C_2HCl_2F_3$) (50/10/40, wt.%). The properties of the mixture were experimentally evaluated in our GHPS.

3. The geothermal heat pump system

3.1. Background

The GHPS is installed for heating purposes in the Tianjin Geothermal Research and Training Center in early winter and late spring in conjunction with the main heating network in the same building. The following experiment was performed on April 6, 2001, and during the experiment, the environment temperature changes by about 9–14 °C.

3.2. The heat consumer

The heat consumer is a building of 3500 m^2. On a 50 W/m^2 basis, the building's total heating load is about 175 kW. The feed water temperature and the return water temperature are designed at 75 and 65 °C, and thus, the water flow rate is determined at about 15 m^3/h. In the experiment, the water flow rate is 13.75 m^3/h because the environment temperature is higher than the design temperature. When a balance has been reached between the GHPS export heat and the building's heating load during the experiment, the water flow rate in the condenser is reduced from 13.75 to 10.55 m^3/h to increase the temperature of the heating network water.

3.3. The geothermal water

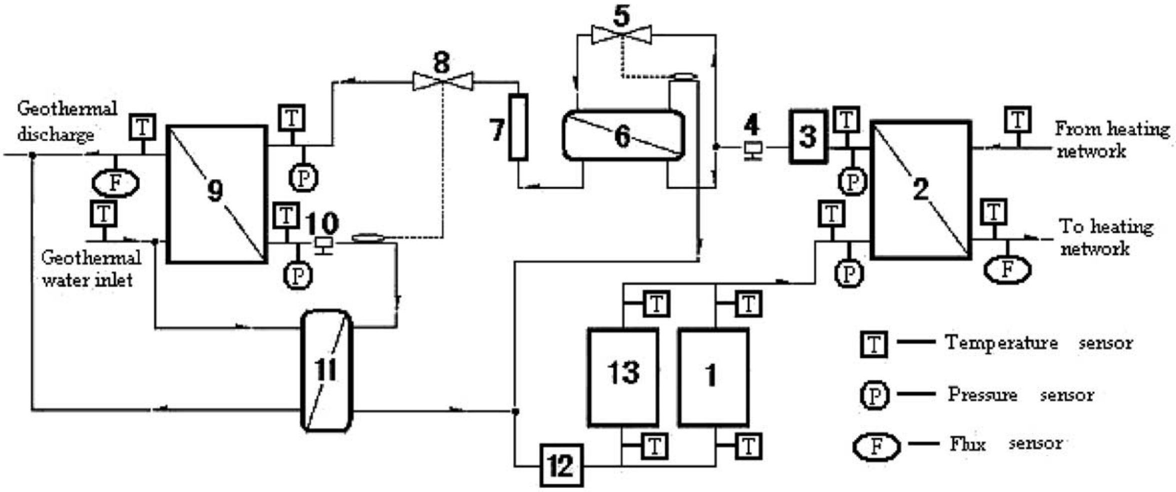
The geothermal water is used as the low temperature source of the GHPS. Its design temperature of 45 °C is decreased to 35 °C after the evaporator. After the evaporator, the water was disposed into the city drainage system. Its flow rate should be at about 11.5 m^3/h, but the flow rate remains at about 10.5 m^3/h because of the high environment temperature.

3.4. The GHPS

Two 22 kW reciprocating compressors are used in the GHPS. The condenser and the evaporator are brazed plate heat exchangers. The condensation area is 11.21 m^2, and the evaporation area is 9.31 m^2. The throttling device is a thermostatic expansion valve. In addition, there are a sub cooler, a superheater, a dry filter, a fluid storage tank etc. in the system. The GHPS is charged with 80 kg of the non-azeotropic mixture working fluid, which consists of 40 kg of R290, 32 kg of R123 and 8 kg of R600a. The thermal sensor's precision is 0.1 °C and the pressure sensor's precision is 0.001 bar. The geothermal and heating network water flow rates are measured by two ultrasonic flow meters whose precision is 0.01 kg/s. The system and its components are shown in Fig. 1. It is noted that although not shown in Fig. 1, a pump is used in each of the two cycles of geothermal water and heating network water. The power consumption of the two pumps is not considered in the total power consumption of the GHPS. As expected, the COP would be somewhat lower otherwise.

3.5. The fluid flows

Fig. 2 schematically shows the fluid flows in the system. The working fluid is compressed by two parallel compressors (1, 13) and then enters the condenser (2), where its heat is transferred to the water for the heating network, causing the working fluid to change from vapor to liquid. Then the working fluid passes through the fluid storage tank (3) and back pressure valve (4). At the exit of the valve, the fluid is divided into two streams. The smaller one flows through expansion valve (5), where it expands and is cooled and then enters the tubes inside the shell tube type sub cooler (6), where it absorbs heat from the other stream on the other side of the tubes. Upon leaving the sub cooler (6) and entering the gas-liquid separator (7), the fluid in the smaller stream has changed into gas. The larger stream, after being separated from the smaller one, goes through the sub cooler (6) and dry filter (7), expands and gets cooled in expansion valve (8) and comes into the evaporator (9), where the working fluid evaporates by absorbing heat from the geothermal water on the other side. After passing back pressure valve (10), the working fluid enters the tubes of the shell tube type superheater (11), where it is heated a second time by the geothermal water outside the tubes. The superheated working fluid leaves the superheater (11) and merges with the smaller stream, and together they enter the gas-liquid separator (12). The working fluid out of the gas-liquid separator (12) again goes into compressors (1) and (13). This is a complete cycle of the working fluid flow. The addition of the sub cooler and the superheater helps increase the COP of



1：compressor① 2：condenser 3：fluid storage tank
4：back pressure valve① 5：expansion valve① 6：supercooler
7：dry filter 8：expansion valve② 9：evaporator
10：back pressure valve② 11：superheater 12：gas-liquid separator
13：compressor②

Fig. 1. Schematic of the geothermal heat pump system.

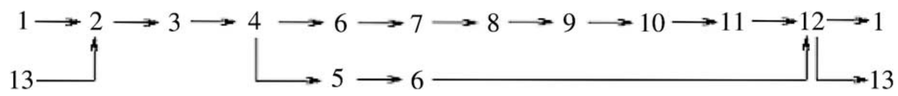


Fig. 2. The fluid flows in the GHPS.

the GHPS. The condensation and evaporation pressures can be adjusted with the two back pressure valves at the exits of the condenser and the evaporator to stabilize the system operation.

4. Experimental results and discussion

The experiment takes 5.5 h. Because the heating network water temperatures at the condenser inlet and outlet are low at the beginning of the experiment, only data collected 3 h after the experiment begins are taken as effective. During the first 3 h, the COP decreases from 4.5 to 3.7, the heating network water at the condenser exit increases from 50 to 74 °C, the geothermal water temperature at the evaporator inlet remains at 40–46 °C and the geothermal water temperature at the evaporator exit keeps in the range of 31–36 °C. In other words, the geothermal water temperature decreases by about 10 °C from the inlet to the exit. Therefore, the GHPS sufficiently utilizes the geothermal energy and reduces the discharge geothermal water temperature. The experimental results are shown in Figs. 3–5. During the 3 h, the geothermal water temperature is not able to be stabilized because of the temperature adjustment lagging. In fact, when the experiment begins, the geothermal water is low at 40 °C, but the temperature rises slowly with experiment continuing. At 2.5 h, the water temperature is above 45 °C. The temperature of the cool water going into the geothermal water results in the geothermal water temperature being reduced to about 41 °C. To improve the status, some controllers with accuracy will be used in the future. Though the geothermal water temperature is changing, the heat network water temper-

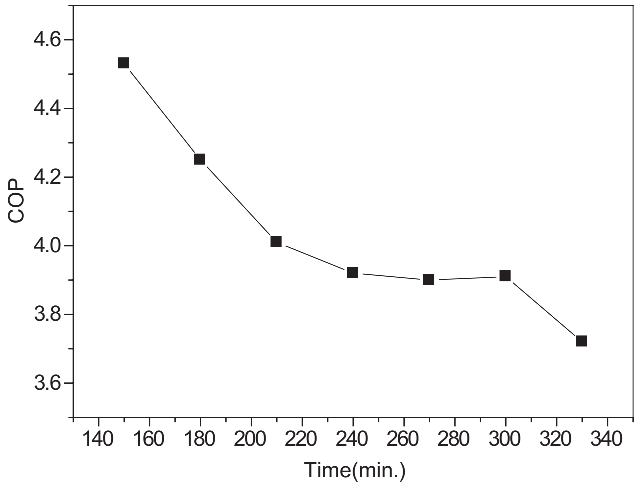


Fig. 3. Variation of COP with time.

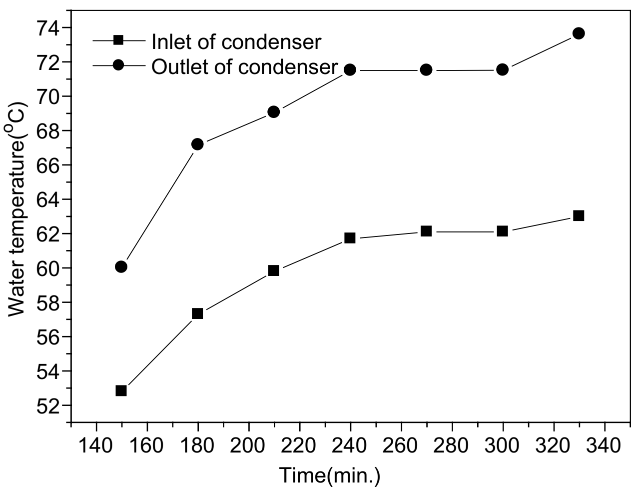


Fig. 4. Variation of the water temperature at the condenser inlet and outlet with time.

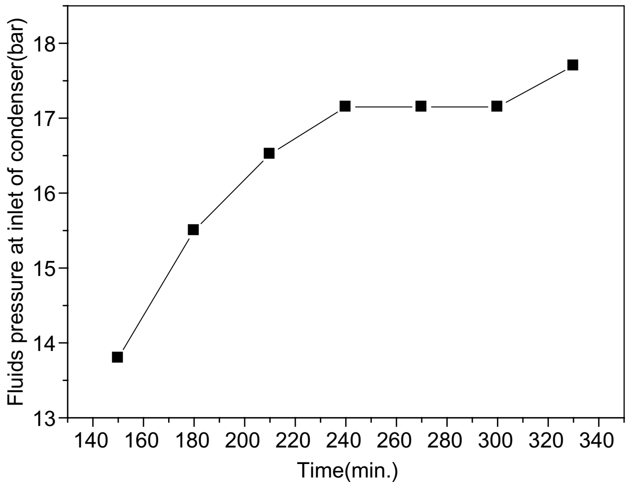


Fig. 5. Variation of the working fluids pressure at condenser inlet with time.

ature reaches a balance, and since the COP is affected mainly by the network water, the experimental data are basically correct.

The variation of COP with time is shown in Fig. 3. In the early stage of the experiment, the heating network water temperature at the condenser inlet is relatively low, so the condensation temperature is low, too. On the other hand, the geothermal water temperatures at the evaporator inlet and outlet only change in small ranges. These factors contribute to a relatively high COP in this stage of the experiment. With the system approaching stabilization, the heating network water temperature at the condenser inlet is rising, resulting in an increasing condensation temperature and more compressor power consumption. As a result, the COP is lowered. When the system has reached steady state, the COP remains at 3.9. In the late stage of the experiment, the COP decreases to 3.72 due to the artificial reduction in the flow rate of the heating network water. The water flow rate is reduced because the temperature has reached 22 °C in the building. On the other hand, more experimental data about different GHPS operations are necessary to master the characters of the GHPS.

Fig. 4 shows the variation of the heating network water temperature with time. In the beginning of the experiment, the water temperature at the condenser inlet is 52.8 °C. As the experiment proceeds, the temperature increases rapidly as the GHPS heating capacity is more than the building heat load at this time. Later on, from the 180th min to the 300th min, as the heat balance is being established, the temperature increases very slightly and finally stays at 63.0 °C. Affected by the inlet temperature, the condenser outlet temperature shows a similar trend, increasing from around 60 °C in the beginning to 74 °C when stabilized but keeps about 10 °C higher than the inlet temperature. The outlet temperature can be raised further, above 80 °C, to meet the requirements of general residence heating design if the flow rate of the heating network water is reduced.

Fig. 5 shows the variation of another important parameter, the working fluid pressure at the condenser inlet, with time. It can be assumed that it is equal to the pressure at the compressor outlets, since the two locations are very close and, thus, the pressure loss is small. This pressure is required to be lower than 25 bar for most reciprocating compressors. In our experiment, the

Table 1
Some experimental data and calculated results

Measured parameters	150 min.	180 min.	210 min.	240 min.	270 min.	300 min.	330 min.
Working fluid pressure at evaporator inlet (bar)	5.61	5.61	5.60	5.61	5.61	5.96	5.96
Working fluid pressure at evaporator outlet (bar)	5.46	5.46	5.46	5.46	5.46	5.62	5.62
Working fluid pressure at condenser inlet (bar)	13.80	15.50	16.52	17.15	17.15	17.15	17.70
Working fluid pressure at condenser outlet (bar)	13.42	15.08	16.13	16.74	16.74	16.75	17.34
No. 1 compressor discharge temperature (°C)	83.26	99.20	97.61	95.71	97.98	94.63	94.55
No. 1 compressor suck temperature (°C)	41.62	41.68	41.67	42.15	40.36	40.32	40.30
No. 2 compressor discharge temperature (°C)	75.21	91.96	89.53	90.14	91.43	89.65	89.25
No. 2 compressor suck temperature (°C)	41.65	41.66	41.65	42.20	40.38	40.35	40.36
Working fluid temperature at condenser inlet (°C)	70.91	88.09	85.49	85.66	86.70	84.81	85.28
Working fluid temperature at condenser outlet (°C)	62.43	71.31	75.89	77.57	79.23	79.44	79.15
Working fluid temperature at evaporator inlet (°C)	33.87	33.91	32.10	31.57	30.98	30.48	30.85
Working fluid temperature at evaporator outlet (°C)	40.55	41.42	41.46	40.85	39.62	39.14	39.15
Water temperature at condenser inlet (°C)	52.80	57.31	59.82	61.70	62.13	62.14	63.00
Water temperature at condenser outlet (°C)	60.02	67.16	69.05	71.50	71.50	71.51	73.62
Geothermal water temperature at evaporator inlet (°C)	43.80	44.99	44.79	45.38	42.74	41.27	41.16
Geothermal water temperature at evaporator outlet (°C)	35.96	34.14	34.24	34.84	32.35	31.56	32.34
Condenser water flow rate (m^3/h)	13.65	13.71	13.75	13.68	13.72	13.70	10.55
Geothermal water flow rate (m^3/h)	10.46	10.38	10.66	10.34	10.13	10.86	10.27
Compressor input current (A)	48.60	70.81	70.58	76.24	73.09	72.80	66.94
Compressor input voltage (V)	375	376	376	376	378	378	377
Calculated results							
The GHPS heating capacity (kW)	114.4	156.8	147.4	155.7	149.3	149.1	130.1
Heat released from geothermal water (kW)	95.2	130.8	130.6	126.5	122.2	122.4	105.2
Actual compressor power consumption (kW)	25.25	36.89	36.77	39.72	38.28	38.13	34.97
Actual COP of the GHPS	4.53	4.25	4.01	3.92	3.90	3.91	3.72

Note: during calculating in the table, the water density is 1000 kg/m^3.

pressure is at about 14 bar initially and at 18 bar at maximum. Therefore, the GHPS with is the working fluid can operate safely and stably in the long term. At the end of the experiment, the working fluids pressure at the condenser inlet rises clearly because the heating network water flow rate artificial reduction results in the working fluids temperature rising at the condenser inlet.

Besides the variations of the four parameters shown in Figs. 3–5, other data are presented in Table 1.

The compressor actual power consumption is calculated as

$$W = \sqrt{3} \cdot \mathrm{COS}\varphi \cdot U \cdot I / 1000 \text{ kW} \quad (1)$$

where U, I and $\mathrm{COS}\varphi$ are voltage (V), current (A) and power factor, respectively. The power factor is taken as 0.8 in the calculation.

The GHPS heating capacity is calculated as

$$Q = c_p \cdot G \cdot \rho \cdot \Delta T / 3600 \text{ kW} \quad (2)$$

where c_p, G, ρ and ΔT are specific heat at constant pressure (4.186 kJ/kg °C), flow rate (m^3/h), water density (1000 kg/m^3) and the temperature difference (°C) between the condenser inlet and outlet, respectively.

The heat released from the geothermal water in the evaporator is calculated in a similar way to Eq. (2).

The actual COP of the GHPS is determined as:

$$\mathrm{COP} = Q/W \quad (3)$$

5. Conclusions

Based on the experimental investigation, some conclusions are drawn as follow.

The GHPS with the non-azeotropic mixture working fluid R290/R600a/R123 (50%/10%/40%) can operate under practical conditions. The condensation temperature is over 80 °C with the condensation pressure below 18 bar and the compressor discharge temperature below 100 °C. The COP of the GHPS is generally over 3.5. The water temperatures at the condenser or evaporator inlet and outlet differ only by 10 °C, indicating a large heat capacity per unit volume of the mixture working fluid. All these facts show that the non-azeotropic mixture working fluid is superior to R22 or R123.

The application of this GHPS technology can lower the discharge geothermal water temperature and, thus, increase the efficiency of using geothermal energy and decrease the pollution to the earth surface. Compared with conventional coal burning heating boilers, this is a clean, efficient and easy to maintain solution to heating needs.

References

[1] Lund JW, Freeston DH. World-wide direct uses of geothermal energy. Geothermics 2001;30:29–68.

[2] Tomasson J, Arason P. Evidence for thermal mining in low temperature geothermal areas in Iceland. Geothermics 2000;29:723–35.

[3] Zacharias A, Athanassios B. The potential of district heating using geothermal energy. A case study, Greece. Geothermics 2000;29:51–64.
[4] Simsek S, Gunay G, Elhatip H, Ekmekci M. Environmental protection of geothermal waters and travertines at Pamukkale. Geothermics 2000;29:557–72.
[5] Kara YA, Yuksel B. Evaluation of low temperature geothermal energy through the use of heat pump. Energ Convers Manage 2001;42:773–81.
[6] Comakli O, Celik C, Erdogan S. Determination of optimum working conditions in heat pumps using nonazeotropic refrigerant mixtures. Energ Convers Manage 1999;40:193–203.