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A Co-axial multi-tube heat exchanger applicable for a Geothermal ORC power plant

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Abstract

The study proposes a Co-axial multi-tube heat exchanger (CMTHE) applicable to geothermal heat extraction. The heat exchanger is integrated with a 50 kW geothermal ORC power plant having a working fluid of R-245fa. Two field tests were performed to examine the system response of the ORC system subject to change of CMTHE. In case 1 where the flow rate in the shell-side of CMTHE is maintained, the pressure variation in the shell-side of CMTHE casts minor variations on heat extraction, ORC power generation, and ORC efficiency during the transient. Moreover, the effect of pressure has barely any influence of the final states of heat extraction, ORC power generation, and ORC efficiency. In case 2 where the pressure is preserved in the CMTHE, it is found that a decrease of flow rate in the CMTHE results in degradation of heat extraction, ORC power generation and ORC system efficiency. On the contrary, increasing the flow rate in the CMTHE leads to a rise of heat extraction, ORC power generation and ORC system efficiency. Unlike that in case 1, the effect of flow rate has a detectable effect on the final states of heat extraction, ORC power generation, and ORC efficiency.

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Geothermal, Co-axial heat exchanger, Organic Rankine Cycle, Heat transfer, Renewable energy

1. Introduction

NOMENCLATURE

CMH	cubic meters per hour
C	flow capacity rate
C*	C_{max}/C_{min}
$T_{h,in}$	temperature inlet of hot side
$T_{c,in}$	temperature inlet of cold side

With the increasing tensions of global warming which casts significant impact on the environment, clean and renewable energy available to relieve the exploitation of electricity from conventional power plants recently had attracted attentions. Geothermal energy is one of the typical kinds of clean energy that can be also integrated with the Rankine cycle to generate electricity. In practice geothermal heat sources vary in temperature from 50 to 350 °C, and can be either dry (mainly steam), a mixture of steam and water, or just liquid water. Normally the high-temperature reservoirs (>220 °C) are the most suitable for commercial production of electricity (Hettiarachch et al., 2007). Dry steam systems use the steam from geothermal reservoirs as it comes from wells, and direct it to turbine/generator units to produce electricity. However, the majority of geothermal resources fall in the medium temperature range whose temperatures

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are typically ranging from 100 to 220°C. Therefore, Organic Rankine cycles (ORC) are considered as the most appropriate selection for this range (Hettiarachch et al., 2007). In normal operation, it extracts heat out of the well via certain heat exchangers in the form such as single U-pipe, double U-pipe, simple co-axial, and complex coaxial (Florides and Kalogirou, 2007).

In this study, a co-axial multi-tube heat exchanger is proposed. The design features a multi-tube configuration which can effectively reduce the size of the geothermal heat exchanger and it is integrated with the geothermal ORC power plant. The working fluid in the tube-side of the heat exchanger is pure water with a flow rate at 13 tons per hour, where in the shell-side the working fluid is geothermal hot water (~120˚C). The working fluid of the organic Rankine cycle is pentafluoropropane, also known as R-245fa. Two field tests were performed to examine the system response of the ORC system subject to change of CMTHE. The influence of pressure variation and flow rate of the CMTHE on the ORC system are reported accordingly.

2. Experimental Setup

In I'Lan, geothermal energy is utilized to generate electricity along with the Organic Rankine Cycle (ORC). To avoid the influence of water quality and carbon dioxide associated with the geothermal water, a two-stage heating system is designed in the geothermal heat exchanger system as shown in Fig. 1, where it contains a geothermal loop and an ORC loop. In the geothermal loop system, the production well erupts geothermal water which exchanges heat in the proposed co-axial multi-tube heat exchanger (CMTHE) with the pure water for the ORC system. The high temperature pure water then enters into the evaporator of the ORC system to heat up R-245fa, and then flows back to CMTHE to complete a full cycle. In the ORC system, R-245fa is evaporated and flows into the screw expander to deliver work output, R-245fa is then condensed by the cooling water where it was further cooled by an additional cooling tower. In order to evaporate the refrigerant, the pure water utilized for heating is designed to have an inlet temperature above 120 °C with a flow rate of 13 tons per hour.

2.1 Multi-tube heat exchanger (CMTHE) design

In standard operation, the heat exchanger is of counter flow arrangement. The size of the heat exchanger is estimated using the standard heat exchanger sizing procedure as described from Wang (2007). Calculation implicates that the dominant resistance is on the shell-side, thereby it is imperative to reduce the shell-side resistance to achieve a better heat transfer capability. The present study proposes a multi-tube design as shown in Fig. 2. Further, through the utilization of smaller tubes (D_o = 12.7 mm, and D_i = 10.7 mm). With the counter-flow arrangement, both the heat transfer and pressure drop can be improved considerably due to the larger temperature difference, causing the increase in ORC water temperature. Also, with the increasing temperature, the fluid viscosity decreases, which results in a better pressure drop. The CMTHE is made of 40 small pipes to extract heat and a larger pipe for gathering the returning hot water with a diameter of 40 mm as shown in Fig. 2(a), the total length of the heat exchanger is 11 meters, and has an effective heat transfer area of 18.6 m². After the CMTHE is built inside an external housing shown in Fig. 2(b), temperature and pressure sensors are installed at the inlets and outlets.

2.2 Two cases of experiment

2.2.1 Case 1

The first experiment was tested for three hours, the inlet pressure and flow rate of the geothermal water has been changing for three main time zones, as shown in Table 1. In fact, the flow rate of the geothermal water fluctuates so the major varying parameter is the inlet pressure, since the flow rate varies only less than 15% but the inlet pressure changes for more than 70%.

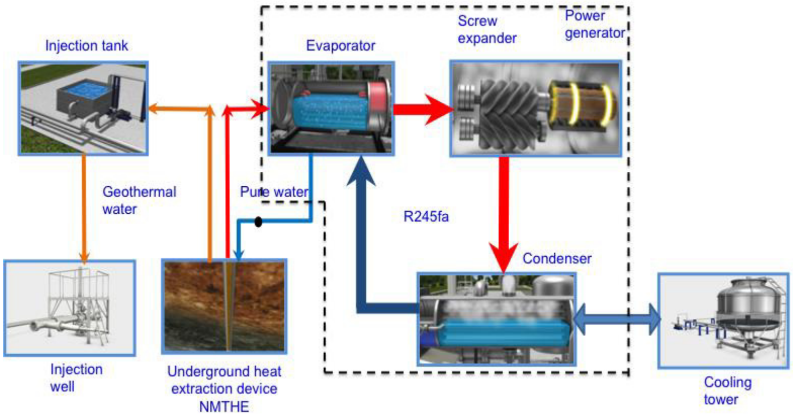

Fig. 1. Schematic figure of ORC system


Fig. 2(a) **Fig. 2(b)**

Table 1 Detailed information for three zones in case 1.

	Time (min)	Flow rate (CMH)	Inlet pressure (bar)	C^*
Zone 1	1~108	6.5	3.5	0.502
Zone 2	109~147	6.72	4.9	0.52
Zone 3	148~	7.56	1.5	0.58

Table 2 Detailed information for three zones in case 2.

	Time (min)	Flow rate (CMH)	Inlet pressure (bar)	C^*
Zone 1	1~72	6.6	2.5	0.52
Zone 2	73~111	3.6	2.5~1.5	0.28
Zone 3	112~	5.04	2.5	0.39

2.2.2 Case 2

In case 2, the testing lasted for 2.5 hours. The testing period are divided into three zones. In zone 1, inlet pressure is around 2.5 bar with the flow rate of 6.6 CMH. In zone 2, the flow rate is decreased to 3.6 CMH and the pressure is around 1.5~2.5 bar. In zone 3, the inlet pressure is still controlled at around 2.5 bar, but the flow rate has increased to 5.04 CMH, the variation can be seen in Table 2. The major variable is the flow rate in the shell side of the heat exchanger while the pressure remains roughly the same.

3. Results and discussion

3.1 Results for Case 1

The corresponding data is depicted in Fig. 3. From zone 1 to 2, despite an appreciably rise of pressure in the shell side, the heat extraction, ORC power, and ORC efficiency remains almost unchanged. The effect of pressure on the heat transfer performance is usually very small for a liquid flow (Incropera et al., 2007). On the other hand, when the pressure is tremendously reduced from 4.9 bar to 1.5 bar (a 70% decline), the relevant change of heat extraction reveals a sharp decline from about 600 kW to about 400 kW during the 10 minutes transient. However, the corresponding maximum drop of ORC power and ORC system efficiency is around 17% during the transient, yet it bounces back vividly right after the 10 minutes. Hence the minimum heat capacity, is always at the shell side throughout the test. Thus the maximum heat transfer rate remains about the same provided that the inlet temperatures ($T_{h,in}$ and $T_{c,\,in}$) are about the same during the test.

3.2 Results for Case 2

As expected in Fig.4, the heat extraction, ORC power, and ORC efficiency reveals a detectable decline as the flow rate is reduced. Analogously, an observable rise of the heat extraction, ORC power, and ORC efficiency is encountered when the flow rate is raised. However, the imposed influences on the system is not only during the transient but also in the final state. The results are not the same as case 1 where the final state is hardly affected by the change of pressure. Again, the results are associated with the heat capacity rate. Contrary to that of case 1, the maximum heat transfer rate varies appreciably since the C_{min} changes with flow rate, thereby the final states varies accordingly. Despite the appreciably change of flow

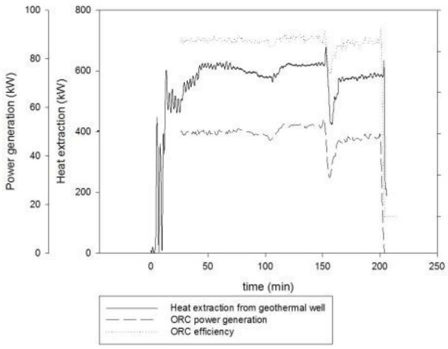

Fig. 3.

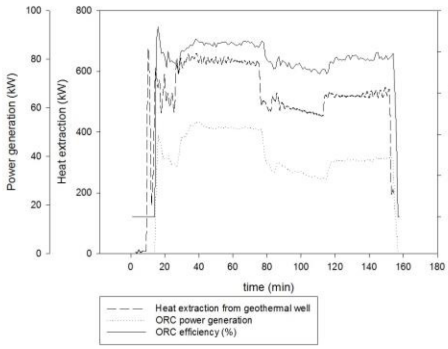

Fig. 4.

rate, the change of heat extraction, ORC power, and efficiency is small. According to a prior analysis of the ORC system (Kuo et al., 2011), the dominant thermal resistance is on the refrigerant side and it comprises about 60-70% of the total resistance.

4. Conclusion

Two field tests were performed to examine the system response of the ORC system subject to influences of the CMTHE. Based on the foregoing discussion, the following conclusions are made.

(1) In case 1 where the flow rate in the shell-side of CMTHE is about the same, the pressure variation in the shell-side of CMTHE casts minor variations of heat extraction, ORC power generation, and ORC efficiency during the transient. Moreover, the effect of pressure has barely any influence of the final states of heat extraction, ORC power generation, and ORC efficiency.

(2) In case 2 where the pressure is about the same in the CMTHE, a decrease of flow rate in the CMTHE results in degradation of heat extraction, ORC power generation and ORC system efficiency. On the contrary, increasing the flow rate in the CMTHE leads to a rise in heat extraction, ORC power generation and ORC system efficiency. Unlike that in case 1, the effect of flow rate has a detectable effect on the final states of heat extraction, ORC power generation, and ORC efficiency.

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