Investigation of waste heat recovery of binary geothermal plants using single component refrigerants

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Abstract. In this study, the availability of waste heat in a power generating capacity of 47.4 MW in Germencik Geothermal Power Plant has been investigated via binary geothermal power plant. Refrigerant fluids of 7 different single components such as R-134a, R-152a, R-227ea, R-236fa, R-600, R-143m and R-161 have been selected. The binary cycle has been modeled using the waste heat equaling to mass flow rate of 100 kg/s geothermal fluid. While the inlet temperature of the geothermal fluid into the counter flow heat exchanger has been accepted as 110°C, the outlet temperature has been accepted as 70°C. The inlet conditions have been determined for the refrigerants to be used in the binary cycle. Finally, the mass flow rate of refrigerant fluid and of cooling water and pump power consumption and power generated in the turbine have been calculated for each inlet condition of the refrigerant. Additionally, in the binary cycle, energy and exergy efficiencies have been calculated for 7 refrigerants in the availability of waste heat. In the binary geothermal cycle, it has been found out that the highest exergy destruction for all refrigerants occurs in the heat exchanger. And the highest and lowest first and second law efficiencies has been obtained for R-600 and R-161 refrigerants, respectively.

1. Introduction

Renewable and eco-friendly energy sources are becoming more and more important every day. Especially with decreasing amount of fossil fuels, this importance also affects energy conversion systems using renewable energy sources (geothermal, wind, solar) which are less harmful to the environment than fossil fuels (petroleum, coal, natural gas). Recovery of waste heat generated by energy conversion systems using renewable energy sources also has an impact on system performance. The performance of an energy conversion system can be improved by the addition of equipment or of systems with different energy conversion techniques. Due to low temperature of waste heat in such systems, working fluid of choice is also very important for energy conversion. Due to low temperature of waste heat, working fluid should provide the necessary conditions at lower temperature than that of waste heat. In the literature, refrigerants are preferred in the recovery of waste heat at low temperature. We can summarize some studies using these fluids as follows [1]-[3]. Satanphol et al. interested heat recovery alternative for low grade heat. The types of fluid, the composition and the operating conditions that achieved the maximum net work output were determined through flowsheet modeling and optimization in Aspen Plus v.8.4 simulation software. They used single component refrigerants in Organic Rankine Cycle (ORC). Among the group of pure working fluids in their study, the ORC using R-227ea provided the best performance in terms of net work output [4]. Zeyghami studied performance of the combined flash-binary geothermal power cycle for geofluid temperatures between 150 and 250°C. A thermodynamic model is developed, and the suitable binary working fluids for different geofluid temperatures are identified from a list of thirty working fluid candidates, consisting
environmental friendly refrigerants and hydrocarbons. Thirty environmental friendly fluids, including refrigerants and hydrocarbons are selected and evaluated to identify suitable working fluids, which yield highest system efficiency. The results show that for low-temperature heat sources using refrigerants as binary working fluids result in higher overall cycle efficiency and for medium and high-temperature resources, hydrocarbons are more suitable. For combined flash-binary cycle, secondary working fluids; R-152a, Butane and Cis-butane show the best performances at geofluid temperatures 150, 200 and 250°C respectively [5]. Astolfi et al. investigated the potential of ORC (organic Rankine cycles) for the exploitation of low-medium enthalpy geothermal brines. A Matlab code was created in order to define the optimal combination of fluid, cycle configuration and cycle parameters. An extensive thermodynamic analysis is performed considering geothermal sources in the temperature range of 120-180°C. All the assumptions for calculating the plant components performance are set on the basis of data from literature and real power plants data sheets. Thermodynamic optimization results, shown in terms of reduced variables, allow defining some general rules for the selection of the optimal combination of working fluid and cycle configuration [6]. Brown et al. investigated working fluids for organic Rankine cycle (ORC) applications with a goal of identifying “ideal” working fluids for five renewable/alternative energy sources. A wide range of “theoretical” working fluids are investigated with the goals to identify potential alternative working fluids and to guide future research and development efforts of working fluids. The study suggests a working fluid's critical temperature and its critical ideal gas molar heat capacity have the largest impact on the cycle efficiency and volumetric work output, with “ideal” working fluids for high efficiency possessing critical temperatures on the order of 100%-150% of the source temperature and possessing intermediate values of critical ideal gas molar heat capacity [7]. Tchanche et al. presented various Rankine cycle architectures for single fluids and other improved versions operating with ammonia/water mixture. Waste heat resources and their potential for driving organic Rankine cycles have been outlined. The nature state and temperature of the heat source significantly influences the choice of the type of organic Rankine cycle machine. Potential of these sources and temperature have been revealed, and led to enormous potential for recovery using organic Rankine cycles and other technologies. Characteristics of a module were recorded: heat source temperature, power output, thermal efficiency, etc. The maximum thermal efficiency of ORC is found close to 25%. The selection of an ORC will be primarily based upon application, heat source temperature and desired power output [8]. Wang et al. examined the relationships between the critical parameters of working fluids and the Rankine cycle performances under defined condensing pressure. The results revealed that the relationship between critical temperature and thermal efficiency for pure fluid would depend on the initial operating conditions. For the binary mixtures, the trend of critical pressure with the quality was basically opposite to that of evaporator irreversibility rate. Therefore, the critical properties could be considered as predictive index for selecting working fluids to achieve a preferred efficiency for pure fluids and reduce the evaporator irreversibility rate for mixture fluids [9]. This study modeled a binary geothermal power plant for waste heat recovery in Germencik Geothermal Power Plant and investigated system performances for 7 different single component refrigerants. The terms energy and exergy were used in the availability of the waste heat for the designed model, and energy and exergy efficiencies were obtained for the refrigerants. In addition, exergy destructions and net power productions for the equipment which is effective in the system performance were obtained from the model.

2. Aydın Germencik geothermal area

Aydin Germencik geothermal area is a high-temperature field located in the west of Menderes Graben and within the boundaries of Allangullu-Omerbeyli. The reservoir temperatures of the field are between 200°C and 215°C. The highest reservoir temperature in the field is 232°C. The total surface area of the field is 50 km². A power generating plant with a net capacity of 47.4 MW has been established by Gurmat Electricity Company since March 2009. Due to its characteristics, it is a steam-dominant field and a double-flash steam power cycle is used in power generation due to high reservoir temperature. There are 6 generation wells and 7 reinjection wells in the field. Geothermal fluid at an average of 210°C and 650 kg/s flow rate is used in the injection wells for power generation at the
power plant. A water-cooled condenser is used for the condensation of the gases which cannot be condensed at the power plant. The geothermal fluid at 110°C, which completes its cycle in the power plant, is transferred to the reinjection wells. More detailed information on the power plant is given in Reference [10].

3. Waste heat recovery and binary geothermal power plant model

This study investigated the availability of the waste heat for recovery purposes before the geothermal fluid, which completes its cycle in Germencik Geothermal Power Plant, is transferred to the reinjection wells. A simple binary cycle was used for the availability of the waste heat. 7 different R-134a, R-152a, R-227ea, R-236fa, R-600, R-143 and R-161 single-component refrigerants were used in the cycle model. Binary geothermal power plants consist mainly of pumps, heat exchangers (evaporators), turbines and condensers. Figure 1 shows the binary geothermal power plant cycle used in this study. The operating conditions for the binary geothermal power plant proposed for waste heat recovery at Germencik Geothermal Power Plant were determined under certain assumptions.

![Figure 1. Schematic diagram of Organic Rankine cycle.](image)

The actual operating conditions of the power plant were also taken into consideration for the determination of the operating conditions for the proposed cycle. In this way, the cycle was investigated in similar situations and under similar thermodynamic conditions applied to real binary power cycles. In the proposed binary geothermal power plant, geothermal fluid used as waste heat is completely re-ejected. Geothermal fluid is a low-temperature reservoir and in the liquid phase during the power cycle. Geothermal fluid (waste heat) is assumed to enter the evaporator at 100 kg/s flow rate, T=110°C (state number: 5) and under P=160 kPa and to be 70 °C (state number: 6) by the time it exits the evaporator. In addition, the thermal efficiency of the heat exchanger is assumed to be 90%. The circulation of refrigerants (working fluids) is based on Organic Rankine Cycle (ORC), which is a closed cycle. The working fluid enters the pump in the saturated liquid phase at T=20°C (state number: 1) and is assumed to be sent to the evaporator under P=900 kPa (state number: 2). The isentropic efficiency of the pump is assumed to be 75%. The working fluid exists the evaporator at T=85°C and under 900 kPa (state number: 3) as superheated steam. Having 90% isentropic efficiency and being in the superheated vapor phase, the working fluid is sent to the water cooled condenser after it generates power in the turbine. The cooling water is assumed to enter the water-cooled condenser at T=10°C (state number: 8) and under P=500 kPa and exit the condenser at T=18°C (state number: 7). Under these conditions, such properties required for 7 different refrigerants as the mass flow rate of the working fluid, amount of cooling water, net power generated and cycle efficiencies were calculated.

3.1. Selected working fluid

Refrigerants are very suitable secondary fluids for binary geothermal cycles. Selection of a suitable working fluid plays an important role in determining system performance. In the evaporator and condenser in a binary cycle, refrigerants transfer the heat from a place to another. Selection of
appropriate refrigerants largely depends on the initial investment and system operating costs as well as fulfilling heat transfer expectations. On the other hand, refrigerants’ climatic damages to the ozone layer and environment should also be taken into consideration. Another important environmental factor is global warming. The fact that refrigerants generate greenhouse gases should also be taken into account to make sure that refrigerants of choice contribute to the global warming as little as possible. Since refrigerants are chemical substances, they can also adversely affect human health. The main harmful characteristics of refrigerants are that they are toxicity and flammable. In applications, the toxicity and flammability characteristics of refrigerants are very important. Although low toxicity and low flammability are the desired properties in refrigerants, flammability is less important if there is no ignition in a given system.

| Type       | Semi-Empirical ODP | GWP (100 year) | Critical Temperature (K) | Critical Pressure (kPa) |
|------------|--------------------|----------------|--------------------------|-------------------------|
| R-134a     | 0                  | 1,430          | 374.2                    | 4059                    |
| R-152a     | 0                  | 124            | 386.4                    | 4520                    |
| R-227ea    | 0                  | 3,220          | 376                      | 2990                    |
| R-236fa    | 0                  | 9,810          | 398.1                    | 3200                    |
| R-143m     | 0                  | -              | 377.9                    | 3635                    |
| R-161      | 0                  | 12             | 375.3                    | 5010                    |
| R-600      | 0                  | 4              | 425.1                    | 3796                    |

Table 1. Physical properties of 7 single working fluids and their some thermodynamic properties.

To briefly summarize the refrigerants used in this study; R-134a, R-152a, R-227ea, R-236fa, R-143m and R-161 are hydrofluorocarbon (HFC) refrigerants while R-600 is a hydrocarbon (HC) refrigerant. HFC refrigerants are commonly used in refrigeration systems. HFC refrigerants do not harm the ozone layer, however, potentially contribute to global warming. HFCs are extremely safe in terms of flammability and toxicity. HCs, natural and non-toxic refrigerants, have low global warming potential and do not harm the ozone layer. Having high efficiency, HC refrigerants are eco-friendly, however, the only problem they have is that they are flammable. Table 1. shows some thermophysical properties of the refrigerants used in this study [11]-[16].

4. Analysis

4.1. Balance equations of mass, energy and exergy

Mass, energy and exergy analyses were carried out in the binary geothermal power plant examined for the availability of waste heat in Germencik Geothermal Power Plant. During the analyses, energy and exergy values for each point in the flow diagram (Figure 1.) were calculated using the formulas defined in thermodynamics [17-20]. The assumptions made in the calculations are as follows. (a)The power plant is at the steady-state conditions. (b) Potential and kinetic energy exchange has been neglected. (c) Heat transfer from the confines of the system (adiabatic) has been neglected. (d) Reference temperature and pressure in the model are 278 K and 101.3 kPa respectively. (e) Friction and pressure drop losses have been neglected. (f) Kinetic exergy, potential exergy and chemical exergy changes have been neglected. (g) The Engineering Equation Solver (EES) program was used for the calculations. (h) The thermophysical properties of geothermal water have been taken as steam_nbs, and therefore the chemical properties of non-condensable gases and other geothermal waters have been neglected.

The overall mass balance equation at continuous flow condition is as follows.

\[
\sum_{i=1}^{n} \dot{m}_i = \sum_{e=1}^{n} \dot{m}_e
\]  

(1)

Where \( \dot{m} \) represents the mass flow rate, and subscript i and e represent input and output respectively.

Energy balance is represented by Equation (2).

\[
0 = \dot{Q}_{cv} - W_{cv} + \dot{m}_i h_i - \dot{m}_e h_e
\]  

(2)
Energy balance of the power plant at continuous flow condition is given in Equation (2) and subscript \(cv\), \(i\) and \(e\) represent control volume, input and output conditions, respectively. \(Q\), \(W\) and \(h\) are enthalpy terms for net heat transfer, net work flow and unit volume, respectively. The first law of thermal systems (energy) efficiency is

\[
\eta_I = \frac{W_{net}}{\sum_i \dot{E}_i}
\]

as described in Equation (3) and \(\dot{E}_i = \dot{m}_i(h_i - h_0)\) obtained. Exergy is expressed as in

\[
\dot{X} = \dot{X}_{PH} + \dot{X}_{KH} + \dot{X}_{PT} + \dot{X}_{CH}
\]

Equation (4) where in subscripts \(PH\), \(KN\), \(PT\), \(CH\) refer to physical exergy, kinetic exergy and potential exergy and chemical exergy, respectively. Specific exergy \(\psi\) and exergy \(X\) expression for the plant is as follows,

\[
\dot{X} = \dot{X}_{PH} = \dot{m}\psi = \dot{m}[(h - h_0) - T_0(s - s_0)]
\]

are defined as. Exergy destruction of system can be defined as follow:

\[
\dot{X}_{dest} = \sum_i \dot{X}_i - \sum_o \dot{X}_o
\]

The second law (exergy) efficiency and exergy losses of organic Rankine power plant are expressed as

\[
\eta_{II-plant} = \frac{W_{net}}{\sum_i \dot{X}_i}
\]

\[
i = \sum_i \dot{X}_i - W_{net}
\]

Equations (7)-(8).

5. Results and discussion

This study investigated the availability of waste heat in Germencik Geothermal Power Plant and analyzed the performance of 7 different single-component refrigerants in the simple binary geothermal power plant. Mass, energy and exergy balance equations were solved under the same inlet conditions to verify calculations for 7 different refrigerants. Selection of an appropriate working fluid has a great effect on the performance of binary geothermal power plants. For this reason, single-component refrigerants were preferred for the power plant given in Figure 1. The refrigerants analyzed in our study are R-134a, R-152a, R-227ea, R-236fa, R-600, R-143 and R-161. These refrigerants were selected and analyzed as they were suitable for the operating conditions of the power plant. The critical temperature and pressure of the selected refrigerants were taken into account and the inlet temperature and pressure of the working fluid in the power plant were selected as 85°C and 900 kPa, respectively. In addition, the freezing point of the refrigerants is below the ambient temperature, which
may cause solidification during the operation of the system. As also stated in section 3, the selected refrigerants work under the conditions given in the binary cycle. Owing to these reasons, this study investigated the performance of 7 different refrigerants with different characteristics. In this study, the dead state temperature and pressure are 278 K and 101.325 kPa, respectively. EES software program was used to calculate the properties of the geothermal water, working fluids (refrigerants) and cooling water. Energy and exergy efficiency values of the cycle for the binary geothermal power plant were calculated in Figure 2, which shows that R-600 obtained the best energy and exergy efficiency. R-236fa also showed similar results to R-600 in terms of exergy and energy. R-161 refrigerant, on the other hand, showed the worst energy and exergy performance. Although R-600 (\(\dot{m} = 24.51 \text{ kg/s}\)) and R-161 (\(\dot{m} = 25.63 \text{ kg/s}\)) refrigerants circulated in the cycle at similar mass flow rates, R-600 performed better than R-161. This is due to the thermophysical properties of R-161 refrigerant under the selected operating conditions for the cycle.

Figure 3 shows the exergy destructions for various components in the power plant.

The results indicate that the highest exergy loss occurred in the heat exchangers and that, in the cycle, the other exergy losses were lower than that in the heat exchangers, which shows that heat exchangers play an important role in determining the performance of a power plant. Net work output is an important parameter affecting the performance of binary geothermal power plants. High net work output improves the power plant performance. Net work is defined as the difference between the generated and consumed work. In this study, the net work is the difference between the work generated in the turbine and the work consumed in the pump. Figure 4 shows the net work output for the refrigerants studied. According to the results of the analysis, R-600 had the highest net work output.
followed by R-236fa, R-227ea, R-143m, R-152a, R-134a and R-161 refrigerants.

6. Conclusions
It is a known fact that working fluids used in binary geothermal power plants, inlet temperature and pressure of waste heat geothermal fluid, re-injection temperature of geothermal fluid and environmental conditions have an effect on power plant performance. The analyses indicate that the heat exchanger (evaporator) has a great impact on the performance of the power plant. Increased exergy losses in the heat exchanger reduced the energy and exergy efficiency. It was observed that R-161 refrigerant had low energy and exergy efficiency and the lowest net work output, while it caused the maximum exergy destruction in the heat exchanger. In the exact opposite situation is obtained for R600 refrigerant. It is, therefore, important to take exergy destructions in the heat exchanger into account when selecting a suitable working fluid. The selected working conditions for the power plant in question also significantly affect net power generation and the losses in the power plant equipment. According to the results of analysis, the working fluid mass flow rates obtained for R-161 and R-600 refrigerants are very close to each other. While there was maximum exergy loss in R-161 refrigerant in the heat exchanger, the net power generation was the lowest. This is due to the small difference in enthalpy between the turbine inlet and outlet, which is one of the operating conditions of the designed power plant. In the exact opposite situation, the net power generation increased as the difference in enthalpy between the turbine inlet and outlet of R-600 refrigerant was higher than the operating conditions. In geothermal binary power plants, energy efficiencies range from 1 to 14% while exergy efficiencies range from 8 to 55%. The exergy efficiency was higher than the energy efficiency in the geothermal binary power plant in question which uses low-temperature geothermal resources as energy source. These results are consistent with the literature [21, 22]. Due to their good performance, single-component refrigerants are preferred in ORC power plants worldwide in general. Irem [23] and Dora-I,II [24], [25] binary geothermal power plants in Aydin, Turkey, operate according to an ORC and use n-pentane fluid as a secondary working fluid. N-pentane was not selected for this study as it did not meet the operating conditions of the power plant in question. In this study, R-600 refrigerant showed the best performance depending on the operating conditions of the power plant. Therefore, R-600 can be the refrigerant of choice in similar ORC power plants. However, air and environmental pollution, global warming and ozone depletion should also be taken into consideration when selecting a suitable working fluid. In addition, the flammability and toxicity values of an appropriate working fluid should be as low as possible. Selection of a suitable working fluid for geothermal power plants should be based on the optimum thermodynamic, thermophysical and environmental properties. Considering all the factors; high energy and exergy efficiencies, reasonable operating conditions, low ozone depletion rate, global warming potential, non-toxicity and non-flammability, it is not easy to find an ideal working fluid.

7. References
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