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Thermodynamic Analysis on the Performance of a Low-Enthalpy Geothermal Field Using a CO_2 Supercritical Binary Cycle

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The exploitation of geothermal energy can play a significant role for providing clean and renewable energy, especially when environmentally-friendly working fluids are used for power production. Along these lines, in the present work a thorough analysis is attempted on the thermodynamic performance and the power production potential of a binary cycle, using supercritical carbon dioxide (sCO_2) as working fluid, for the exploitation of a low-enthalpy geothermal field, located in Sidirokastron, Greece. As regards the associated analysis, simplified thermodynamic models of the sCO_2 cycle were developed, attempting to incorporate the binary-cycle main components performance characteristics, based on the literature-available data of similar applications. For further improvement of the thermodynamic cycle performance, the use of preheating of the working fluid after the condenser, with the use of solar power, was also considered. The effect of cycle heat-addition pressure and heat-rejection temperature conditions were assessed through parametric studies, taking into consideration the annual regional variations. Furthermore, the effect of the technology level of the critical cycle components, such as the heat exchangers, on the thermodynamic cycle performance was considered. The results were compared to similar, low-enthalpy configurations described in literature. The aforementioned analysis clearly reveals the effect of cycle-operating conditions on the thermodynamic performance of the binary cycle and the high potential of using sCO_2 as working fluid, for the exploitation of low-enthalpy geothermal fields, in the pursue of an environmentally-friendly power production.

1. Introduction

The continuous increase of world population has led to a significant increment of energy demands, the major part of which is currently covered by using fossil fuels which, however, have a detrimental impact on the environment, through the increase of pollutants emissions. The gradual transition from fossil fuels to renewable energy sources can provide a sustainable roadmap to energy sufficiency, economic growth and environmental protection. In this direction, the exploitation of geothermal energy sources can play a significant role. More specifically, much research is now available (see, Chen, 2011), that targets to the utilization of low-enthalpy geothermal energy sources, to properly investigate their potential, since low-enthalpy geothermal fields compose more than 40% of the total geothermal energy potential in the South-East Europe (Sigfusson and Uihlein, 2015). In these works, there is a particular interest in the utilization of environmentally-friendly working fluids for providing clean power production.

In this context, at the present work a thorough analysis on the thermodynamic performance and the power-production potential of a binary cycle that uses supercritical carbon dioxide as working fluid was performed. The reason for this study rests in the exploitation of a low-enthalpy geothermal field located in the region of Sidirokastron, a city in Northern Greece. The selection of carbon dioxide as working fluid provides significant benefits, since it is non-toxic, non-combustible, relatively inexpensive, non-explosive and abundant, as mentioned in Chen et al. (2006). Furthermore, carbon dioxide is an environmentally friendly working fluid, since it possesses a low Global Warming Potential (GWP = 1) and no Ozone Depleting Potential (ODP), as mentioned in Chen (2011). Of course, other, more conventional, working fluids can also be considered for

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geothermal applications as presented in the work of Tian and You (2018). Currently, the utilization of low-enthalpy geothermal energy sources in Greece is limited to agricultural applications for heating greenhouses (see, e.g., Andritsos et al., 2015). On international level, the attempts to efficiently produce electric power using low-enthalpy geothermal fields are very rare, with the most famous case being the example of Chena Geothermal ORC Power Plant in Alaska (see, e.g., Aneke et al., 2011), which operates with geothermal source temperature of 73.33ºC, cooling water source temperature of 4.44 ºC and R-134a as working fluid. On the other hand, the case study of Seomko-Do in South Korea, with geothermal source temperature of ~70 ºC, as presented in Kho et al. (2014), also demonstrates that, with a careful design, ORC power plants operating with low enthalpy geothermal sources can be efficiently applied for electricity production. Additional efforts for the assessment of the geothermal power potential for low-temperature geothermal resources are presented in the work of Barkaoui et al. (2017).
The present work is a first attempt to quantify, even at a preliminary level, the thermal efficiency of a low-enthalpy geothermal heat source in Greece. The aim of the paper is to show the potential of low-enthalpy geothermal heat source exploitation, which is abundant in Greece. The novelty is focused on the consideration of carbon dioxide as working fluid since the application of sCO_2 in such applications is not easily found in international literature, while at the same time can provide significant environmental advantages.

2. The geothermal field in the region of Sidirokastron, Greece

The geothermal field under study is located in the municipality of Sintiki, Serres, in the broader area of the Greek town Sidirokastron (see Figure 1). In this geothermal field, the maximum temperature of the low enthalpy reservoir is 75 ºC, as earlier studies – performed by the Greek Institute for Geological and Mineral Exploration (IGME) between 1983 and 2011 – have confirmed.

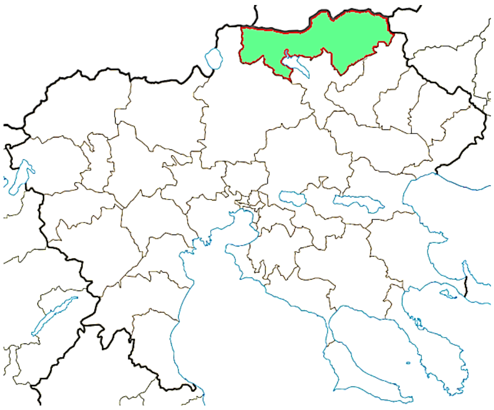

Figure 1: The region of Sidirokastron in the Municipality of Sintiki, Greece, where the geothermal field under study is located.

3. The geothermal installation models

For the assessment of the supercritical carbon dioxide binary cycle simplified models of the geothermal binary cycle plant using the CAPE-OPEN/COCO software, (COCO - the CAPEOPEN simulator, 2018) were developed. At the present work, two variations of the geothermal power plant installation are considered, as shown in Figures 2 and 3. More specifically, the geothermal power plant installation model of Figure 2 consists of a combination of heat exchangers (evaporators, internal heat exchangers-recuperators, condensers), pumps (brine pump, feed pump), turbine and valves. The geothermal installation consists of three separate flow circuits, the first one for the geothermal water, the second one for the supercritical carbon dioxide and the third one for the cooling water. Furthermore, in the geothermal power plant installation model shown in Figure 3, an additional water circuit has been added, which is heated by a solar collector, aiming at the preheating of the working fluid after the condenser, in order to improve the thermodynamic cycle performance. In both models, internal heat exchange is performed with the use of an intermediate heat exchanger, to reduce the water-cooling requirements. In both models, the thermo-physical properties of the models for the carbon dioxide were based on the Peng-Robinson equation of state following the conclusions of Mohan et al. (2013), while water-properties tables were used for the geothermal and cooling water circuits.

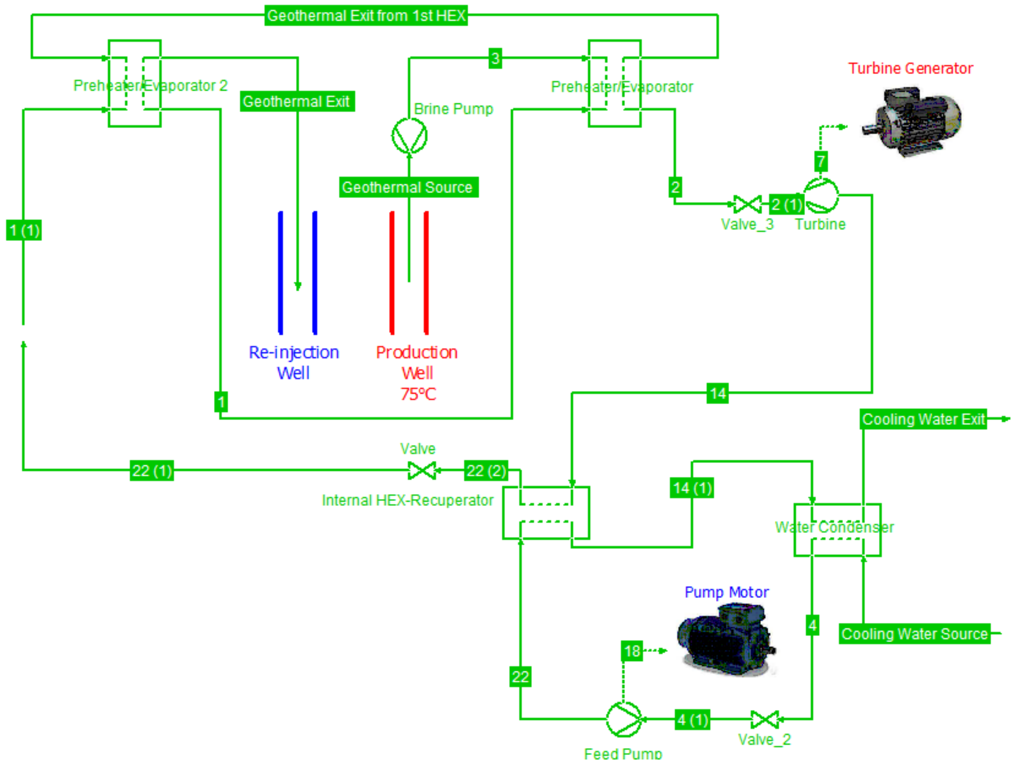

Figure 2: Model of geothermal installation with the use of intermediate heat exchanger

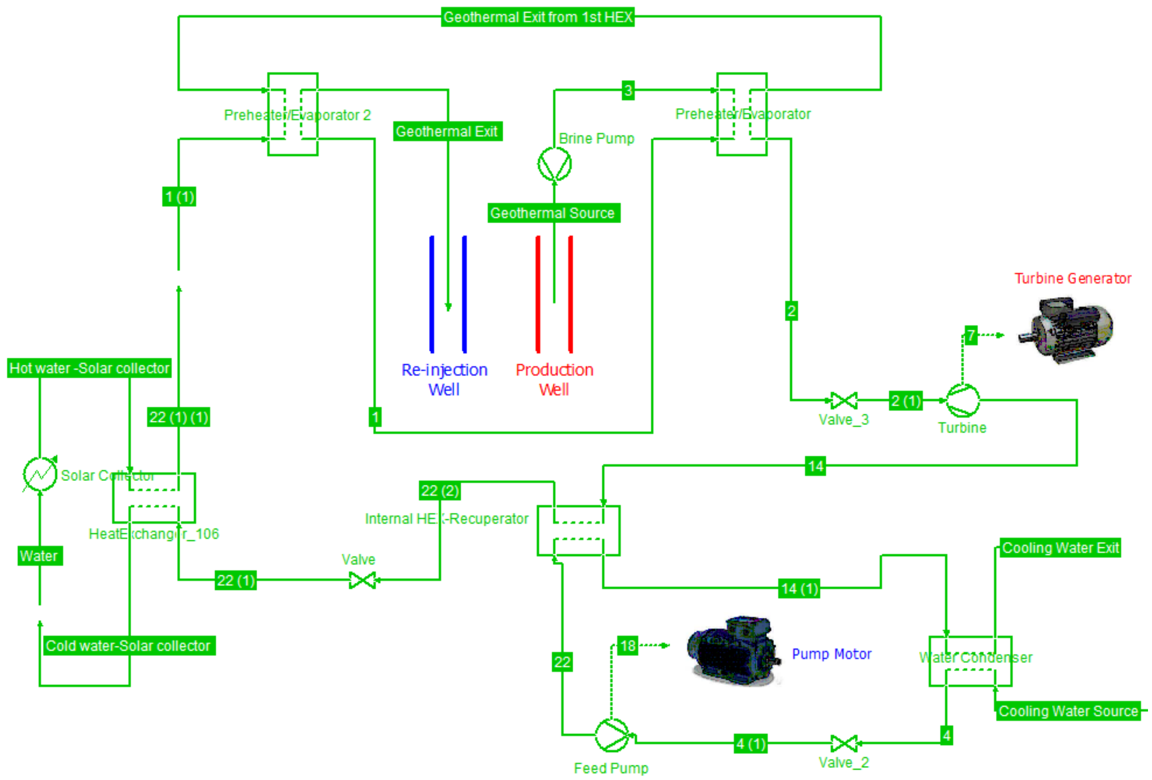

Figure 3: Model of geothermal installation with the use of intermediate heat exchanger and solar collector preheater

4. The geothermal installation components performance characteristics and operational conditions

The performance of the supercritical carbon dioxide binary cycles is strongly affected by the performance of the geothermal installation components, in relation to the cycle thermodynamic conditions. At the present work, these values were selected, mainly, based on the conclusions of the work of Chen et al. (2006) and Chen (2011), as presented in Table 1. Regarding the geothermal cycle operational conditions, the geothermal water temperature was selected equal to 75 ºC, i.e., at the maximum temperature of the low enthalpy reservoir, and the condensation cooling water temperature was taken to range between 8.3 ºC and 23.8 ºC, to attribute the annual variations of the cooling water temperature to the region of Sidirokastron (from January to August, see Figure 4). Regarding the gas heater pressure, typical pressure values for supercritical carbon dioxide cycles were selected, ranging from 100 to 120 bar. All these values were applied to the models of the geothermal installation, in order to assess its performance. The intermediate heat exchanger was used only in the cases where the turbine outlet temperature was higher than the pump outlet temperature, in order to reduce the water-cooling requirements. In every other case, the effect of the intermediate heat exchanger was not considered. The geothermal water mass flow was always set equal to the value of the geothermal field mass flow rate while the cooling water mass flow rate was properly adjusted in each case in order to achieve full condensation of the carbon dioxide at the condenser outlet. The heat exchangers pressure losses were not considered in this analysis since the prime target was focused on the heat exchange and heat utilization processes of the geothermal installation cycle and thus, the heat exchange processes were considered as isobaric. The turbine pressure ratio was adjusted each time in order to have full vapour phase at the turbine outlet and also achieve a mean temperature difference for the carbon dioxide condensation process of ~10 degrees, following an approach similar to the one of Chen et al. (2006). In all cycle conditions the carbon dioxide mass flow rate was adjusted targeting a net power of approximately 300 kW. The utilization of the solar collector for preheating the intermediate heat exchanger outlet with hot water at 45 ºC (heated by solar power) was also considered for the most promising cases in order to assess possible further improvement in the geothermal installation cycle thermal efficiency, even though the implementation of solar collectors would result in additional cost for the power plant and, therefore, additional analysis should be performed to conclude on the actual benefit of such an approach. Such analysis is planned to be performed in the near future which will include a technoeconomic feasibility study.

Table 1: Cycle components performance for the sCO_2 binary cycle

Parameter	Typical value
pump efficiency	80 %
turbine efficiency	80 %
geothermal heat exchangers effectiveness	90 %
Intermediate heat exchanger effectiveness	90 %
condenser effectiveness	95 %
gas heater pressure	100 - 120 bar

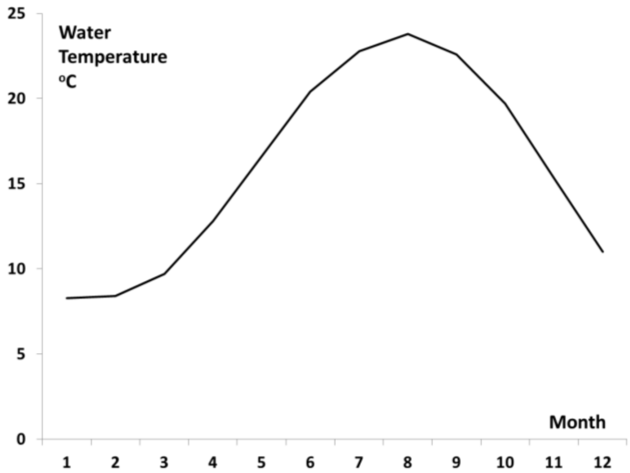

Figure 4: Water temperature annual variation – on a monthly basis – for the region of Serres, Greece

Furthermore, at the present work a constant effectiveness approach was applied for the heat exchangers of the geothermal cycle following an approach similar to the one presented in the work of Salpingidou et al. (2018). In the future a more detailed comparison is planned to be performed which will include the calculation of the dimensions of the heat exchangers of the geothermal cycle and the calculation of the developed heat transfer coefficients in both flow streams so as to calculate the overall heat transfer coefficient. The methodology will follow the methodology presented in the work of Germakopoulos et al. (2018).

5. Thermodynamic performance of the geothermal installation

A summary of the investigated cases in this work is presented in Table 2, together with the achieved thermodynamic cycle thermal efficiency values. The results of Table 2 are also illustrated in Figure 5 for a clearer interpretation of the thermal efficiency variation of the various cases under investigation. As it can be seen the thermal efficiency of the binary cycle using supercritical carbon dioxide achieves values in the range of ~4 to ~10%, which is a typical range for low enthalpy geothermal applications, since such installations are characterized by low temperature ratios and low thermal efficiency values, e.g., below 10 %.

Table 2: Summary of investigated cases conditions

Case	Cooling water temperature [ºC]	Heat addition pressure [bar]	Intermediate heat exchanger use	Solar collector utilization	Components efficiency	Thermal efficiency [%]
1	8.3	100	No	No	Table 1	6.20
2	8.3	120	No	No	Table 1	5.76
3	15.95	100	Yes	No	Table 1	5.18
4	15.95	120	No	No	Table 1	5.36
5	23.8	100	Yes	No	Table 1	4.41
6	23.8	120	No	No	Table 1	4.28
7	8.3	100	No	Yes	Table 1	9.63
8	8.3	100	No	No	85 % for turbine and pump	7.03

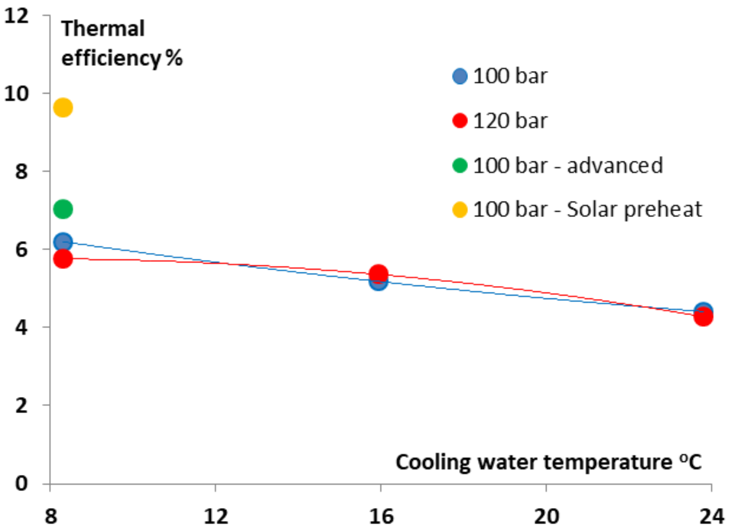

Figure 5: Thermal efficiency variation in relation to cooling water temperature and gas heater pressure

6. Conclusions

This article is focused on the thermodynamic analysis of a low enthalpy geothermal power plant, operating with a binary cycle that uses supercritical carbon dioxide as working fluid. The thermodynamic models developed, included the effect of the performance characteristics of the binary cycle main components, together with the effect of different cycle operational conditions, such as heat addition pressure and heat rejection temperature. In addition, the preheating of the working fluid, upon the use of solar power, was also assessed. The analysis was performed using the cycle thermal efficiency as the main criterion, by targeting an almost constant net power generation of the geothermal power plant in order to have a proper comparison between the various cases under investigation.

In view of the thermodynamic cycle analysis presented in Figure 5, the following conclusions are derived:

i) the geothermal power plant (using typical components efficiencies and without solar preheating) can achieve thermal efficiency over 6 %, i.e., a value close to the thermal efficiency of the most well-known examples of such applications, as, for instance, in the case of the low-enthalpy geothermal plant in Hot Springs, Alaska, which achieves an 8.2 % cycle efficiency, by utilizing geothermal water temperature of 73.33ºC and cooling water temperature of 4.44 ºC (Aneke et al., 2011).

ii) the achieved cycle thermal efficiency value is reduced by ~2 % as the cooling water temperature increases from 8.3ºC to 23.8ºC for both heat addition pressure values.

iii) the effect of the efficiency advancement of the main cycle components (i.e., turbine and pump efficiency) on the cycle thermal efficiency has been assessed (in the Nr 8 case of Table 2) by using more advanced efficiency values for both components (i.e., 85 %), thus resulting in a noticeable increase in the cycle thermal efficiency, which can surpass 7 %.

iv) the utilization of a solar-collector preheating can increase the cycle thermal efficiency up to 9.63 %, even though, in this case, a detailed technoeconomic analysis would be necessary in order to assess the long-term benefits of the additional investment cost. Such an analysis is about to be performed in a future work.

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