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Wellhead Power Plants Improvement by Introduction of Double Flashing Cycle

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ABSTRACT

Kenya Electricity Generating Company Ltd (KenGen) has harnessed geothermal energy for over thirty seven years at the Olkaria geothermal field. The total installed capacity of geothermal energy in Kenya currently stands at 703.5 MW generated mostly by single flash and binary geothermal power plants. In the 1990s KenGen considered the Wellheads concept in which modular containerized single flash power plants were to be designed, customized and built on a wellpad for optimized well potential; this approach has largely been successful currently having an installed capacity of 83.5 MW and accounting for 15.7% of KenGen's total geothermal installed capacity. This was done to address an inherent deficiency in the construction of conventional geothermal power plants which was identified as the long period taken to put up the power plants. The wells that have been drilled by KenGen and GDC, tested and shut in awaiting the installation of power plants are rated at about 600 MW.

The Wellhead power plant cycle is a single flash geothermal power plant; this research intended to improve the current Wellheads power cycle by introducing a second low pressure separator to harness more energy from the wellheads, design a turbine to be driven by the low pressure steam and evaluate an economic justification for introducing the double flashing cycle. A case study was carried out at Wellhead 914 and Wellhead 915. Data collected indicated that the combined mass flow rate of brine from wells in the two wellpads was 240.4 tonne per hour. This brine was saturated at 13.5 bar-a and at a temperature of 193.4^{0}C as it exits the high pressure separator for disposal. The optimal pressure of the low pressure separation was designed at 2.5 bar-a, 127.4^{0}C and had an ability to generate 3871 kW of electric power. A turbine operating at a steam inlet pressure of 2.5 bar-a, a speed of 6804 rpm and having an exhaust pressure of 0.075 bar-a was designed. The designed turbine had 4 stages of both stationary and moving blades with a maximum rotor disc diameter of 0.62 meters and an output of 4195 kW.

The simple payback period for this project was estimated to be 1.9 years with a rate of return on investment of 42.24%. This would also minimize energy wastage by improving efficiency and footprints on the environment arising from the Wellhead power plants.

Keywords: Geothermal, Wellheads, Cycle, Flashing, Design, Low pressure separator and Low pressure turbine.

I. INTRODUCTION

Energy has proven to be a part of the human development equation that cannot be ignored. A key example is how energy growth can be intricately equated to the growth indicators; the gross national product (GDP) and the gross national income (GNI) in an economic set up. The generation and consumption of electricity by a country in all sectors of the economy from the dynamic transport sector to the intensive manufacturing sector to the delicate domestic sector and cooking in homes represents the whole picture of the wellbeing of a population. Coal and thermal energy sources have been the modes of electricity generation for years powering the world through the industrial revolution and even the contemporary world. In Kenya, a generation mix involving hydroelectricity, thermal, geothermal and some wind generation has been embraced through the years. The mode of generation the country has relied on for base-load supply has been hydroelectricity. However, it has been observed that recurrent droughts linked to climate change have constantly caused hydroelectricity to be unreliable in Kenya. [11]

In pursuit of geothermal generation, in 2010 the government of Kenya embarked on execution of Wellhead project under a research and development program culminating into successful implementation of a pioneer plant in early 2012 with an aim of availing early geothermal generation. [10] This marked a paradigm shift in the geothermal generation mix. Currently the wellheads projects have an installed capacity of 83.5 MW providing an estimated 12% of the energy total national geothermal output and the project was completed and commissioned in April 2017.

In the single flash Wellhead power plants design, the turbine inlet pressures are between 13-15 compared to conventional geothermal Power Plants at the Olkaria Geothermal field with inlet pressures of between 4.5-5.5 bar-g. [2]

The Wellhead power plant is a modular type geothermal power plant design. The design can be broken down into four major subsystems. These systems are shown in Figure 1. The first subsystem is the hot end (highlighted in red in Figure 1) which consists of the production well, the steam separator, the steam gathering system and steam silencer.

The second subsystem consists of the turbine and generator assembly where energy conversion takes place.

The third subsystem is the Cold end consisting of the condensing system, the gas extraction system and the cooling towers.

The last system in the Wellhead power plant design is the electrical and control system- the previously described systems are controlled and monitored via a PLC system.

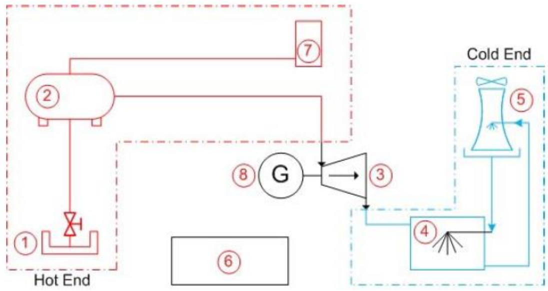

Figure 1. Simplified process diagram for a Wellhead power plant [7]

The current Wellhead power plant design has the hot end where the two-phase fluid is channelled to the separator at a set separation pressure of 13-15 bar-a before the steam is admitted to the turbine for power generation. This presents an opportunity for improvement of the generation cycle with the introduction of a second flashing of the brine at lower separation pressure which can provide an opportunity for heat recovery. Figure 2 presents an illustration of energy losses at the silencer in the Wellhead power plants.

Figure 2. Energy and fluids loss at the silencer by flashing of brine.

II. METHODS AND MATERIAL

2.1 Area of Study

The case study was done at Wellhead 914 and Wellhead 915 which have a combined installed capacity of 37.8 MW. The research sought to establish the possibility of generating electricity from brine produced from the six wells in the two wellpads.

The research involved collection of data on wells at Wellhead 914 and Wellhead 915 wellpads. Wellhead 914 wellpad has 4 wells namely Well OW914, OW914A, OW914B, OW914C and the adjacent Wellhead 915 has two wells OW915C and OW915D connected to the Wellhead power plants. Data on brine flow rates, temperatures and pressures were collected for the wells. The optimal second flashing pressure for the low pressure separator was determined by deriving the optimal amount of steam that could be generated from the second flashing which was mainly dictated by the EES simulated enthalpies and simulated electrical energy output from the turbine. EES was especially useful for the thermodynamic design problems where several parameters varied and their effects on the overall output were determined. [5]

TABLE I
CASE STUDY WELLS AT WELLHEAD 914 AND WELLHEAD 915

Wellpad	Well	Installed Power Plant
Wellhead 914	OW914	KWG06 & KWG07
	OW914A	KWG04
	OW914B	KWG05
	OW914C	KWG08
Wellhead 915	OW915 C	KWG09
	OW915 D	KWG10

2.2 Data Collection

Wells studied in this research are all production wells. [1] These types of wells have been thoroughly tested after completion of drilling to establish brine flow rates that are a vital input for this research. These tests are crucial to determine expected input for the low pressure separator. The wells are also constantly monitored during operation. Completion tests in the Olkaria geothermal field are done thoroughly after drilling over a period of approximately two months. These tests involve a multidisciplinary approach with reservoir engineers, geophysicists, geochemists and geologists. Temperature, pressure as well as spinner logging establish geothermal feed zones. [1] The purpose of thorough testing is mainly to establish and design the production capacity of the well. Russel James method is used to determine the output of the well. Olkaria geothermal field is a two phase field with the well producing both steam and brine. The brine output of the well in Russel James method is measured at the weir box and for purposes of this research the data obtained during completion test was used for computation. [4]

Other measurements taken included:

i) Flow temperature and pressures at the well
ii) Flow temperature and pressures at the separator
iii) Flow temperature and pressures of steam at the turbine inlet.
iv) Instrument logs filtered out and sampled for a frequency of twice a week for one month

Data obtained for this research involved the various instruments deployed in the field and are discussed in this chapter, which included:

i) PT100 temperature transmitters
ii) Pressure transmitter (model Endress Hauser Cerabar s)
iii) Weir Vee-notch height spot readings obtained using a steel rule.

Key parameters determined and required for this research were:

i) Brine flow rates for the wells which will determine the turbine and separator sizing
ii) The current separation temperature and pressure which dictates the properties of saturated exiting the high pressure separator for flashing in the low pressure separator.
iii) Low pressure separation pressures obtained from EES simulation to obtain optimum output
iv) Determination of steam velocity at the entry to the low pressure turbine.

2.3 Measurement Principle

2.3.1 Temperature

Temperature is a key thermodynamic property of the fluids under investigation in this paper. PT100 temperature transmitters were used in the determination of temperatures of steam and brine at various points. PT100 temperature measurement instruments are based on the RTD (Resistance temperature detectors) principle of temperature measurement. They work on the principle that since conductors have the outer orbital electrons of the atoms loosely bound a change in temperature results in a change in electron movement. An increase in temperature results to an increase in resistance hence for known and tested current values one can determine the degree of change which translates to accurate temperature measurements.

The relationship between temperature and resistivity can be expressed in the equation.

$$R(T) = R(T_0)(1 + \alpha\Delta T)$$

R is the resistivity of the material in Ohm meter

T is the final temperature ^{0}C

T_0 is the reference temperature ^{0}C

α is the coefficient of resistivity

ΔT is the change in temperature.

2.3.2 Pressure

For saturated steam and brine, pressure and temperature are dependent variables. Using any one of the two parameters from pre-calculated steam tables one can obtain the other parameter. For purposes of monitoring in the power plant these properties are measured independently. Ceramic diaphragm pressure transducers are installed for pressure monitoring in various points. Endress + Hausser Cerabar® S model have been installed in the Wellheads power plants and were used for data collection. The functioning principle of these transducers involves a mechanism where variation of pressure causes a ceramic diaphragm to move resulting to a change in capacitance.

2.3.2 Brine flow rates

Brine flow rates were obtained for the 6 wells from weir box flow rate measurements. During completion test after well drilling, to determine the brine flow rates; the two phase flow consisting of brine and steam from the well was connected to the silencer where steam was vented to the atmosphere. Water separated via scrubbing action of the baffle plates in the silencer and gravity separation, since its density is higher than that of steam. The water (brine) was connected to the weir box open to the atmosphere. Measurements were taken against the height of the vee-notch in the weir box. Figure 3 represents a wier box showing flow through the Vee-notch.

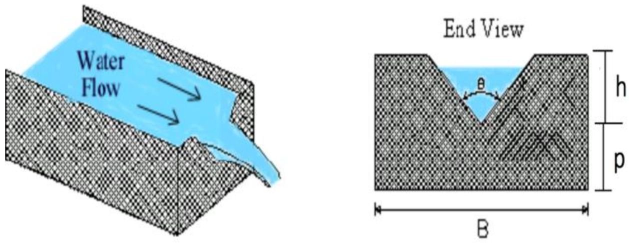

Figure 3. Weir box flow [3]

A rectangular weir box was used in the measurement of flow. The following equations were applied in the computation of the actual flow rates.

$$q = \frac{8}{15} c_e (2g)^{\frac{1}{2}} tan\left(\frac{\theta}{2}\right) h^{\frac{5}{2}}$$

rate (m^3/s)

h= head of the weir (m)

c_e= Discharge constant for the weir; well defined for measuring within specified head.

$$\theta = V - Notch\ angle$$

g= Gravity constant 9.81 (m/s^2) [4]

2.3.3 Steam velocity

Flow velocities at the separator inlet and exit, turbine inlet, in the steam piping, turbine nozzles and inlet to the condenser determine the steam energy levels at those points. It is the manipulation of steam velocity using inlet pipe diameters and turbine blades that determines energy available for work and hence overall power output of the turbine. [9] Turbine flow meters mounted on the steam piping can help determine the flow velocity. They however face a challenge of condensation. Steam flow velocity at points of interest stated in the turbine stages were determined by plotting accurate velocity diagrams using Autodesk Inventor software. Earlier techniques involved manually plotting the velocity diagrams on a paper hence the compromised accuracy and turbine efficiency. Autodesk Inventor allows a designer to optimize on the blade angles for maximum turbine efficiency. A blend of calculation using steam velocity formulas and the plotting was used in the design of the turbine and calculation of the output. Figure 4 is an illustration of the first stage blade angles velocity diagram construction. This inter-stage steam velocity was computed by creating the turbine velocity equations into excel sheets to allow for multiple computation from stage to stage.

Steam velocity computation equation was used.

$$v = \frac{m_s . V}{3600\pi\left(\frac{d}{2}\right)^2}$$

i) d: Pipe inner diameter (m)

ii) m_s: steam flow rate (kg/h)

iii) v: steam velocity (m/s)

iv) V : Specific volume (m³/kg)

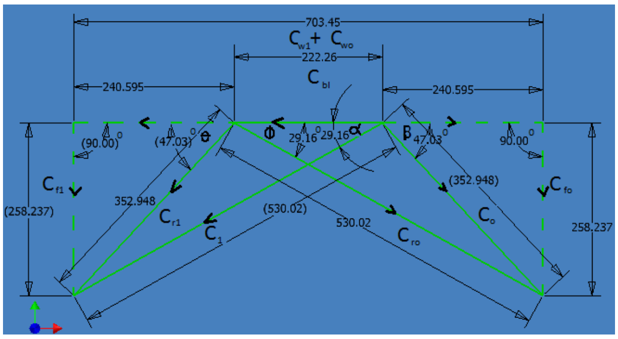

Figure 4. Velocity diagram for steam inlet velocity for 0.15 m diameter inlet stage 1

2.4 Engineering equation solver EES

To achieve an objective of this research that involved an analysis of the second flashing cycle engineering equation solver EES came in handy as an important tool for the tasks. Brine flow rates, temperatures and pressures were the inputs for this software. Various thermodynamic equations governing the heat flow of brine as it transitions from high temperatures to low temperature in line with the second law of thermodynamics were input as codes to the software. The software was able to process these inputs and provide an optimum pick for the second flashing pressure. The job of processing this data and optimizing on the second flashing pressure would have been, though rigorous, inaccurate due to the human aspect. This justified the approach taken to process this data; otherwise it would have involved carrying out every single calculation for trial values manually with objective of deriving an optimal second flashing pressure.

The data was then presented in graphs, charts and tables. These inputs and outputs can also be used in the sizing and selection of other auxiliary equipment including valves, condenser and cooling tower.

2.5 Evaluation of economic feasibility

This research involved collection of data on the pricing for main components of a geothermal power plant. It involved seeking costs of the components supplied by various manufacturers towards construction of various geothermal installations in Kenya and around the world. Engineers' estimates also came in handy in order to acquire data critical to the evaluation of the economic justification of this approach. This was crucial in helping address an objective of this research on evaluation of the economic justification for the second flashing approach. The upper limit for these pricing values was taken in some instances simulating a worst case scenario while procuring the items. Computation of the economic values and pricing of equipment was done in USD for consistency and clarity. A breakdown of these costs has been provided in Table II.

TABLE II
ESTIMATES OF PROJECT COST FROM PREVIOUS PROJECT DATA AND OEMS INQUIRIES

Item No.	Description	Cost (USD)
1	Turbine (Rotor, Casings, lube oil system, Protection	600,000
2	Condenser	400,000
3	Cooling towers	1,000,000
4	Hotwell Pump	500,000
5	Steam Piping	250,000
6	Separator	400,000
7	Breakers/ Switch gear, Cable, Protection, SCADA System and Instruments	1,080,000
8	Labour	700,000
9	Civil Works	300,000
10	Valves	70,000
Total Cost		5,300,000

III.RESULTS AND DISCUSSION

3.1 Potential thermal energy recoverable from waste brine

The brine coming from the high pressure separator, some of it venting in the silencer and part of it being taken for re-injection contains recoverable energy.

Typically, the brine is disposed while saturated at about 13.5 bar-a pressure and 193.4^{0}C; the saturated brine has enthalpies of up to 830 kJ/Kg that can be derived from steam property charts. With the high brine output of Olkaria wells, this is too much energy sent for reinjection without being harnessed. We now systematically outline the specific energy that can be harnessed by second flashing the brine in a low pressure separator at the optimum pressure.

3.2 Tabulation of brine flow rates, temperatures and pressures

The parameters under investigation were tabulated in Tables III and IV. From Table III, the total flow rate value was 240.4 tonne per hour of brine. This flow was the inlet to the low pressure separator.
Table IV represents the measured pressures at different points critical for the low pressure separation and turbine system design. It is important to point the fact that the temperature and pressure of saturated steam are two thermodynamic properties that are directly proportional to each other. For this reason an increase in pressure will result to a rise in temperature. [8] The focus of this research was on utilization of saturated brine exiting the high pressure separator.
The average pressures as tabulated in Table III were found to be 13.5 bar-a and the average temperatures were found to be 193.4^{0}C. These are the values that were used as input values for the low pressure separator alongside the brine flow rates obtained.

TABLE III
MEASURED AVERAGE BRINE FLOW RATES OF WELLS AT WELLHEAD 914 AND WELLHEAD 915

Wellpad	Well	Installed Power Plant	Average Brine Flow Rates (tph)
Wellhead 914	OW914	KWG06 & KWG07	45.3
	OW914A	KWG04	58.2
	OW914B	KWG05	42.1
	OW914C	KWG08	51.4
Wellhea d 915	OW915 C	KWG09	8.7
	OW915 D	KWG10	34.7
Total brine flow rates for Wellhead 914 & Wellhead 915			240.4

TABLE IV
MEASURED BRINE TEMPERATURE AND PRESSURES AT OW914 AND OW915

1) Well	2) Power Plant 3) 4) 5)	6) Wellhead Pressure 7) (bar-a)	8) Separation Pressure (bar-a)	9) Separation temperature	10) Power plant Set operating pressures (bar-a)	11) Plant rated Output MW
12) OW914	13) KWG06 &KWG07	14) 45	15) 13.65	16) 193.55	17) 13.5	18) 10.0
19) OW914A	20) KWG5U1 &UNIT 1	21) 37.16	22) 13.53	23) 193	24) 13.5	25) 6.4
26) OW914B	27) KWG4U1 &UNIT 1	28) 25.03	29) 13.5	30) 193	31) 13.5	32) 6.4
33) OW914C	34) KWG08	35) 20.27	36) 12.58	37) 190.63	38) 12.5	39) 5.0
40) OW915C	41) KWG09	42) 45.37	43) 13.62	44) 194.7	45) 13.5	46) 5.0
47) OW915D	48) KWG10	49) 60.97	50) 14.1	51) 195.7	52) 14.0	53) 5.0

3.3 Optimal second flashing pressure derivation from EES simulation

Having obtained the accurate values for brine flow rates, saturated brine temperatures and pressures; these parameters were sufficient to express how much energy was available in the brine. The T-S diagram in Figure 5 illustrates the new cycle that was attained on the introduction of the low pressure separator and low pressure turbine. The set of equations given from

Equation 1- Equation 3 govern the transition of steam from a high pressure to a low pressure and express the amount of low pressure steam that can be generated.

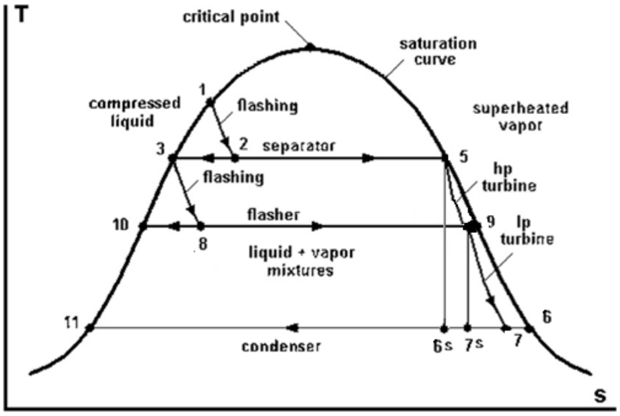

Figure 5 Temperature-Entropy diagram of a Double-flash plant on introduction of LP turbine modified from [2]

$x_2 = \frac{h_{10} - h_8}{h_9 - h_8}$ ……………………….....Equation 1

$\dot{W}_t = \dot{m}(h_9 - h_6)$. ……………………..Equation 2

$\eta_t = \frac{h_9 - h_7}{h_9 - h_{7s}}$…………………………....Equation 3

Where x_2 is the quality of steam at the low pressure separator

$\dot{m}$ is the mass flow rate of steam at the low pressure separator tph

$\dot{W}_t$is the work done by the steam turbine in kW

η_t is the efficiency of the steam turbine.

h_7 is the enthalpy of steam at exhaust to the lp turbine

h_8 is the enthalpy of low pressure steam after flashing

h_9 is the enthalpy of steam at inlet to the lp turbine

h_{7s} is the enthalpy of steam after isentropic expansion in the turbine

From the above computations and considering cost-benefits optimization presented in Figure 6 and scaling an optimum pressure of 2.5 bar-a at a temperature 127.4^{0}C was selected. Geothermal fluids especially from deep wells (like Wellhead 914 and Wellhead 915) drilled to depths of about 3000m are rich in minerals. Previous research in the Olkaria project area reveals that the risk of silica scaling and other mineral scaling occurring when brine is cooled to a temperature of down to 110^{0}C is minimal. [6] As shown in Figure 6 the optimal second flashing pressure must be carefully selected because it affects the projected revenues. A second flashing pressure of 2 bar could generate twice as much revenue as compared to a pressure of 8 bar. According to the simulations done via the EES software, maximum output of 4001 kW can be achieved when a second flashing pressure of 1.6 bar-a and temperature of 113.3 ^{0}C is adapted as shown in Figures 6 and 7. The mass flow rate of low pressure steam at this pressure is 37.59 tph. Moving down from this pressure, again the output starts dropping even though higher mass flow rate of 39.24 tph of lower enthalpy steam can be generated at 1.4 bar-a giving an output of 3990 kW at 109.3^{0}C. However, to remain in the safer region of reduced risk of scaling, and yet still optimize on load output, a low separation pressure set point of 2.5 bar-a and a temperature of 127.4^{0}C was selected. The load output at this pressure was 3871 kW. In Table V the proposed optimum operation set point for the low pressure system have been highlighted in yellow.

TABLE V

TABULATION OF OUTPUT PARAMETERS FOR DIFFERENT SEPARATION PRESSURES FROM EES

	Press bara	Enthalpy kJ/kg	X_2	Mdot steam tph	Power Output kW	Annual Revenue (KES/yr)		
104.8	1.20	2683	0.876	41.07	3952	286,130,332.80	Revenue/kWh (KES)	8.7
109.3	1.40	2690	0.8693	39.24	3990	288,881,586.00	Capacity factor	0.95
113.3	1.60	2696	0.8635	37.59	4001	289,678,001.40	Hours in a year	8760
115.2	1.70	2699	0.8606	36.77	3992	289,026,388.80		
116.9	1.80	2702	0.8584	36.09	3992	289,026,388.80		
118.6	1.90	2704	0.856	35.39	3982	288,302,374.80		
120.2	2.00	2707	0.8536	34.71	3969	287,361,156.60		
127.4	2.50	2717	0.8441	31.66	3871	280,265,819.40		
133.5	3.00	2725	0.8362	29.01	3736	270,491,630.40		
143.6	4.00	2738	0.8237	24.54	3411	246,961,175.40		
151.8	5.00	2749	0.8139	20.79	3055	221,186,277.00		
158.8	6.00	2757	0.8059	17.52	2687	194,542,561.80		
165	7.00	2763	0.7991	14.59	2316	167,681,642.40		
170.4	8.00	2769	0.7932	11.92	1948	141,037,927.20		
175.4	9.00	2774	0.788	9.445	1583	114,611,416.20		
179.9	10.00	2778	0.7832	7.139	1222	88,474,510.80		
184.1	11.00	2781	0.7789	4.968	866.9	62,764,773.66		
188	12.00	2784	0.775	2.91	516.5	37,395,323.10		

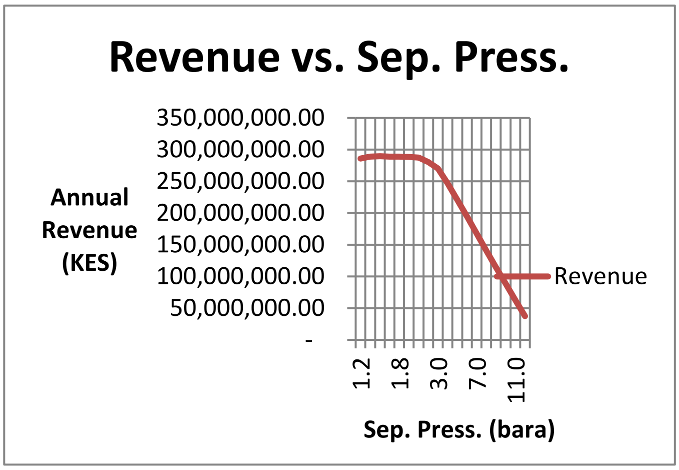

Figure 6. Graph showing expected annual revenues vs 2nd flashing temperature.

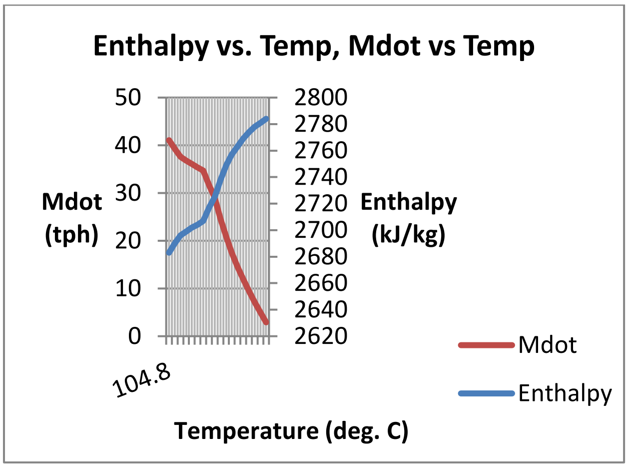

Figure 7. Graph showing mass flow rate & enthalpy vs 2nd flashing temperature

IV. CONCLUSION

From the findings in this research study, there is untapped potential in generation of electricity from waste brine within the Olkaria geothermal field wellheads power plants. Geothermal well drilling is quite an expensive venture both financially and environmentally. Putting into consideration the above stated circumstances and the demand for cheap clean renewable energy, it is vital to fully utilize every bit of the resource that is brought to the surface. Such initiatives will help Kenya to completely alleviate energy poverty and meet our energy goals. With the design and sizing of the second flashing and low pressure system this research has demonstrated and proven that it is possible to economically generate electricity from waste brine in a geothermal set up. The approach proposed in this research provides not only an alternative for injecting clean renewable electricity to the grid but also reducing the footprints of geothermal on the environment by getting rid of excessive venting to the atmosphere and wastage of valuable fluids and energy. Despite the initial investment cost seeming huge the payback time is short and the rate of return on investment is high. The operation and maintenance costs are minimal considering there will be no fuel cost and the plant will be manned by the staff already working at the Wellhead power plants. Evacuation of electricity will be done via additional capacity available at the 11/220 kV substation at Wellhead 914.

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