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Steam Flow Measurements in the Maibarara Geothermal Field: A Case Study Between Flow Testing and Online Steam Flowmeters

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ABSTRACT

Two types of steam flowmeters are used in the Maibarara Geothermal Field. The vortex flow meter, installed at the main steam line, measures the total steam flow from the separator while the orifice flow meter, installed at the interface, measures the steam flow going into the steam turbine. Periodic flow testing measurements such as tracer flow test (TFT) and horizontal discharge testing are also being conducted. This paper presents a comparison between flow testing and online steam flowmeters using the Bland-Altman analysis to determine the degree of agreement between two steam flow measurement methods. Results show that the vortex and orifice flow meters can substitute for TFT measurements at the main steam line and interface, respectively.

1. INTRODUCTION

The Maibarara Geothermal Field is located in the Philippines, situated 70 kilometers southeast from capital city of Manila (Figure 1). The field is sited within a 1,600-hectare service contract area at the western flank of Mt. Makiling, an extinct stratovolcano. It is adjacent to the Mak-Ban Geothermal Field. The steamfield, power plant, and switchyard complex are located within the compact 7.5-hectare development. The total installed capacity as of is 32 MW comprising of two single-flash plant units. Commercial operations started in February 2014 for the 20 MW Maibarara-1 Geothermal Power Plant (M1GPP), and April 2018 for the 12 MW Maibarara-2 Geothermal Power Plant (M2GPP).

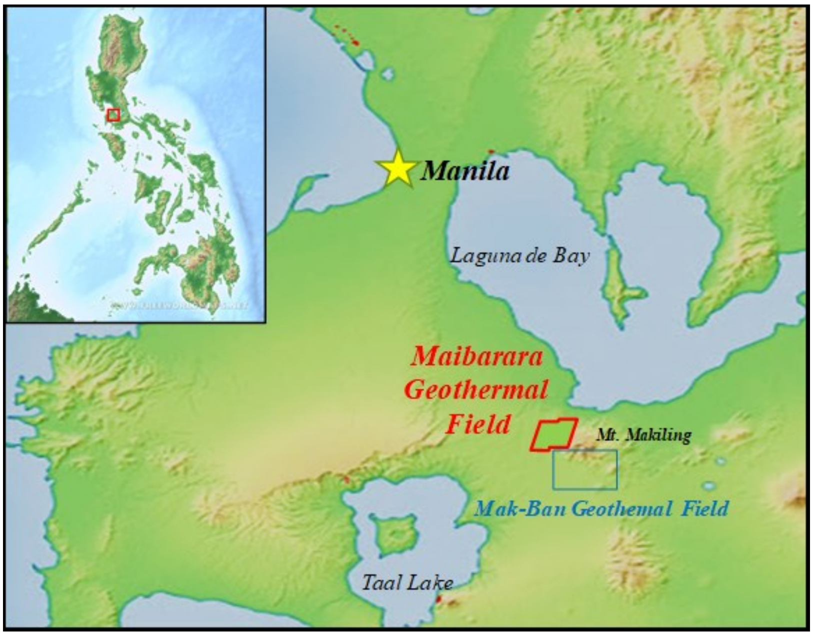

Figure 1: Location Map of the Maibarara Geothermal Field

Steam is a vital parameter of every power-generating geothermal field since it is the medium that drives the turbine-generator for electricity generation. Due to its inherent complex physical nature as a geothermal fluid, there are accompanied challenges in steam flow measurement such as its saturated condition and corrosive non-condensable gas (NCG) content. Despite these, steam flow rate data is important for overall field management, individual well output monitoring and reservoir production forecasting. Hence, accurate and reliable measurements are desirable.

Existing techniques for steam flow measurement include flow testing methods and commercially available flow instruments. For flow testing methods, the James lip pressure and tracer dilution had been documented in several field applications. In terms of flow instruments, the orifice plate meter has been widely used for steam flow measurement due to its simplicity and accuracy while the vortex meter is a relatively modern flowmeter for geothermal applications.

However, these measurement techniques have their particular disadvantages leading to intrinsic degree of error. When two instruments or methods are compared, neither provides an explicitly correct measurement, so it could be interesting to determine a certain "degree of agreement" between two different measurement techniques.

To consider this degree of agreement, the correct statistical approach is not obvious. Many studies give the product–moment Pearson correlation coefficient "r" between the results of two measurement methods as an indicator of agreement. However, correlation studies the relationship between one variable and another, not the differences, and it is not recommended as a method for assessing the comparability between methods (Giavarina, 2015).

In the pursuit to validate steam flow data and establish a degree of agreement from different steam flow measurement techniques, this study investigated the application of the Bland-Altman analysis. The Bland-Altman analysis is a statistical technique that has been extensively used in clinical medicine and analytical chemistry to evaluate the agreement between two different measuring instruments.

In the following sections, steam flow data measurement methods in the Maibarara Geothermal Field are explained, and the Bland-Altman analysis is described and applied to Maibarara steam flow data.

2. STEAM FLOW MEASUREMENTS

Two types of steam flowmeters are installed and used in Maibarara Geothermal Field: the vortex flowmeter, installed in the main steam line, measures the total steam flow from the separator; and the orifice flowmeter, installed at the interface, measures the steam flow going into the steam turbine. Both flowmeters are connected to the Distributed Control System with mass flow data in kilograms per second (kg/s) recorded real-time. Periodic flow testing measurements such as the tracer dilution method – tracer flow test (TFT) and discharge testing are also being conducted. TFT is conducted about twice a year while discharge testing is conducted by diverting flow to the silencer for 1 - 4 hours. Laboratory results from TFT is acquired typically 30 - 40 calendar days after the conduct. Operation-wise, TFT is more practical to conduct than discharge testing because there is no need to isolate a well and thus, stop production.

Accurate and reliable measurement of steam mass flow rate is essential for both short-term availability and long-term sustainability objectives. Short-term objectives cover steamfield operations management and individual well output monitoring while long-term objectives involve reservoir performance monitoring, production forecasting and make-up production well scheduling.

Validation of steam flow measurements from flowmeters and TFT currently relies on explicit calculation of relative percent difference between two measurement data using the following equation

$$\%\,Difference = \frac{|E_1 - E_2|}{\frac{1}{2}(E_1 + E_2)} \cdot 100 \tag{1}$$

where E1 and E2 are measurements from two different instruments. The performance accuracy specifications for vortex flowmeter is ±2.0% based on manufacturer information whereas for TFT is ±4.3% as studied by Hirtz and Lovekin (Hirtz & Lovekin, 1995).

Figure 2 shows the plot of steam flow measurements percent differences at the main steam line from TFT and vortex flow meter with respect to time. Generally, TFT presents majority higher measurements relative to the vortex meter. The calculated absolute percent difference ranges from 3% to 8%. None of the data points was acceptable within the ±2% vortex accuracy specification. This implies inconsistency between steam line TFT and vortex data.

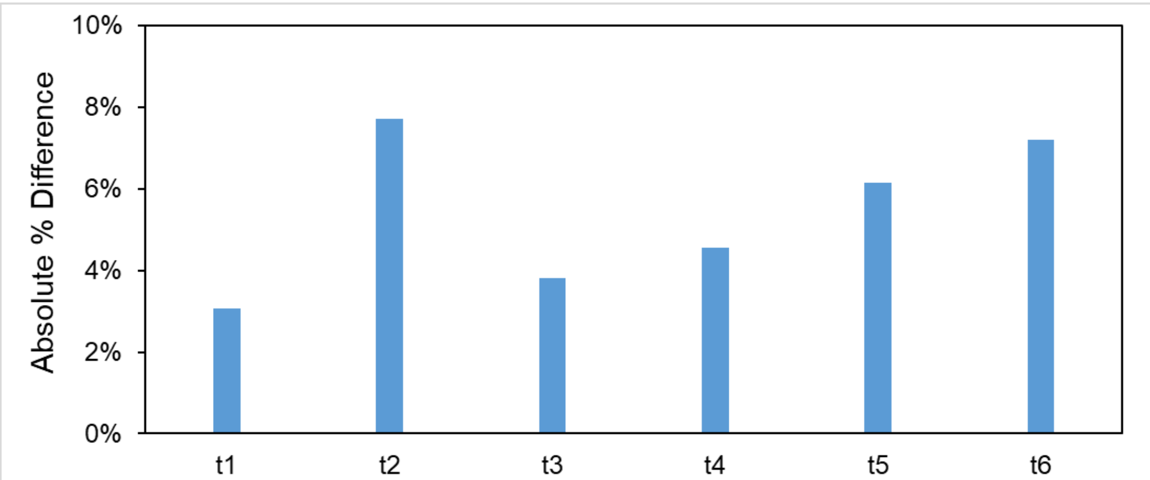

Figure 2: Main Steam Line Flow Measurement Percent Difference: TFT vs Vortex

On the other hand, Figure 3 depicts the plot of steam flow measurements percent differences at the interface from TFT and orifice meter with respect to time. The absolute percent difference ranges from 1% to 6%. This narrow range of calculated percent difference range denotes good consistency between interface TFT and orifice data. Three (t2, t3, and t6) of the seven points are acceptable within ±4.3% TFT accuracy specification.

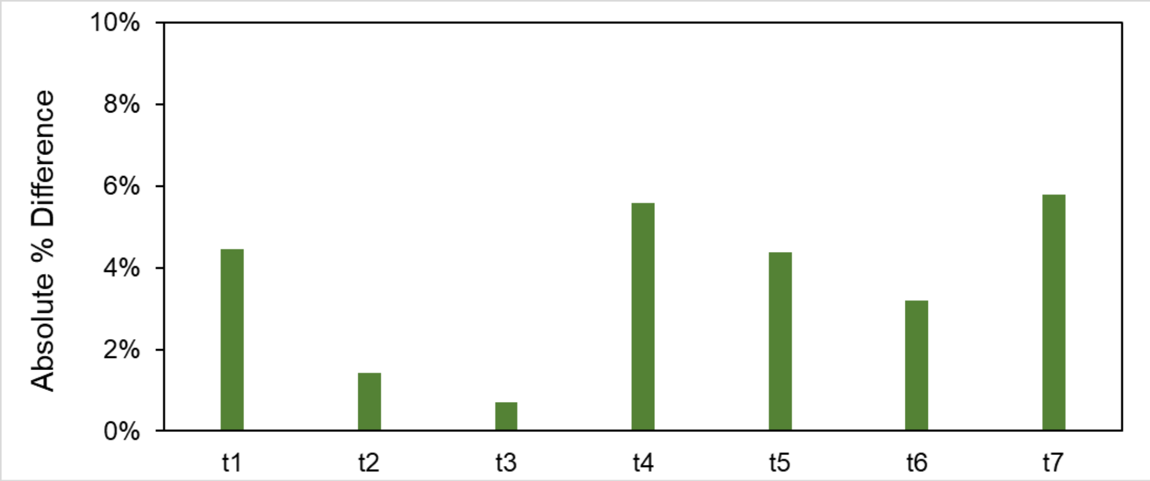

Figure 3: Interface Steam Flow Measurement Percent Difference: TFT vs Orifice

3. BLAND-ALTMAN ANALYSIS

For many years, correlation analysis has been used to evaluate the relationship between one variable and another. It is classified under a larger class of statistical techniques known as regression. Regression analysis uses the principles of correlation, but it does more than just to describe the strength of a relationship between two variables (Greenfield, Kuhn, & Wojtys, 1998). The Pearson correlation, also known as the "product moment correlation coefficient" (PMCC), is calculated using the following equation

$$r = \frac{N\sum xy - (\sum x)(\sum y)}{\sqrt{[N\sum x^2 - (\sum x)^2][N\sum y^2 - (\sum y)^2}} \tag{2}$$

where N, Σxy, Σx, Σy, Σx^2 and Σy^2 is the number of pairs, sum of products of paired scores, sum of x scores, sum of y scores, sum of squared x scores and sum of squared y scores, respectively. The computed correlation coefficient (r) ranges from −1.0 to +1.0. The strength of correlation is described using the rule of thumb (Evans, 1996) suggested for the absolute value of r (Table 1).

Table 1: Rule of Thumb for Interpreting the Absolute Value of r

Absolute Value of r	Interpretation
0.00 – 0.19	Very weak
0.20 – 0.39	Weak
0.40 – 0.59	Moderate
0.60 – 0.79	Strong
0.8 – 1.00	Very strong

However, the correlation coefficient only provides a link between variables which just happen to occur together, without having an association in between. This can be handled as a linear measure for the relationship between variables without providing their agreement. Thus, a dataset with high correlation may or may not produce high degree of agreement.

The Bland-Altman (B&A) analysis was proposed by J.M. Bland and D. Altman in 1986 as a technique to assess the agreement between two bronchial airflow meters. It constructs statistical limits calculated using the mean and the standard deviation (SD) of the differences between two measurements. The best way to use the B&A analysis is to define *a priori* the limits of maximum acceptable differences (MAD) or the expected limits of agreement, based on analytically relevant criteria, manufacturer information or domain-specific knowledge. This defines how far apart measurements can be without causing difficulties. The maximum acceptable difference, commonly expressed in ±%, is multiplied to the closest known true value which is the overall mean of the dataset.

To begin with the B&A analysis, the two sets of data are plotted into a scatter plot XY with an ideal line of equality drawn to which all points would lie if the two instruments gave exactly the same measurements every time (Figure 4). This plot helps in gauging the degree of agreement between the measurements. Additionally, this illustrates how perfect correlation differs from perfect agreement. The former exists when all points lie within any given straight line while the latter exists when all points lie within a proportional straight line.

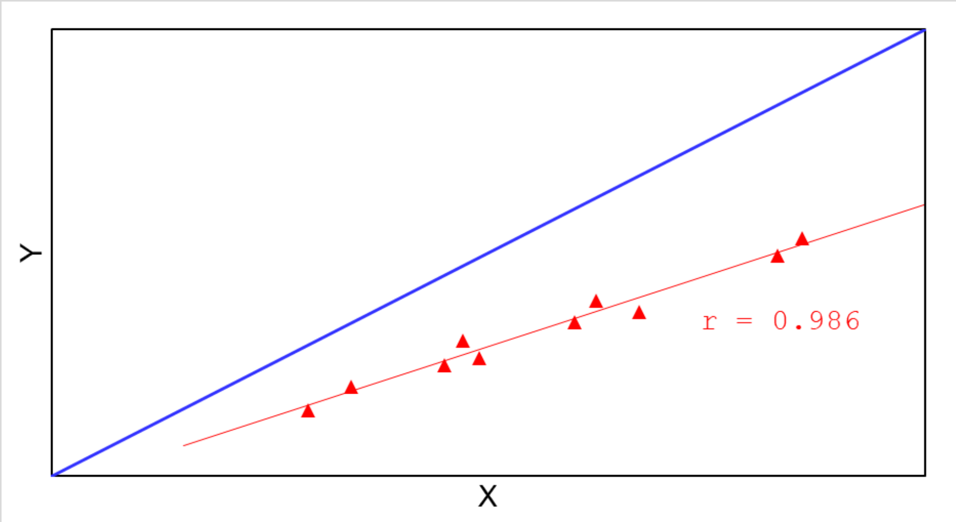

Figure 4: Plot with Regression Line (red) and Line of Equality (blue)

Next, the mean and difference data are plotted into another scatter plot, as detailed in Figure 5. The X-axis represents the means while the Y-axis represents the differences. After the plot is made, the mean difference ($\bar{X}_{Diff}$) and its statistical limits of agreement (LOA) are quantified using the difference of measured data and SD. The data points can be statistically restricted using ±2 SD to demonstrate a 95% confidence interval (CI; precisely defined: mean ± 1.96 standard deviations) of distributed data (Özgür Doğan, 2018). The equations to calculate the statistical LOA are given as $\mathbf{\bar{X}_{Diff} + (1.96 \times SD)}$ for the upper limit, and $\mathbf{\bar{X}_{Diff} - (1.96 \times SD)}$ for the lower limit. To summarize these, the B&A plot (Figure 5) should contain the mean difference, the MAD and the statistical LOA.

As shown in Figure 5, Instrument Y underestimated the 100% (all points are located on the positive y-axis) by the magnitude of the mean difference. Only 40% (4/10) of the difference was within the ±10% MAD of the true value. Furthermore, the statistical LOA range is relatively wide compared to expected error range. It can also be observed that the magnitude of difference increases as with the mean. Therefore, instrument Y is in proportional error agreement with Instrument X. Given the following findings, instrument Y cannot substitute instrument X as measuring device.

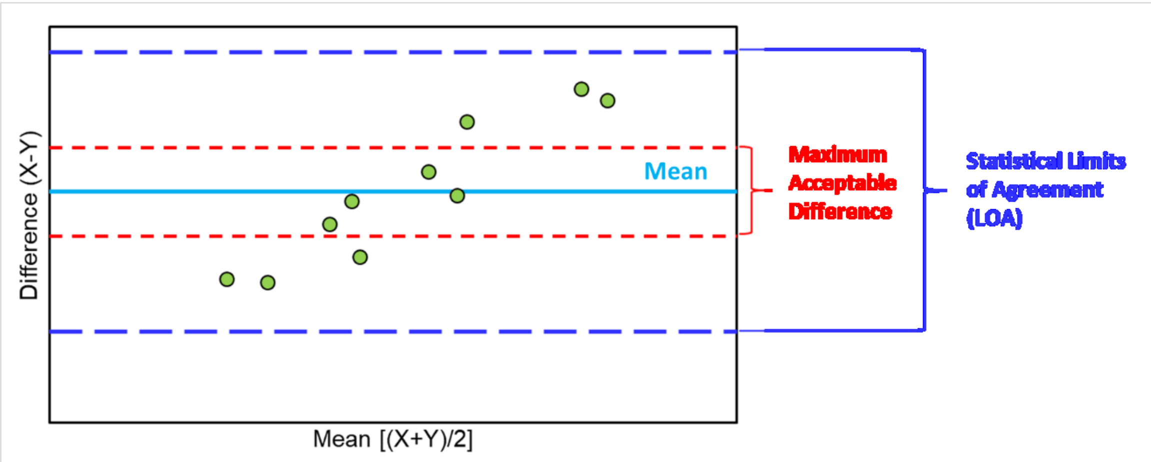

Figure 5: Bland-Altman (B&A) Plot

4. APPLICATION TO MAIBARARA DATA

Having introduced the Bland-Altman analysis, it is known that the technique provides better evaluation of the agreement of two measurement variables. In the application to the Maibarara data, the scope was limited to the two measurement locations mentioned in Section 2: the main steam line and the interface.

4.1 Main Steam Line

In this dataset (

Table 2), the steam flow measurements (in kg/s) from TFT and vortex meter are shown. The analysis used ±2% accuracy specification of the vortex meter as reference for the maximum acceptable difference (MAD).

Table 2: Steam Flow Measurements at Main Steam Line

Method X (TFT)	Method Y (Vortex)	Mean	Difference
60.00	61.87	60.93	-1.87
58.60	63.30	60.95	-4.70
60.00	62.33	61.17	-2.33
60.20	63.00	61.60	-2.80
59.30	63.07	61.18	-3.77
59.00	63.40	61.20	-4.40
X̄		***61.17***	***-3.31***
SD			***1.15***

The regression plot (Figure 6) with a -0.703 r coefficient indicated strong correlation, based on Table 1, between main steam line TFT and vortex meter. The B&A plot (Figure 7) detailed a mean difference of -3.31 ± 1.15 SD, the statistical LOA are -1.05 and -5.57 while the MAD limits are -2.09 and -4.53.

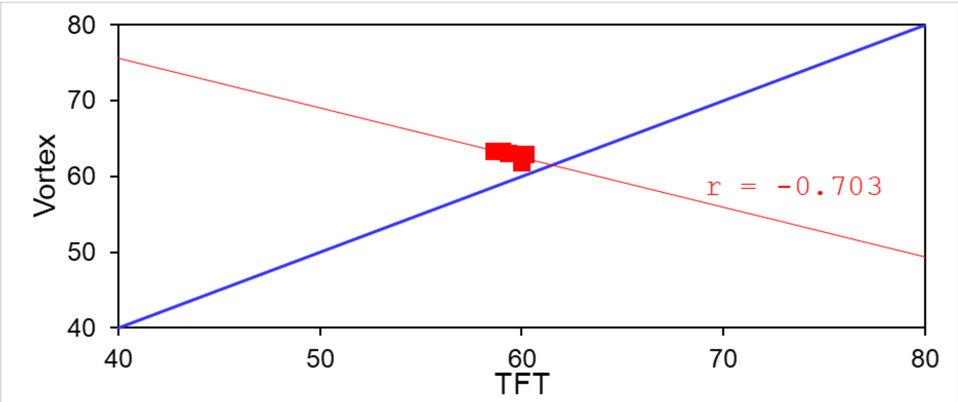

Figure 6: Main Steam Line Plot with Regression Line and Line of Equality

As shown in Figure 7, the vortex meter overestimated 100% (all points are in the negative Y-axis) of the true steam flow by an average of 3.31 kg/s. It can be observed that 67% (4/6) of the steam flow difference was within the ±2% MAD limits of the true steam flow. The statistical LOA range was relatively narrow at ~4 kg/s and comparable to acceptable difference range of ~2 kg/s. The feasible percentage (67%) of difference data within the ±2% MAD limits indicated high degree of agreement between TFT and vortex meter and TFT. These results suggested that the vortex meter can substitute TFT as steam flow measuring method at the main steam line.

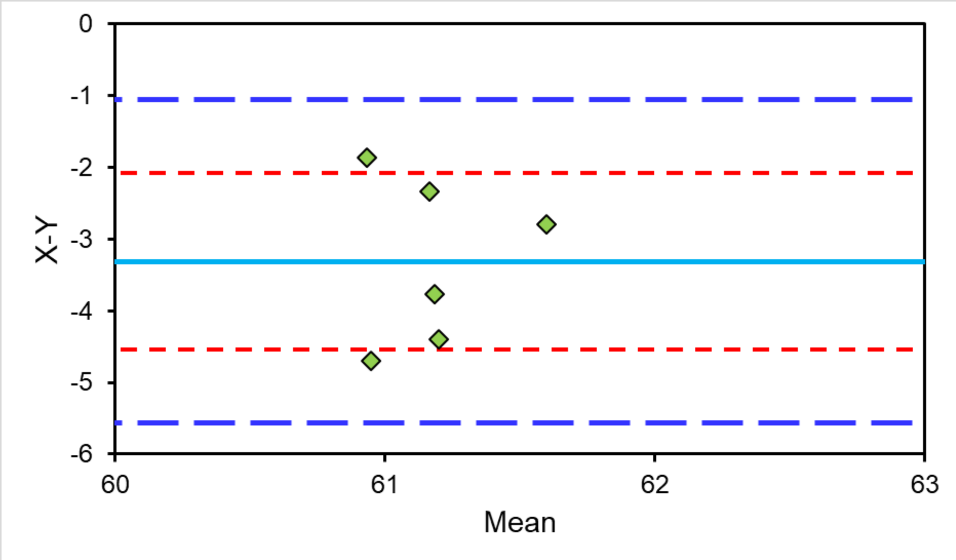

Figure 7: Main Steam Line B&A Plot

4.2 Interface

In this dataset (Table 3), the steam flow measurements (in kg/s) from TFT and orifice meter are shown. The analysis used ±4.3% accuracy specification as maximum acceptable difference (MAD).

Table 3: Steam Flow Measurements at Interface

Method X (TFT)	Method Y (Orifice)	Mean	Difference
39.6	41.4	40.5	-1.8
42.2	41.6	41.9	0.6
42.3	42.6	42.5	-0.3
40.1	42.4	41.3	-2.3
40.2	42.0	41.1	-1.8
44.4	43.0	43.7	1.4
41.2	43.7	42.4	-2.5
X̄		***41.9***	***-1.0***
SD			***1.5***

The regression plot (Figure 8) with a 0.422 r coefficient indicated moderate correlation, based on Table 1, between interface TFT and orifice meter. The B&A plot presented a mean difference of -1.0 ± 1.5 SD, the statistical LOA are -3.93 and 2.03 while the MAD limits are -2.75 and 0.85. The relatively low magnitude mean difference (-1) is an initial indicator of good agreement between the measurements.

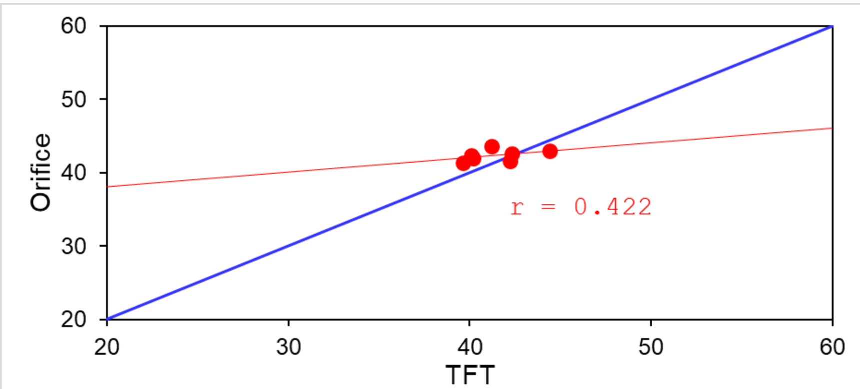

Figure 8: Interface Steam Flow Plot with Regression Line and Line of Equality

As shown in Figure 9, the orifice meter overestimated 71% (5/7 of points are in the negative Y-axis) of the true steam flow by an average of 1 kg/s. It can be seen that 85% (6/7) of difference was within the ±4.3% MAD limits of the true steam flow. The statistical

LOA range is relatively narrow at ~5 kg/s and is comparable to acceptable difference range of ~3 kg/s. The very feasible percentage (85%) of difference data within the 4.3% MAD limits indicated very high degree of agreement between orifice meter and TFT. These findings suggested that the orifice meter can substitute TFT as steam flow measuring method at the interface.

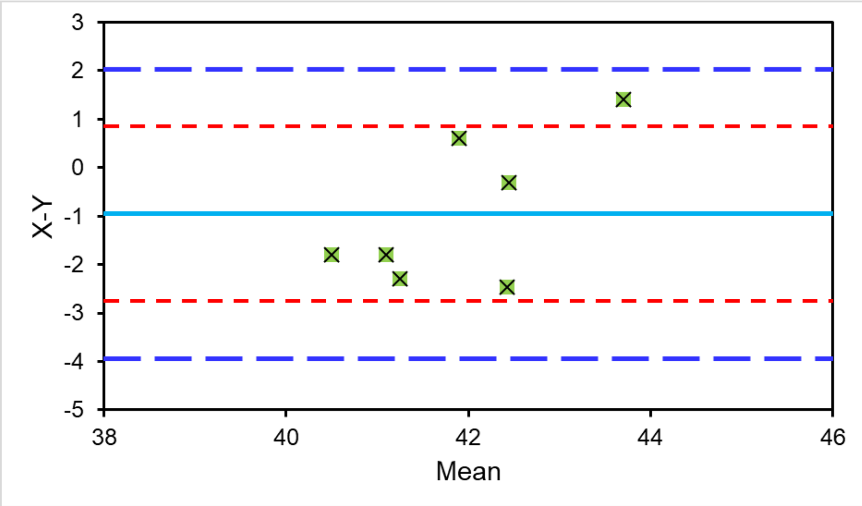

Figure 9: Interface B&A Plot

5. CONCLUSIONS

The Bland-Atlman analysis is a useful technique to determine the degree of agreement and establish the maximum acceptable differences between two steam flow measurement methods or instruments. The B&A analysis was applied to the steam flow data at the main steam line and interface of the Maibarara Geothermal Field. The analyses showed a high degree of agreement of measurements between installed flowmeter and TFT. The results indicated that the vortex and orifice flowmeters can substitute TFT steam flow measurements at the main steam line and interface, respectively.

The quantitative agreement of orifice and TFT is 85%, which is relatively greater than the 67% agreement of vortex and TFT. With this finding, MGI has adopted the use of orifice metering on the main steam line of M2GPP and no significant pressure drops were incurred upon installation. The current orifice meters are intended to optimize the cost of third-party TFT measurements.

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REFERENCES

Bland, J., & Altman, D. G. (1986). Statistical methods for Assessing Agreement between Two Methods of Clinical Measurement. Lancet 1, 307-310.

Bland, J., & Altman, D. G. (1999). Measuring Agreement in Method Comparison Studies. Statistical Methods in Medical Research 8, 135-160.

Dallal, G. E. (2019, July). Comparing Two Measurement Devices Part I. Retrieved from www.jerrydallal.com: http://www.jerrydallal.com/LHSP/compare.htm

Evans, J. D. (1996). Straightforward statistics for the behavioral sciences. Pacific Grove.

Giavarina, D. (2015). Understanding Bland Altman Analysis. Biochem Med (Zagreb), 141-151.

Greenfield, M. L., Kuhn, J. E., & Wojtys, E. M. (1998). A statistics primer. Correlation and regression analysis. Am J Sports Med, 26:338–343.

Hirtz, P., & Lovekin, J. (1995). Tracer Dilution Measurements for Two-Phase Geothermal Production: Comparative Testing and Operating Experience. World Geothermal Congress.

Illinois State University. (2019, July). Department of Physics. Retrieved from physics.illinoisstate.edu: http://www.phy.ilstu.edu/slh/percent%20difference%20error.pdf

Özgür Doğan, N. (2018). Bland-Altman Analysis: A Paradigm to Understand Correlation and Agreement. Turkish Journal of Emergency Medicine 18, 139-141.