Testing of Early Stage of BPPT-3MW Condensing Type Small Scale Geothermal Power Plant – Kamojang - Indonesia

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Abstract. Geothermal power plant (GPP) technology is one of the prospective renewable energy technologies and a priority in the development of national electricity today. The Electricity Supply Business Plan (RUPTL) 2018-2027 shows the plan to increase GPP capacity in the period of 4.583 GW, or 8% of all national power plants development, and 30% of all new & renewable energy-based power generation. Until 1st quarter 2018, the installed GPP capacity of 1.924 GW and all of them are imported technology. So efforts to develop national GPP technology are very strategic to support national energy independence in the future. The Indonesian Agency for the Assessment and Application of Technology (BPPT) has developed and operated a 3 MW GPP of condensing type technology in Kamojang - Indonesia, which is the first prototype GPP manufactured by national company. The GPP design is based on KMJ-68 well data characteristics, owned by Pertamina Geothermal Energy, and steam turbine specifications designed in reverse engineering. The manufacturing process of the main components of the plant such as turbines, generators, condensers, etc. carried out by the national industry. In this paper it is discussed about the process of test operation in the early stage, starting from the preparation of SOP, conducting free load generator test, dummy load testing, and load testing. Until early 2018, the BPPT’s GPP has generated 15,572 kWh of electricity, with the highest load of 1.3 MW. During testing all process parameters, particularly vibrations, bearing temperatures and lubricants, all within safe limit. The thermal efficiency of the turbine-generator system reaches 13% for loads of about 1 MW.

1. Introduction

Indonesia has the potential of 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.

Geothermal power plant (GPP) technology is one of the prospective renewable energy technologies and a priority in the development of national electricity today. The Electricity Supply Business Plan (RUPTL) 2018-2027 shows a plan to increase GPP capacity in the period of 4.583 GW, or 8% of all national power plant development, and 30% of all new & renewable energy-based power plants. Until the first quarter of 2018, GPP installed capacity of 1.924 GW and all of them are imported technology. Therefore, efforts to develop national GPP technology are very strategic to support national energy independency in the future. The Indonesian Agency for the Assessment and Application of Technology (BPPT) has developed and operated a 3 MW GPP of condensing type technology in Kamojang - Indonesia, which is the first prototype GPP manufactured by national company.
Referring to the direct steam plant working principle [1], BPPT has developed and operated a 3 MW condensing type GPP in Kamojang - Indonesia, which is the first prototype of a GPP fabricated by the national industry. The design of the GPP is based on the characteristic data of the KMJ-68 geothermal well owned by Pertamina Geothermal Energy, the atmospheric conditions around the plant, and the specifications of the steam turbine that has been reverse engineered. Some of the data used in design calculations refer to a number of literatures, such as in Table 1. Process Flow Diagrams (PFD) of 3 MW GPP from the calculation of energy and mass balance are shown in Figure 1 and Table 2.

Table 1. Reference parameters for calculation of mass and energy balance.

| No. | Parameter                                      | Value | Unit | References                          |
|-----|------------------------------------------------|-------|------|-------------------------------------|
| 1   | Steam Pressure at well head                    | 12    | bara | Well test - KMJ-68, [2]              |
| 2   | NCG content                                    | 1.7   | %    | Well test - KMJ-68, [2], [3] and [4]|
| 3   | Steam Pressure at inlet turbine                | 6.5   | bara | Adjusted to turbine design          |
|     |                                                |       |      | Adjusted to the condensation        |
|     |                                                |       |      | temperature (affected by environmental conditions), [2] |
| 4   | Turbine outlet pressure                         | 0.16  | bara |                                    |
| 5   | Cooling Water Temperature to CT                 | 45    | ℃    |                                    |
| 6   | Cooling water Temperature from CT               | 30    | ℃    |                                    |
| 7   | Turbine isentropic efficiency (ηₜ)              | 86 – 90 | % | [5], [6], [7], [8] |
| 8   | Generator efficiency (ηₐₐₜ)                     | 98.6 – 98.7 | % | [5], [9] |
| 9   | Mechanical efficiency (ηₘ)                      | 98.6 – 99 | % | [6] |
| 10  | Geo-fluid mass flowrate                         | 30    | tonne/hr | Well test - KMJ-68, [2] |

Explanation of the working principles of the system are as follows: The pressure of geofluid from the production well is reduced using restriction orifice (RO) to meet the turbine operating pressure. The steam is then separated from the solid particles inside the separator. Calculation of separator dimensions refers to requirements in [10, 11 and 12]. 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. The NCG removal system (GRS) design refers to [4, 13, 14, and 15], while the standards [16, 17, 18] are used in SJE design.

In the turbine, the process of converting thermal energy into mechanical energy takes place to rotate the generator to produce electricity.

Figure 1. PFD of BPPT’s Small Scale 3MW GPP Diagram Of The 3 MW GPP Pilot Plant, Kamojang – West Java, Indonesia
Exhaust steam from the turbine is condensed in the main condenser. Direct contact condenser is used in this installation. Thermal-fluid condenser calculations refer to [19], and for mechanical calculations refer to [20]. By using a hot-well pump, the condensate is pumped to the cooling tower (CT) to be cooled. Water from CT, mostly used as cooling media, flows gravitationally to the main condenser. The rest is to cool the ejector condenser and the liquid range vacuum pump (LRVP) with the help of the auxiliary cooling water pump (ACW). The excess water in CT is collected in the pond to be re-injected into the injection well. CT dimension calculations refer to standards [21].

Fabrication of the main components of the GPP such as turbine, generator, condensers, etc. is carried out by local industries. The following Table 3 shows the main components and the manufacturer. The integration of the main equipment of the turbine-generator is shown in Figure 2.

### Table 2. Process Parameters for each BPPT’s 3MW GPP Components

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

| 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 | 49 | 55.3 | 99.6 | 35 | 35 |
| SMF (kg/s) | 0 | 0 | 0 | 0 | 0 | 0.021 | 0.594 | 0.038 | 0 |
| NCG MF (kg/s) | 0 | 0 | 0 | 0 | 0 | 0.130 | 0.139 | 0.00065 | 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 | 0.004 | 0.004 | 0 | 0.004 |

NOTE: *)

SMF = Steam Mass Flow, NCG MF = NCG Mass Flow, WMF = Water Mass Flow, AMFR = Air Mass Flow Rate

### Table 3. Main Components of 3MW GPP and its Manufacturer

| 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 |
2. Testing Methodology

The testing activity begins with preparing the Standard Operating Procedure (SOP) for the operation of the plant. In the SOP, the order of activities starts from preparation of the test, start-up plant, no-load test, synchronous test, plant shut-down, and emergency plant system.

2.1. Test Preparation

Some preparatory activities related to plant operations include:

- Operate pressurized air circuits to ensure the pressurized air system is functioning properly to produce dry air with sufficient pressure and flow rate.
- Check the function of the instrument connected with Supervisory Control and Data Acquisition SCADA, Governor Control Panel (GCP), and Programmable Logic Controller to ensure that all important data is recorded and the plant security system functions properly.
- Operate a steam circuit into a rock muffler (RM) to warm up the pipeline and ensure that the steam is completely dry before being sent to the turbine.
- Operate a cooling water circuit to ensure that the cooling water for main condenser, ejector condenser, LRVP, and oil cooler is fulfilled.
- Operate lubricating oil circuits intended to allow bearings and governors to receive adequate oil supply in terms of cleanliness, pressure, temperature and flow rate.
- Operate the GRS circuit and condenser vacuum system, starting with running LRVP followed by feeding the motive steam to the SJE until the condenser pressure reaches 0.16 bara.

2.2. Start-up plant

For turbine start up, a separate SOP is prepared by taking into account several important things including: alignment, critical rotation, thermal growth turbine-generator system, and steam control system (manual / automatic).

2.2.1. Shaft Alignment. Measurement of alignment of the turbine shaft connected to the gearbox and gearbox shaft connected to the generator is done using spacer coupling and short flex coupling respectively (Figures 3a and 3b).
Measurement is done by laser alignment method (multipoint mode). The misalignment tolerance value recommended by Rotalign [26] is shown in Table 4. The success criteria of the alignment refer to [22 and 23] and for this plant alignment, the target value of the position/alignment specifications to be achieved is shown in Table 5.

### Table 4. Misalignment tolerance values based on Rotalign

| Measurement       | Gap   | Offset | Gap   | Offset |
|-------------------|-------|--------|-------|--------|
| Spacer [thous]    | 3.4   | 1.3    | 4.8   | 1.8    |
| Shortflex [mm]    | 0.18  | 0.06   | 0.25  | 0.09   |

### Table 5. Target position/alignment specifications

| Measurement       | Vertical | Horizontal |
|-------------------|----------|------------|
|                   | Gap      | Offset     | Gap      | Offset |
| Spacer [thous]    | 0.0      | 5.0        | 0.0      | 0.0    |
| Shortflex [mm]    | 0.00     | -0.15      | 0.00     | 0.00   |

2.2.2. **Critical speed measurement and vibration monitoring.**

- **Critical speed.** The critical speed of the system is predicted by performing a Frequency Response Function (FRF) test. The FRF test scheme can be seen in Figure 4a. The object being tested is excited using an impact hammer so that it produces vibration and this vibration will be damped naturally. The force arising from this excitation is measured using a load cell attached to the end of the hammer. The amount of vibration that occurs is measured using a vibration sensor. Output signals from load cells and vibration sensors are recorded with A/D Converter.

After the output signal is recorded, data processing is then performed to obtain the Data Frequency Response Function (FRF) which contains data about the value of natural frequency, vibration magnitude, and coherence factor. Coherence factors are used to evaluate the confidence level of the FRF test results.

FRF test is carried out on 6 measurement points on bearing housing i.e. at Turbine (downstream, T1, and upstream, T2), at Gearbox (turbine connecting shaft, GB1, and generator connecting shaft, GB4), and at Generator (gearbox connecting shaft, G1, and rear bearing, G2). Figure 4b shows the position of the measurement points. Vibration at each measurement point will be measured in horizontal, vertical, and axial directions.
For the purposes of vibration monitoring during operation, vibration sensors (accelerometers) are installed in each bearing house of the turbine, gearbox and generator, and are connected with SCADA so that vibration can be measured simultaneously and continuously. At each measuring point 3 (three) sensors were installed which measured vibration in vertical, horizontal and axial directions. The measurement sensor is given symbols as in Table 6.

### Table 6. FRF measurement symbols on bearings according to Figure 4b.

| Sensor  | Turbine Downstream | Turbine Upstream | Gearbox Shaft-Turbine connection | Gearbox Shaft-Generator connection | Generator Shaft-Gearbox connection | Rear |
|---------|--------------------|------------------|---------------------------------|-----------------------------------|-----------------------------------|------|
| Vertical| \( T_{1V} \)        | \( T_{2V} \)     | \( GB_{1V} \)                 | \( GB_{4V} \)                     | \( G_{1V} \)                      | \( G_{2V} \)                  |
| Horizontal| \( T_{1H} \)          | \( T_{2H} \)     | \( GB_{1H} \)                 | \( GB_{4H} \)                     | \( G_{1H} \)                      | \( G_{2H} \)                  |
| Axial   | \( T_{1A} \)          | \( T_{2A} \)     | \( GB_{1A} \)                 | \( GB_{4A} \)                     | \( G_{1A} \)                      | \( G_{2A} \)                  |

### 2.2.3. Turbine-generator rolling / no-load test

Steam flow to the turbine starts with manual mode. Steam flows into the gland-seal and into the turbine through bypass pipes, with a relatively small amount of flow, to warm up the turbine without turning the rotor. At this stage the governor valve is fully open, and the main steam pipe is fully closed. Thermal growth of the turbine components is monitored by observing the turbine casing temperature.

After the casing temperature has reached steady-state, the amount of steam flow is increased until the turbine rotates at a speed of about 1000 rpm, and is maintained until the casing temperature reaches another steady-state again. Furthermore, the turbine-generator rotation speed increase is carried out by paying attention to the critical speed shown in Table 7. At critical speed values marked with underscore, it must be passed quickly. All this time, the rotation speed increase is 1000 - 2000 - 3000 - 4000 - 5000 - 6485. From 0 - 4000 rpm the control is done manually, and from 5000 - 6485 automatic control by the governor. Holding time in each round is determined by observing the steady state temperature casing. At each holding time, all process parameters and other important operating parameters are observed such as vibration, lubricating temperature, temperature cooling water, vacuum, etc.

After an operating speed of 6485 rpm is reached, before loading starts, the steam flow to the turbine is shifted from the bypass pipeline to the main pipeline by closing the bypass valve and opening the main valve.

### 2.2.4. Test with dummy load

Before loading the dummy, the generator is first secured by limiting the maximum allowable current, adjusted to a maximum load of 500kW, and also doing open circuit testing. The load is carried out in stages with an increase of 50kW each. At a load of 200 kW, load rejection test is performed to test the governor’s response in controlling the rotation speed and its effect on plant stability. Furthermore, the loading test is continued and has been successful up to 500 kW.
When the plant operates with a load of 500 kW, the operating conditions are observed, especially the vibration level.

2.2.5. Synchronous testing to the 20kV electricity grid of PLN Garut-5 Region. After the preliminary testing phase is carried out, the plant operation is returned to an operational speed of 6485 rpm without load. Before synchronous loading, all the main parameters of the process are observed to ensure the plant is in sync condition. PLN Pusertif has provided synchronous recommendations after validating / verifying unloaded plant operating conditions which include short circuit test up to 100% to steady coil temperature or reaching saturation conditions, interlock AC / DC oil pump, mechanical trip system, relay documents, and things others related to protection.

3. Results and Discussion

3.1. Results of Shaft Alignment.
When data alignment is taken, the positions of the machine shafts which is connected to both the spacer and shortflex is still in a misalignment condition, so that correction is made to the stand of the turbine, gearbox and generator. After several corrections, the final result of the engine shaft position based on the target coupling value to be achieved (Table 5) is shown in Figures 5a and 5b.

From Figures 5a and 5b, it is concluded that;
- Alignment results have met the target / specifications in both vertical and horizontal directions even though the spacer alignment value in the vertical direction can only be corrected to the limit of acceptable tolerance.
- If there is no detrimental effect on rolling turbine testing due to the effect of misalignment, it is recommended to keep using the tolerance value given by Rotalign.

![Figure 5. a.) Final result of Spacer alignment, measurement (Turbine-Gearbox), b.) Final result of Shortflex alignment measurement (Gearbox-Generator)](image)

3.2. Results of critical speed measurements
The bump test results in the form of amplitude at its natural frequency are shown in Table 7. From Table 7, a list is then made showing natural frequency data that needs special attention (underlined) for turbines, gearboxes, and generators where the response frequency is dominant in the velocity range of 0 (zero) rpm to system operating speed, 6485 rpm (Table 8).
Table 7. Bump test results, amplitude at natural frequencies

| Sensor | RPM | Amplitude (mm/s) | Sensor | RPM | Amplitude (mm/s) | Sensor | RPM | Amplitude (mm/s) |
|--------|-----|-----------------|--------|-----|-----------------|--------|-----|-----------------|
| T1V    | 1350| 0.037           | GB1V   | 2310| 0.014           | G1V    | 4734| 0.007           |
|        | 2310| 0.015           |        | 3215| 0.56            |        | 6939| 0.1             |
| T1H    | 1455| 0.022           | GB1H   | 2745| 0.044           | G1H    | 5512| 0.008           |
|        |      |                 |        | 2895| 0.048           |        |      |                 |
| T1A    | 1350| 0.015           | GB1A   | 1350| 0.021           | G1A    | 4799| 0.27            |
|        | 1875| 0.013           |        | 1860| 0.027           |        |      |                 |
|        | 2310| 0.02            |        | 2310| 0.113           |        |      |                 |
| T2V    | 1335| 0.008           | GB1V   | 1875| 0.012           | G2V    | 6874| 0.006           |
|        | 1965| 0.008           |        | 3315| 0.054           |        |      |                 |
| T2H    | 1455| 0.016           | GB1H   | 2580| 0.035           | G2H    | 5577| 0.008           |
|        |      |                 |        | 2895| 0.048           |        |      |                 |
| T2A    | 1350| 0.013           | GB1A   | 1350| 0.018           | G2A    | 4864| 0.019           |
|        | 1875| 0.009           |        | 1875| 0.025           |        |      |                 |
|        | 2325| 0.022           |        | 2310| 0.126           |        |      |                 |

Table 8. Natural frequencies of the turbine-generator system

| Sensor | Units | Number of the natural frequency |
|--------|-------|---------------------------------|
|        |       | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     |
| T1V    | RPM   | 1350  | 2226  | 3228  | 3798  | 4452  | 4632  | 5040  |       |       |
| T1H    | RPM   | 1416  | 3912  | 4434  | 5412  | 5904  | 6390  |       |       |       |
| T1A    | RPM   | 1344  | 1854  | 2088  | 2178  | 3228  | 4446  | 5250  | 5484  |       |
| T2V    | RPM   | 1866  | 2010  | 4464  |       |       |       |       |       |       |
| T2H    | RPM   | 1416  | 4146  | 5460  | 6156  | 6396  |       |       |       |       |
| T2A    | RPM   | 1338  | 1854  | 2004  | 3246  | 4464  | 5466  | 5610  | 5868  | 6408  |
| GBv    | RPM   | 2592  | 2736  | 2886  | 3336  | 4444  |       |       |       |       |
| GBH    | RPM   | 2592  | 2742  | 2892  | 3312  | 4128  |       |       |       |       |
| GBa    |       | 2322  | 2826  |       |       |       |       |       |       |       |
| G1V    | RPM   | 1116  | 1650  | 2184  | 4284  | 5274  | 5784  |       |       |       |
| G1H    | RPM   | 1332  | 2754  | 2892  | 3960  | 4602  | 5280  | 5826  |       |       |
| G1A    |       | 1140  | 2124  | 2754  | 3372  | 3948  | 4614  |       |       |       |
| G2V    | RPM   | 1590  | 1854  | 2202  | 3498  | 4314  | 4674  | 5238  | 5712  | 5772  |
| G2H    | RPM   | 1362  | 2736  | 3918  | 4596  | 5346  |       |       |       |       |
| G2A    |       | 1146  | 2112  | 3360  | 3948  | 4590  | 5250  |       |       |       |

Among all the natural frequencies that appear, the frequency of 109.00 Hz (6540 RPM) in T1H and 109.25 Hz (6555 RPM) in T2H are the frequencies that most need attention because they are near the Turbine operating speed (6485 RPM). The frequency of 26.75 Hz (1605 RPM) in G1V and 26.50 Hz (1590 RPM) in G2V also need to be watched because it is around the Generator operating speed (1500 RPM). For gearboxes, there are several natural frequencies located between 2300 RPM and 3500 RPM. Examples of FRF results in the form of Magnitude vs. Turbine frequencies for T1H are shown in Figure 6.
Figure 6. The result of FRF T1H

Figure 7. Vibration level at zero load and dummy load of 500kW

3.3. Results of testing with dummy load

The plant can respond well during open circuit testing, and is also stable during the test with a dummy load of 500 kW. The observation of vibration level during operation with load compared to no-load is shown in Figure 7. All vibration levels tend to be lower when dummy load is 500 kW, and all are still below the safe limit according to ISO 10816-3 (11.0 mm/s for Turbine and Generator) and manufacturing standards (4.0 mm/s for Turbines and Generators, and 8.0 mm/s for Gearboxes).

Vertical vibration measurements on turbine bearings, gear box and generator on the downstream and upstream sides of each are T1V, T2V, GB1V, GB4V, G1V and G2V as shown in Table 9. The table also contains observations of the maximum temperature of lubricating oil on turbine bearings, gear box, and generator respectively TT003, TT010, and TT012.

Table 9. Vibration and maximum oil temperature measurements

| Test | Turbine Vertical vibration (mm/s) | Gearbox | Generator | Turbine | Gearbox | Generator |
|------|----------------------------------|--------|-----------|---------|--------|-----------|
|      | T1V | T2V | GB1V | GB4V | G1V | G2V | TT003 | TT010 | TT012 |
| 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 | 42.33 | 73.00 |
| 14   | 1.16 | 1.82 | 1.07 | 1.05 | 3.33 | 2.56 | 62.36 | 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 |

From the test parameters in Table 10, specific enthalpy and entropy at the turbine inlet, $h_i$ and $s_i$, are determined using the steam-water properties table. There are difficulties in determining the actual condition of steam at the turbine outlet, this is because the plant is not equipped with an instrument to measure the amount of the condensed steam fraction. Therefore, in determining the condition of steam at the turbine outlet, the expansion process in the turbine is considered isentropic. The intersections of the isentropic line from point $P_i$, $T_i$ with the isobar line $P_0$ or isotherm line $T_0$ are the conditions of
steam coming out. However, $P_0$ and $T_0$ measurement results are not a pair of $P$ and $T$ saturated values when condensing, so that two intersect points will be obtained. The two intersect points are taken as the condition of steam coming out of the turbine, which is then used to analyze the performance of the turbine. The intersection of the isentropic line with the isobar line $P_0$ is considered the actual condition and the intersection with the $T_0$ isothermal line is ideal. Then the actual and ideal thermal power of the turbines $W_{\text{th}}$ and $W_{\text{thid}}$, as well as the actual thermal efficiency of the plant $\eta_{\text{th}}$ and the isentropic efficiency of the turbine $\eta_{\text{thid}}$ are calculated as shown in Table 11 and Figures 8 and 9.

### Table 10. Performance parameter measurements

| Test | rpm | $W_e$ (kW) | $m$ (kg/s) | $P_i$ (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        | 1.411      | 6.597        | 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       |

### Table 11. Steam properties and Calculation Result

| Test | $m$ (kg/s) | $h_i$ (kJ/kg) | $s_i$ (kJ/kg-K) | $h_{\text{th}}$ (kJ/kg) | $h_{\text{thid}}$ (kJ/kg) | $X_{\text{th}}$ | $W_{\text{th}}$ (kW) | $W_{\text{thid}}$(kW) | $\eta_{\text{th}}$ | $\eta_{\text{thid}}$ |
|------|------------|---------------|-----------------|-------------------------|--------------------------|--------------|---------------------|----------------------|----------------|------------------|
| 1    | 0.581      | 2781.9        | 6.7964          | 2193.6                  | 8.32                     | 2109.2       | 0.81                | 335.3                | 383.4          | 0.00             | 0.87             |
| 2    | 1.427      | 2782.9        | 6.7972          | 2225.6                  | 8.42                     | 2159.2       | 0.82                | 795.3                | 890.0          | 0.62             | 0.89             |
| 3    | 1.6        | 2783.9        | 6.7957          | 2232.0                  | 8.42                     | 2187.5       | 0.83                | 883.0                | 954.2          | 0.67             | 0.93             |
| 4    | 1.376      | 2790.5        | 6.8223          | 2233.9                  | 8.42                     | 2198.7       | 0.83                | 765.9                | 814.3          | 0.59             | 0.94             |
| 5    | 1.824      | 2791.5        | 6.8175          | 2217.3                  | 8.42                     | 2185.4       | 0.83                | 1047.3               | 1105.5         | 0.83             | 0.95             |
| 6    | 1.468      | 2787.6        | 6.8262          | 2212.0                  | 8.42                     | 2177.5       | 0.83                | 845.0                | 895.6          | 0.76             | 0.94             |
| 7    | 1.631      | 2792.3        | 6.8272          | 2212.3                  | 8.42                     | 2184.1       | 0.83                | 946.0                | 992.0          | 0.78             | 0.94             |
| 8    | 1.754      | 2789.9        | 6.8073          | 2205.8                  | 8.42                     | 2170.7       | 0.83                | 1024.5               | 1086.1         | 0.81             | 0.94             |
| 9    | 1.443      | 2787.9        | 6.8267          | 2212.2                  | 8.42                     | 2175.2       | 0.83                | 830.7                | 884.1          | 0.74             | 0.94             |
| 10   | 1.654      | 2788.6        | 6.7922          | 2200.8                  | 8.42                     | 2163.6       | 0.82                | 972.2                | 1033.8         | 0.78             | 0.94             |
| 11   | 1.415      | 2788.9        | 6.7934          | 2192.7                  | 8.42                     | 2159.8       | 0.82                | 843.6                | 891.3          | 0.73             | 0.95             |
| 12   | 1.411      | 2788.7        | 6.7917          | 2192.1                  | 8.42                     | 2158.3       | 0.82                | 841.8                | 889.5          | 0.72             | 0.95             |
| 13   | 1.348      | 2788.6        | 6.7922          | 2192.2                  | 8.42                     | 2150.1       | 0.82                | 803.9                | 860.7          | 0.73             | 0.93             |
| 14   | 1.362      | 2788.6        | 6.7942          | 2192.9                  | 8.42                     | 2151.6       | 0.82                | 811.3                | 867.6          | 0.75             | 0.94             |
| 15   | 1.682      | 2787.8        | 6.7791          | 2196.6                  | 8.42                     | 2167.2       | 0.82                | 994.4                | 1043.8         | 0.79             | 0.95             |
| 16   | 1.656      | 2792.5        | 6.8334          | 2214.4                  | 8.42                     | 2187.4       | 0.83                | 957.3                | 1002.0         | 0.81             | 0.96             |
During operation, the inlet and outlet steam parameters are relatively stable (Figure 10). Fluctuations of pressure and temperature at inlet turbine are in the range ± 5% and ± 5%, while at outlet turbine are ± 10% both. The steam condition at the inlet turbine is slightly superheat. With an isentropic expansion process approach in the turbine, there are some things 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 11). The thermal efficiency of the turbine-generator system ($\eta_{tha}$) gradually rises up to 81% at electrical loads around 776kW. This thermal efficiency is close to the design efficiency of the system ($\eta_{gen} \times \eta_{t} \times \eta_{m}$) which is in the range of 83% - 88% when calculated using the data in Table 1. While the ideal efficiency of the system ($\eta_{thid}$) ranges between 86% - 96%.

Observations on the vertical vibrations of the turbine bearings, gear boxes, and generators (Table 10 and Figure 11) show that all measurements are still below the allowable values of 4mm/s, 10mm/s, and 4mm/s respectively. All vibrations tend to decrease as the electrical load increases, except for $V_{T001}$, which is the vibration of the bearings in the downstream turbine. Observations on the maximum temperature of lubricating oil in turbine bearings, gear boxes, and generators (Table 6) are all below the maximum allowable value, which is about 100°C.

4. Conclusion
The results of the design calculations have been expressed in the form of drawings and PFD tables. This PFD design has been followed up with the technical drawings of P & ID and GA, fabrication, and construction. The SOP for 3MW GPP early stage testing was successfully compiled and implemented after several revisions which were adjusted to the characteristics of the plant from preparation to synchronous testing. The plant is successfully aligned with the results according to the target /
specifications both in vertical and horizontal direction although the spacer alignment value in the vertical direction is only able to be corrected to the limit of acceptable tolerance. The FRF test results show several critical speeds that must be avoided at start-up, ie 1500, 2600, 2800, 3300, 4500, 4700, 5400, 5800, and 6100 rpm Turbine rotation speeds. If holding speed is carried out, it is recommended to do it at 2000 and 4000 RPM Turbine speeds. Plant has successfully undergone load rejection test and testing with a dummy load of up to 500kW. All vibration levels tend to be lower when dummy loads are 500kW, and all are still below the safe limits both according to ISO 10816-3 (11.0 mm / s for Turbine and Generator) and the standard of the manufacturer (4mm / s for Turbine and Generator, and 8.0 for Gearbox) Plant also managed to undergo initial synchronization operations to PLN's power grid to a load of about 1MW. The test results show that the plant performance is quite good with thermal efficiency close to its design value. The resulting vibration is still below the maximum allowable value, and there is a downward trend for higher loading. Similarly, the maximum value of the oil temperature is still lower than the maximum allowable value. Thus, it can be concluded that 3MW GPP is feasible to proceed for operations at higher loads.

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