Thermodynamic analysis to a geothermal power plant

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Abstract

In the current situation of climate change, the use of geothermal energy is becoming increasingly important. As a source of renewable energy, it avoids the problems related with the use of fossil fuels, namely the pollutants emissions.
Its exploration is growing globally and is especially applied in regions with volcanic origin, such as the Azores Islands, namely on São Miguel and Terceira.
The main purpose of this master thesis is the thermodynamic analysis of a geothermal power plant – through use of an algorithm developed in MATLAB – taking into account the geothermal wells degradation, based on the design conditions of Pico Alto geothermal power plant, on Terceira island.
The cyclopentane, working fluid currently used, was compared with R141b and n-Pentane, both fluids referenced in articles as fluids that present good results in the operation of a geothermal power plant. In this analysis, it was concluded that, under the current working conditions, the cyclopentane is the most suitable choice. In addition, by doing a sensitivity analysis for the maximum cycle pressure and superheating, it was possible to understand the impact of both variables in the thermodynamic cycle. The existence of a minimum reinjection temperature imposes a limit to the maximum pressure value. On the other hand, the comparison between a saturated cycle and a superheated cycle, showed that, superheating improves the cycle's useful power and the efficiency with values of [13,7;33,3]%, as well as increasing the reinjection temperature.
Keywords: Geothermal power plant, Binary cycle, Geothermal wells degradation, Azores

1. Introduction

1.1. Motivation

The widespread use of fossil fuels since the beginning of the industrial revolution has been threatening the survival of marine and terrestrial ecosystems, with devastating social and economic consequences in short term. The various climate summits have been warning for the need of a drastic reduction in carbon dioxide emissions, in the order of 50%, which requires an urgent conversion of energy production systems, giving priority to the use of renewable energies.

Among many environmentally friendly energies that are known, geothermal energy should be highlighted. The energy produced through the heat coming from within the Earth has, in relation to other renewable energies, the advantage of a non-intermittent operation, contrasting with wind or solar energy (both thermal and photovoltaic).

Comprehensibly, not all countries have the possibility to explore geothermal energy, which is especially indicated in regions with volcanic origin. In this field, the Azores Archipelago has all the necessary conditions for the exploitation of this resource, which started in 1980, with the first power plant in São Miguel island.

The Azores Islands are at the junction of three tectonic plates. It consists of nine islands, distant from each other, which justifies that geothermal energy is a priority in decentralised energy production.

Finally, the motivation in choosing this theme emerged from the interest in understanding and predicting how this geothermal power plant under study, based on the design conditions of a recent geothermal power plant, will work over the years, taking into account the geothermal wells degradation.

1.2. Objectives

The main objective of this dissertation is to analyse, throughout its lifetime, the operation of a geothermal power plant, considering the geothermal wells degradation, using the design conditions of Pico Alto geothermal power plant, on Terceira island. It is not intended to carry out the thermodynamic analysis of this power plant, since the current working conditions are not known.

In order to consider the geothermal wells degradation, its necessary to vary the temperature and mass flow rate of the geothermal fluid.

Furthermore, the behaviour of the power plant with other parameters was analysed, changing the working fluid, alongside with the maximum cycle pressure and the superheating degrees. The results of the respective changes were then compared with those initially placed in operation at the power plant, in order to conclude if the choices were correctly made or if it is more advantageous to change the variables.

2. Background study

2.1. Geothermal energy

Geothermal energy is a renewable energy produced through the heat coming from the Earth's core. When the magma reaches the groundwater in circulation, heats it up, resulting in high pressure hot water reservoirs (Figure 1). In volcanic regions, this water can reach the surface as steam and be extracted through perforations.

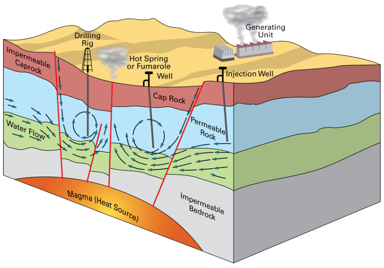

Figure 1: Geothermal energy [1].

These areas of the earth's crust are located at high depths, where the knowledge of fluid movements is not rigorous, and therefore it is difficult to predict how the reservoir will behave over the years.

As is known, the characteristics of each reservoir vary among themselves and the geothermal fluid can present different types of physical states, such as superheated vapour (also known as dry steam), saturated vapour, mixture of saturated liquid and saturated vapour and compressed liquid. The liquid part of the geothermal fluid, called brine, consists of high concentrations of salts and sulphur.

Depending on the temperature at which the geothermal reservoir is located, these can be named as high enthalpy resources, for temperatures above 220 ºC, medium enthalpy resources, for temperatures between 100 ºC and 220 ºC, or low enthalpy resources, where temperatures are below 100 ºC [2]. According to this classification, geothermal energy can be used for different purposes, such electricity production or direct use.

Despite the initial high costs, the principal disadvantage of this energy, geothermal energy is a strong competitor to the fossil fuels, once it is considered not only a clean, sustainable and flexible energy, but also allows a reduced maintenance [3].

2.2. Geothermal energy around the world

Since the beginning of mankind, this type of heat has been used by Man for different purposes, such as cooking, comfort or medicinal ends. Over the years, it was also possible to use it to produce electric energy.

Currently, the production of electricity using geothermal energy is widely used around the world, increasing progressively from year to year, as shown in Figure 2.

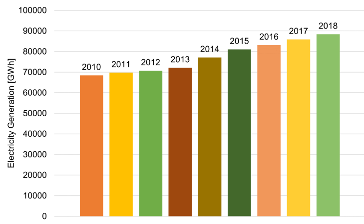

Figure 2: Electricity generation, using geothermal energy, in the world over the years [4].

2.2.1 Portugal

In Portugal, the production of electricity from geothermal sources is restricted to the Autonomous Region of the Azores.

The Azores Islands are located in the Atlantic Ocean, at the junction of three tectonic plates: North American, Eurasian and African, forming the "Azores Triple Junction" (Figure 3). Due to its location, intense seismic and volcanic activity is frequent.

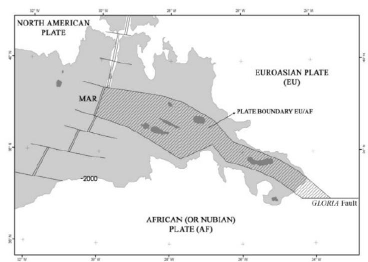

Figure 3: The Azores Islands location [5].

An important aspect in these nine islands is the isolation and distance they have from each other, which favours energy decentralisation.

In terms of using geothermal energy, of the nine islands in the archipelago, there are two islands, namely São Miguel and Terceira, where there are geothermal power plants in operation, belonging to the company EDA Renováveis, S.A.

In São Miguel, two geothermal power plants are operating: Pico Vermelho geothermal power plant and Ribeira Grande geothermal power plant. Currently, the installed capacity is 27,8 MW, and the production capacity of both power plants is expected to increase to 30 MW [6], until 2021. In 2018, the geothermal energy produced in São Miguel represented about 42,0% of the island's consumption and about 23,1% of the total consumption of the nine islands.

Regarding Terceira island, it is here that is located the power plant used as example for this study, Pico Alto geothermal power plant. It has been operational since August 2017, when began the first phase of exploration with three production wells and one for reinjection and a capacity of 4 MW. A second phase of exploration is expected, striving to increase the power plant's capacity to around 10 MW, until 2021. The production of this power plant represented, in 2018, 10,8% of the island's consumption and 2,6% of the consumption registered in the entire archipelago.

2.3. Geothermal power plants

2.3.1 Electricity production

The production of electricity through heat, that is originated from the interior of the planet, can be carried out considering different processes, depending on the characteristics of the geothermal fluid. Therefore, we can highlight three types of technologies, namely dry steam, flash steam and binary cycle (Figure 4).

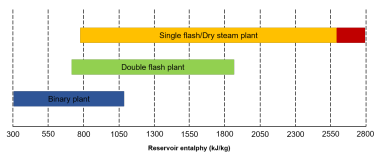

Figure 4: Conversion technologies as function of the enthalpy per unit of mass of the geothermal reservoir [7].

The power plants that operate with binary cycle are used when the enthalpy of the geothermal fluid is low. These power plants work using the Organic Rankine Cycle (ORC), in which there is the use of one more fluid, the working fluid.

In these power plants, the geothermal fluid transfers heat to the working fluid in exchangers, promoting the exchange between both without mixing.

The working fluid must satisfy several requirements, that can be consulted in [2, 8].

2.3.2 Reinjection process

Over the years and with the possible over-exploitation of the power plant, occurs the geothermal reservoir degradation, causing the loss of qualities, such as ideal pressure and temperature. With the implementation of the reinjection well, the geothermal fluid, after going through the thermodynamic cycle, is injected back into the reservoir, to ensure its pressure and temperature are kept in optimum values, as represented in Figure 5.

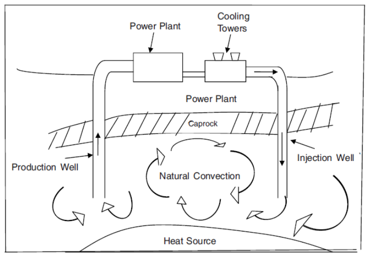

Figure 5: Production and reinjection well of a geothermal power plant, [9].

In addition, the environmental impact of the implementation of a reinjection well must be emphasised, since, with this well, most of the non-condensable gases such as carbon dioxide (CO_2) and hydrogen sulphide (H_2S) are also injected. When reinjected, they help the reservoir to maintain its pressure, improve its productivity and inhibit the formation of silica [10].

Finally, the reinjection temperature presents an interval with lower and upper limits that are very rigid, since can occur the formation of silica, the heat transfer process with the working fluid can be impaired, compromising the efficiency of the entire power plant, and may occur the geothermal reservoir degradation [11].

2.3.3 Geothermal reservoir degradation

All reservoirs have optimal characteristics to be explored, which vary according to the geographical areas. In this regard, it is necessary to understand what these ideal properties are and maintain them over the years, so that the power plant can be in constant operation.

An aspect of great relevance regarding the wells degradation is the temperature control during the reinjection process. As already mentioned, the injection of fluid at very low temperatures (below 70 ºC) reduces the temperature of the reservoir, influencing its long-term behaviour.

3. System description and modelling

3.1. Geothermal power plant under study

The geothermal power plant under study was analysed using data from Pico Alto geothermal power plant. It has three production wells (Figure 6) and a reinjection well, working with a binary cycle and using cyclopentane as working fluid.

In each of the production wells, the geothermal fluid at the well's exit goes to a separator, where occurs the separation between steam and brine. Then, the brine of each well goes through a pump and, after being mixed, enters the production system of the power plant. The steps of separation, mixing and entering the production system take place, similarly, for steam.

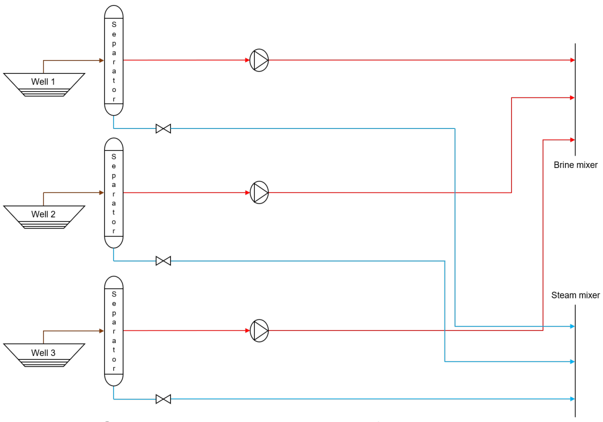

Figure 6: Separation and mixing steps for the three production wells of the geothermal power plant under study.

According to the data provided from Pico Alto geothermal power plant, the geothermal power plant under study is represented in Figure 7.

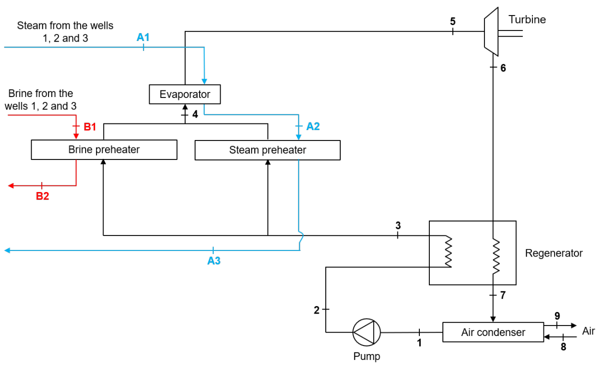

Figure 7: Geothermal power plant under study.

As Figure 7 shows, the geothermal fluid transfers energy, as heat, to the cycle fluid, in the evaporator and in two preheaters. After passing through these exchangers, the geothermal fluid goes to the reinjection well.

For the working fluid, after receiving heat from the geothermal fluid, it passes through a radial turbine, where the fluid expands, reducing pressure and enthalpy. Then, it goes to a regenerator, where takes place a preheating process before entering the exchangers previously mentioned. The cycle transfers energy, as heat, to the outside, in an air condenser with forced air convection.

3.2. Modelling and simulation

3.2.1 Thermodynamic analysis

For the implementation of the developed algorithm, energetic and exergetic analysis were made not only at the components, but also globally, using mass, energy and exergy balances equations exposed in [12].

Assuming that the components work in a steady and adiabatic regime, and disregarding the contributions of potential and kinetic energy, the equations previously mentioned are simplified:

$$\iint \rho \; \overrightarrow{v} \; . \; \overrightarrow{n} \; dA = 0 \tag{1}$$

$$-\dot{W} = \iint h\rho \; \overrightarrow{v} \; . \; \overrightarrow{n} \; dA \tag{2}$$

$$-\dot{W} - \dot{E}_d = \iint e_f \rho \; \overrightarrow{v} \; . \; \overrightarrow{n} \; dA \tag{3}$$

After doing the balances for each component, the global energetic and exergetic balances are:

$$\eta_{en} = \frac{\dot{W}_{ciclo}}{\dot{Q}_{in}} \tag{4}$$

$$\eta_{ex} = \frac{\dot{W}_{ciclo}}{\dot{E}_{in}} \tag{5}$$

Also, is important to refer that, due to the geothermal wells degradation, the working conditions of the turbine will vary over time. In [13] is suggested a method to calculate the turbine isentropic efficiency in off-design conditions.

3.2.2 Imposed conditions and acquired data

For the initialisation of the algorithm, some values and hypotheses were assumed:

1. The isentropic efficiency of the turbine, pump and regenerator were established at 85%, 85% and 68%, respectively;
2. The minimum reinjection temperature was considered to be 70 ºC;

3. The ambient temperature and pressure were established at 17,1 ºC and 1 bar, respectively;
4. The useful lifetime of the geothermal power plant was established at 30 years;
5. The head losses in the ducts and heat exchangers were considered negligible;
6. The presence of non-condensable gases was not considered;
7. It was considered that the efficiency of the generator coupled to the turbine was equal to 100%;
8. The properties of the geothermal fluid were assumed to be those of water.

The data used as example for this study, given by the company EDP, S.A., is exposed in Table 1.

Table 1: Initial data used in the algorithm.

Pressure at point 1 (p_1)	0,66 bar
Pressure at point A1 (p_{A1})	5,50 bar
Pressure at point A2 (p_{A2})	5,46 bar
Pressure at point A3 (p_{A3})	5,41 bar
Pressure at point B1 (p_{B1})	10,00 bar
Pressure at point B2 (p_{B2})	8,99 bar
Mass flow rate at point A1 ($\dot{m}_{A1}$)	9,1 kg/s
Mass flow rate at point B1 ($\dot{m}_{B1}$)	14,4 kg/s
Temperature at point A1 (T_{A1})	159,5 ºC
Temperature at point B1 (T_{B1})	174,8 ºC

Regarding the geothermal wells degradation, it was followed the Budisulistyo *et al.* [13] approach, analysing the power plant considering the following years: 1, 7, 16 and 30. In the adopted degradation scenario, there is a decrease of 0,1 ºC/year in the temperature of the geothermal fluid at the entrance of the power plant, as well as a decrease in its mass flow rate to 75% of the initial value in year 7, and for 65% of the initial value from year 16 (Figure 8).

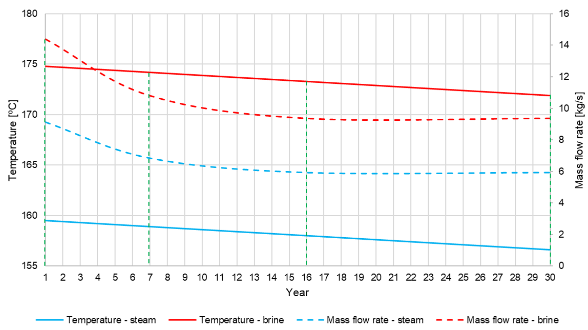

Figure 8: Temperature and mass flow rate of steam (point A1) and brine (point B1) as function of the useful lifetime of the geothermal power plant.

3.2.3 Algorithm description

To simulate the geothermal wells degradation of the power plant, an algorithm was developed in MATLAB, imposing the conditions referred in Section 3.2.2. In addition, an online library, CoolProp [14], was used in order to obtain the properties of both fluids (geothermal fluid and working fluid), in the sections indicated in Figure 7.

The main objective of the algorithm (Figure 9) is to calculate the cycle's useful power, exergy destruction rate and energetic and exergetic efficiency.

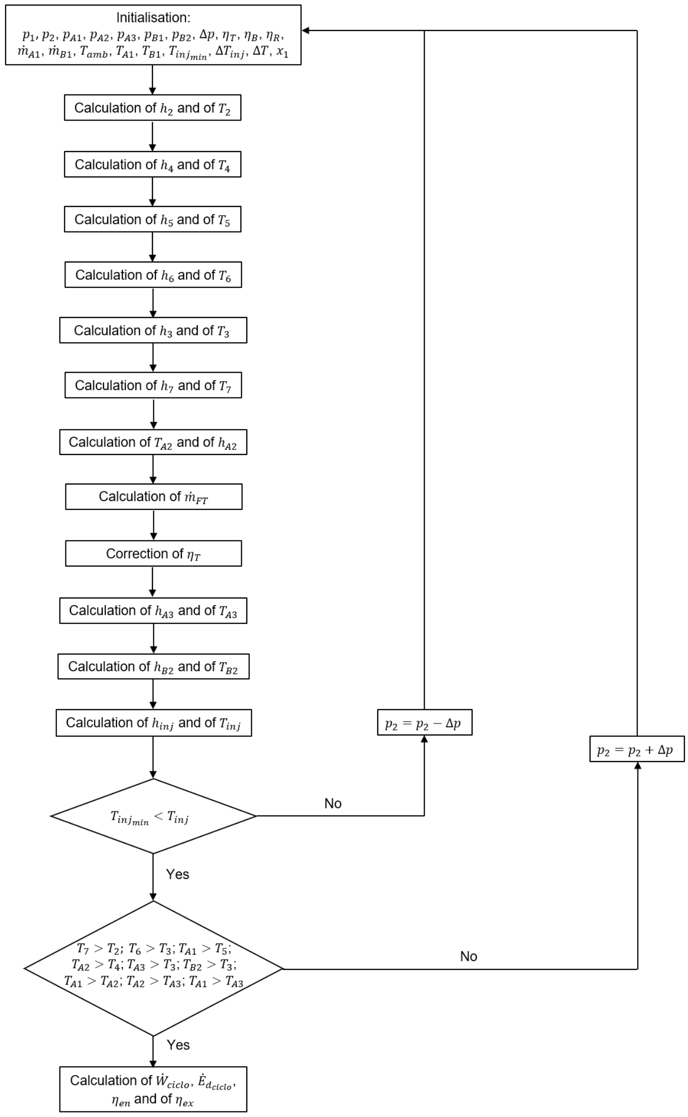

Figure 9: Algorithm developed in MATLAB.

4. Results

In this chapter, the geothermal wells degradation is studied and a sensitivity analysis is made to the pressure p_2 and to the superheating degrees ΔT_{sa}.

In the degradation study, the current working fluid (cyclopentane) is compared with R141b and n-Pentane over the lifetime of the power plant. These last two fluids were chosen because were referenced by Aali *et al.* [8] and Hettiarachchi *et al.* [2], as good working fluids for presenting good results in geothermal power plants, namely in the variables cycle's useful power, energetic and exergetic efficiency.

In both sensitivity analyses, is considered only the cyclopentane in the first year of operation of the geothermal power plant.

4.1. Geothermal wells degradation

As indicated in Figure 9, it is necessary to initialise the algorithm with a pressure p_2, which validates all imposed conditions, taking into account the initial data referred in Table 1. Therefore, the pressure p_2 used in the power plant is 6,55 bar.

In order to have the power plant operating under the best parameters, an analysis is made to the values of ΔT and x_1 in year 1.

It can be concluded that the values of ΔT and x_1 that maximise the cycle's useful power and the efficiencies are 19 ºC and 0,2, respectively. The value of ΔT will be maintained throughout the analysis of the wells degradation.

For R141b, the maximum allowable pressure p_2 is 4,80 bar. For this fluid, based on the analyses of x_1, the best choice is 0,3.

For n-Pentane, the maximum pressure p_2 is 4,15 bar and the best x_1 is 0,3.

In Figures 10, 11 and 12, the p-h diagram of each working fluid in year 1, were assumed a pressure p_2 of 6,55 bar, 4,80 bar and 4,15 bar for the cyclopentane, R141b and n-Pentane, respectively.

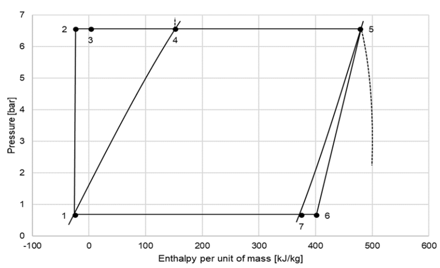

Figure 10: p-h diagram in year 1 for cyclopentane.

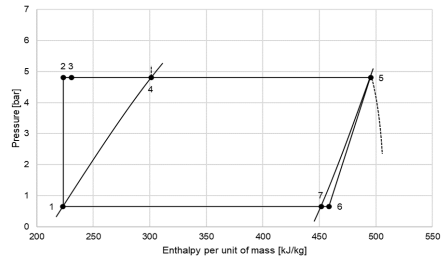

Figure 11: p-h diagram in year 1 for R141b.

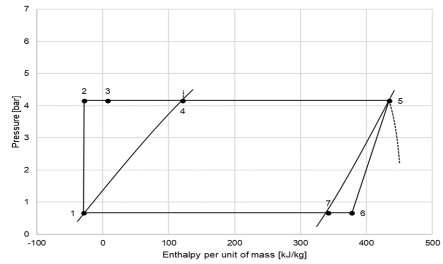

Figure 12: p-h diagram in year 1 for n-Pentane.

As shown, points 1, 6 and 7 have the same pressure: pressure p_1; points 2, 3, 4 and 5 have a different pressure, pressure p_2. According to the figure, points 1 and 4, corresponding to the pump inlet and the evaporator inlet, respectively, have saturated liquid conditions, in contrast to point 5, the turbine inlet, which has saturated steam conditions.

So, it can be concluded that cyclopentane, as it has a higher pressure p_2, will have a greater expansion in the turbine, presenting, consequently, a greater cycle's useful power.

Regarding the exergy destruction rate, according to Figures 13, 14 and 15, the component that has the highest value for all working fluids is the evaporator, because is where the biggest temperature differences between the geothermal fluid and the working fluid are registered.

It should be noted that the components with the highest exergy destruction rate require special attention in their design, since they are the ones that have most influence in the exergetic efficiency of the entire power plant [15].

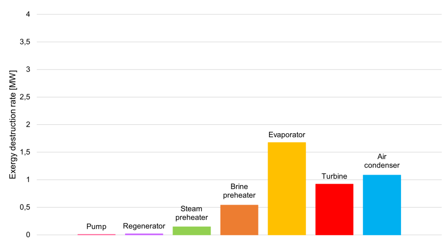

Figure 13: Exergy destruction rate in year 1 for cyclopentane.

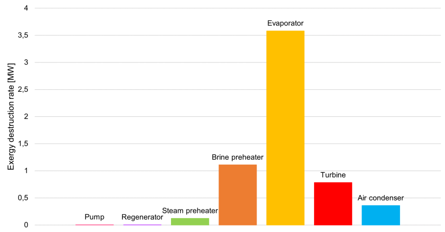

Figure 14: Exergy destruction rate in year 1 for R141b.

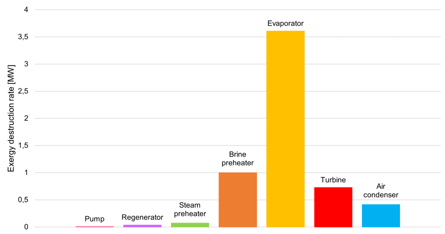

Figure 15: Exergy destruction rate in year 1 for n-Pentane.

Due to the variation of the geothermal fluid conditions, the values of pressure p_2 vary over time, as shown in Table 2.

Table 2: Variation of the maximum cycle pressure over the lifetime of the geothermal power plant, for the working fluids under analysis.

	Cyclopentane	R141b	n-Pentane
Year 1	$p_2 =$ 6,55 bar	4,80 bar	4,15 bar
Year 7	$p_2 =$ 6,50 bar	4,75 bar	4,10 bar
Year 16	$p_2 =$ 6,45 bar	4,70 bar	4,05 bar
Year 30	$p_2 =$ 6,35 bar	4,60 bar	4,00 bar

The Figures 16, 17 and 18 show the evolution over time of the cycle's useful power and energetic and exergetic efficiency. The wells degradation also leads to a deterioration in the power plant's working conditions, between values of [36,3; 37,1]% for the cycle's useful power, [1,3; 1,9]% for energetic efficiency and [1,2; 2,1]% for exergetic efficiency. A further conclusion is that cyclopentane, for the working conditions of this power plant, is the most appropriate choice.

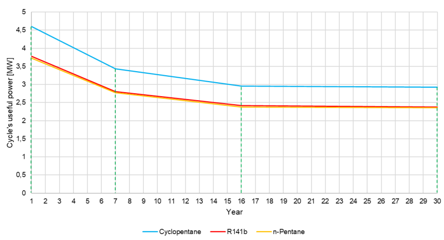

Figure 16: Cycle's useful power as function of the useful lifetime of the geothermal power plant, for all the working fluids.

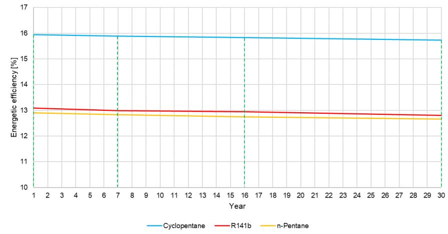

Figure 17: Energetic efficiency as function of the useful lifetime of the geothermal power plant, for all the working fluids.

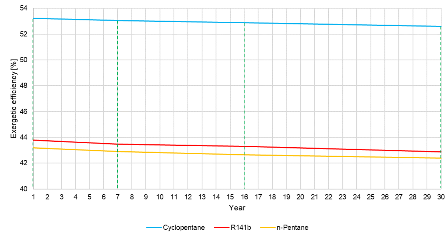

Figure 18: Exergetic efficiency as function of the useful lifetime of the geothermal power plant, for all the working fluids.

4.2. Sensibility analysis

4.2.1 Maximum cycle pressure variation effect

As previously mentioned, this analysis was made only for cyclopentane in the first year of the power plant's life. The pressure p_2 was changed in the range 2,0 bar $\leq p_2 \leq$ 15,0 bar and the pinch point in the range 4 ºC $\leq \Delta T \leq$ 19 ºC, taking into account the constraint $\Delta T \leq T_{A1} - T_{sat(p_2)}$. For each value of the pressure p_2, the value of the pinch point was chosen in order to maximise the cycle's useful power. With this choice, the restriction of the minimum reinjection temperature was only satisfied when it was possible to do so. A x_1 of 0,2 was always considered.

4.2.2 Superheating effect

In the sensitivity analysis to the superheating degrees ΔT_{sa}, the procedure explained above is repeated, but for a ΔT_{sa} of 15 ºC (in the previous analysis $\Delta T_{sa} =$ 0 ºC).

The following figures show the results of the two sensitivity analyses.

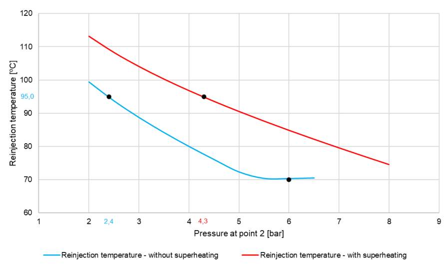

Figure 19: Reinjection temperature as function of the maximum cycle pressure.

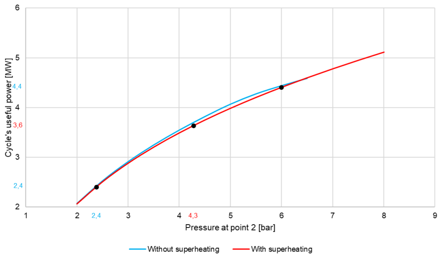

Figure 20: Cycle's useful power as function of the maximum cycle pressure.

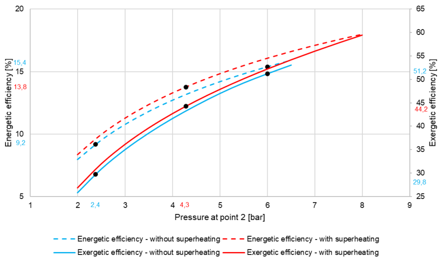

Figure 21: Energetic and exergetic efficiency as function of the maximum cycle pressure.

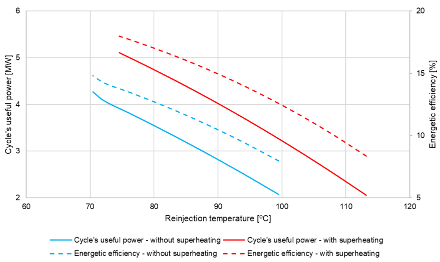

Figure 22: Cycle's useful power and energetic efficiency as function of the reinjection temperature.

Both sensitivity analysis provide two general conclusions:

1. The cycle's useful power and the energetic and exergetic efficiency improve with the increase of the pressure p_2 at the turbine inlet, with a maximum limit for this pressure due to the need to guarantee a minimum reinjection temperature;
2. The cycle with superheating shows better results than without superheating.

The following step is to analyse each figure of the sensibility analysis results:

1. The Figure 19 shows that the reinjection temperature decreases with the increase in pressure p_2, as expected, because the increase in pressure p_2 implies bigger expansion of the fluid in the turbine, biggest cycle's useful power and, therefore, biggest heat power extracted from the geothermal fluid, decreasing the temperature of this fluid at the exit of the cycle. This figure also shows that, with superheating, the minimum set reinjection temperature value ($T_{inj_{min}} = 70$ ºC) does not impose limitations on the pressure p_2, while for a minimum reinjection temperature of 95 ºC, the maximum pressure value at the turbine inlet is 4,3 bar. Without superheating, a maximum pressure p_2 of 6,0 bar is obtained for a minimum reinjection temperature of 70 ºC and a maximum pressure p_2 of 2,4 bar for a minimum reinjection temperature of 95 ºC;
2. The Figure 20 shows that the cycle's useful power increases with the pressure p_2. Comparing the cycle with and without superheating, it is also seen that the values of the cycle's useful power have a little variation, with a maximum of 2,1%, considering the same pressure p_2. However, the domain of possible values for the pressure p_2 associated with the restriction of the value established for the minimum reinjection temperature is higher in the case with superheating, which means that, in this case, the maximum value of the cycle's useful power is 5,1 MW, while, without superheating, the maximum useful power is 4,4 MW. A value of 95 ºC for the minimum reinjection temperature penalises both cycles, but more the cycle without superheating, obtaining, respectively, maximum values for the cycle's useful power of 3,6 MW and 2,4 MW, that is, a relative decrease of 29,4% with superheating, and 45,4% without superheating;
3. The Figure 21 shows that both energetic and exergetic efficiency increase with pressure p_2. This result was expected, because the increase in the temperature difference between the evaporator and the air condenser improves the energetic efficiency of a power cycle. On the other hand, the fact that the temperature of the working fluid in the evaporator approaches the temperature of the geothermal fluid reduces the temperature difference at which the heat transfer occurs, which increases the exergetic efficiency. The Figure 21 also shows that superheating favours efficiencies. Taking into account the restriction of the minimum reinjection temperature of 70 ºC, with superheating, maximum values of energetic and exergetic efficiency of 18,0% and 59,4% are obtained, respectively, whereas, without superheating, the values of energetic and exergetic efficiency are 15,4% and 51,2%, respectively. For the minimum reinjection temperature of 95 ºC the efficiencies decrease, changing to values

of 13,8% for energetic efficiency, and 44,2% for exergetic efficiency with superheating, and 9,2% and 29,8% for energetic and exergetic efficiency, respectively, without superheating. Calculating the relative decreases associated with the minimum reinjection temperature change, a value of 40,3% is obtained for the energetic efficiency and 41,8% for exergetic efficiency, for the case without superheating, and 23,3% and 25,6% for energetic and exergetic efficiency, respectively, for the case with superheating. It is concluded, again, that the case with superheating is less penalised;

4. The Figure 22 shows that when the reinjection temperature increases, the cycle decreases both the useful power and the efficiencies, obtaining, for the same value of the reinjection temperature, higher values of the cycle's useful power, energetic and exergetic efficiency (omitted curve) in the case of superheating. However, in both cases the curves are approximately parallel, which means that the decrease in cycle's useful power and energetic efficiency, per centigrade degree of increase in the reinjection temperature, is similar, obtaining an approximate value of $-$ 77,0 kW/ºC.

5. Conclusions

The Azores Islands, in particular São Miguel and Terceira islands, have characteristics favourable to the use of geothermal energy. The fact that the nine islands are far apart, makes any renewable energy extremely useful in this region, leading not only to less dependence on fossil fuels, but also to the reduction of associated economic costs.

The realisation of the study presented in this dissertation had as main objective to understand the functioning of a geothermal power plant over its useful lifetime, having used, as a reference, the design conditions of Pico Alto geothermal power plant, on Terceira island.

Using an algorithm produced in MATLAB, the geothermal power plant was studied, taking into account the geothermal wells degradation, over its 30 years of life.

The analyses carried out had as main purpose to verify the behaviour of the power plant when subjected to several changes.

First, cyclopentane, the current working fluid, was compared with R141b and n-Pentane. In this analysis, it was found that cyclopentane is the fluid that leads to the best results of the thermodynamic cycle, being, therefore, the most appropriate choice.

In the sensitivity analysis to the maximum cycle pressure, it was found that its increase is beneficial for the operation of the power plant, being the main restriction the reinjection temperature, which decreases as the maximum cycle pressure increases. The need to guarantee a minimum value of reinjection temperature imposes a severe limitation on the cycle operation and is one of the factors responsible for the low energetic efficiency of geothermal power plants (rarely exceeding 15,0%).

Finally, the comparison between the saturated cycle and the superheated cycle allowed us to conclude that superheating is a strategy to be adopted. The cycle's useful power increases, as well as the energetic and exergetic efficiency, and the restriction to the minimum reinjection temperature is guaranteed without limitations of the maximum cycle pressure.

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