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Case Studies in Thermal Engineering 10 (2017) 292–301

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

journal homepage: www.elsevier.com/locate/csite

Preliminary analysis of dry-steam geothermal power plant by employing exergy assessment: Case study in Kamojang geothermal power plant, Indonesia

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ARTICLE INFO

Keywords:
Geothermal
Exergy
Thermodynamic
Optimization
Indonesia
Kamojang

ABSTRACT

The objectives of this study are to perform the exergy analysis and ambient temperature optimization of the Kamojang geothermal power plant by employing Engineering Equation Solver (EES). The geothermal capacity is 55 MW and the field is vapor-dominated reservoir with temperature 245 °C. In the initial state temperature, pressure and mass flow data are collected from the plant operation. The study results show that system has overall efficiency of 35.86% which means that only 111,138.92 kW electrical power can be extracted from 309,000 kW thermal power being produced by 10 production wells of Kamojang. This low efficiency is due to irreversibility associated with different processes and components in the system. The largest irreversibility occurs in condenser due to which 53% of total energy is disposed into the environment. Ambient temperature at Kamojang varies from 17 to 20 °C. The effect of this variation in temperature is also investigated and it is observed that higher temperature does not have any significant impact on system efficiency.

1. Introduction

Geothermal energy uses heat from deep under the surface of the earth as an energy source. It originates from fluid heated by magma and trapped underneath the cap rock. This fluid attempts to rise to the surface naturally through fissures. Once it reaches the surface, manifestations such as fumaroles, hot springs, and geysers appear. In the ancient Roman Empire, geothermal heat sources were used to heat rooms in cold-weather climates. It is still popular in Japan for similar situations in bathing facilities. However, in the modern era, most geothermal heat is utilized for electricity [1]. One reason is because geothermal power generation offers a sustainable and low-emission energy source [2]. The use of geothermal energy for conversion into electricity was first completed by Prince Piero Ginori Conti, who became its pioneer in July 1904 in the city of Lardello, Italy. This marked the beginning of geothermal

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http://dx.doi.org/10.1016/j.csite.2017.07.006
Received 13 May 2017; Received in revised form 17 June 2017; Accepted 18 July 2017
Available online 22 July 2017
2214-157X/

Nomenclature

Symbols

$\dot{m}$	mass flow (kg/s)
$\dot{Q}$	heat flow (kJ/s)
$\dot{W}$	work flow (kJ/s)
$\dot{EX}$	exergy (kJ/s)
h	enthalpy (kJ/kg)
g	gravity (m/s^2)
Z	elevation (m)
ex	specific exergy (kJ/kg)
$\dot{I}$	irreversibility (kJ/s)
T	temperature (K)
s	entropy (kJ/kg K)

Subscript

CV	control volume
i	inlet
o	outlet
k	specific stream
ke	kinetic
po	potential
ph	physical
ch	chemical
p	product

List of abbreviations

I	irreversibility
EES	engineering equation solver
MW	MegaWatt
kW	KiloWatt
GWh	Giga Watt Hour
FiT	feed-in-tariff policy.
ORC	Organic Rankine Cycle
IHE	internal heat exchanger
PLN	Indonesian government-owned corporation
Pertamina	Indonesian state-owned oil and natural gas corporation
PGE	Pertamina Geothermal Energy
KV	KiloVolt
SRH	steam receiver headers
NCG	non-condensable gas

power plant technology. Various innovations have developed to advance geothermal power use, including flash-steam power plants and binary cycle power plants. The current total installed capacity of geothermal power plants in the world is 12,635 MW, which produce 73,549 GWh of electricity [3].

The countries with the largest installed geothermal capacity are the USA with 3700 MW, Philippines with 1904 MW, Indonesia with 1438 MW, Italy with 996 MW, Iceland with 665 MW, and Japan with 519 MW [3]. Indonesia has the largest reserved potential, with around 40% of the world's total geothermal energy at 28,910 MW spread across 312 locations [4]. This is because of its location in the Ring of Fire, part of a string of volcanoes and seismic activity. However, Indonesia does not appear to have maximized its usage of this energy resource and it only utilizes around 4.9% from its total potential.

In an effort to increase geothermal power capacity by installing new geothermal plants, the Indonesia Government introduced a feed-in-tariff (FiT) policy. Alongside this, through the new National Energy Policy, the government plans to increase spending on energy expenditure by constructing a 9.5 MW geothermal power plant in 2025. However, notwithstanding these developments, the current capacity still falls short of the new of the target of 6200 MW. To support the government's expansion project, it is necessary to optimize and maximize the capacity of existing plants. This can be achieved by the use of energy and exergy analysis which uses the 2nd law of thermodynamics to investigate process irreversibility by measuring changes in the quality of energy. This is because the transformation of energy causes changes in its quality, which are measured as exergy parameters [5]. Exergy analysis is carried out using exergy balances based on physical models of thermal systems by the combination of energy and entropy parameter. This type of analysis is suitable for determining unused and lost energy due to better understanding of energy transfer and inversion.

The energy and exergy analysis of geothermal power plants has been carried out by several researchers. Exergy analysis and optimization of the Dieng single-flash geothermal power plant has been carried out by Pambudi et al. [6]. This research showed that the plant has operated with almost maximum resources. However, to expand the existing system, a double-flash and binary can be included [7,8]. The optimization of the plant by employing inter-stage reheating has improved efficiency by 3–5% [9]. Murat and Cerci calculate the exergy efficiency in the Germencik geothermal power plant [10]. The results shows that second law efficiency of the turbine-generator to be 87.4% and the second law efficiency of the overall plant has been found to be 35.34%. In Iran, Saeid, et al. applied second law efficiency research to flash cycle optimization in Sabalan [11]. The analysis suggests a double flash should be introduced to expand the system. Degdas, et al. investigated a thermodynamic optimization of the DenizliKızıldere power plant using real data [12]. They found the optimum flashing pressure to be 200 kPa. Yari et al. analyses various types of geothermal power plants such as The considered cycles for this study are a binary geothermal power plant using a simple organic Rankine cycle (ORC), a binary geothermal power plant using an ORC with an internal heat exchanger (IHE), a binary cycle with a regenerative ORC, a binary cycle with a regenerative ORC with an IHE, a single-flash geothermal power plant, a double-flash geothermal power plant and a combined flash-binary power plant [13]. Exergy analysis also be used for several researcher to develope hybrid analysis between geothermal and other renewable energy resouces such as solar and wind [14–17].

This research aims to analyze the exergy and irreversibility of Kamojang geothermal power plant in Indonesia. In this work, efficiency and magnitude as well as location of irreversibility in whole system are determined. The obtained results are used to optimize the system, which can considerably improve its efficiency. Actual data was collected during plant operation. This data is then used in a mathematical model and a simulation, which is performed, by using Engineering Equation Solver (EES). The results thus obtained are important for government, engineers and researchers who have special interest in Kamojang. Furthermore, this study fills the research void as only few research publications related to Kamojang are available.

2. An update of geothermal power plant in Indonesia

As the key drive toward the realization of the goals of national energy development policy, geothermal energy through the comprehensive national approach will help Indonesia achieve its energy objectives. As the pressure for clean energy increase globally, it is high time that Indonesia rises to the occasion and taps into its geothermal energy potential. Geothermal energy as a source of energy is not only clean, renewable but also environmentally friendly. The use of geothermal energy will not only increase national energy security but shield the country from global fossil fuel price fluctuations. There are eleven geothermal power plant in Indonesia such as 12 MW Sibayak, 110 MW Ulubelu, 377 MW Gunung salak, 55 MW Patuha, 270 MW Darajat, 227 MW Wayang windu, 235 MW Kamojang, 60 MW Dieng, 10 MW Ulumbu,2.5 MW Mataloko, 120 MW Lahendong as shown in Fig. 1.

History reveals that exploration of geothermal energy in Indonesia was first proposed in 1918 [18]. Several studies suggest that Indonesia has a total estimated geothermal potential of 28.8 GW across its seven islands that serve as the home to 312 geothermal fields. However, the country has remained one of the lesser energy producing countries despite its potential of producing over 40% of total global geothermal resources. The country has remained behind countries such as the USA and the Philippines which have the capacity to produce 3700 MW and 1904 MW respectively [19,20]. This relatively low production of geothermal energy can be attributed to factors such as regulatory measures, autonomy, government policies, tendering, negotiation, licensing policy among others.

3. Kamojang geothermal field and power plant

Kamojang is located in Laksana village, in the west of Java province in Indonesia, 1500 m above sea level (ASL). It is about 100 km to the south of Jakarta, the capital city of Indonesia. The average yearly temperature and pressure of this locality are 19 °C and 850 mbar respectively. In the vicinity of site, geothermal manifestations such as steamy soil surfaces, warm soil, fumaroles, hot mud pools and hot springs can be seen. This has made the location a tourist attraction over the years. Geothermal potential was discovered in this area when the first volcanological survey was conducted by Netherland East Indies between 1916 and 1928 [21,22]. Initially only five wells were drilled at the location. Later on, collaboration work between Indonesian and New Zeeland paved the way for first power plant in 1979. which hada total capacity of 30 MW at that time. Between 1971–1979, ten wells were dug during drilling and exploration work. In 1987 a second plant was installed which increased the total capacity up to 55 MW [21].

The current capacity of Kamojang geothermal power plant is 235 MW. Unit 1 has a capacity of the 30 MW, Units 2 and 3 which both have a capacity of 55 MW and are owned and operated by (Indonesian government-owned corporation (PLN)). Unit 4 which has a capacity of 60 MW and is owned and operated by Pertamina Geothermal Energy (PGE). A new Unit 5 was just inaugurated with additional capacity of 35 MW.

The production wells have been producing steam at 1500 t/hour since 1976 for three generating units. After 30 years, steam production is now decreasing at the rate of 3% per year, primarily due to the reduction in reservoir temperature and pressure. Over the years the pressure has been reduced to 9.3 bar and the temperature has dropped to 190 °C [21,23]. The Kamojang reservoir is vapor-dominated with an average temperature of 245 °C and its reservoir is different from the majority of reservoirs in Indonesia, as those are dominated by liquid.

The schematic diagram of Kamojang Geothermal Power Plant is represented in Fig. 2. The plant unit is equipped with Steam Receiver Headers (SRH) to prevent steam fluctuations which can directly impact electricity production. The SRH are connected with a vent valve system which discharges excessive steam entering the plant. Steam then enters into a the separator, which removes debris and other substances from steam by employing centrifugal force. The function of this separator is different from single-flash technology, which is used to separate brine from steam. To ensure high quality, steam is then passed through a demister. This is a device which is employed to remove water droplets from steam. It utilizes turbulence and collision force between high speed steam and its own components. The trapped water is then drained through the flash tank. After the demister majority of the steam enters a turbine, whereas a small quantity of steam is diverted to a steam ejector in the gas removal system. For safety measures, the system is

Fig. 1. Location of 11 geothermal power plants in Indonesia.

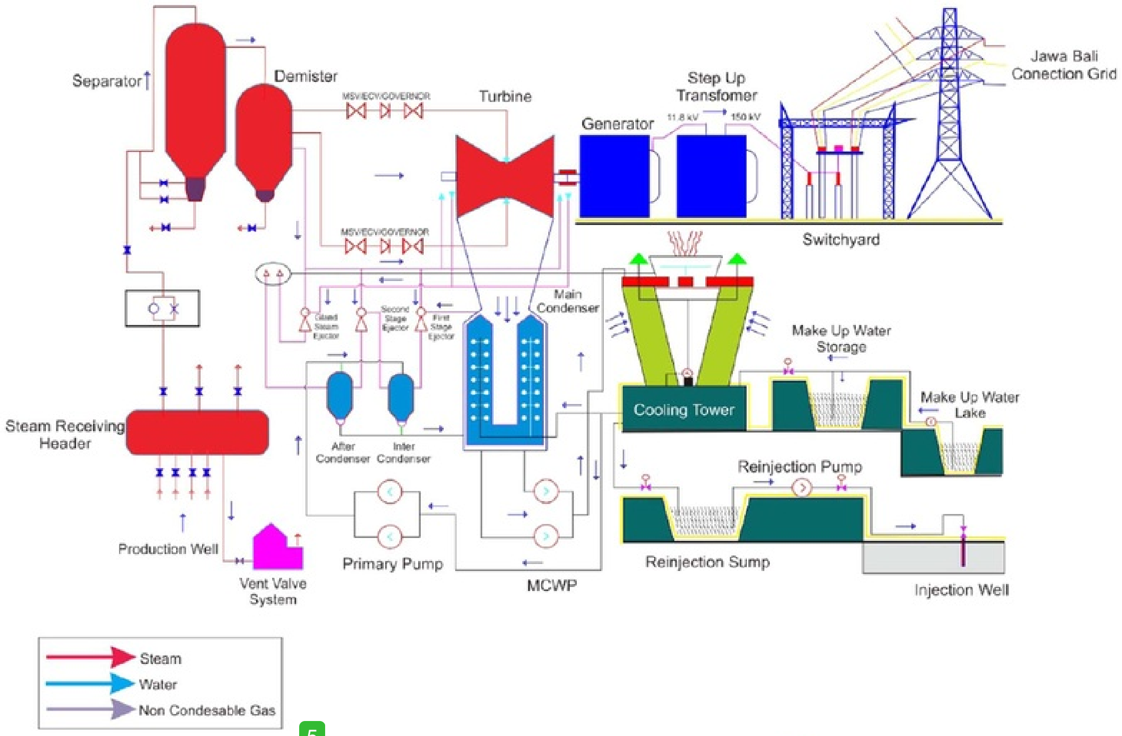

Fig. 2. Schematic diagram of Kamojang geothermal power plant [24].

equipped with a main stop valve which protects it from overpressure and other emergency situations.

Table 1 shows the specifications of turbines installed in Kamojang. They are two-stage and double-flow turbines manufactured by Mitsubishi Heavy Industries. The power of Unit 1 turbine is 30 MW whereas for Unit 2–3 the turbine rating is 55 MW. The inlet turbine temperature and pressure are 161.9 °C and 6.5 bar, respectively. Turbine outlet pressure is 0.133 bar for Unit 1 and 0.1 bar for Unit 2–3. Total mass flow rate in Unit 1 is 244,190 kg/h while in Unit 2–3 it is 366,300 kg/h. All three turbine units are equipped with 3000 rpm generators which produce electricity with voltage level of 11.8 kV and 300 A current. Step-up transformers are installed to increase the voltage from 11.8 to 150 kV to transmit it to switchyard.

From the turbine outlet, fluid enters into a condenser where it dissipates its heat to the cooling water coming from cooling towers. The gas removal system keeps condenser pressure as close to vacuum pressure as possible. Table 2 shows values of different condenser parameters such as pressure, flow rate, NCG, cooling fluid temperature and exhaust steam temperature.

4. Method

Sequence analysis consists of initial data, the necessary calculations and outcomes, as well as optimization of the results as shown in the methodology diagram in Fig. 3. Initial data mostly are operating data and assumptions such as the parameters of pressure, temperature, and the mass flow rate of each component in the generator. The calculation is done by building a mathematical equation for energy and exergy using EES software. The outcomes of the calculation results are data, tables and diagrams. Based on these results, optimization is done to improve the performance of the plant.

Table 1
Turbine specification in Kamojang geothermal power plant [24].

Parameter	Unit 1	Unit 2–3
Manufacturer	Mitsubishi heavy industries	
Nominal power (MW)	30	55
Maximum power (MW)	37.5	57.75
Steam inlet pressure (bar)	6.5	
Steam inlet temperature (°C)	161.9	
Vapor Pressure Outlet (bar)	0.133	0.1
Mass flow rate of steam (Kg/h)	244,190	388,300

Table 2
Condenser specification in Kamojang geothermal power plant [13].

Parameter	Unit 1	Unit 2–3
Manufacturer	Mitsubishi Heavy Industries	
Pressure (bar)	0.133 bar absolute	0.1 bar absolute
Cooling water temperature (°C)	29	27
Exhaust steam temperature (°C)	49.6	42.8
Outlet mass flow rate (kg/h)	232,700	376,910
NCG flow rate (kg/h)	2.350	1.885
NCG outlet temperature (°C)	32	29

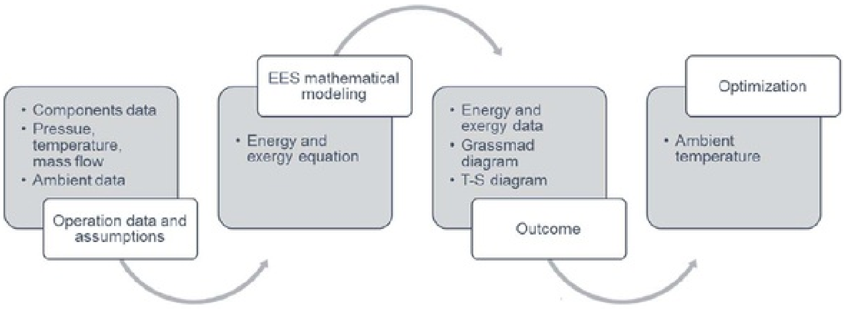

Fig. 3. Methodology algoritma.

4.1. Energy and exergy equation

Energy and exergy analysis is performed to determine the value of thermal energy based on thermodynamic properties in each of state Exergy analysis is a tool used to evaluate and measure thermal loss in terms of type, quality and quantity. To calculate this method first and second law thermodynamic method are employed as follows:

$$\sum \dot{m}_{i,cv} = \sum \dot{m}_{0,cv} \tag{1}$$

where $\dot{m}_{i,cv}$ is the mass flow rate entering the control volume and $\dot{m}_{0,cv}$ is the mass flow rate flowing out the control volume. Eq. (1) represents the law of mass conservation that the mass that enters a control volume is a system. The total mass flow entering the control volume is equal to the outlet. The Eq. (1) is then expanded to the Eq. (2) as follows:

$$\dot{Q} - \dot{W} = \sum \dot{m}_0 h_0 - \sum \dot{m}_i h_i \tag{2}$$

where $\dot{Q}$ is the heat added into the system, $\dot{W}$ is the work produces and h is the enthalpy. Subscript o is the outlet and i is the inlet. Eq. (3) is the expansion of the Eq. (2) with kinetic, $\frac{C^2i}{2}$ and potential energy, gZ_i is fully considered.

$$\sum \dot{Q} + \sum \dot{m}\left(h_i + \frac{C^2i}{2} + gZ_i\right) = \sum \dot{m}\left(h_0 + \frac{C^20}{2} + gZ_0\right) + \sum \dot{W} \tag{3}$$

After observing the expression of energy, the exergy equation as in Eq. (4)–(9) are further examined.

$$\sum \left(1+\frac{T_0}{T}\right)Q_k + \sum (\dot{m}_i ex_i) = \sum \psi_w + \sum (\dot{m}_0 ex_0) + \dot{I}_{destroyed} \tag{4}$$

$\dot{I}_{destroyed}$ is Irreversibility is used to determine how much exergy in a component is lost during the process.

$$EX_k = \dot{m}ex_k \tag{5}$$

The Exergy rate in specific stream, k, is equal to specific exergy in stream k as shown in Eq. (5). Then, Eq. (4) is substituted into Eq. (6).

$$Ex_k = \dot{m}((h_k - h_0) - T_0(s_k - s_0)) \tag{6}$$

where exergy in specific stream can be written as Eq. (7):

$$ex_k = (h_k - h_0) - T_0(s_k - s_0) \tag{7}$$

In the system, the total specific exergy is equal to kinetic, potential, phisic and chemical exergy as shown in Eq. (8). However here we ignored the kinetic, potential and chemical exergy.

$$ex_{total} = ex_{ke} + ex_{po} + ex_{ph} + ex_{ch} \tag{8}$$

4.2. Efficiency based on Second Thermodynamic Law

To evaluate the performance of the power plant using exergy analysis, the formula based on exergy efficiency expressed in Eq. (9). It can be applied in the whole system or component efficiency.

$$\eta = \frac{\sum E_{in}}{\sum E_{out}} \tag{9}$$

whereas ΣE_{in} is total exergy which enters from the components of the geothermal power plant system and ΣE_{out} is total exergy which exits. Each component has exergy inlet and exergy outlet. For example, exergy inlet at the separator comes from the steam receiving header and exergy outlet is exergy which flows into the demister. Another definition of exergy efficiency is exergy outlet divided by exergy inlet.

5. Result and discussion

5.1. Enthalpy, entropy and energy rate

There are six major components in Kamojang geothermal power plant: SRH, separator, demister, turbine, condenser and cooling tower, with inter-condenser and after-condenser as auxiliary equipment. The working fluid is water as vapor, liquid and a small amount of non-condensable gases at various states throughout the power plant. Because of the small amount of non-condensable gases, they have negligible impact on the calculations and results, and therefore they are disregarded while carrying out the analysis. Temperature, pressure and other important parameters including flow rates, entropy, enthalpy and energy rates are stated in Table 3. Some important parameters which can affect calculations and the results are not presented in the table because they were not available in the plant operation data sheet, and therefore some valid assumptions are to be made during calculations.

Turbine is an important component of a geothermal power plant and the ideal work for turbine in this case is estimated to be 68,165 kW. However, due to mechanical and thermal losses only 55 MW power output is obtained.

In the SRH energy rate is 84.47 kW and in separator it is 354.2 kW. Further component is demister to separate liquid droplets entrapped in steam before it enters the turbine since water droplets can cause damage to the blades. The demister also splits the steam to flow to turbine and gas ejector to remove non-condensable gas. After passing through the turbine, steam flows to the condenser where considerable amount of heat was absorbed by cold liquid from the cooling tower. The heat latent absorbed in condenser is absorbed by liquid as it evaporates into vapor phase or the amount of heat releases when vapor changes into liquid. The energy rate at outlet of inter-condenser is 4790.3 kW and at outlet of after-condenser is 3334.16 kW. Non-condensable gases affect the condenser function and they should be removed from the system. Gas removal system at condenser and after-condenser are used for this purpose. In gas removal system, the first stage ejector has energy rate of 12,318 kW while the second stage ejector has energy rate of 9522 kW.

5.2. Exergy efficiency at components

To calculate exergy efficiency at each component, inlet and outlet exergy amount are required, which are tabulated in Table 4. It can be seen that the exergy at inlet of SRH is 309,953 kW while at the outlet is 309,857 kW. The difference between the exergy inlet

Table 3
Enthalpy, entropy and exergy at different states.

Component name	State	Pressure (bar)	Temperature (°C)	Mass flow rate (Kg/s)	Enthalpy (kJ/kg)	Entropy (kJ/kg K)	Energy rate (kW)
From Well	0	6.5	165.5	126.4	2760	6.733	84.47
SRH	1	6.4	165.5	126.4	2759	6.738	84.47
Separator	2	6	165.5	126.4	2757	6.76	354.2
Demister	3	5.3	165.5	126.4	2751	6.802	
Turbine	4	5.3	165.5	122.6	2751	6.802	62,771
Condenser	5	0.14	54	122.6	2239	6.937	247,296.5
MCWP	6	2.7	53	3486	221.9	0.7424	277,130
Cooling Tower	7	2.7	33	3311	138.2	0.4777	291,778.2
1st Ejector	8	0.14	29	0.2044	2239	6.937	104.65
Motive Steam 1st	9	5.3	165.5	2.053	2751	6.802	12,318
Motive Steam 2nd	10	5.3	165.5	1.587	2751	6.802	9522
Int-Cond In	11			2.257	2332	6.471	21.84
Int-Cond Out	12		50	43.45	209.3	0.7037	4790.93
Primary Int-Cond	13		33	0.04208	138.2	0.4777	2992
2nd Ejector	14	0.41	40	0.06	2174	6.335	34.62
Aft-Cond In	15			1.65	2230	6.125	859.65
Aft-Cond Out	16		50	43.21	209.3	0.7037	3334.16
Primary Aft-Cond	17		33	0.04208	138.2	0.4777	2992
Final Ejector	18	0.95	50	0.04583	2221	6.158	24.2899

Table 4
Inlet and outlet exergy amounts and component efficiency.

Component name	Exergy inlet (kW)	Exergy outlet (kW)	Irreversibility	Exergy efficiency (%)
SRH (Steam receive header)	309,953	309,857	96	99.97
Separator	309,857	309,456	401	99.87
Demister	309,456	308,696	760	99.75
Turbine	299,381	236,356	63.025	78.95
Condenser	236,706.2	55,923	180.783	23.63
Int-Condenser	5407.2	288.5	5118	5.34
Aft-Condenser	3988.9	262.7	3726	6.59

and outlet is 96 kW which is the amount of irreversibility caused by the SRH. At inlet of separator exergy amount is 309,857 kW while at the outlet from steam and brine parts it is found to be 309,456 kW. Small leak in the system caused due to small gaps in rubber packings used to join separator with pipes at inlet and outlet is the main reason of irreversibility in separator. These small gaps provide steam a narrow path to leak into the environment.

The demister has 309,456 kW exergy at inlet and 308,696 kW at the outlet. In the turbine, the amount of exergy at inlet and outlet are 299,381 kW and 236,356 kW respectively. The efficiency of the turbine is then calculated to be 78.95%. The turbine operation includes a main stop valve and a governor valve. These valves throttle the steam and cause a pressure drop. Also, the steam expands at the expense of pressure energy at the blades of the turbine, which causes a significant pressure drop. These two pressure drops are responsible for irreversibility in the turbine.

Condenser operation completes in three different components, the main condenser, inter-condenser and after-condenser. Efficiency of these condensers is 23.63%, 5.34%, and 6.59% respectively and it is found to be the lowest among all other components. Residual steam from turbine having 236,706.2 kW of exergy enters the condenser. Heat losses such as heat rejection to the environment is responsible for the condenser irreversibility. Due to these irreversibility, exergy at the outlet of the condenser is reduced to 55,923 kW and the steam flows ahead to the cooling towers.

5.3. Temperature-entropy diagram

Thermodynamic process for producing electrical energy from geothermal plant is represented in form of Temperature-Entropy diagram in the Fig. 4. Two-phase steam at 165.5 °C temperature and 6.5 bars pressure flow from the production wells, with vapor phase dominating the liquid phase. To separate the liquid fraction from vapor, steam is passed through the separator. It then enters into turbine at 5.3 bar. Steam expansion takes place in turbine to produce work and the pressure drops to 0.14 bars at the turbine outlet. The isentropic efficiency of the turbine is 92%. The pressure of the condenser should be maintained close to the vacuum by extracting non-condensable gases. These gases are extracted by using gas ejector within the gas removal system which removes and directs residual gases to the cooling tower through a discharge pipe.

5.4. Grassmann diagram

Fig. 5 shows the exergy flow within Kamojang geothermal power plant. It shows the amount of total available exergy, exergy efficiency, irreversibility and the individual component efficiency. The exergy flow analysis can help to evaluate the performance of an individual component, as well as the whole system. This analysis helps to discover new ways to improve the system power capacity by increasing its efficiency. It can be observed that reservoir fluid provides total exergy of 309,953 kW but only 111,138.92 kW of electrical energy is being produced by the generator. Due to the irreversibility in different components of plant, the exergy efficiency

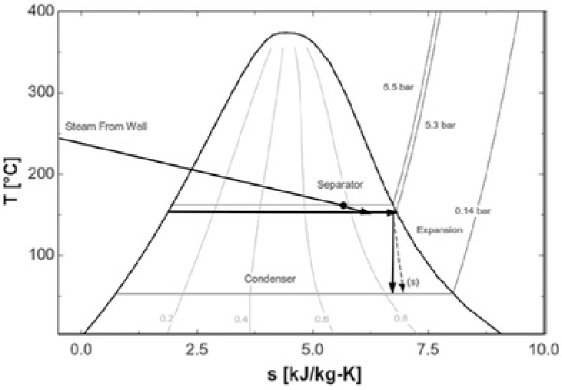

Fig. 4. Temperature-entropy diagram.

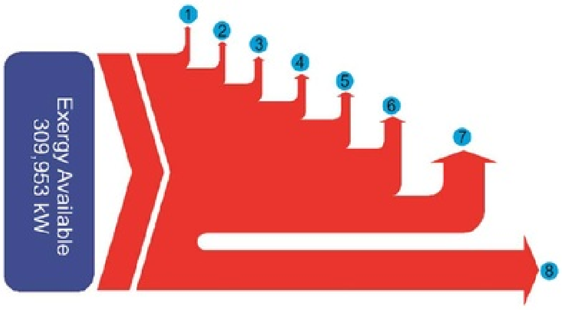

Fig. 5. Grassmann diagram of Kamojang geothermal power plant. Note: 1. Steam Receiving Header 96 kW, 0.03%. 2. Separator 401 kW, 0.13%, 3. Demister 760 kW, 0.25%, 4. After Condenser 3726 kW,1.2%, 5. Inter Condenser 5118 kW, 1.65% 6. Turbine 8025 kW, 2.59%, 7. Main Condenser 180,783 kW, 58.33%, 8. Electricity, 111,044 kW, 35.83%.

of whole system comes out to be 35.86%.

The lowest irreversibility of 96 kW occurs in the SRH component. Other components such as separator and demister also have low irreversibility of 401 kW and 760 kW respectively. The turbine contributes to 8025 kW exergy loss, which is much higher loss than in previous components and contributes 2.59% of the total exergy loss in the whole system. In the condenser, 180,783 kW exergy is lost which contributes 58.33% of the total exergy loss from the whole system and is the highest loss among all the components.

5.5. *Effect of ambient temperature efficiency against exergy*

Fig. 6 illustrates the effect of ambient temperature on exergy efficiency. Exergy analysis was carried out at different ambient temperature including 17, 18, 19 and 20 °C. Temperature variation occurs during night and day time in Kamojang and therefore is considered as dead state during exergy rate calculations in EES calculation. It can be seen that exergy efficiency is slightly decreased with the increase in ambient temperature during daytime. The highest efficiency obtained is 35.86% at 17 °C. As the temperature rises to 18 °C, efficiency is reduced to 35.78%, and is further dropped to 35.74% at 19 °C. The lowest efficiency of 35.7% is witnessed at 20 °C. The higher temperatures approach the dead state which leads to higher entropy. Therefore, more exergy will leave the system and go into the environment to maintain the equilibrium. This situation can be identified with continued analysis in the performance of several components.

5.6. *Effect of ambient temperature on exergy efficiency at each component*

The effect of ambient temperature on exergy efficiency of individual components of a power plant is illustrated in Fig. 7. This figure shows that which component efficiency experiences more significant change with varying ambient temperature. With the increase in temperature the exergy efficiency in condenser, inter-condenser and after condenser increases. Once the ambient temperature increases heat tends to remain within the system. Furthermore, once ambient temperature increases, it requires less exergy to exit from the system to attain equilibrium. This heat exchange mechanism in the condenser is opposite to that of turbine, where rising ambient temperature causes decrease in exergy efficiency.

5.7. *The influence of ambient temperature on the irreversibility*

Fig. 8, illustrates the relationship between increase in ambient temperature and irreversibility. In SRH the amount of irreversibility increases from 96 kW to 97 kW when the ambient temperature rises from 17 °C to 18 °C. It further rises to 98 kW when ambient

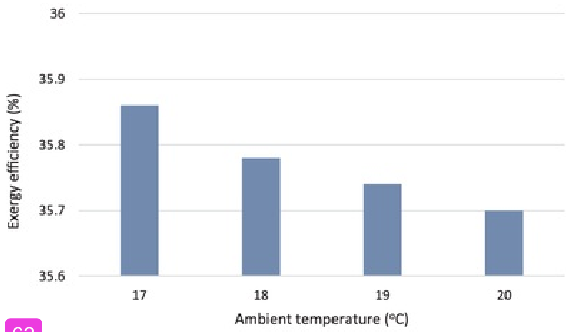

Fig. 6. Effect of air temperature environment, the exergy efficiency system.

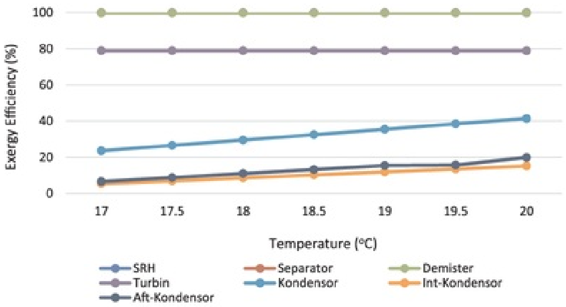

Fig. 7. Exergy efficiency each component by temperature fluctuation in Kamojang.

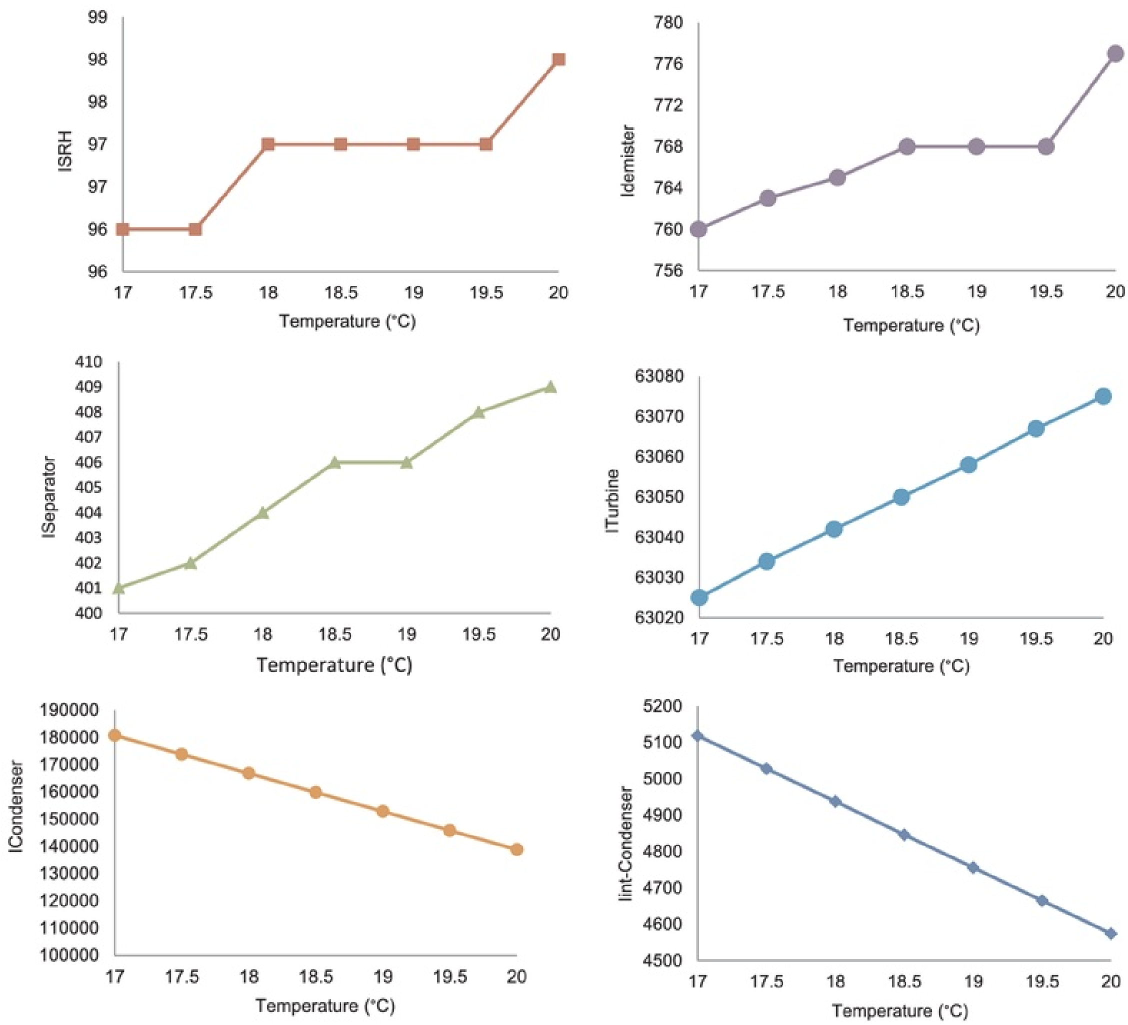

Fig. 8. Irreversibility in component as an ambient temperature function.

temperature is further increased to 20 °C. Irreversibility of separator also has direct relationship with ambient temperature. The amount of irreversibility is 401 kW, 404 kW, 406 kW and 409 kW at 17 °C, 18 °C,19 °C and 20 °C respectively. The demister shows irreversibility of 760 kW at 17 °C, 765 kW at 18 °C, 772 kW at 19 °C and 777 kW at 20 °C. The irreversibility in these three components changes with the change in ambient temperature. Therefore, these three components have lower exergy efficiency when the ambient temperature is increased.

With the increase in outside temperature the irreversibility of turbine also increases. The irreversibility value in turbine observed is 63,029 kW at 17 °C, 63,042 kW at 18 °C, 63,058 kW at 19 °C and 63,075 kW at 20°. As a result, exergy efficiency and the exergy value at the outlet of condenser are reduced. But in the case of the condenser, the results are totally opposite. Unlike the turbine the increase in ambient temperature at condenser decreases the irreversibility associated with it. Likewise, irreversibility increases with the drop in ambient temperature. This effect of ambient temperature on the condensers can be explained by taking cooling water in to account. The temperature of cooling water supplied by cooling tower affects the performance of three condensers. Variation in ambient temperature has an effect on the temperature of cooling water. The temperature decreases when the ambient temperature is low, which will increase the overall efficiency of the system.

6. Conclusion

In this paper, exergy analysis and ambient temperature optimization are investigated. This study also gives insight about the location and the magnitude of irreversibility along with efficiency in Kamojang geothermal power plant. The reservoir in the Kamojang field is vapor-dominated at temperature of 245 °C and is quite different from many other geothermal fields in Indonesia.

It is estimated that 303,953 kW total exergy is available from 10 production wells. The exergy then enters into SRH which has 96 kW of irreversibility. The fluid then passes through separator with 309,857 kW of exergy and the 401 kW irreversibility. In demister the amount of exergy is 309,456 kW with 760 kW irreversibility. The steam then splits to the turbine and gas ejector in gas removal system. The turbine produces 55 MW and has irreversibility of 8025 kW with an efficiency of 35.86%. The main condenser is the unit that has the largest irreversibility of 180,783 kW and lowest exergy efficiency of 23.63% which is due to the residual steam from turbine. Turbine is the key component in power generation system and is influenced by the change of ambient temperature. After performing energy and exergy calculations, it is evaluated that at 17 °C turbine has highest efficiency of 78.95% and it has lowest efficiency of 78.8% at 20 °C.

In this preliminary research, analysis is focused on unit 2 which has total capacity of 55 MW. However, we are going to perform complete analysis of Kamojang geothermal power plant which will be comprised of unit 1, 3–5 as well. We are also looking forward to improve the exergy efficiency of Kamojang geothermal field by minimizing the heat wasted via the injection well.

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