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Thermodynamic Cycle of the 32-MW Maibarara Geothermal Field, Philippines

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ABSTRACT

The Maibarara Geothermal Field has been in commercial operation since February 2014 commencing with 20-MW generation. In April 2018, an additional 12-MW facility was completed providing total installed capacity of 32 MW for the field. The thermodynamic cycle of the geothermal field including its energy facilities was analyzed using a pressure-enthalpy diagram. Geochemical data and tracer flow testing results were the references used for thermodynamic analysis. The thermodynamic cycle provides a better understanding and holistic view of how the Maibarara production system works, especially on fluid transport from the reservoir to surface facilities.

1. INTRODUCTION

The Philippines, through its Department of Energy (DOE), has initiated a policy that passed the Renewable Energy (RE) Act of 2008, also known as Republic Act (RA) No. 9513, to provide both fiscal and non-fiscal incentives for promoting and accelerating the exploration, development and utilization of renewable resources including geothermal energy. This law has enabled the country to award additional Geothermal Service and Operating Contracts in which the Maibarara Geothermal Power Project became the first successful geothermal development since 2007 (Fronda, Marasigan, & Lazaro, 2015).

The Maibarara Geothermal Field is located at the western flank of Mt. Makiling, approximately 70 km southeast of the capital city Manila and bounded by the two provinces of Laguna and Batangas (Figure 1). It is being operated by a joint venture company called Maibarara Geothermal Inc. (MGI) having an initial 20-MW Power Plant (M1) commissioned in February 2014 and an additional 12-MW installed capacity (M2) commissioned in April 2018 within the same compact development area. The field has a current total installed capacity of 32 MW with three production wells supplying steam to two single flash plant facilities and accommodating injection loads using two reinjection wells. Fluids in the reservoir have neutral-pH and with temperatures more than 300°C (Maturgo, et al., 2015).

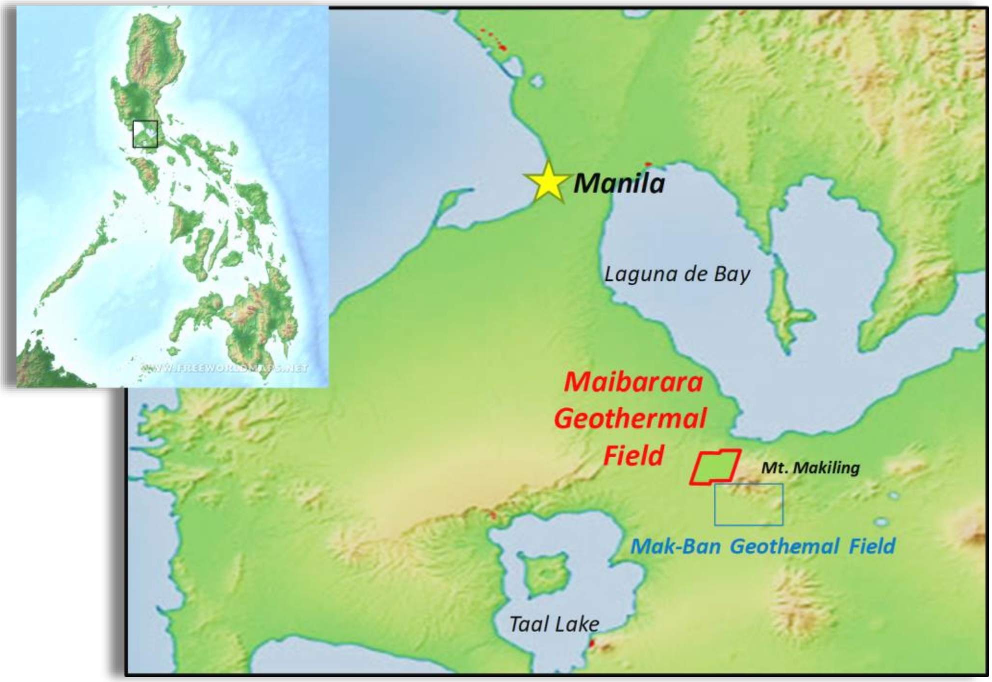

Figure 1: Maibarara Geothermal Field and facilities located southeast of Manila, Philippines (Maturgo, et al., 2015).

The current production focuses on a relatively small 2.5 km^2 resource area vulnerable to dynamic changes in response to exploitation. Therefore, it is prudent to have a holistic overview of the heat and fluid transport in the reservoir and surface facilities. This paper intends to provide an understanding of how the Maibarara production system works based on a practical approach using the fundamentals of Thermodynamics. It also aims to determine the overall conversion efficiency of Maibarara production system consisting of the resource and energy facilities.

According to DiPippo and Marcille (1984), analysis using the exergy concept is a detailed process to assess the performance of geothermal power systems but was not commonly used in the past due to its relatively difficult methodology. Nevertheless, their paper was able to offer a simplified yet systematic approach which various works like Fričovský et al. (2018), Jalilinasrabady, Itoi, Fujii, and Tanaka (2010), Kwambai (2010), and Pambudi, Itoi, Jalilinasrabady, and Khasani (2013) were able to demonstrate. This paper aims to contribute in refining the thermodynamic understanding of a geothermal production system prior to exergy analysis. It focuses on the usability of a pressure-enthalpy diagram as a tool to demonstrate thermodynamic states and processes occurring.

2. MAIBARARA PRODUCTION SYSTEM

The thermodynamic cycle analysis divides the Maibarara production system into three sections: (1) Reservoir, (2) Steamfield and (3) Power Plant. The liquid-dominated reservoir assumes fluids drawing from and replenishing to a representative portion, indicated by pressure control points, of both production and reinjection wells. Geochemical data, particularly the Silica geothermometer, was the basis to predict reservoir temperatures in correlation with downhole measurements while flow rates and specific enthalpy values were results from tracer flow testing conducted at the steamfield. Power plant parameters monitored through the Distributed Control System (DCS) complete the values required for thermodynamic cycle analysis of the Maibarara production system.

2.1 Reservoir Production

Thermodynamic cycle of the Maibarara production system begins with three production wells drawing two-phase fluids from -1100 to -1600 mRSL in reference to their pressure control points. Figure 2 is a linear fit of all Maibarara wells during pre-exploitation state to represent the hydrostatic pressure profile of the reservoir. These wells have an average reservoir enthalpy of 1418 kJ/kg with temperature more than 300°C. At the wellhead, fluids are produced around 8 – 11 bar abs when operated at full bore with enthalpy ranging from 1894 to 2085 kJ/kg. However, one well supplying for M2 is throttled to operate at a higher pressure (26 bar abs) for optimum condition.

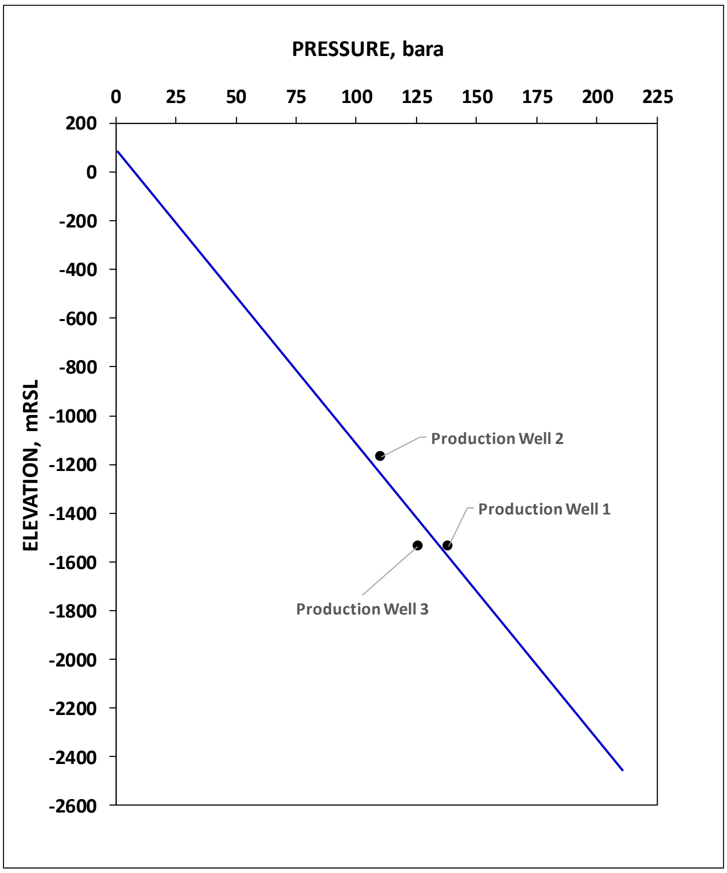

Figure 2: Hydrostatic pressure profile of Maibarara reservoir showing the three production wells in use.

2.2 Steamfield Process

From the wellhead, two-phase fluids enter the separator vessel for steam and brine separation at 7.4 – 7.7 bar abs. Since there are two production wells for M1, two-phase fluids mix at a header before entering the separator vessel. Equation (1) calculates the total enthalpy of the two production wells.

$$H_T = \frac{M_1H_1+M_2H_2}{M_T} \quad (1)$$

where H_T, H_1, H_2, M_T, M_1 and M_2 correspond to total enthalpy (kJ/kg), production well 1 enthalpy (kJ/kg), production well 2 enthalpy (kJ/kg), total mass flow (kg/s), production well 1 mass flow (kg/s) and production well 2 mass flow (kg/s).

Before steam enters the power plants to drive the turbines for electricity generation, the scrubber vessels further eliminate from the fluid stream any suspended solids such as formation materials, iron and other precipitates that may have developed during the process flow. The two production wells supplying the M1 Power Plant exceed the steam requirement for 20-MW generation. An interconnection system combines this excess steam with the other production well's separated steam to serve the 12-MW generation at the M2 Power Plant. In cases when there is disruption of steam demand at the power plant, the rock mufflers function as blow-off to relieve pressure from the steamfield pipes and thereby not reaching any thresholds that will subject equipment or components at risk.

For disposal of liquid effluents such as brine and power plant condensates, the field adopts a cold reinjection scheme by cascading fluids from the separator vessels collectively in a series of sumps called thermal ponds for cooling to about 43°C before pumping to two injector wells and back into the reservoir. Figure 3 is a simplified schematic of the steamfield process starting from reservoir production to steam gathering and brine reinjection systems.

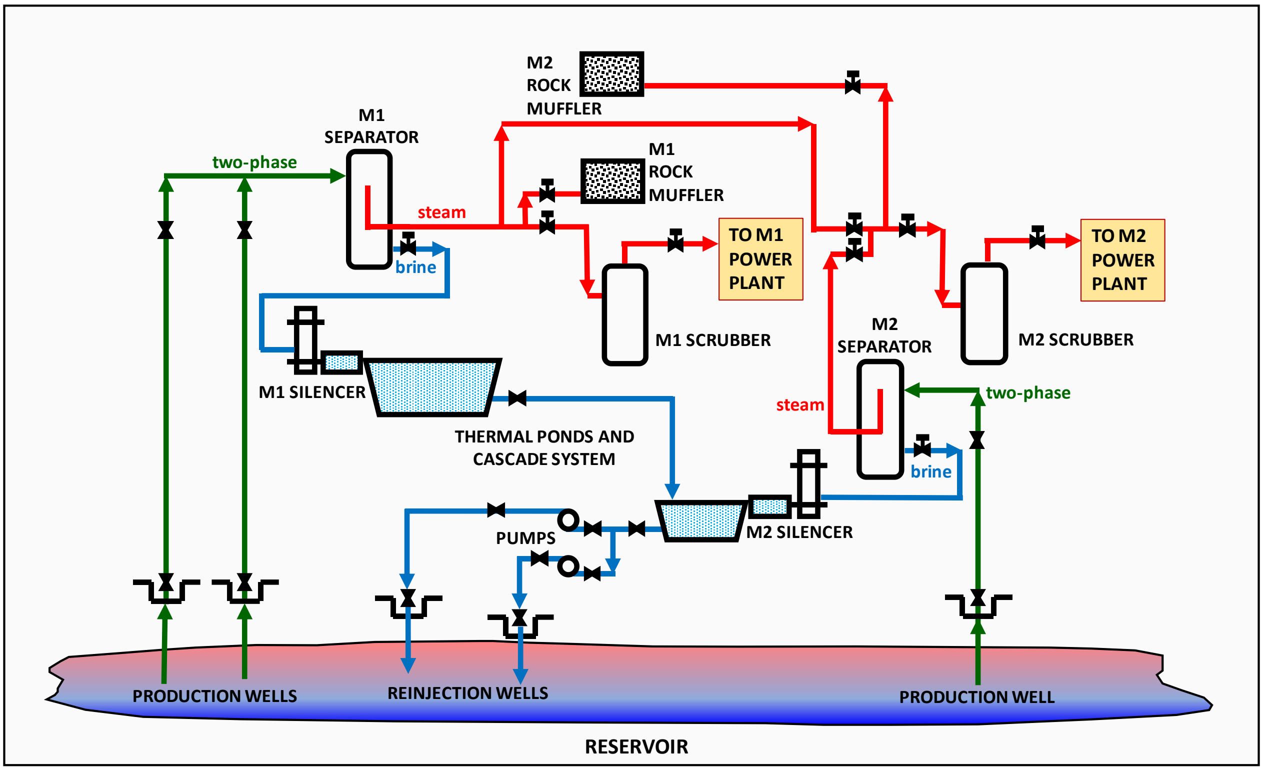

Figure 3: Maibarara steamfield simplified schematic for M1 and M2.

2.3 Power Plant generation

From the scrubber vessels, the power plants admit steam at pressures around 7.2 – 7.5 bar abs and condense the turbine's exhaust steam at vacuum pressures of 0.120 – 0.139 bar abs. Steam expands and condenses as it exits the turbine. Equation (2) estimates the isentropic efficiency using turbine inlet and condenser vacuum pressures.

$$\eta_s = \frac{h_{in}-h_{out'}}{h_{in}-h_{out}} \quad (2)$$

where η_s, h_{in}, h_{out} and $h_{out'}$ are isentropic efficiency, inlet enthalpy (kJ/kg), isentropic outlet enthalpy (kJ/kg) and actual outlet enthalpy (kJ/kg), respectively.

In the study of Moon and Zarrouk (2012), the turbine's isentropic efficiency is one of the factors that affect the overall conversion efficiency of the power plant. It decreases by about 1% due to presence of 1% average moisture content in the steam as supported by the Baumann rule. This suggests that the desirable condition at the turbine inlet is either dry saturated or superheated steam to compensate for the expansion and condensation. As for the conversion efficiency, its worldwide average based on reports is around 12% while the highest is approximately 21% at Darajat Geothermal Field. It is beneficial in estimating the power potential of newly drilled wells and resource studies. Equation (3) calculates the overall conversion efficiency of the power plant.

$$\eta = \frac{Net\ Power\ Generation\ (MWe)}{M_T \times H_{res}} \tag{3}$$

where η, M_T, and H_{res} are conversion efficiency, total mass extraction of fluid (kg/s) and average reservoir enthalpy (kJ/kg), respectively.

Temperature of hot condensates leaving the condensers ranges from 46 – 48°C. Air at 23 – 25°C cools them down to around 30 – 32°C inside the mechanical draft cooling towers. To achieve desirable vacuum pressures, the colder condensates recirculate to the condensers. Furthermore, the gas extraction systems remove non-condensable gases from the condensers to maintain their vacuum state. Excess condensates, through the blowdown, mix with steamfield brine to serve as dilution or additional cooling medium prior to reinjection. Figure 4 is a simplified representation of the process flow at the power plants. There is an apparent difference between M1 and M2 power plants, wherein the M1 turbine is an axial exhaust type while the M2 turbine has a down exhaust connected to the condenser.

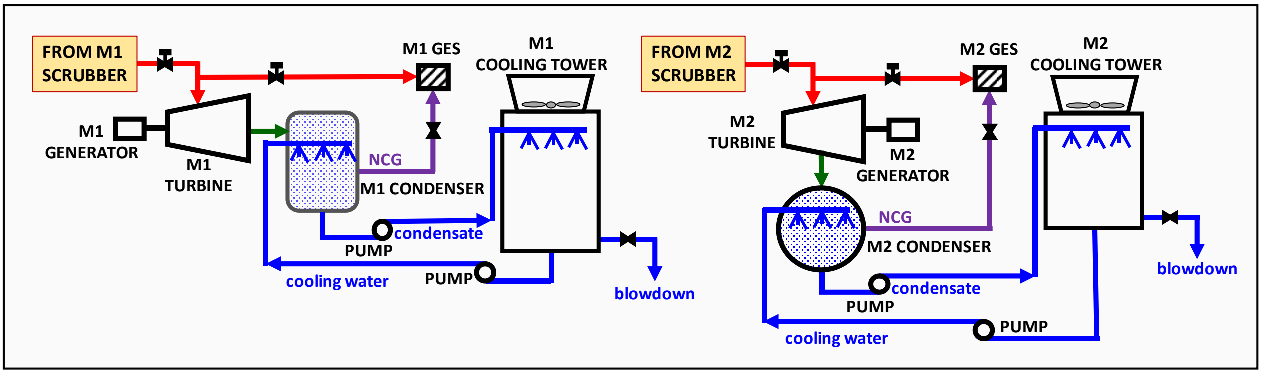

Figure 4: Simplified schematic of Maibarara power plants for M1 and M2.

3. THERMODYNAMIC CYCLE ANALYSIS

Energy exists as heat or work within a bounded system while exergy is the maximum available energy of the system as it approaches equilibrium with its environment. During a process, energy only transforms from one form to another and can neither be created nor destroyed as indicated by the First Law of Thermodynamics. Connecting the processes involved in a bounded system with the final state returning back to the initial forms a cycle (McGoodwin, 2016). This paper focuses only on identification of key states within the Maibarara geothermal production system and delineation of the corresponding thermodynamic cycle. Pressures within the system categorize the thermodynamic states into eight (Table 1). An integration of M1 and M2 subsystems comes after analyzing them separately using pressure-enthalpy diagrams. Lastly, the conversion efficiencies for M1 and M2 are calculated using the net power generation, total mass flow and reservoir enthalpy.

Table 1: Categories to identify the key thermodynamic states within the system.

STATE	CATEGORY
1	Resource
2 and 8	Reservoir
3 and 7	Wellhead
4	Steamfield
5	Power Plant
6	Reinjection Facility

3.1 Maibarara 1

Commercial exploitation in M1 started last February 2014 with two production wells continuously supplying steam to the power plant. Table 2 summarizes the components and processes involved in the pressure-enthalpy diagram presented in Figure 5. Fluids in the liquid-dominated reservoir having temperatures more than 300°C becomes two-phase as pressure drops along the wellbore. The total mass produced for M1 is 93 kg/s with a total enthalpy of 2000 kJ/kg. The wells having excess enthalpy around 470 – 670 kJ/kg suggests that steam does not come alone from boiling as the fluids enter the well. This indicates that there is extra heat at the liquid phase of the fluids during extraction. Two-phase fluids mix in a header and attain a single pressure before entering the separator vessel.

At the separator vessel, steam becomes saturated vapor while the brine becomes saturated liquid. Although slight condensation takes place due to small pressure drop along the steam pipeline, turbine inlet condition presumes that the steam remains saturated vapor because of sufficient insulation. Since the two production wells exceed the 20-MW requirement, pressure control valves throttle steam at the steamfield and power plant interface that diverge to blow-off at the rock muffler.

Saturated steam expands at the turbine to produce work and condenses to saturated liquid at the condenser due to heat rejection. Hot condensates exit the condenser and enter the cooling tower to cool down and recirculate as cooling water into the condenser. The excess condensates are blown-down and mixed with the steamfield brine prior to reinjection by pumping into two injector wells. Reinjected fluids heat-up from 43°C at the wellhead to around 240°C at the production reservoir and eventually to more than 300°C at the deeper reservoir.

Table 2: Thermodynamic processes of Maibarara 1 components.

STATE	COMPONENTS	PROCESS	RESULTING FLUID
1 to 2a/b	Resource to Production Reservoir	Throttling	Compressed or Saturated Liquid
2a/2b to 3a/b	Production Reservoir to Wellhead	Boiling	Two-Phase
3a/b to 4a	Wellhead to Separator Vessel	Mixing	Two-Phase
4a to 4b	Separator Vessel to Turbine Inlet	Separation	Saturated Vapor
4a to 6b	Separator Vessel to Reinjection Facilities	Separation	Compressed Liquid
4b to 5a	Turbine Inlet to Turbine Outlet	Expansion	Two-Phase
4b to 6b	Interface Steam Line to Blow-off Valve Downstream	Throttling	Superheated Vapor
5a to 5b	Turbine Outlet to Condenser	Condensation	Saturated Liquid
5b to 5c	Condenser to Cooling Tower	Heat Rejection	Compressed Liquid
5c to 6a	Cooling Tower to Reinjection Facilities	Heat Addition	Compressed Liquid
6a to 7a/b	Reinjection Facilities to Reinjection Wells	Heat Rejection	Compressed Liquid
7a/b to 8a/b	Reinjection Wells to Production Reservoir	Heat Addition	Compressed Liquid
8a/b to 1	Production Reservoir to Resource	Heat Addition	Compressed Liquid

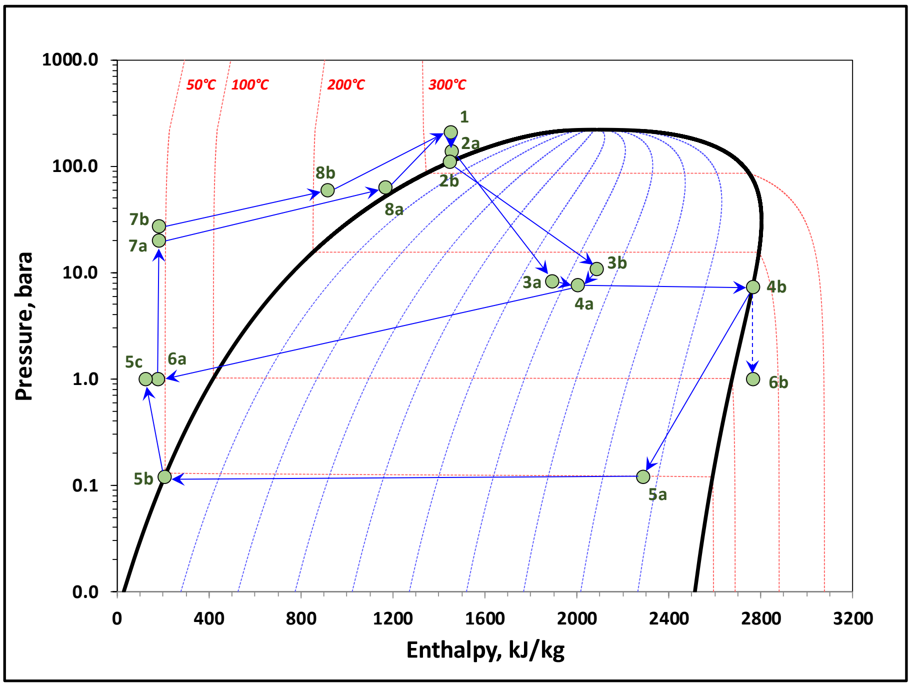

Figure 5: Thermodynamic cycle of Maibarara 1.

3.2 Maibarara 2

Processes involved in the thermodynamic cycle of M2 are similar to M1 since they both use a single flash plant system. M2 started commercial exploitation April 2018 with one production well hooked-up to a separate steam gathering system from M1. Excess steam of the two M1 production wells mix with separated steam of M2 at an interconnection system to provide the requirement for 12-MW generation. Pressure control valves at the blow off compress steam at the interface to supply the remaining flow needed by the power plant. Total mass produced for M2 by the third production well is 36 kg/s with an enthalpy of 1900 kJ/kg. The well has an excess enthalpy of around 490 kJ/kg. Table 3 summarizes the components and processes involved in the pressure-enthalpy diagram presented in Figure 6.

Table 3: Thermodynamic processes of Maibarara 2 components.

STATE	COMPONENTS	PROCESS	RESULTING FLUID
1 to 2	Resource to Production Reservoir	Throttling	Compressed or Saturated Liquid
2 to 3	Production Reservoir to Wellhead	Boiling	Two-Phase
3 to 4a	Wellhead to Separator Vessel	Throttling	Two-Phase
4a to 4b	Separator Vessel to Turbine Inlet	Separation	Saturated Vapor
4a to 6b	Separator Vessel to Reinjection Facilities	Separation	Compressed Liquid
4b to 5a	Turbine Inlet to Turbine Outlet	Expansion	Two-Phase
5a to 5b	Turbine Outlet to Condenser	Condensation	Saturated Liquid
5b to 5c	Condenser to Cooling Tower	Heat Rejection	Compressed Liquid
5c to 6a	Cooling Tower to Reinjection Facilities	Heat Addition	Compressed Liquid
6b to 4b	Blow-off Valve Upstream to Turbine Inlet	Compression	Saturated vapor
6b to 7a/b	Reinjection Facilities to Reinjection Wells	Heat Rejection	Compressed Liquid
7a/b to 8a/b	Reinjection Wells to Production Reservoir	Heat Addition	Compressed Liquid
8a/b to 1	Production Reservoir to Resource	Heat Addition	Compressed Liquid

3.3 Overall Maibarara Production System

Combining M1 and M2 subsystems provides a concise yet holistic thermodynamic cycle of the Maibarara system (Figure 7). Throttling takes place in the reservoir as hot resource fluids at more than 300°C flow from higher to lower pressure. The compressed or saturated liquid boils with excess enthalpy ranging from 470 – 670 kJ/kg as fluids reach the wellhead for production. At the steamfield, mixing and separation of fluids occur. A header combines the two-phase fluids from two production wellheads of M1 before steam and brine separation while an interconnection system combines M1 excess steam with the separated steam of M2 production well.

The power plant admits steam for electricity conversion at 7.4 – 7.7 bar abs turbine inlet pressure and rejects excess or unused steam to the atmosphere by blowing-off through the rock muffler. Steam expands at the turbine and condenses between 0.120 and 0.139 bar abs vacuum pressure with the aid of cooled condensates from the cooling tower. The reinjection facility accommodates both power plant condensates and separated brine from the steamfield to convey fluids back into the reservoir and resource.

At current wellhead conditions, simultaneous operation of M1 and M2, with 32-MW gross generation and approximately 2.3-MW auxiliary load, has an overall conversion efficiency around 16% based on 1418 kJ/kg and 129 kg/s reservoir enthalpy and total mass production, respectively. Operating M1 and M2 separately yields to lower conversion efficiency of 14% and 6%, respectively, due to unused excess steam.

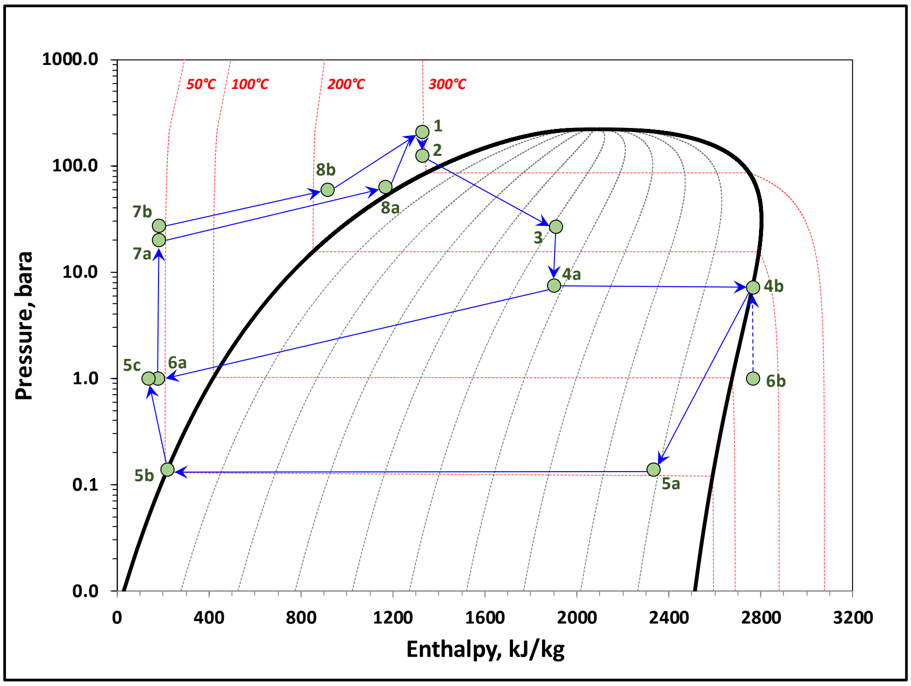

Figure 6: Thermodynamic cycle of Maibarara 2.

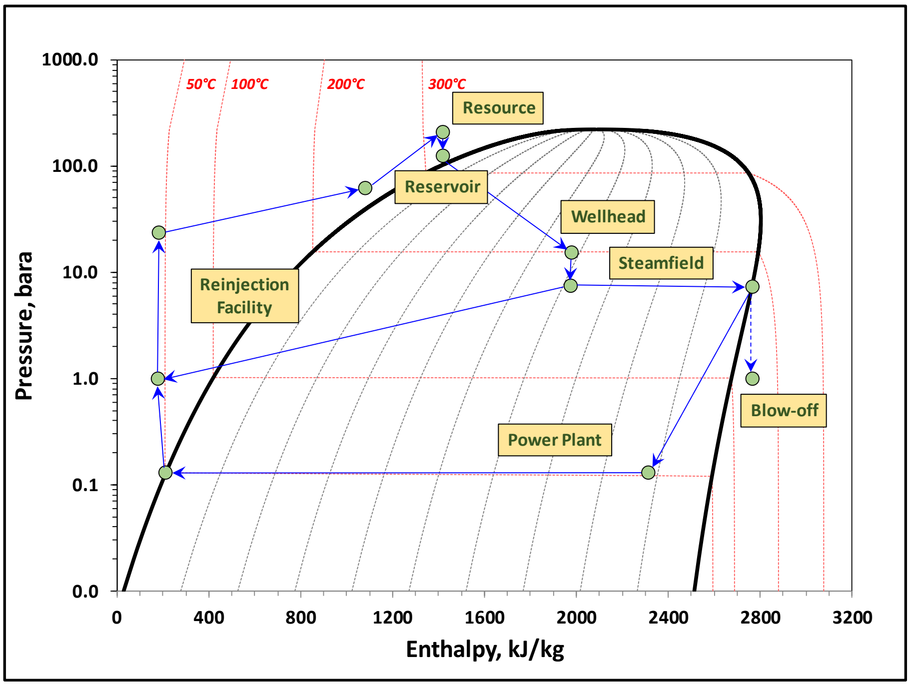

Figure 7: Overall thermodynamic cycle of Maibarara Geothermal Field.

4. CONCLUSION

Most of the literature related to thermodynamic analysis in geothermal utilization demonstrate exergy analysis. In this paper, a simpler approach, applying only the fundamentals up to the First Law of Thermodynamics, was able to describe the processes in a geothermal production system. The thermodynamic cycle conceptualized, using parameters from both reservoir and surface facilities, was able to provide a holistic overview of heat and mass transport within the Maibarara production system. Pressure-enthalpy diagram as a tool to demonstrate the thermodynamic properties in each state and process was useful to evaluate strengths and weaknesses of the field, including the efficiencies involved. Applying this approach is optional, but recommendable, in preparation for a more sophisticated method using exergy analysis.

Thermodynamic cycle analysis of the 32-MW Maibarara Geothermal Field indicates that its conversion efficiency of 16% is above the worldwide average of 12%. The resource, through a liquid-dominated reservoir with wells having excess enthalpy, provides hot two-phase fluids to the steamfield and thereby producing high enthalpy steam to the power plant for electricity generation.

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