CANDITATE'S DECLARATION

We hereby declare that the project report entitled **'Performance analysis of a geothermal power plant. Case study: Comoros'** submitted by us to the department of Mechanical **and Production Engineering** at **ISLAMIC UNIVERSITY OF TECHNOLOGY**, is a record thesis work carried out by us under the guidance of Prof. Dr. Md Nurul Absar Chowdhury. We further declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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‘Performance analysis of a geothermal power plant. Case study: Comoros’

A thesis report submitted to the department of mechanical and production Engineering (MPE), Islamic University of Technology (IUT)

Prepared by:

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Abdoul-enziz Imamou

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Abstract:

The Khathala geothermal field in the Grande Comoros is under development. We propose design of a double flash geothermal power plant, which has a geofluid temperature of 250^0 C. The performance analysis of this double flash geothermal power plant was evaluating by using the second law of thermodynamics, which was based on energy and exergy analysis. COCO Simulator was used to develop and simulate a dynamic model of this geothermal power plant. The energy flow rate, exergy flow rate and efficiency are calculated at several plants components, including the turbine, separator, condenser and for the whole power plant. While doing the calculation, we have accepted dead state temperature of 25^0C, and dead state pressure of 100 KPa. According to the simulation result, the electrical net power output is estimated to be 9.099 MW and 10.03 MW from the Optimum first and second flashing respectively. Based on the exergy of the geothermal fluid at the well reservoir, the overall second and first law efficiencies are calculated to be 6.48% and 27.76%, respectively.

1. Introduction:

Declining energy resources, increasing energy demand, and the environmental impact of conventional energy resources development emphasize the need for a sustainable approach to the management and development of earth's system resources [1]. In this regard, the use of geothermal resources and better understanding of conversion systems are becoming highly more important. The most attractive and demanding geothermal fields for developers are those that produce high enthalpy fluids and high temperature [2]. Geothermal energy has been classified as renewable energy resource [3]. And it is identified as sustainable energy because of its continuous formation process as long as the condition of the geology is maintained [4]. Moreover, the amount of emission released in the energy conversion processes is significantly low and minor comparing to the other conventional fuel resources like gas, coal and oil. This was also reported by Armannsson et Al that the geothermal source has low $CO2$ emission characteristics. The use of geothermal energy for electricity generation was firstly realized in Italy, precisely in Lardrello in 1904, whereby geothermal steam was used to drive a small turbine that was used to power light bulbs. This program was extended and in 1913, a plant with a capacity of 250 KW was connected to the Italian grid system [5]. The development of geothermal power plants has continued up to date, by using various technologies such as dry steam, binary and flash cycles. Huttrer [6] reported that the geothermal power and energy generation statistics for 2015 through 2020 is estimated to 15,950.46 MWe of power and generated 95,098.40 GWh/year of electricity. With respect to the 2020 data, an increase of approximately 3.649 GW has been achieved (about 27%) in the last five-year term 2015-2020. And it has been noted that five new countries generated geothermal power for the first time. They are Chile (48 MWe), Belgium (0.8 MWe), Croatia (16.5 MWe), Hungary (3 MWe), and Honduras (35 MWe). Table 1 lists the ten nations that generate the most geothermal electric power as of 2020 [6].

Despite the small amount of electricity produced by the geothermal source. The future development of this type of energy is becoming attractive because of the increasing of fossil-fuel costs as the sources of these fuels are becoming diminished [7].

Table1: Ten Nations with the most installed geothermal power generation in 2020

Country	MWe installed in 2020
1. U.S.A	3,700
2. Indonesia	2,287
3. Philippine	1,918
4. Turkey	1,549
5. Kenya	1,193
6. Mexico	1,105
7. New Zealand	1,064
8. Italy	916
9. Japan	550
10.Iceland	755

Table 2: power plant distribution

Category	Installed capacity	Percentage (%)
Dry steam	2,863	22,65%
Single flash	5,079	40,18%
Double flash	2,544	20,12%
Triple flash	182	1,44%
Binary	1,790	14,16%
Hybrid	2	0,02%
Back pressure	181	1,43%
Total	12,641	100,00%

The worldwide distribution of all geothermal power plants with respect to electricity generation technologies is shown in table 2 [8]. As it can be seen from the table that, the most commonly used system in all geothermal system is the single flash technology. plants, which is estimated to 40.18%. One more flashing can be performed in order to obtain more steam, if the geo-fluid remaining from the single flash separator has enough temperature and pressure The electricity produced from all geothermal power comes from single flash.

And the excess steam that has been produced from the second flashing can enter either in a separator low pressure turbine or in a suitable suitable pressure stage of the same steam turbine. This technology is called ‘double flash cycle’. This technology produces a capacity of 20.12% from the geothermal-based electricity produced all over the word (Table 2). The condensation and flashing pressures have a very important effects the performance and the economy of the power plant. For this reason, these pressure should be optimized as function of local environmental conditions and economics limits.

2. Methodology

2.1. Karthala Geothermal field:

The karthala field is located in the Grande Comoros which is the westernmost and largest island of the archipelago (Figure 1). This island encompasses an area of 1024 Km^2. It is also having the most recent in geological terms and the highest elevation. Its elevation is 2361 m above the sea level.

Almost all the eruption of this volcano were located along two rift zones, which were well described with distribution of eruptive feature and both topographic feature. The southeast rift zone is about 12 Km, and the north rift zone prolonged over 25 Km to the north of the central caldera [9]. Most of the surface manifestations of this volcano are found in the nested summit calderas (Figure 2).

The rifts of the karthala terminate prior to reaching sea level. And the recharge is estimated to be rain water which has been fallen on the highest northern slope and then percolated down the upper part of the rifts thus giving sufficient hydraulic head that the water is pushed along the rift (Figure 3). Initially, the geothermal reservoir will be dynamically constrained by the presence of the overlying ground water that is originated from the lower elevations.

However, the temperature will be high enough for the steam to formed, which upon the condensation into the overlying ground waters alters the rock to form the clay cap that exclude the shallow ground waters.

The clay cap that has been formed propagated down the rift with time. Once it does, the amount of cold water that coming into the rift will be restricted to that coming from the higher elevation. This phenomenon will slow cooling of the rift particularly since where the rift terminates at lower elevation onward to the outside the rifts may be restricted by the lack of normal faulting. The geophysical exploration was conducted in July 2015 by Jacobs associating GNS science, and BGC teams [10]. The goal of this exploration has been fully achieved.

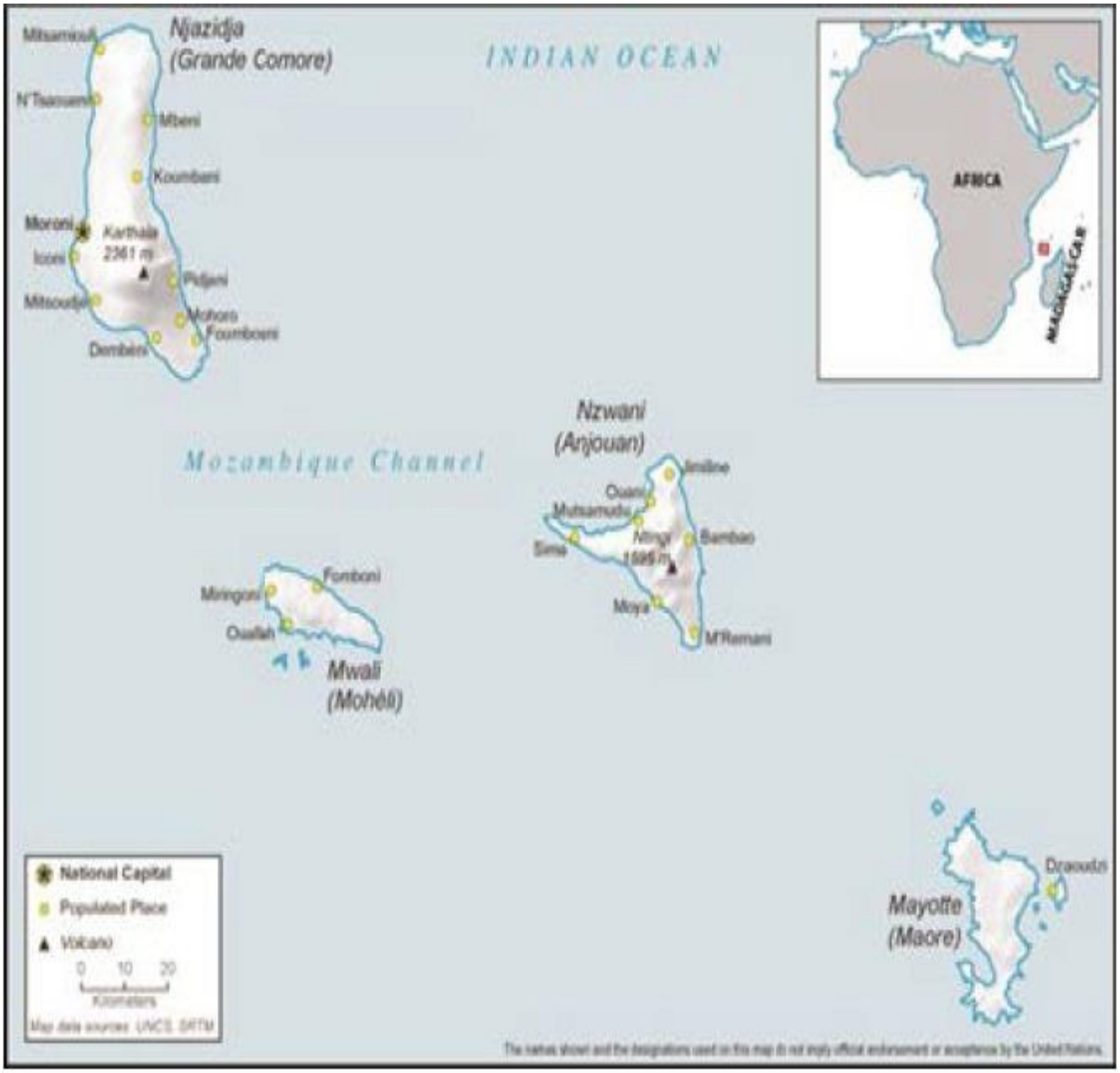

Figure 1 : Location Map [9]

And the studies carried out reveal the existence of geothermal reservoir at a depth between 1700 and 1900 m, and a heat resource at a depth of more than 5000 meters.

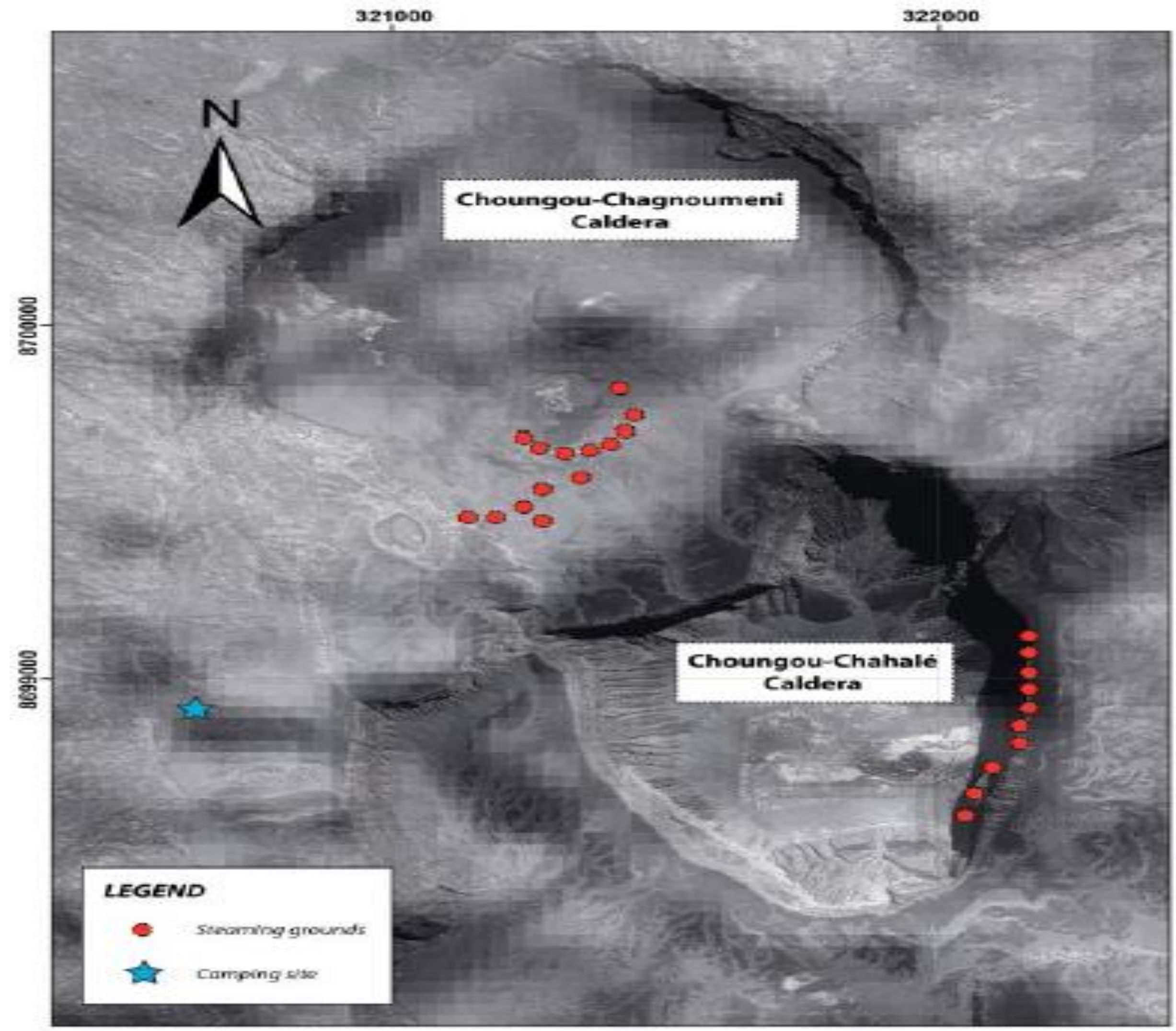

Figure 2: thermal activity location in the calderas [9].

The results of this geothermal studies shows the availability of geothermal system with a potential temperature of the order of 250 to 300^{0}C.

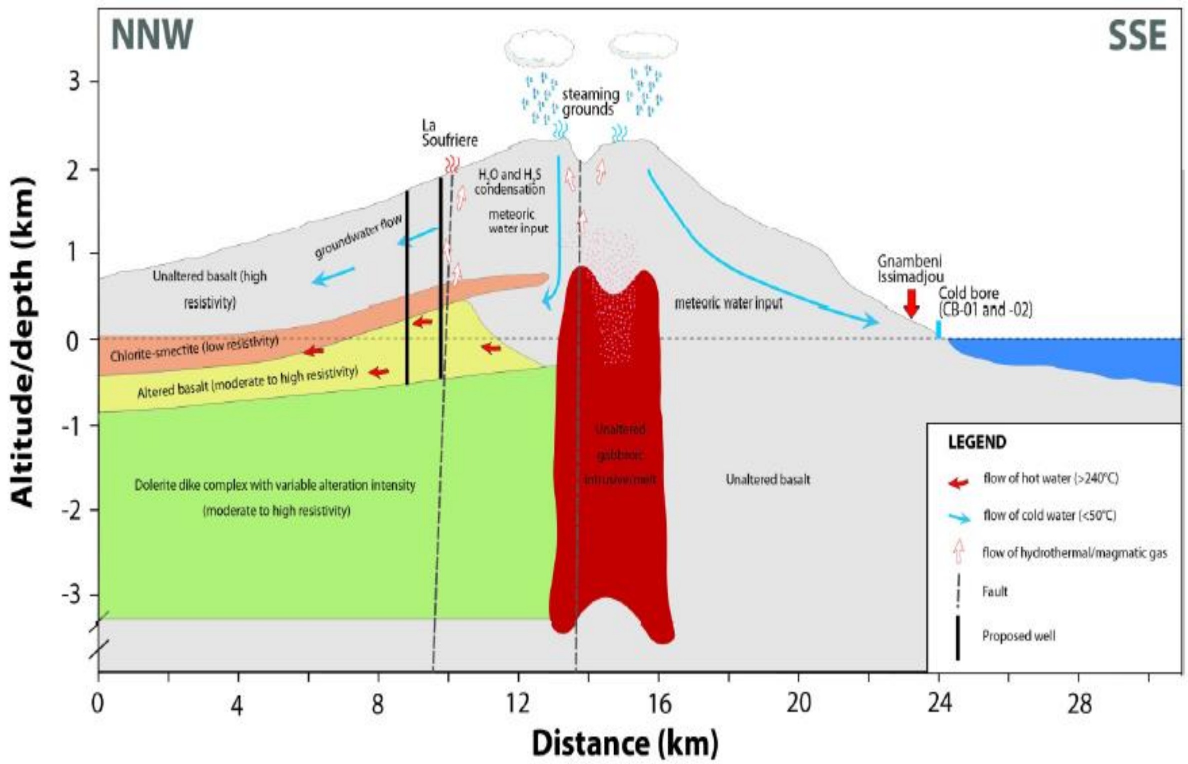

Figure 3: Schematic conceptual model along the rift hosting known thermal activity [9]

2.2. Description of the double flash geothermal power plant:

A simplified scheme of a double-flash geothermal power plant is showing in Figure 4. Once the geofluid leave the geothermal source to the surface, evaporation takes place because of the decrease in pressure. However, the steam obtained at this state is not enough for power generation. Therefore, the pressure of the geofluid should be decreased at constant enthalpy. This process is known as 'Flashing process. 'And there is an optimum value of the flashing pressure for maximum power generation[11][12][13]. Just after the flashing process, two- phase (steam and liquid) fluid enter enters a separator to separate liquid and steam with their different specific volumes.

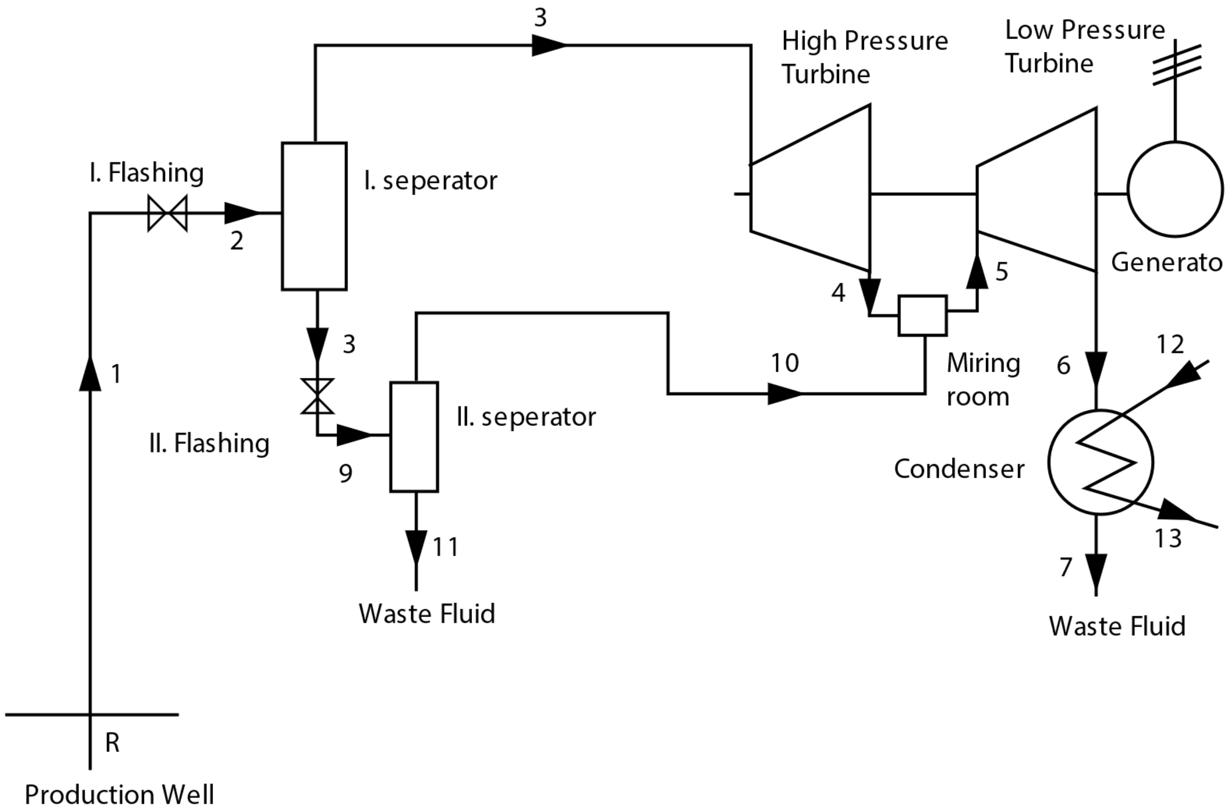

Figure 4: A simplified scheme of double-flash geothermal power plant

The steam released from the separator passes through a high pressure turbine, and a generator connected with the turbine generates electricity. If the fluid extracted from the separator has a temperature and pressure high enough, the second flashing can be performed. However, the two phase can also be acquired again.

This process is known as the 'second flashing process.' The two phase fluid obtained is separated for the second time in the second separator. The saturated steam extracted from the second separator is mixed in a mixing box with other wet steam from the high pressure turbine to obtain greater steam quality. The extra steam obtained after mixing passes through a low pressure turbine and additional power from the generator coupled with the second turbine.

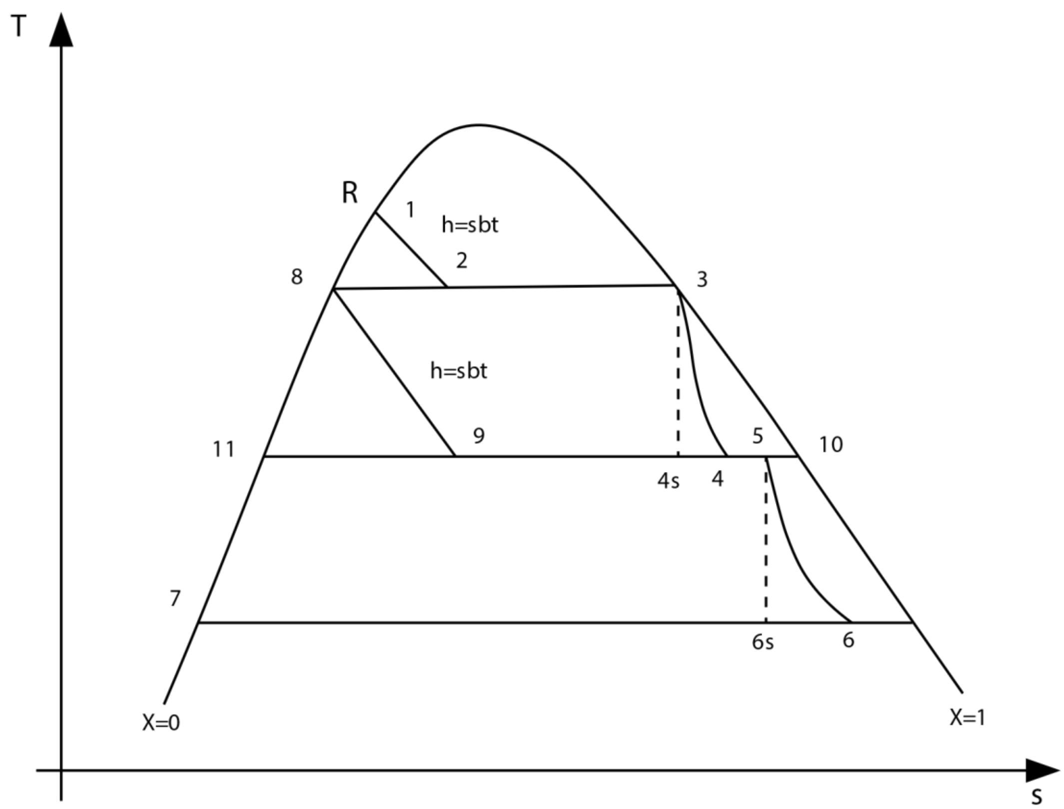

Figure 5: *T-s* diagram of the double-flash geothermal power plant

Figure 5 shows a temperature (T-S) diagram of the double-flash geothermal plant. The flashing processes are achieved at constant enthalpies (R-1-2 and 8-9). The separation processes are accomplished at constant pressure and constant temperature (2-8-3 and 9-11-10). The expansion processes that are produced in the high and low pressure turbine are real process (3-4 and 5-6). In the T-s diagram, the processes

‘3-4s’ and ‘5-6s’ are isentropic processes. These processes characterize the turbine expansion at constant entropy.

3. Analysis:

In this thesis, we perform the flashing pressure optimizations and performance analysis of a hypothetical double – flash geothermal power plant shown in Fig. CAPE OPEN to CAPE OPEN (COCO) simulation environment software has been used for analysis [14]. the CAPE-OPEN Flowsheet Environment (COFE) is an intuitive graphical user interface to chemical flowsheeting. COFE has sequential solution algorithm using automatic tear streams. COFE displays properties of streams, deals with conversion of units and provides plotting facilities. COFE flowsheets can be used as CAPE-OPEN unit operations; so it can be used as a unit operation inside COFE (flowsheets in flowsheets) or inside other simulators.

COCO's Thermodynamics for Engineering Applications(TEA), is based on the thermodynamic library code of ChemSep and includes a data bank of over 430 commonly used chemical properties. The package exhibits more than 100 methods of property calculation with their analytical or numerical derivatives.

The chosen values for the geothermal field and power plant are those of condition in Grande Comoros. The reservoir temperature is selected to be 250^0C. And other purpose for this study is to find out the power capacity and the efficiency values of a possible installment of a double – flash power plant in this region.

3.1. Determining the optimal flashing pressure:

As mentioned earlier, the flashing pressure have optimal values. In this study, the selected optimal values are the flashing pressures that yield maximum net power output. According to our computer analysis, the optimal first and second flashing pressure has been determined to be 2092.6 KPa and 100.6 KPa respectively (Fig6). Other analyses were performed after finding the optimal flashing pressures. Table 3 list the inlet data of the computer program.

Table 3: The input data for computer analysis

Geofluid temperature at reservoir	250 ^{0}C
Geofluid mass flowrate	200 Kg/s
First flashing pressure	2092.6 KPa
Second flashing pressure	100.6 KPa
Steam pressure at low pressure turbine outlet	10.6 KPa
Wellhead pressure of geofluid	3062.6 KPa
Turbine isentropic efficiency	0.70
First separator vapor fraction	0.118
Second separator vapor fraction	0.1058
Dead state temperature	25 ^{0}C
Dead state pressure	100 KPa

3.2. Exergy and Energy analysis of the geothermal power plant:

The most effective way to evaluate a power plant and other thermal system Is by using the first and second laws of thermodynamics which are related to energy and exergy concept, respectively. In this way, the energy and exergy values of each states can be calculated.

In the absence of nuclear, electrical , magnetics, and surface tension effect, the total Exergy of a system Ex can be dived into four components: Kinetic Exergy, Physical Exergy, Chemical exergy and potential exergy [15].

$$Ex = E^{kn}x + E^{pt}x + E^{ch}x + E^{ph}x \quad 1$$

Exergy is an extensive property. however, it is more convenient to express it according to units of mass. The total specific exergy on a mass basis e can be given as:

$$e\mathrm{x} = ex^{ph} + ex^{pt} + ex^{kn} + ex^{ch} \quad 2$$

Geothermal power plants are considered to be steady-state systems with only one inlet and one outlet. The first law of thermodynamics for an open system can be written as follows:

$$Q - \dot{\mathrm{W}} = \dot{\mathrm{m}}[(h - h0) + \frac{1}{2}(V^2 - V0^2) + g(z - z0)] \quad 3$$

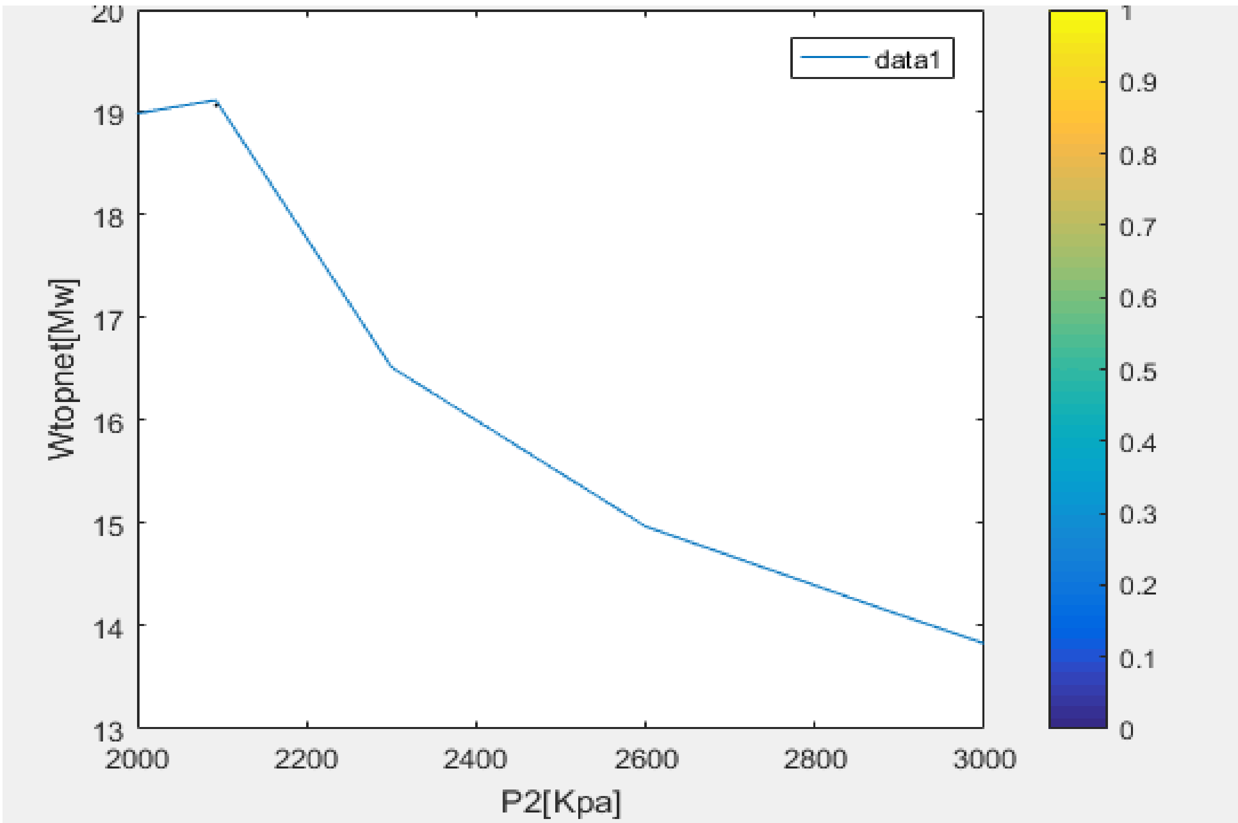

Figure 6: Optimum first flashing pressure of the double-flash geothermal power plant. Second flashing pressure is 2092.6 KPa

Where:

Q: $heat\ rate$

$\dot{W}$: $Power$

$\dot{m}$: masse flow rate

h: enthalpy of the fluid

V: the velocity

Z: the height

And the potential and kinetic energy difference are very small relative to the enthalpy difference of the geothermal power plants. However, if these terms are neglected; the simplified equation can be written as:

$$Q - \dot{W} = \dot{m}(h - h0) \quad 4$$

The total entropy generation($\dot{s}_{gen}$) that may be include heat transfer only with the surroundings can be given as[16]:

$$\dot{s}gen = \dot{m}(s - s0) - \frac{Q}{T0} \quad 5$$

where:

T_0: Dead state temperature

S: Entropy

In a reversible process, there is no entropy generation. In case the geothermal system is accepted as a reversible, the previous equation becomes:

$$Q = \dot{m}T0(s - s0) \quad 6$$

The maximum work can be obtained by combining equation (4) and (6)

$$\dot{W}max = \dot{m}[(h - h0) - T0(s - s0)] \quad 7$$

In case the entropy generation is equal to zero, then the maximum work of the geofluid can be calculated with Eq. 7. Since the last state is the environmental condition, this work can be considered equal to the "exergy." All exergy quantities at each base points of the power plant have been calculated with this equation.
The subscript "0." Represent the dead state condition. And the term in square brackets in Eq. (7) is equal to the specific exergy (*ex*) as follows in Eq. (8):

$ex = (h - h0) - T0(s - s0)$ 8

Eq. (9) calculate The specific energy (*en*) of geofluid:

$en = h - h0$ 9

where *h* is known as the enthalpy of geofluid at the given base point.
By multiplying the specific energy to the mass flow rate of the geofluid gives the energy rate:

$\dot{E} = \dot{m}\, en$ 10

The overall net power output of the plant ($\dot{W}totalnet$) can be calculated as follows:

$\dot{W}totalnet = \dot{W}netI + \dot{W}netII$ 11

Where the $\dot{W}netI$ is known as the net power output of the high pressure turbine and the $\dot{W}netII$ is also known as the net power output of the low pressure turbine. The geofluid enthalpy before the low pressure turbine can also be calculated as follows:

$\dot{m}_{10}h_{10} + \dot{m}_3h_4 = \dot{m}_5h_5$ 12

with respect to the notation of Fig. 1.
The overall first law efficiency of the plant is by the Eq.12:

$$\eta 1 = \frac{\dot{W}totalNet}{\dot{E}nR}$$ 13

where $\dot{E}nR$ is known as the energy rate of the geofluid in the reservoir, and second law efficiency is given as follow:

$$\eta 2 = \frac{\dot{W}totalNet}{\dot{E}xR} \qquad 14$$

where $\dot{E}$xR is known as the exergy rate of the geofluid in the reservoir. To achieve this, some assumptions in the analysis were considered. And some of them are as follows:

- the enthalpy decrease of the geofluid is neglected, Where the geofluid exits the reservoir to the surface.
- in the reservoir, the geofluid is assumed to be at a saturated liquid condition,
- Use of Fresh water properties in the analysis, instead of the thermodynamic properties of the geofluid, since the chemical exergy of the geofluid is quite small, it has been omitted in the analysis.
- Neglecting of temperature and pressure losses of the geofluid in the separation and condensation processes.
- Flashing process is considered to be accomplished at constant enthalpy.
- Conditions in the Grande Comoros Island have been selected for the dead state data.

4. Result and Discussion:

The temperature, pressure, mass flow rate, specific enthalpy, specific entropy, and energy and exergy flow rates of the geothermal power plant at the base state are listed in Table 4.

Table 4: Characteristic values of the double flash geothermal power plant at each state of the plant (At optimal pressure)

State	Temp. T(0C)	Pressure P(KPa)	Masse Flow rate (Kg/s)	Enthalpy h(Kj/Kg)	Entropy S (Kj/Kg.k)	Energy Flow rate En(KW)	Exergy Flow rate Ek(KW)
0	25	100		104.93	0.367	0	0
R	250	3975.9	200	1085.68	2.793	196,150	51,560.4
1	235	3062.6	200	1085.68	2.793	196,150	51,560
2	214.79	2092.6	200	1085.68	2.809	196,150	50,607
3	214.79	2092.6	23.61	2799.33	6.322	63,615	21,716
4	99.78	100.6	23.61	2443.87	6.69	55,222	10,735
5	99.78	100.6	42.18	2560.46	7.025	103,574	19,885
6	46.9	10.6	42.18	2327.32	7.33	93,740	11.497
7	46.9	10.6	42.18	196.46	0.664	3,861	127.5
8	214.79	2092.6	176.4	919.18	2.468	143,602	24,327
9	99.78	100.6	176.4	919.18	2.636	143,602	24,359
10	99.78	100.6	18.57	2677.05	7.36	47,764	9,066
11	99.78	100.6	18.57	418.17	1.304	49,235	5,416

After the analyzing the power plant, the output values are shown in Table 5. The results found that the net power output of the double-flash geothermal power plant is 19.129 MW. Where by 9.099 MW comes from the high pressure turbine, and the other remaining 10.03 MW comes from the lower low pressure turbine. The overall first and second law efficiencies of the power plant are 6.48% and 27.76%, respectively. There are some important points to consider during the reinjection process. For example, the geofluid must be reinjected in a suitable place to be for reheated. While the geofluid return to its original reservoir, the original temperature and pressure should be maintained. Thus, the reservoir can be replenished and the geothermal energy can be called fully “renewable”, the temperature of the reservoir and the net power output of the power plant decrease. To avoid the decrease of the reservoir temperature just after power production, a cascaded use of the geofluid in various heating applications is required. However, the remaining geofluid that is left from the power plant should be forced into reinjection wells. Therefore, If the waste fluid is reinjected into the reservoir, the pressure and temperature of the resource can be preserved. And this process should not be considered as an exergy destruction process.

5. Conclusions:

In this study, a geothermal double-flash power plant is examined, and first and second flashing pressures are analyzed. The performance analysis of the double-flash power plant is then performed by energy and exergy concepts for Grande Comoros island conditions. The Geofluid temperature and mass flow rate are selected as 250°C and 200 kg/s, respectively. A mathematical model of the power plant is set using computer software. The objective of the optimization is to find out the pressure values that maximize the net power output of the plant. These pressures are called optimal values. The optimum flashing pressures of the designed power plant are obtained as 2092.6 kPa for the first flashing and 100.6 kPa for the second flashing. According to the results, the net power output of the plant has been determined as 19,133 kWe with optimal flashing pressures. Where the total net power output, 9,099 kWe comes from the high pressure turbine, whereas the remaining 10,034 kWe comes from the low pressure turbine. The overall first and second law efficiencies of the power plant are 6.48% and 27.77%, respectively.

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