Probabilistic approach: back pressure turbine for geothermal vapor-dominated system

Angga Alfandi Ahmad¹, Fransiscus Xaverius Guwowijoyo¹, Heru Berian Pratama¹

¹Geothermal Engineering Study Program, Faculty of Mining and Petroleum, Bandung Institute of Technology, Jl. Ganesha No.10 Bandung, Indonesia 40132

Email: anggaalfandi@gmail.com

Abstract. Geothermal business nowadays needs to be accelerated in a way that profit can be obtained as soon as reasonable possible. One of the many ways to do this is by using one of geothermal wellhead generating unit (GWGU), called backpressure turbine. Backpressure turbine can be used in producing electricity as soon as there is productive or rather small-scale productive well existed after finished drilling. In a vapor dominated system, steam fraction in the wellhead capable to produce electricity based on each well productivity immediately. The advantage for using vapor dominated system is reduce brine disposal in the wellhead so it will be a cost benefit in operation. The design and calculation for backpressure turbine will use probabilistic approach with Monte Carlo simulation. The parameter that will be evaluated in sensitivity would be steam flow rate, turbine inlet pressure, and turbine exhaust pressure/atmospheric pressure. The result are probability for P10, P50, and P90 of gross power output which are 1.78 MWe, 2.22 MWe and 2.66 Mwe respectively. Whereas the P10, P50, and P90 of SSC are 4.67 kg/s/MWe, 5.19 kg/s/MWe and 5.78 kg/s/MWe respectively.

1. Introduction
Geothermal vapor dominated system, as the name implies, consist steam fraction dominantly. In an early geothermal development plan, many wells can be drilled and remain idle as the plan continue. Surface facilities in early development are still not complete and steam that already produced in a drilled well can be wasted unwantedly. In order to utilize the produced steam, even just a little, geothermal wellhead generating unit (GWGU) can be used to utilize the produced steam and turn it into electricity.

In Kenya, KenGen lost a potential of 11,211 GWh by not utilizing steam in the idle wells, which is approximately one billion usd lost in revenue [6].

| Year | Field | Country      | Type               | Capacity         |
|------|-------|--------------|--------------------|------------------|
| 1978 | Kamojang | Indonesia    | Backpressure Turbine | 1 x 0.25 MW     |
| 1982 | Los Azufres | Mexico       | Backpressure Turbine | 5 x 5 MW        |
| 1997 | Miravalles | Costa Rica   | Backpressure Turbine | 1 x 5 MW        |
| 2012 | Eburru   | Kenya        | Mini Condensing Unit | 1 x 2.5 MW      |
Kamojang Geothermal Field can be a representative data for vapor dominated system in this calculation and design, which had more than 40 years of production history and still operating in present time. It will become good practice for vapor dominated system near Kamojang which still in the development process and able to use GWGU for increasing their negative income in the beginning of the project.

2. Back Pressure Turbine
Geothermal Wellhead Generating Unit (GWGU) has short pipelines because of its location which is close to the production well and steam supplied from one production well or more in a single wellpad, usually able to generate electricity less than 10 MW [2]. Generally, GWGU can be divided into two distinguished types namely non-condensing type and condensing type. In time, for condensing type GWGU can be utilized for many technologies especially related to binary technology.

Backpressure turbine is the most simple GWGU type. This type does not require condenser, cooling system, gas removal system, and separator (for vapor-dominated system only). This type only needs scrubber, turbine-generator, and electric transmission. Steam from production well flow into scrubber to purify the steam. Then from scrubber, steam used to rotate turbine which will generate electrical power. The steam from turbine will goes out from atmospheric exhaust and flow to the atmosphere/environment directly.

![Figure 1. Simplify Schematic Diagram of Steam Flow](image-url)

Backpressure turbine is ideal for new developed project. The productive well that being used for backpressure turbine is ideally the well that will be used for the big project in the next phase of development. From the components itself, backpressure turbine components are easily to relocate to any available and possible well. It has simple yet effective components. One concern from backpressure turbine is atmospheric turbine exhaust system utilization. The system would produces noisy sound because higher pressure steam out from turbine directly goes to atmospheric with lower pressure.

In GWGU, steam can driving turbine-generator system directly to produce electricity immediately. The gross power output produced by turbine-generator system [1] is given by:

\[ W_e = \frac{m_s \times \eta_t \times \eta_m \times \eta_g \times (h_{HP} - h_{LP, sen})}{1000} \]
The performance of GWGU application for vapor dominated field determined by specific steam consumption of turbine as termed SSC. SSC is the ratio of steam consumed by turbine per unit gross power output. Unit of SSC basically is kg/s/MWe or commonly it uses kg/MWh [1]. The formula of SSC is given by:

$$SSC = \frac{\dot{m}_{steam}}{W_e}$$

Where:
- $\dot{W_e}$: gross power output [MWe]
- $\dot{m}_{s}$: steam flow rate [kg/s]
- $\eta_t$: isentropic turbine efficiency [%], which is ratio of the actual work to the isentropic work
- $\eta_m$: mechanical losses of turbine-generator system [%]
- $\eta_g$: generator efficiency [%]
- $h_{HP}$: specific enthalpy of the steam at the turbine inlet pressure [kJ/kg]
- $h_{L,Pisen}$: specific enthalpy of the steam [kJ/kg]

3. Methodology

This study used probabilistic approach, so the calculation might be estimated by using a polynomial response or proxy equation for full factorial of 3 factors, as follows:

$$Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_{AB} + \beta_{AC} + \beta_{BC} + \beta_{ABC}$$

Where $\beta_0$ is the average value of the response and $\beta_1, \beta_2, \ldots, \beta_7$ is regression linear. The polynomial describes the behavior of the responses between parameter including the interaction effects between parameters.

Experimental design concept were applied in GWGU application to calculate the performance with probabilistic approach based on several main parameters. There are three main parameters investigated in this paper: steam flow rate ($\dot{m}_{steam}$), turbine inlet pressure (TIP), and turbine exhaust pressure (TEP) or in this case we use atmospheric pressure as turbine exhaust pressure. The parameter of back pressure unit are summarized in table 2 where the low and high value are categorized based on typical value of average vapor dominated field in Kamojang as representative data [7].

| Table 2. Parameter for Sensitivity |
|-----------------------------------|
| Parameter                          | Low (-1) | High (+1) |
| Steam flow rate [kg/s]             | 8        | 15        |
| Turbine inlet pressure [bar abs]   | 3        | 5         |
| Atmospheric pressure [bar abs]     | 0.8      | 1         |

A two level (low and high) of full factorial with three factor for ED was implemented using Minitab 17 free trial software. The total run in these study is 8 runs. In the design table (table 3), the standard order column is an experimental design idea to do the experiments in a random order (run order) and avoid run-dependent effects.

| Table 3. A two level of full factorial design |
|---------------------------------------------|
| StdOrder | RunOrder | Msteam | TIP | TEP |
|---------|----------|--------|-----|-----|
| 7       | 1        | -1     | 1   | 1   |
| 2       | 2        | 1      | -1  | -1  |
| 4       | 3        | 1      | 1   | -1  |
| 6       | 4        | 1      | -1  | 1   |
| 8       | 5        | 1      | 1   | 1   |
| 1       | 6        | -1     | -1  | -1  |
| 5       | 7        | -1     | -1  | 1   |
| 3       | 8        | -1     | 1   | -1  |
The polynomial equation of gross power output and specific steam consumption as a function of three independent parameters are the results in these study. A two level proxy model using -1 and +1 parameters to generate the gross power output (GPO) and SSC responses GWGU back pressure are represented below:

\[
GPO = 2.253 + 0.6857 M_{\text{steam}} + 0.3933 TIP - 0.1571 CIP + 0.1197 M_{\text{steam}} \times TIP
\]

\[
SSC = 5.295 + 0.000000 M_{\text{steam}} - 0.9344 TIP + 0.3946 CIP - 0.000000 M_{\text{steam}} \times TIP
\]

4. Data, Results, and Analysis

The basic data design for vapor dominated fields is obtained from Kamojang geothermal field [7] which are presented below:

| Table 4. Data Design |
|----------------------|
| Parameter | Value |
| Well Head Pressure (WHP) | 15 bar abs |
| Quality of steam in well head | 100% |
| NCG content | 1% |
| Isentropic turbine efficiency | 85% |
| Mechanical losses of turbine-generator system | 95% |
| Generator efficiency | 98% |

The results of GWGU back pressure model calculation shown in table 5. The minimum and maximum gross power output is 1.2 MWe and 3.7 MWe, and the minimum and maximum SSC value is 4.1 and 6.8 kg/s/MWe.

| Table 5. The result of GWGU back pressure performance |
|----------------|----------------|----------------|
| RUN ORDER | Gross Power Output MWe | SSC kg/s/MWe |
| 1 | 1.7 | 4.6 |
| 2 | 2.6 | 5.7 |
| 3 | 3.7 | 4.1 |
| 4 | 2.2 | 6.8 |
| 5 | 3.2 | 4.6 |
| 6 | 1.4 | 5.7 |
| 7 | 1.2 | 6.8 |
| 8 | 1.9 | 4.1 |

The next steps are running Monte Carlo simulation based on generated polynomial equation of gross power output and SSC with 50,000 iterations using spreadsheet. The result is a probability distribution function of the gross power output covering the full range of possible outcomes. The cumulative distribution results of the gross power output shown in figure 2, the P10, P50 and P90 are 1.78 MWe, 2.22 MWe and 2.66 MWe respectively. In other side, The cumulative distribution results of the SSC shown in figure 3, the P10, P50 and P90 are 4.67 kg/s/MWe, 5.19 kg/s/MWe and 5.78 kg/s/MWe.
Figure 2. Monte Carlo simulation results for Gross Power Output (left side) and SSC (right side) with histogram and cumulative distribution function with P10, P50 and P90 indicated

In the Monte Carlo simulations, we also know about the most sensitive parameters of calculation based on Pareto Chart. As shown in figure 4 and 5, the highest effect for gross power output calculation is steam flow rate whereas for SSC calculation is turbine inlet pressure. It is important things for the next development project of back pressure unit in some vapor dominated field to select the best parameter in order to obtain the optimum performance.
5. Conclusion
GWGU back pressure model is the best model for green field development project uses a well to generate electricity meanwhile drilling campaign still on going until the end of project. The probabilistic approach using Monte Carlo simulation for gross power output and SSC based on 50,000 iteration has successfully represented and applied of GWGU experimental design. The P10, P50, and P90 of gross power output are 1.78 MWe, 2.22 MWe and 2.66 MWe. Whereas the P10, P50, and P90 of SSC are 4.67 kg/s/MWe, 5.19 kg/s/MWe and 5.78 kg/s/MWe respectively.

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