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Design, Construction and Preliminary Test Operation of BPPT-3MW Condensing Turbine Geothermal Power Plant

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BPPT of Indonesia has developed 3MW condensing turbine type geothermal power plant (GPP) with maximum local content. The design of GPP is based on KMJ-68 well characteristic data of Pertamina Geothermal Energy located at Kamojang West-Java. KMJ-68 well data are; steam dominated, 12bara well head pressure, 1.7% NCG, 33ton/hour steam flow rate. The construction has been completed and is currently being operated for early stage performance testing. Until early 2018, the BPPT's GPP has generated 15,572kWh of electricity, with the highest load of 1.3MW. The thermal efficiency of the turbine-generator system reaches 81% for loads of about 1MW.

Keywords: renewable energy resource, small scale geothermal power plant, condensing turbine

1. Introduction

1.1 Potential of small scale geothermal power plant development.

Indonesia has an abundant geothermal energy sources, with a total potential of more than 28 GW, from low to high enthalpy, which is spread along volcanic path from the islands of Sumatra, Java, Bali, NTT, Sulawesi and Maluku. However, to date only 1,808.5 MW (6.5%) has been utilized to generate electricity.

In the Presidential Regulation No. 22 of 2017 on the General Plan of National Energy (RUEN), the utilization of geothermal energy for power plants in the energy mix is targeted at least 4.6% of the total installed power plant capacity in 2025. The development target of the Geothermal Power Plant (GPP) until 2025 is 7,241.5MW.

The Geothermal energy development also meaningful for enhancing the national energy security in regard to those abundant potential, along the so called Ring of Fire of Indonesian Islands. As Gima and Yoshitake¹⁾ concluded in their study on energy security (2016), that the diversification of thermal power generation and innovation regarding clean energy are important key factors for island energy security. Therefore, the availability of local capability in Geothermal energy power plant should be an immediate goal of the development.

The potential of geothermal energy sources is widely distributed in the eastern Indonesia such as NTB, NTT, Maluku, North Maluku and other remote areas. Until now these areas are still using Diesel Power Plants (DPP) as the dominant source of electrical energy supply. Based on BPPT's survey at the early phase of the study (2010), there are more than 480 units of the DPP with a total capacity of more than 300 MW, where the capacity per unit is relatively small (<5MW) due to corresponding demand capacity in those area. Small-scale GPP as a substitution for DPP can give a significant and an immediate improvement to the national economic because the current electricity subsidy is very burdening the Government's budget (Rp.51, 9 Trillion, in 2009).

BPPT in accordance with its role has been developing and prototyping the small-scale geothermal power plant with a high local content. One of which is a 3MW GPP with a condensing turbine type, in which all the main component was designed and manufactured locally. This RD&E (Research, Development & Engineering) activities involves a number of local manufacture industries, such as engineering design work by BPPT in cooperation with PT Rekayasa Industri, turbine manufacturing by PT Nusantara Turbin & Propulsi (NTP), generator by PT Pindad, etc.

1.2 GPP condensing turbine.

Almost all of the operating GPP in Indonesia currently

use condensing turbine technology with a direct steam plant type. Referring to the working principle of the direct steam plant²⁾, a small 3 MW GPP is designed as shows in Figure 1.

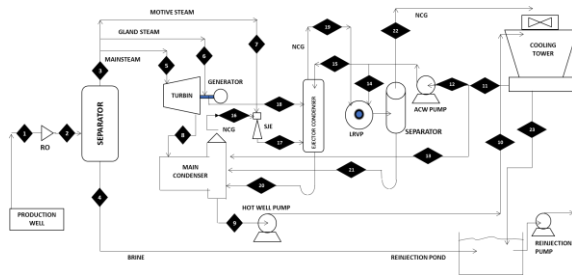


Fig.1:Schematic Diagram Of The 3 MW GPP Pilot Plant, Kamojang – West Java, Indonesia

The following describes the working principle of the system. The geo-fluid from the production well is depressurized using restriction orifice (RO) to meet the turbine operating pressure. The steam is then separated from the solid particles and the dry vapor or steam inside the separator. The steam out from the separator is then separated into three functions. First, the steam with the largest portion is used to drive the turbine. Second, the least steam portion, is used for the gland seal of the turbine after it taken into a lower pressure using RO. Third, with a large portion, is used as a motive steam on steam jet ejector (SJE) to attract non condensable gas (NCG) from inside the condenser.

In the turbine, the process of converting thermal energy of the steam into mechanical energy takes place. The resulted mechanical energy drives the generator to produce electricity. The steam out of the turbine is then condensed in the main condenser. Direct contact condenser is used in this installation. Using a hot-well pump, the condensate is pumped towards the cooling tower (CT) to be cooled down. The water from the CT gravitationally flows and mostly used as a coolant in the main condenser. The rest is then used to cool the ejector condenser and the liquid range vacuum pump (LRVP) with the help of auxiliary cooling water pump (ACW). Excess water from the CT is then collected in the pool to re-injected into the injection-well.

2. Methodology

The development of the 3MW GPP in Kamojang-West Java, Indonesia begins with the calculation of the thermodynamic process design to produce a process flow diagram (PFD), a piping & instrumentation diagram (P & ID), and a general arrangement. Based on the PFD and the P & ID, the design of mechanical, electrical, instrumentation and control equipment, civil structures and other supporting equipment are calculated. In this

paper the discussion is focused in the thermodynamic processes, major mechanical equipment and the generator.

The early operation testing stages of the 3MW GPP has been carried out gradually for several times. That is, starting with no-load testing, testing with a dummy load, and finally by synchronizing the load testing to the 20 kV grid. Synchronize test results in early 2018 for up to 1MW load are shown in this paper.

The calculation of heat and mass balance of each 3MW GPP components is established by taking into account the important parameters related to the characteristics of wells, atmospheric conditions and the environment around the plant. In addition, turbine design parameters are also considered, because most parts of the turbine is designed through a reverse engineering of an existing turbines. Some of the design parameters referred to among others as in Table 1.

No.	Parameter	Value	Unit	References
1	Well-head steam pressure	12	bar _a	KMJ-68 Well Testing Result, and ¹⁰⁾
2	NCG content	1.7	%	KMJ-68 Well Testing Result, ¹⁰⁾ and ¹⁸⁾
3	Steam pressure at turbine inlet	6.5	bara	Adjusted to turbine design
4	Steam pressure at outlet turbine	0.16	bara	Adjusted to condensation temperature (as a function of ambient condition), and ¹⁰⁾
5	Cooling water temperature at CT inlet	45	°C	Adjusted to the ambient condition around and design of the CT, and ¹⁰⁾
6	Cooling water temperature at CT outlet	30	°C	Adjusted to the ambient condition around the CT, and ¹⁰⁾
7	Turbine isentropic efficiency (η_t)	86-90	%	³⁾ , ⁴⁾ , ⁵⁾ and ⁹⁾
8	Generator efficiency (η_{gen})	98.6-98.7	%	⁴⁾ and ⁷⁾
9	Mechanical efficiency (η_m)	98.6-99	%	⁴⁾
10	Mass flow of geofluid	30	Ton/hr	KMJ-68 Well Testing Result, and ¹⁰⁾

Table1:Reference parameters for calculation of mass and energy balance.

The process of changing state in each of the main components of geothermal power plants is considered reversible, so that by ignoring the kinetic and the potential energies for fluid flow at the inlet and outlet of the system, the application of the mass and energy conservation laws for each component of GPP is as in Table 2. Heat and mass balance calculations are performed with the use of EES (Engineering Equation Solver) software. The parameters in Table 1 are used as input.

No	Main Equipment	Process, Energy and mass balance
1	Turbine:	Process: isentropic Energy conservation: $m_1 h_1 = W + \dot{m}_2 h_2$ Mass conservation: $m_1 = \dot{m}_2$ where \dot{m} : mass flow, h : specific enthalpy, W : Power
2	Direct Contact Condenser:	Process: Isobar Energy conservation: $m_1 h_1 + \dot{m}_2 h_2 = m_3 h_3$ Mass conservation: $m_1 + \dot{m}_2 = m_3$
3	Wet Cooling Tower	Process: Isobar Energy conservation: $m_1 h_1 + \dot{m}_2 h_2 = m_3 h_3 + m_4 h_4$ Mass conservation: $m_4 = m_1 + (\dot{m}_2 - m_3)$
4	Separator:	Process: Isenthalpic Energy conservation: $m_1 h_1 = \dot{m}_2 h_2 + m_3 h_3$ Mass conservation: $m_1 = \dot{m}_2 + m_3$
5	Pump:	Process: isentropic Energy conservation: $m_1 h_1 + W = \dot{m}_2 h_2$ Mass conservation: $m_1 = \dot{m}_2$
6	Steam ejector	Process: Polytropic Energy conservation: $m_1 h_1 + \dot{m}_2 h_2 = m_3 h_3$ Mass conservation: $m_1 + \dot{m}_2 = m_3$

Table2:Conservation of energy and mass within the main component of the GPP.

Some of the major equipment have been designed and manufactured domestically i.e. separator, steam turbine, condenser, SJE, and CT (Table 3). Steam separators and scrubbers are designed on the basis of process data of thermodynamic calculations as outlined in the PFD. Sizing calculations begin by defining the type, configuration and dimensions of the inlet pipe separator to meet the design requirements¹¹⁾. Then the sizing of some of the separator components (vessel diameter, demister pad, liquid level, etc.) were designed using the best practice references^{11,12)}. The result of the dimensional or sizing calculations were then validated with the requirements specified by Couper et.al.¹³⁾.

No	Equipment	Brand	Manufacturer
1	Turbine	BPPT & NTP	PT. Nusantara Turbine and Propulsion (NTP) - Bandung
2	Main & Ejector Condenser	BPPT	PT. BomaBismaIndra (BBI), Pasuruan
3	Cooling Tower	Hamon	PT Hamon Indonesia, Serpong
4	Separator	BPPT	PT. BomaBismaIndra (BBI), Pasuruan
5	Pump	Torishima	PT TorishimaGuna Engineering, Puloagung
6	Steamjet ejector	BPPT	PT. Boma Bisma Indra (BBI), Pasuruan
7	Generator	Pindad	PT Pindad, Bandung

Table3:The main components of 3 MW GPP and Manufacturer.

The 3MW Kamojang GPP's steam turbine is the reverse engineering design process of the Sibayak geothermal steam turbine in North Sumatra. This process was actually returned the turbine design from a 5-stage back pressure turbine to its original design of a 6-stage condensing turbine by redesigning the 6th stage rotor and stator. The type of turbine used is a multistage reaction turbine. Turbine design data consist of; 3MW power at 6500rpm, with the vapor pressure in and out of the turbine as shown in Table 1.

The condenser for this GPP is of direct contact condenser type which gives a considerable heat transfer coefficient, while taking into account the length of contact time required for the condensation process to be completed. The calculation of the thermal-fluid process refers to Kakac¹⁴⁾, whereas for the calculation of the mechanical dimension refers to HEI Standard¹⁵⁾. The process data for the design is shown in Table 1.

Mechaelidas¹⁶⁾ conducted a performance analysis study of various NCG removal systems (GRS) such as ejectors, LRVP, compressors and a combination of ejectors and compressors. In the design of this GPP, hybrid systems are used which combine the SJE and the LRVP, because according to the previous works^{17,18,19)}, this system is very beneficial when associated with net power output and the cost required for investment and operation of GPP. For this purpose, the SJE is designed to one level that raises the NCG pressure in the condenser to the LRVP entry pressure. The design data refers to the calculation of PFD, among others; condenser pressure, NCG mass flow from the condenser, pressure and flow rate of motive steam mass, and atmospheric

environmental pressure. Furthermore, the standard^{20,21,22,23,24)} is used in the role of SJE

For the design of CT, cooling water and environmental conditions data are adjusted to the plant requirements as in Table 1. The CT design sizing is then established using the standard practice from CTI²⁵⁾. The required data are: wet bulb temperature, relative humidity, drift loss, evaporation loss, wind pressure, and seismic load. While the selected operating conditions, among others; number of cells, configuration, pumping head, and total fan power.

Generators are designed to meet the requirements and specifications such as; type, operating condition, output power, voltage, current, power factor, phase, rotation, rotation more refer to IEC, pole number, stator connection, isolation class, stator class, class rotor, excitation method, protection index, cooling system, machine, bearing along with its temperature meter, efficiency assurance, with reference to IEC 60034 - 1 standard.

Almost all of the 3MW GPP main components are fabricated in Indonesia. The following table 3 shows the main components and manufacturers.

3. Results and analysis

Referring to PFD as in Figure 1, the results of the calculation of heat and mass balance (pressure, temperature and mass flow rate) of main component of 3MW GPP for steam, air, water and NCG at inlet and outlet of each equipment are shown as in Table 4, while P&ID as shown in Figure 2.

Stream No.	1	2	3	4	5	6	7	8	9	10
Pressure (bara)	12	7	6.5	6.5	6.5	6.5	6.5	0.16	0.16	2.5
Temperature (°C)	188	165	165	162	162	162	162	55.3	49	49
SMF (kg/s)	8.316	8.316	8.233	0	7.622	0.038	0.573	6.667	0	0
NCG MF ^(*) (kg/s)	0.141	0.141	0.140	0	0.13	0.001	0.001	0.001	0	0
WMF ^(*) (kg/s)	0	0	0	0.083	0	0	0	0.955	226.33	226.33
AMFR ^(*) (kg/s)	0	0	0	0	0	0	0	0	0	0

Stream No.	11	12	13	14	15	16	17	18	19	20
Pressure (bara)	1	1	1	1	1	0.16	0.4	1	0.4	0.16
Temperature (°C)	30	30	30	30	30	49	55.3	99.6	35	35
SMF (kg/s)	0	0	0	0	0	0.021	0.594	0.038	0	0
NCG MF ^(*) (kg/s)	0	0	0	0	0	0.130	0.139	0.000	0.139	0
WMF ^(*) (kg/s)	219.07	69.373	149.7	0.303	69.07	0	0	0	0	69.664
AMFR ^(*) (kg/s)	0	0	0	0	0	0.004	0.004	0	0.004	0

Stream No.	21	22	23
Pressure (bara)	1	1	1
Temperature (°C)	30	35	30
SMF (kg/s)	0	0	0
NCG MF ^(*) (kg/s)	0	0.139	0
WMF ^(*) (kg/s)	0.303	0	7.261
AMFR ^(*) (kg/s)	0	0.004	0

NOTE: *)
SMF = Steam Mass Flow, NCG MF = NCG Mass Flow, WMF = Water Mass Flow, AMFR = Air Mass Flow Rate

Table 4: The process parameter values on the 3MW GPP flow components.

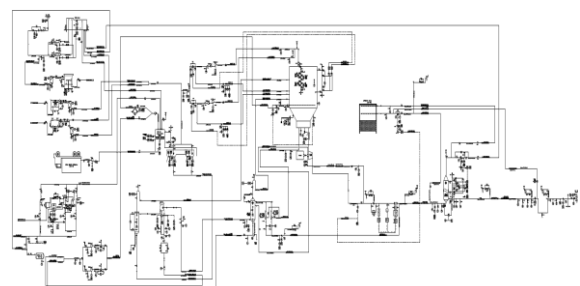


Fig.2:P& ID of the 3MW GPP, Kamojang, Indonesia.

The design results of mechanical equipment and generator after being fabricated and integrated are shown in Figure 3.



Fig.3: The pilot plant, a 3MW GPP at Kamojang, Indonesia

In March 2018 the initial synchronize operation to the 20 kV electricity grid was successfully carried out until the maximum load allowed by the PLN Garut region, i.e. up to 1 MW. Observations made for almost 6 (six) operation hours has focused on the performance parameters, vibration of the system and the temperature of the bearing lubricants before and during loading on the electricity network. The results of performance parameter measurement (rpm, network electricity load W_e , steam mass flow rate \dot{m} , the pressure and temperature at the inlet and outlet turbines P_i and T_i , P_o and T_o) are shown in Table 5. The stability of pressure and temperature of steam entering and exiting the turbine during operation is shown in Figure 4.

Test	rpm	W_e (kW)	\dot{m} (kg/s)	Steam Inlet Turbine		Steam Outlet Turbine	
				P_i (bara)	T_i (°C)	P_o (bara)	T_o (°C)
1	6472	0	0.581	6.27	170.4	0.16	38.85
2	6498	497	1.427	6.31	171.0	0.18	46.85
3	6489	593	1.600	6.38	171.6	0.19	51.57
4	6506	452	1.376	6.212	173.9	0.18	52.00
5	6474	865	1.824	6.312	174.6	0.16	50.07
6	6487	641	1.468	6.167	173.9	0.15	48.32
7	6478	740	1.631	6.162	174.0	0.15	49.35
8	6480	832	1.754	6.405	174.2	0.15	48.20
9	6485	615	1.443	6.167	174.0	0.15	47.92
10	6487	757	1.654	6.587	174.2	0.15	47.85
11	6504	612	1.415	6.577	174.3	0.14	47.02
12	6505	609	1.411	6.597	174.3	0.14	47.00
13	6495	584	1.348	6.587	174.2	0.14	45.65
14	6492	607	1.362	6.555	174.1	0.14	45.77
15	6482	786	1.682	6.757	174.4	0.15	49.12
16	6477	776	1.656	6.097	174.1	0.15	49.55

Table5: Measurement values of the performance parameters.

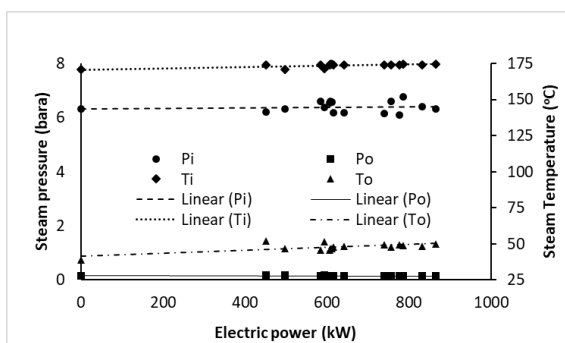


Fig. 4: Steam P and T stability.

Vibration measurements on turbine bearings, gear box and generator on the downstream and upstream sides of each are VT001, VT002, VT003, VT004, VT005 and VT006 as shown in Table 6. The table also contains observations of the maximum temperature of lubricating oil on turbine bearings, gear box, and generator respectively: TT003, TT010, and TT012.

Test	Vertical vibration (mm/s)						Max. Oil temperature (°C)		
	Turbine		Gearbox		Generator		Turbine	Gearbox	Generator
	VT ₀₀₁	VT ₀₀₂	VT ₀₀₃	VT ₀₀₄	VT ₀₀₅	VT ₀₀₆	TT ₀₀₃	TT ₀₁₀	TT ₀₁₂
1	1.70	2.17	1.25	1.28	2.92	2.77	63.63	40.91	69.00
2	1.43	1.92	0.99	1.03	3.00	2.75	61.23	41.7	71.00
3	1.43	2.05	1.06	1.04	3.04	2.63	60.66	42.78	71.00
4	1.51	1.84	0.99	1.04	3.24	2.61	60.63	44.32	73.00
5	1.55	1.79	1.03	0.98	3.27	2.44	61.57	47.58	73.00
6	1.32	1.92	1.11	1.02	3.05	2.43	62.06	47.47	73.00
7	1.32	1.99	1.15	1.07	2.96	2.42	61.57	47.43	73.00
8	1.18	2.00	1.17	1.16	3.06	2.46	61.8	46.57	73.00
9	1.28	1.90	1.11	1.13	3.31	2.50	61.72	46.53	73.00
10	1.17	2.07	1.16	1.12	3.12	2.50	61.91	46.42	73.00
11	1.20	2.12	1.18	1.10	3.21	2.56	61.98	45.97	73.00
12	1.17	1.99	1.15	1.14	3.28	2.60	61.98	45.97	73.00
13	1.14	1.91	1.10	1.06	3.19	2.60	62.43	42.53	73.00
14	1.16	1.82	1.07	1.05	3.33	2.56	62.56	45.2	73.00
15	1.33	2.15	1.18	1.11	3.06	2.47	61.27	46.8	73.00
16	1.62	1.88	1.00	1.02	3.61	2.40	61.27	46.72	73.00

Table6: Measurement values of the vertical vibration and the maximum oil temperatures.

From the measurement values in Table 5, and the steam-water properties table, the enthalpy and entropy values of $h_{i, \text{sat}}$ at the turbine inlets can be obtained. There is a difficulty in determining the actual condition of the steam out of the turbine because the plant is not equipped with a measuring instrument to determine the amount of the condensed vapor fraction. Therefore, to determine the steam-out condition of the turbine, the expansion process in turbines is considered isentropic. The intersection of the isentropic line from the point P_i , T_i with the isobar P_o or T_o isotherm is the steam state of the outgoing turbine. However, P_o and T_o measurement results are not the pair of the P and the T values of the saturated vapor when the condensation process occurs, and so that two points of intersection exist. Both intersection points are taken as the turbine steam outlet conditions, which are then used to analyze the turbine performance. The intersection of the isentropic line with the isobar line P_o is considered as an actual condition, and the intersection with the isothermal T_o line for an ideal condition. Then the actual and ideal thermal power of the turbines W_{tha} and W_{thid} , as well as the actual thermal efficiency of the plant η_{tha} and the isentropic efficiency of the turbine η_{thid} are calculated as shown in Table 7 and Figures 5 and 6.

Test	\dot{m} (kg/s)	Steam Inlet Turbine		Steam Outlet Turbine				W_{ha} (kW)	W_{thid} (kW)	η_{ha}	η_{thid}
		h_i (kJ/kg)	s_i (kJ/kg-K)	h_{sat} (kJ/kg)	x_{sat}	h_{act} (kJ/kg)	x_{act}				
1	0.581	2781.9	6.7964	2193.6	0.83	2109.2	0.81	335.3	383.4	0.00	0.87
2	1.427	2782.9	6.7972	2225.6	0.84	2159.2	0.82	795.3	890.0	0.62	0.89
3	1.6	2783.9	6.7957	2232	0.84	2187.5	0.83	883.0	954.2	0.67	0.93
4	1.376	2790.5	6.8223	2233.9	0.84	2198.7	0.83	765.9	814.3	0.59	0.94
5	1.824	2791.5	6.8175	2217.3	0.84	2185.4	0.83	1047.3	1105.5	0.83	0.95
6	1.468	2787.6	6.8262	2212	0.84	2177.5	0.83	845.0	895.6	0.76	0.94
7	1.631	2792.3	6.8272	2212.3	0.84	2184.1	0.83	946.0	992.0	0.78	0.95
8	1.754	2789.9	6.8073	2205.8	0.83	2170.7	0.83	1024.5	1086.1	0.81	0.94
9	1.443	2787.9	6.8267	2212.2	0.84	2175.2	0.83	830.7	884.1	0.74	0.94
10	1.654	2788.6	6.792	2200.8	0.83	2163.6	0.82	972.2	1033.8	0.78	0.94
11	1.415	2788.9	6.7934	2192.7	0.83	2159	0.82	843.6	891.3	0.73	0.95
12	1.411	2788.7	6.7917	2192.1	0.83	2158.3	0.82	841.8	889.5	0.72	0.95
13	1.348	2788.6	6.792	2192.2	0.83	2150.1	0.82	803.9	860.7	0.73	0.93
14	1.362	2788.6	6.7942	2192.9	0.83	2151.6	0.82	811.3	867.6	0.75	0.94
15	1.682	2787.8	6.7791	2196.6	0.83	2167.2	0.82	994.4	1043.8	0.79	0.95
16	1.656	2792.5	6.8334	2214.4	0.84	2187.4	0.83	957.3	1002.0	0.81	0.96

Table7: Steam properties and calculation results

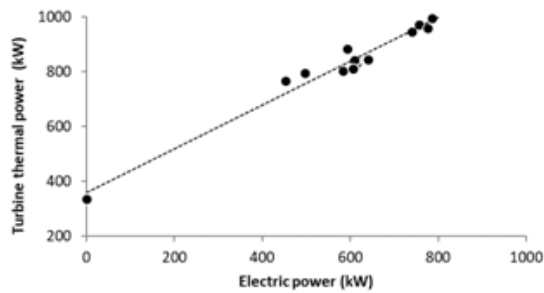


Fig. 5: Thermal Vs Electric Power

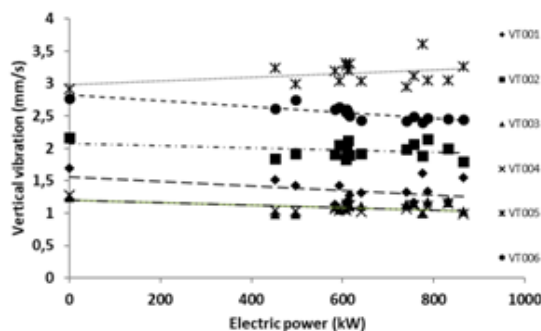


Fig. 6: Turbine eff. vs electric power

The Turbine's steam inlet and outlet parameters are relatively stable during the testing operation (Figure 4). The fluctuations of the Turbine's inlet steam pressure and temperature are in the range of $\pm 5\%$ and $\pm 5\%$, while the steam outlet values are within the ranges of $\pm 10\%$. The steam condition at the turbine inlet is slightly or near superheat. With an isentropic expansion process approach in the turbine, there are some aspects related to the performance of the turbine-generator that can be explained. When there is no electrical load, thermal power required to turn the system is around 335kW (Table 7). The thermal efficiency of the turbine-generator system (η_{tha}) gradually rises up to 81% at electrical loads around 776kW. This thermal efficiency is close to the design efficiency of the system ($\eta_{gen} \cdot \eta_t \cdot \eta_m$) which is in the range of 83% - 88% when calculated using the data in Table 1. While the ideal efficiency of the system (η_{thid}) ranges between 86% - 96%.

From the observations of vertical vibrations on the turbine bearings, gear boxes, and generators (Table 6 and Figure 4) show that all is still below the allowable values i.e; 4mm/s, 10mm/s, and 4mm/s, respectively for turbines, gearboxes, and generators. All vibrations tend to decrease as the electrical load increases, except for VT001, the vibration of the bearing in the downstream of the turbine. The results of observation shows that the maximum temperature of lubricating oil on turbine

bearings, gear box, and generator (Table 6), are all remain below the maximum allowable value, which is about 100°C.

4. Conclusion

Heat and mass balance calculations have been performed as a thermodynamic process design of the small-scale 3MW GPP. The calculation is established by using the condition parameters of the well and the environment around the plant. In addition, the design also is based on the reverse engineering results of the steam turbine. More importantly, this design has also considered the ability of the domestic manufacturing industry to improve the local content. The results of the design calculations have been translated into the drawings and PFD tables. The design of this PFD has been proceed by making the P & ID, GA, fabrication, construction, and initial testing operation until successfully deliver and synchronize load up to 1 MW to the electrical grid. The test results show that the plant has a quite good performance, with the thermal efficiency close to its design value. The observed vibration of the turbine island is remaining below the maximum allowable value, and there is a decreasing trend for a higher load. Similarly, the maximum value of oil temperature is still under the maximum allowable value. From the results of the testing operation it can be concluded that 3MW GPP is feasible to proceed for operation at a higher load to its design capacity.

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