Comparative investigation of working fluids for an organic Rankine cycle with geothermal water

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Abstract   In this paper, the thermodynamic investigation on the use of geothermal water ($130\,°C$ as maximum) for power generation through a basic Rankine has been presented together with obtained main results. Six typical organic working fluids (i.e., R245fa, R141b, R290, R600, R152a, and 134a) were studied with modifying the input pressure and temperature to the turbine. The results show that there are no significant changes taking place in the efficiency for these working fluids with overheating the inlet fluid to the turbine, i.e., efficiency is a weak function of temperature. However, with the increasing of pressure ratio in the turbine, the efficiency rises more sharply. The technical viability is shown of implementing this type of process for recovering low temperature heat resource.

Keywords: Geothermal water; Energy efficiency; Organic Rankine cycle

1   Introduction

Using fossil fuels can lead to some serious environment problems such as global warming, pollution, and ozone depletion. In recent years, because renewable energy sources can avoid environmental problems and refresh

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themselves in the natural process, they have currently gained great importance. It is required to utilize new energy suitable for power generation without causing serious environmental pollution. With the new technologies developing, low-grade heat sources can be converted to appropriate energy type. Solar heat, waste heat, and geothermal energy are typical examples for low-grade heat sources with their available temperatures ranging between $60\,°C$ and $200\,°C$ [1].

Geothermal resources can be found anywhere in the world, and geothermal heat sources vary in temperature from $50\,°C$ to $350\,°C$ [2–4]. There are two categories technologies for geothermal energy utilization, i.e., direct uses for space heating and cooling, industrial processes and electric energy production [5–10]. Three major types of electric generation plants from geothermal sources are operating today: dry-steam plants, flash-steam plants, binary cycle plants where binary and combined flash/binary plants are relatively new designs [11]. As a renewable energy source, low-temperature geothermal heat sources have a very large potential [12–14]. Due to the low temperature, the electricity conversion efficiency is low. Therefore, when the temperature of the geothermal water is less than $200\,°C$, binary cycle method may be most suitable and cost-effective for generation of electricity [12].

In a binary cycle power plant, a secondary working fluid, usually an organic fluid, has a lower boiling point and higher vapor pressure than water at a given temperature [15,16]. Traditionally, binary plants have been small modular units varying in size from a few hundred kilowatts to several megawatts [17]. Organic fluid plays an important role in the cycle, since selection of organic working fluid affects considerably the system performance. There are various examples of papers regarding selection of the organic working fluid for the cycle [18–29].

In this paper, the inlet and output pressure to the turbine are parameterized for each studied fluid at a given temperature and, therefore, the ratio of inlet pressure to turbine to discharge pressure of turbine (P_1/P_2) is maintained equal to 1.5, 2.5 and 3.0, seeking a minimum, an intermediate and a maximum that were common to all fluids. The results obtained allow determining whether the rise of the inlet pressure to the turbine centributes to increase or decrease of the cycle performance qualitatively, but, similarly, allows realizing in how much increase or decrease this efficiency.

2   Theoretical process

The principle of operation of conventional and organic Rankine cycle is same, while the difference is that the organic Rankine cycle uses an organic agent as the working fluid. A pump pressurizes the liquid fluid, and it is injected in the evaporator to produce vapor that is expanded in a turbine connected to a generator; finally, the exit vapor is condensed, starting the new cycle (Fig. 1).
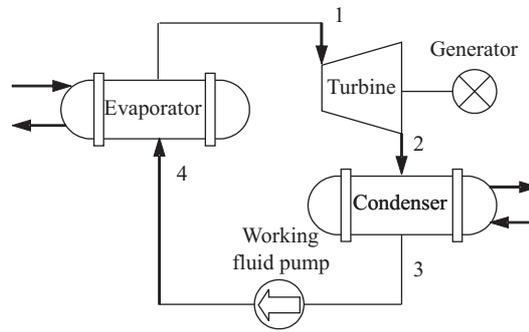
Figure 1: Schematics diagram of the Rankine cycle.

The analysis assumes steady state conditions, no pressure drop or heat loss in the evaporator. The cycle's total energy efficiency is given by

$$\eta = \frac{W_{turbine} - W_{pump}}{Q_{evaporator}} \ , \tag{1}$$

where η is the total energy efficiency, $W_{turbine}$ is the mechanical work of turbine, W_{pump} is the mechanical work of the pump, and $Q_{evaporator}$ is the quantity of heat of heat exchanger defined as follows

$$W_{turbine} = h_1 - h_2 \ , \tag{2}$$

where h_1 and h_2 are enthalpies of the working fluid at state 1 and 2 of the cycle,

$$W_{pump} = h_4 - h_3 \ , \tag{3}$$

where h_3 and h_4 are enthalpies of the working fluid at state 3 and 4 of the cycle, and

$$Q_{evaporator} = h_1 - h_4 \ . \tag{4}$$

In the heating process, overheating of the inlet fluid to the turbine, T_1, is considered from the condition of saturated steam up to its critical temperature. The condensation temperature of working fluid, T_3, is equal to $35\,°C$. The discharge pressure of the turbine, P_2, is equal to the saturation pressure of the fluid in liquid state, P_3, to the temperature $T_3 = 35\,°C$, while the inlet pressure to the turbine, P_1, maintains the ratio P_1/P_2 equal to 1.5, 2.5 and 3.0. In our study, the Engineering Equation Solver (EES) software [31] was used in the analysis of the thermodynamics of the cycle.

3   Results and discussion

According to the assumptions presented in Section 2, six typical organic working fluids, i.e., R245fa, R141b, R290, R600, 152a, and 134a (general properties are given in Tab. 1.) with constant P_1/P_2 ratio have been studied, and the results obtained on the cycle efficiency by increasing the inlet temperature to the turbine T_1 were shown in Fig. 2(a–f).

Table 1: Characteristics of six typical organic working fluids.

Fluid	Fluid type	Molecular (g/mol)	P_{cr}(MPa)	T_{cr} (°C)
R245fa	dry	134.05	3.65	153.85
R141b	dry	116.95	4.21	204.25
R290	wet	44.10	4.25	96.55
R600	dry	58.12	3.80	151.85
R152a	wet	66.05	4.52	113.15
R134a	isentropic	102.03	4.06	100.95

In Fig. 3, the results on the η of the cycle by increasing the T_1 at a constant P_1/P_2 ratio for six typical fluids were presented. To achieve a better visual comparison in the same graph, only the pressure ratio and each one of the three ratios were analyzed. It can be obviously found that when $P_1/P_2 = 1.5$ (which is the lowest of those studied, see Fig. 3a), with the increasing of the temperature T_1, the efficiency, η, of six typical organic working fluids rarely change. It implies that the efficiency, η, is a weak function of temperature T_1, and overheating the inlet fluid to the turbine does not cause a significant change in the efficiency, η.

Nevertheless, with the increasing of the ratio P_1/P_2, obtained are much higher values of the efficiency, η, for all six fluids as shown in Fig. 3b,c. With
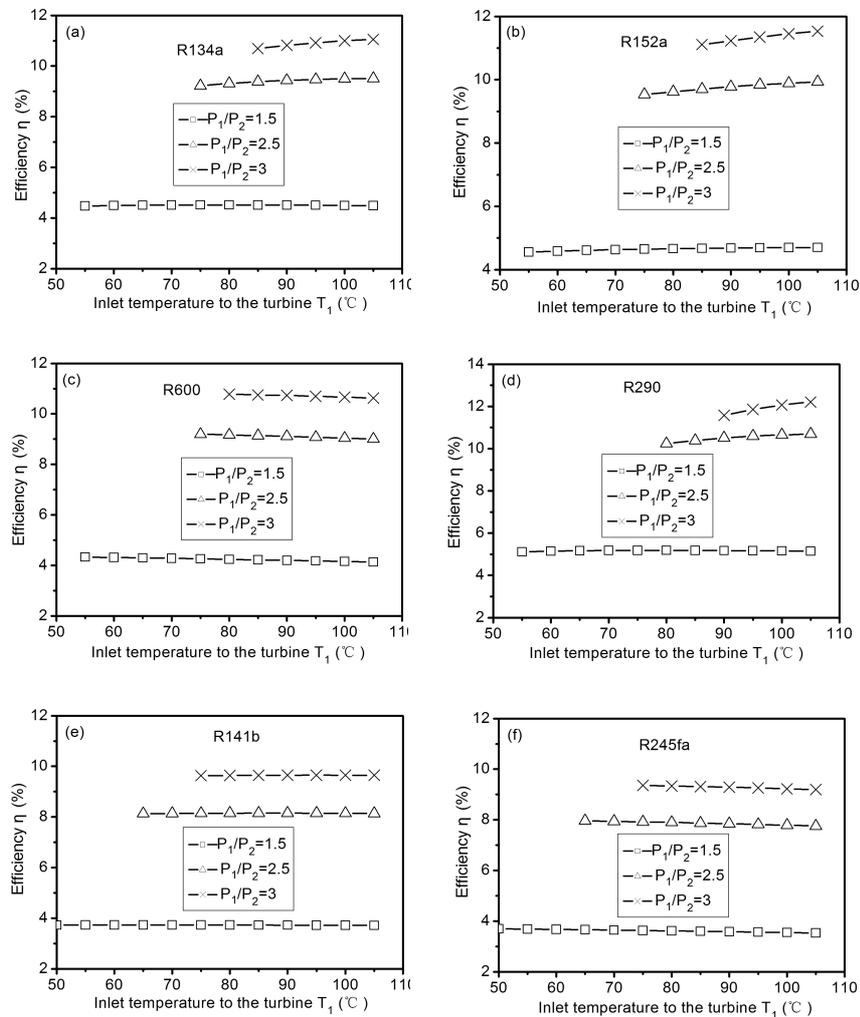
Figure 2: Influence of the inlet temperature to the turbine, T_1, on the overall efficiency of the cycle with constant P_1/P_2 ratio for: R134a (a), R152a (b), R600 (c), R290 (d), R141b (e), R245fa (f), respectively.

the increasing of the inlet temperature to the turbine, this effect increases more steeply, i.e., for the greater pressure ratio studied ($P_1/P_2 = 3.0$).

It is interesting to indicate that Fig. 3 also shows that with the pressure ratio fixed and for the temperature range approximately between 80 °C and 105 °C, R600 offers the best performance, by contrast that the efficiency of
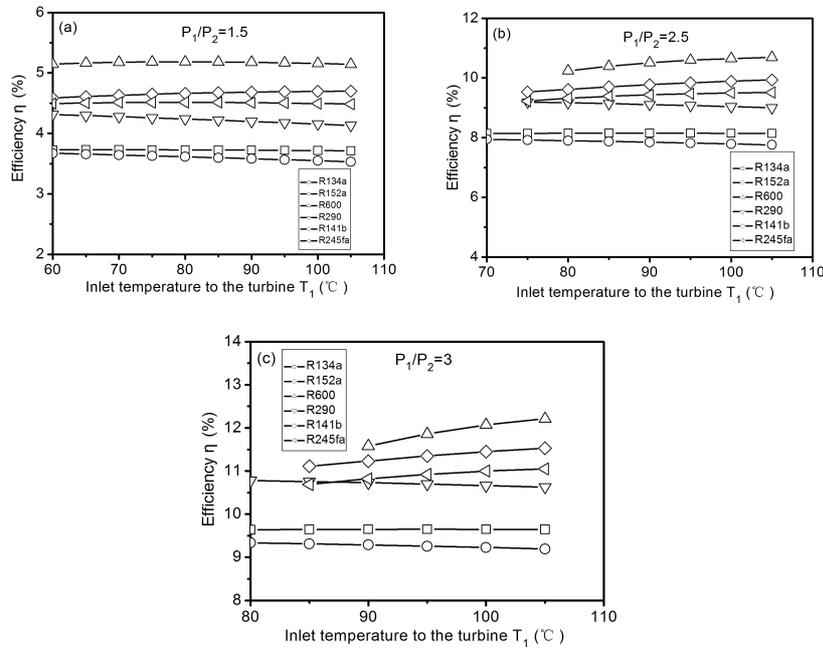
Figure 3: Influence of the input temperature to the turbine, T_1, on the total efficiency of the cycle with a constant ratio $P_1/P_2 = 1.5$ (a), 2.5 (b) and 3.0 (c), respectively.

R152a is the lowest. For the R134a, which is an isentropic fluid, it remains unchanged.

It can be observed that with the increasing pressure ratio, the efficiency of the system raises for all six fluids (see Fig. 4). However, when the pressure ratio $P_1/P_2 = 1.5$ or $P_1/P_2 = 2.5$, with higher temperature T_1, the efficiency of the system is rarely changed, and when the pressure ratio $P_1/P_2 = 3$, the efficiency of the system increases with the increasing of temperature T_1.

In Fig. 5, the efficiency of the system enhances with the increase of the pressure ratio for all the fluids used at a constant T_1 shown. The six fluids were studied for a single inlet temperature to the turbine, T_1, and each of the two was studied at 90 and 100 °C for a better visual comparison. Higher P_1 increases both the net work as the evaporator heat that leads to an improvement in the efficiency of the system. However, the increase in the net work is higher than that in the heat of the evaporator.
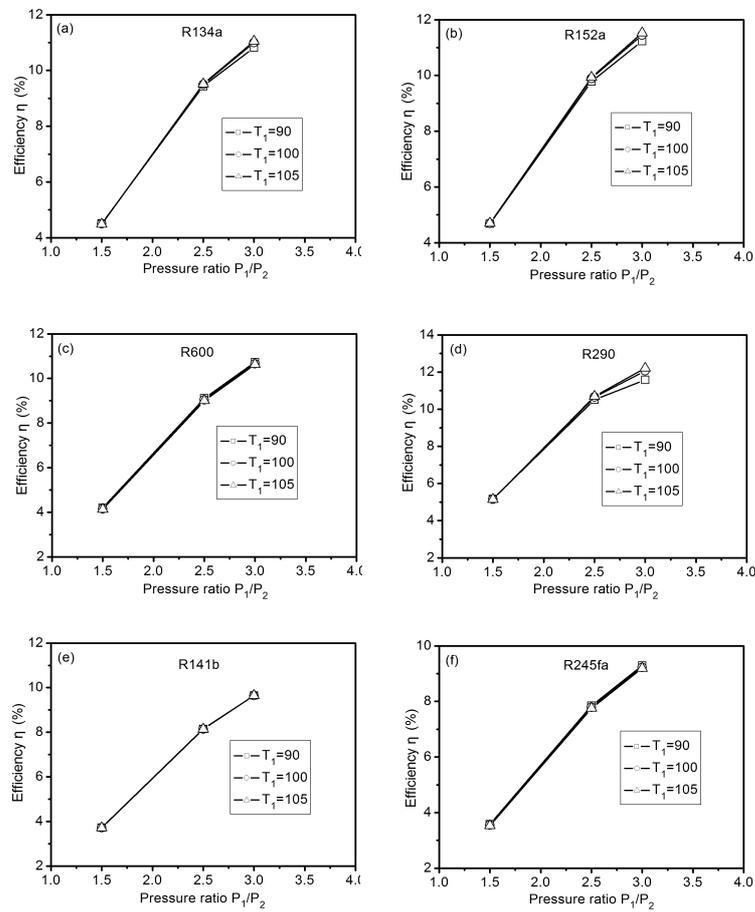
Figure 4: Influence of the P_1/P_2 ratio on the overall efficiency of the cycle, with constant inlet temperature to the turbine, T_1, for R134a (a), R152a (b), R600 (c), R290 (d), R141b (e), R245fa (f), respectively.

4 Conclusions

In this paper, the thermodynamic investigation on the use of geothermal water ($130\,^\circ$C as maximum) for power generation through a basic Rankine cycle has been presented. Based on the simulations carried out, it can be mentioned that overheating the inlet fluid to the turbine does not cause a significant change in the overall efficiency of the cycle, since the conclusion can be obtained that the system's efficiency performed a weak function of

temperature. Interestingly, with the increasing of the pressure ratio in the turbine, much larger values of efficiency are obtained and also, as the inlet temperature to the turbine rising, the efficiency increases more sharply.
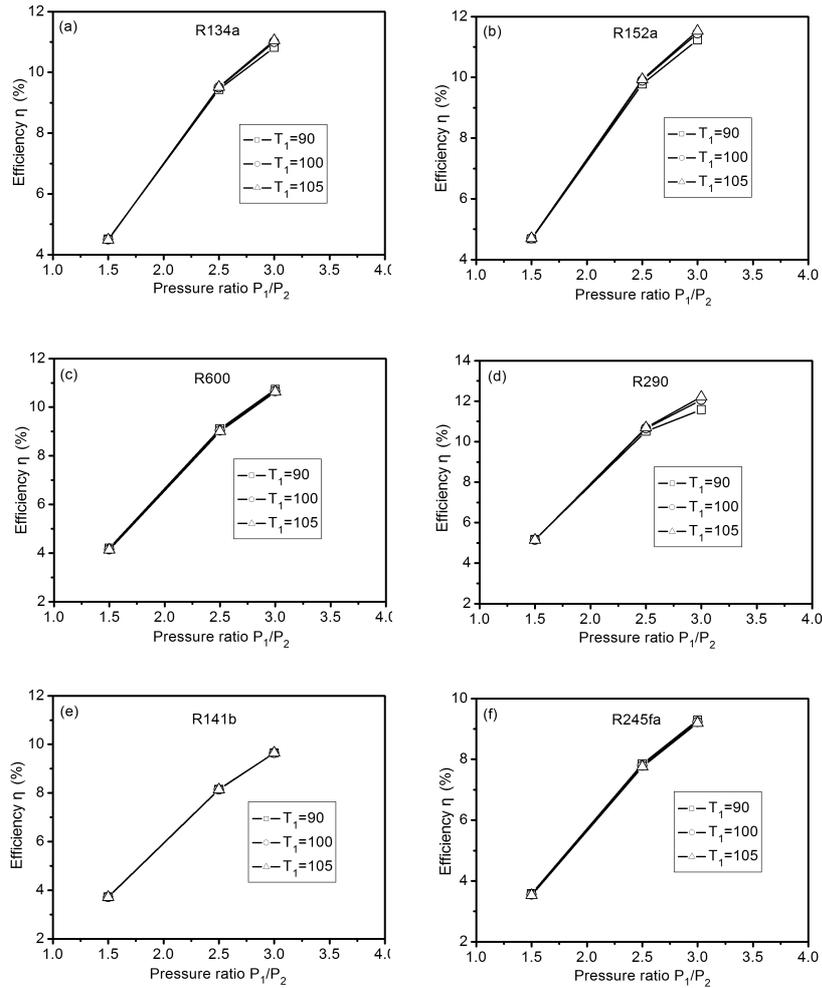
Figure 5: Influence of the ratio P_1/P_2 on the total efficiency of the cycle with a constant input temperature to the turbine $T_1 = 90\,^{\circ}\mathrm{C}$ (a) and $100\,^{\circ}\mathrm{C}$ (b), respectively.

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