Energy Analysis of a Proposed Wellhead Geothermal Plant in Menengai Field

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ABSTRACT

Geothermal power is a sustainable, clean and cheap source of electricity which can supplement the current national grid. Geothermal Development Company began drilling in February 2011. It is about 10 years since the commencement of drilling and to date, no installation of a conventional power plant has taken place. KenGen adopted the wellhead technology in the year 2012 after a long period of testing. The objective of this study is to analyze the feasibility of installing a wellhead power plant in Menengai based solely on energy analysis. The design used was single flash cycle with condensing turbine and combined flash-binary cycle by bottoming the flash plant using binary cycle at well MW-18A. Kuster downhole logging tools were used to obtain pressure and temperature data of the well while it underwent discharge tests for 4 months. Pressure gauges for wellhead and lip pressure were used. The optimum wellhead pressure was 18.5bara for a total mass flow rate of 105t/hr with an enthalpy of 1618kJ/kg. The reservoir temperature obtained from temperature logging was 280°C. Modelling and simulation of the plant cycles with preliminary well data was done using Engineering Equation Solver (EES). The result of power output and plant efficiencies for the single flash was 9,442kW, 20.1% and combined flash-binary cycle had a higher output of 11,227kW, 23.79%. The efficiency for the flash plant seems to be higher than that of dry steam plants (15.1 – 17.5%) while binary plants usually range from 10-13%. In conclusion, it is feasible to have a wellhead power plant using combined flash-binary cycle, while awaiting the construction of a conventional power plant. It is recommended that further studies be carried out to analyze the economic and exergy aspects.

1. Introduction

Kenya is transected by the East African Rift from the North to South. There is high-temperature geothermal potential approximately 10,000 MW within the Great Rift Valley. Menengai volcano is located at the intra-continental crustal triple junction north of the Nakuru-Naivasha basin where the Nyanza Rift joins the Kenya Rift, Patlan et al. (2011) as shown in Figure 1. Since 2011 a number of exploration wells and production wells have been
drilled with maximum reservoir temperatures recorded in excess of 390°C, demonstrating the potential of the field for energy production, O’Sullivan et al. (2015). Kenya’s installed electricity generation capacity was 2,351 MW and recorded a peak demand of 1,802 MW in 2018. Geothermal sources account for 47%, hydro 30.1% and thermal plants 43.6% making up the energy mix, KPLC Annual Report (2018).

Figure 1: Location of the Menengai Field and other geothermal prospects in the Great Rift Valley, Kanda et al. (2019)

GDC was formed in 2008 to accelerate utilization of geothermal resources in a bid to provide energy for the ever growing demand arising from the rising population in Kenya, which stands at 47.6 million, KNBS (2019). Drilling in Menengai Field started in February 2011 with the aim of harnessing steam for electricity power production, Suwai (2011). It has been 10 years with no installation of a conventional power plant. During this period a lot of potential has been shut-in and lays idle while it could have been used to generate electricity and revenue concurrently. The objective of this study is to analyze the feasibility of installing a wellhead geothermal plant in Menengai by performing energy analysis. Well MW-18A located to the east of the Menengai caldera as shown in Figure 2 is used for this purpose as a case study. It was spudded on 4th February 2016 and completed on 18th September 2016. Various tests including well discharge tests, pressure and temperature logging and discharge chemistry tests were conducted for four months providing preliminary data for the study.
2. Wellhead Geothermal Power Plants

These power plants are installed directly at the well head. They can either be a temporary installation which will be relocated to new well as conventional larger scale power plant is built or a permanent wellhead power plant, Gudmundsson and Hallgrimsdottir (2016). Before a geothermal power plant can be designed, the available resource must be characterized to the maximum extent feasible. This translates to measurement or prediction of three critical characteristics of the geofluid; thermodynamic state, flow rate and chemical composition, Clarke (2014). There are 3 types of geothermal power plants used namely single flash (back pressure or condensing type), double flash and binary plants. This study focuses on the implementation of a wellhead unit using single flash cycle and later a possibility of incorporating a binary cycle by bottoming the single flash plant to maximize on the heat from the waste brine before reinjection. Analysis was done based on fundamental thermodynamic principles, namely the principle of energy conservation first law of thermodynamics and principle of mass conservation using EES.

2.1 Single Flash Power Plants

Single flash plants are the most commonly used in geothermal. Their simple design and low cost tend to make them the first plant installed at a new geothermal power plant site, Clarke (2014). Single flash steam technology is used where the hydrothermal resources are in liquid form, Jalilinasrabady and Itoi (2012). Figure 3 shows a simple schematic of a single-flash power plant. The wellhead generators currently installed at Olkaria are of condensing steam turbine cycles, Saitet and Kwambai (2015). The silencer is used for emergency venting. The
brine flows to the re-injection well through state 6 with a pressure equal to that of separation pressure. Steam flows from the separator and through a demister to remove any traces of water. This is to prevent any damage to the turbine blades. The steam is assumed to have a quality of 1. The steam expands in the turbine thus producing electricity in the generator. The exhaust steam is cooled in the condenser by circulating cool water from the cooling tower. The condensate from the cooling tower is reinjected into the reservoir.

Figure 3: Schematic of a single flash plant (EES Modelling and Simulation, Okoth (2019))

2.2 Binary Cycle Plants

The binary cycle which employs the Organic Rankine Cycle (ORC), is a closed loop system that involves heating of a working fluid by the geothermal fluid through a heat exchanger as shown in Figure 4 below. The working fluid, which has a lower boiling point, evaporates and expands in the turbine producing electricity. An ORC plant can basically be divided into three technical subsystems: the geothermal fluid/brine, power conversion cycle and cooling system for the removal of heat, Gitobu (2016). The brine is re-injected into the reservoir after being passed through the pre-heater. Advantages of binary cycle are that they are good in case of corrosion and scaling in the field. They are also cheaper to replace evaporator than turbine, as it is the most expensive component in a geothermal power plant. They are also easier to control in terms of low-pressure fluids, since binary cycles tend to have thermal efficiencies in the 10-13% range, any further reduction in net power can have a serious impact on plant performance, DiPippo (2012).
The cooled working fluid from condenser at state 32 is pumped by the feeder pump to the pre-heater through state 32 to 33. The pre-heater raises the boiling point of the working fluid and is passed to the evaporator where it vaporizes. The steam enters the turbine and expands producing electricity. The exhaust steam is cooled by circulating water from the cooling tower and the cycle is repeated. Binary power plants have no emissions and because geofluid is not in contact with cycle components (except the evaporator) face no problems regarding scaling and corrosion, Zeyghami and Nouraliee (2015).

Assumptions made with reference to conditions in Kenya and those in various papers were,

- Saturated liquid of working fluid at condenser outlet,
- Isentropic efficiency of turbine 80%.
- Isentropic efficiency of pump 75%.
- Temperature of water leaving condenser 39°C.
- Ambient temperature of air into cooling tower 25°C.
- Atmospheric pressure in Kenya 86kPa.
- Pinch point of evaporator 8°C.
- Cooling tower head 20m
- Temperature difference in water leaving and entering cooling tower 13°C.

### 2.3 Combined Flash-Binary Cycle Plants

The flash cycle has the benefit of low investment, and the binary bottoming cycle serves to increase the efficiency – for substantially increased investment cost, Valdimarsson (2011). Instead of reinjecting the brine from the separator at the single flash plant, it is used as input for the binary cycle, as shown in Figure 5 below.
3. Thermodynamic Analysis

Analysis was done according to the first law of thermodynamics which states that energy is conserved during any process while it is transformed from one form to another, DiPippo (2012). This law works on the principle of energy and mass conservation.

The first law of thermodynamics of a system is given by eqn 1,

\[ \dot{Q} - \dot{W} = \dot{m}(h_2 - h_1) + 1/2(v_2^2 - v_1^2) + g(z_2 - z_1) \] (1)

Where \( \dot{Q} \), \( \dot{W} \), \( \dot{m} \), \( h_1 \), \( h_2 \), \( v \), \( g \) and \( z \) are amount of heat transferred (W), power (W), mass flow rate (kg/s), enthalpy at state 1(kJ/kg), enthalpy at state 2 (kJ/kg), velocity (m/s²), gravity (m/s²) and elevation (m) respectively. By ignoring the difference between kinetic and potential energies relative to the enthalpy difference, equation 1 is expressed as,

\[ \dot{Q} - \dot{W} = \dot{m}(h_2 - h_1) \] (2)

The processes undergone by the geofluid are best viewed in a thermodynamic state diagram in which the fluid temperature is plotted on the ordinate and the fluid specific entropy is plotted on the abscissa, DiPippo (2012). The analysis for single flash plant are as below.
3.1 Parameters at the Well

Geothermal fluid flows from the reservoir state 1 through the well and is directed to a separator. The pressure in the separator is lower than the reservoir pressure causing the fluid to flash thus separate into steam and water. The process is assumed to be isenthalpic thus the enthalpy of geothermal fluid at production well and reservoir is shown in equation 1. Changes in kinetic and potential energy are neglected.

\[ h[0] = h[1] \]

(3)

3.2 Separator

The process at state 2 is under constant pressure i.e., isobaric. The fluid enthalpy and pressure for MW-18A are 1618kJ/kg and 18.5bara respectively. Dryness fraction is obtained by equation 4:

\[ x_1 = \frac{m_2}{m_1} = \frac{h_2 - h_3}{h_4 - h_3} \]

(4)

The pressure of steam and brine leaving separator is same as that in separator.

\[ P_2 = P_3 = P_4 \]

(5)

3.3 Turbine

The steam undergoes an isentropic process through states 4 to 5. Thus, entropy at turbine inlet is the same as at turbine outlet as shown in equation 6,

\[ s_3 = s_4 \]

(6)

The quality of steam entering the turbine should not have any moisture and was set as one. This prevents any corrosion and damage to the turbine blades. The mass flow rate into the turbine is equal to the steam mass flow rate from the separator assuming negligible loss through the demistifier. Mass flow rate at turbine entry and exit are the same. The pressure after turbine P4 is optimized and fixed. Enthalpy after turbine is calculated using EES. The work done in the turbine is computed using the equation 7,
Where \( W_T \), \( \eta_t \), \( \dot{m}_3 \), \( h_3 \) and \( h_{4s} \) are turbine work (kW), isentropic turbine efficiency, mass flow rate (kg/s), turbine inlet specific enthalpy (kJ/kg) and turbine outlet ideal specific enthalpy (kJ/kg) respectively.

Turbine efficiency is given by equation 8,

\[
\eta_t = \frac{h_3 - h_4}{h_3 - h_{4s}}
\]  

Isentropic efficiency of turbines in a geothermal power plant can range from 81 to 85% Jalilinasrabady et al. (2012). \( \eta_t \) is assumed as 85% for this study.

### 3.4 Condenser

A condenser is a type of heat exchanger in which vapors are transformed into liquid state by removing the latent heat with help of a coolant such as water, Najafabadi (2015). The main purpose of the condenser is to maximize turbine efficiency by maintaining a proper vacuum by condensing steam, removing dissolved non-condensable gases from the condensate and conserving the condensate for re-injection or as feed water for the cooling tower. A direct-contact condenser was used for the plant. The non-condensable gases were assumed to be minimal and the gas extraction system was assumed to have a load of 75W. Mass flow rate of the cooling water from the cooling tower into the condenser was given by equation 9,

\[
\dot{m}_4 + \dot{m}_7 = \dot{m}_5
\]

Condenser temperature difference between inlet and outlet was assumed to be 3°C. The density \( \sigma \) was calculated from EES. The volumetric flow is given by equation 11,

\[
Q_5 = \frac{\dot{m}_5}{\sigma} \times 3600
\]

Condenser work is given by the equation 12,

\[
W_{\text{cond}} = \frac{\dot{m}_5 \times (h_4 - h_5)}{1000}
\]

### 3.5 Condenser pump work

Assumptions made were:

- Condenser pump efficiency, \( \eta_{cp} \) of 0.8
- Condenser pump motor efficiency, \( \eta_{cm} \) of 0.95
- Head given by pump manufacturer, 43m

Work done was given by equation 13 below,
The cooling water is usually obtained from a cooling tower that recirculates a portion of the condensed steam after it has been cooled by partial evaporation in the presence of a moving air stream. This means that geothermal flash-steam plants do not need a significant supply of cooling water, a major advantage in areas that are arid. However, a small amount of fresh water is needed to provide for replacement of tower blowdown in wet cooling towers.

Mass balance was obtained by equation 14,

\[
W_{CP} = \frac{\left(\dot{m}_s \cdot 9.81 \cdot h_{12}\right)}{\eta_{cp} \cdot \eta_{cm}} \bigg/ 1000 \tag{13}
\]

### 3.6 Cooling Tower

The cooling tower fan efficiency, \(\eta_{CTF}\) is assumed to be 0.7. Cooling tower fan motor efficiency, \(\eta_{CTM}\) is assumed to be 0.8. Pressure change across the cooling fan, \(\Delta P_{CTF}\) is 328kPa. The work done is given by equation 19,

\[
W_{CTF} = \frac{\left(\dot{m}_{11} \cdot \Delta P_{CTF} \cdot \eta_{CTF} \cdot V_{CT}\right)}{\eta_{CTM} \cdot \eta_{CTM}} \bigg/ 1000 \tag{19}
\]

### 3.7 Cooling Tower Fan

\[
\eta_{CTM} = \frac{\dot{m}_{loss, evap}}{m_3} \cdot 100 \tag{17}
\]

### 3.8 Plant Parasitic Loads

Assumptions made:

- \(W_{RWP} = 800\) W, power for steam gathering reinjection pumps
- \(W_{\text{transformer losses}} = 155\) W, dependent on substation configuration
- \(W_{loss\text{ others}} = 500\) W, used for power station lighting, workshop, compressors.
- \(W_{loss\text{ NCG}} = 75\) W, Non-condensable gas extraction system

Net power calculation,

\[
W_{\text{paras.load}} = W_{CP} + W_{CTF} + W_{loss\text{ NCG}} \tag{20}
\]

\[
W_{\text{net}} = W_T - W_{\text{paras.load}} \tag{21}
\]

The plant efficiency is given by the equation,
3.9 Analysis for Binary Cycle

Two candidate working fluids were investigated i.e. Isobutane and Isobutene. Isobutane was chosen for the binary cycle with a boiling point of -11.7°C, critical temperature and pressure of 134.66°C and 3,630kPa respectively. The brine inlet temperature was 208.5°C and had a mass flow rate of 14.45kg/s.

The components that were analyzed were the turbine, heat exchangers, condenser and feed pumps.

4. Results

![T-s diagram for steam in Single flash](image1)

![Optimization of W\text{net} with turbine outlet pressure P4](image2)

Figure 7: a) T-s diagram for steam in Single flash  b) Optimization of $W_{\text{net}}$ with turbine outlet pressure $P4$

(EES Modelling and Simulation, Okoth (2019))

Table 1: Power output for the two power plant cycles

<table>
<thead>
<tr>
<th>Powerplant cycle</th>
<th>Single Flash Cycle</th>
<th>Combined Flash-Binary Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Output (kW)</td>
<td>9,442</td>
<td>11,227</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>20.01</td>
<td>23.79</td>
</tr>
</tbody>
</table>

5. Discussion

The single flash and combined flash-binary plant cycles were modelled and simulated using Engineering Equation Solver (EES). Total mass flow from the well was 29.17 kg/s with an enthalpy of 1618kJ/kg. The single flash plant operated well within the T-s diagram as shown in Fig 7a) yielding a power output and plant efficiency of 9,442kW and 20.1% respectively. The single flash plant was then bottomed using a binary cycle to maximize the heat in the brine before reinjection. Two working fluids were tested, namely Isobutane and Isobutene. Isobutane was selected for its suitable properties. Optimization of net work done with reference to turbine outlet pressure $P4$ was achieved at 6.8kPa. The combined flash-binary plant yielded an output of 11,227kW with a plant efficiency of 23.79%. 

\[
\eta_{\text{th}} = \frac{W_{\text{net}}}{\dot{Q}_{\text{in}}} \tag{22}
\]
6. Conclusion
The combined binary cycle produced more power than single flash cycle by 1,785 kW. The efficiency of combined binary was highest with 23.79%. It is feasible to have a wellhead power plant in Menengai while awaiting the construction of a conventional power plant.

RECOMMENDATION
Further studies should be conducted for exergy analysis and economic analysis.

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NOMENCLATURE

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>EES</td>
<td>Engineering Equation Solver</td>
</tr>
<tr>
<td>h</td>
<td>enthalpy (kJ/kg)</td>
</tr>
<tr>
<td>ORC</td>
<td>Organic Rankine Cycle</td>
</tr>
<tr>
<td>P</td>
<td>pressure (kPa)</td>
</tr>
<tr>
<td>T</td>
<td>temperature (°C)</td>
</tr>
<tr>
<td>$W_{net}$</td>
<td>net power output (kW)</td>
</tr>
<tr>
<td>$W_t$</td>
<td>power of the turbine (kW)</td>
</tr>
<tr>
<td>$\eta_t$</td>
<td>isentropic efficiency of turbine</td>
</tr>
<tr>
<td>$\eta_{Plant}$</td>
<td>overall plant efficiency</td>
</tr>
<tr>
<td>$\eta_{pump}$</td>
<td>efficiency of the pump</td>
</tr>
<tr>
<td>$\Delta p$</td>
<td>pressure head (kPa)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>water density of water (kg/m³)</td>
</tr>
</tbody>
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REFERENCES


