THE GEOTHERMAL TWO-PHASE ORIFICE PLATE

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ABSTRACT

A real time measurement of the mass flow rate and enthalpy of two-phase wells is important for the management of geothermal development and monitoring individual well outputs. Existing techniques for measuring the output of two-phase wells are either expensive (separators), low in accuracy (tracer dilution) or require the geothermal well to be taken out of production (horizontal discharge) for testing. Several new real time two-phase flow measurement methods are being investigated using both laboratory and field testing. The two-phase orifice plate is the most widely examined method and has also been implemented in several geothermal fields worldwide.

In this work, geothermal field data was used to examine five existing correlations for two-phase flow measurement using the concentric sharp-edge orifice plat. These correlations are relatively complex and include several empirically derived and calibration parameters. A new simple correlation was developed which has similar accuracy to that of Helbig & Zarrouk (2012) for measuring two-phase flow using the orifice plate.

NOMENCLATURE

A	Cross sectional area (m^2)
a	Pressure coefficient of modified correlation
C	Orifice discharge coefficient
C_h	Enthalpy coefficient
D	Inside pipe diameter (m)
d	Orifice diameter (m)
F_a	Orifice thermal expansion factor
F_C	Correlation factor
F_T	Time ratio correction factor
h	Enthalpy (kJ/kg)
K	Two-phase coefficient
K_C	Correction factor
$\dot{m}$	Mass flow rate of the fluid (kg/s)
p	Pressure (Pa)
p_1	Pressure upstream of the orifice plate (Pa)
p_2	Pressure downstream of the orifice plate (Pa)
Re_D	Reynolds number for inner pipe diameter
T_F	Fluid temperature (K)
U, V	Substitution factors to calculate orifice design coefficient
v	Fluid velocity (m/s)
W	Substitution factor to calculate orifice design coefficient
X, Y	Substitution factor to calculate orifice design coefficient
x	Dryness fraction of the fluid
x_m	Corrected orifice dryness fraction of the fluid

Greek letters

α	Thermal expansion coefficient (m/mK)
β	Rate of the orifice diameter to the inside pipe diameter ($\beta = d/D$)
ε	Void fraction
θ	Corrective coefficient
κ	Isentropic coefficient
μ	Dynamic viscosity (kg/ms)
ρ	Density (kg/m^3)
σ	Time ratio coefficient
τ	Passing time of the liquid phase (s)
Δ_p	Differential pressure (Pa)

Subscripts

1Φ	Single-phase
2Φ	Two-phase
G	Gaseous/steam phase
H	Homogenous
L	Liquid phase
OP	Orifice plate

Superscripts

n	Exponent of the corrected orifice dryness fraction

1. INTRODUCTION

Measurement of geothermal fluid output from geothermal wells is mandatory in the geothermal industry for day-to-day field management of a geothermal field, and required by law for resource consent. The parameters that have to be monitored during the operation of wells are mass flow rate and enthalpy. These measurements also help in detecting potential problems in wells if monitored continuously.

All new geothermal power developments use a centralized separation system for their steam field facilities design (Mubarok & Zarrouk, 2016). This is because it involves relatively low capital investment and has simpler operation and maintenance than having individual wellhead separators (Mubarok & Zarrouk, 2016; Purwono, 2010). Consequently, the monitoring of mass flow rate and enthalpy from each production well is difficult because the two-phase pipeline of the well is connected directly to other wells in the same and different well pads and delivered to the central separator. Thus, the mass flow rate and enthalpy in the central separator is a mixture of several wells. Nowadays, many geothermal industries are using the orifice plate technique to measure a mass flow rate due to the simplicity, low install cost and the high reliability (Helbig & Zarrouk, 2012).

2. COMMON GEOTHERMAL TWO-PHASE FLOW MEASUREMENT TECHNIQUES

At the moment there are four common two-phase flow measurement techniques in geothermal applications: total flow calorimeters (Bixley et al., 1998); the lip pressure method (James, 1962); the separator method (Grant & Bixley, 2011) and the tracer dilution method (Broaddus, Katz, Hirtz, & Kunzman, 2010; Lovelock, 2001).

2.1 Total Flow Calorimeter

The calorimeter is a simple and practical method to measure mass flow rate and flowing enthalpy in geothermal wells (Bixley et al., 1998). Geothermal fluids are discharged and mixed with cold water inside a known volume tank. The fundamental ideas of this method are measuring the initial and final volumes and temperature inside the tank to calculate the mass flow rate and flowing enthalpy. This method is only appropriate for geothermal wells with low (1-2 MWth) capacities due to the limitation of the tank size (Bixley et al., 1998).

2.2 Lip Pressure Method

The lip pressure method was developed by James (1962) and used for well production testing, with relatively good accuracy over a short time period. If the fluid is discharged to the atmosphere through a pipe, the gauge pressure at the pipe outlet will be zero. However, when the fluid velocity increases significantly, the pressure close to the pipe outlet increases proportionally to the mass flow rate of the fluid. The lip pressure method can be applied to the vertical discharge of geothermal wells and horizontal discharge into a silencer (flash drum). The horizontal discharge is more accurate; however it involves more equipment and higher cost than vertical discharge.

2.3 Separator Method

The separation of the two-phase fluid in a dedicated separator allows the measurement of the mass flow rates of saturated steam and water (brine). The enthalpies of steam and water at the separator pressure are used to calculate the total enthalpy of the two-phase fluid. The efficiency of separation that can be achieved is at least 99.9% (Grant & Bixley, 2011). This method has the highest accuracy; nevertheless, the capital cost is quite high due to the cost to provide facilities including the separator and silencer. Equipment transport costs to site also contribute to the high overall cost of this method.

2.4 Tracer Dilution Method

The total enthalpy and mass flow rate from a two-phase well can be calculated by injecting chemical tracers of known concentrations into a two-phase pipeline (Lovelock, 2001). Two types of tracers are used for the liquid and steam phases respectively. A recent study by Broaddus et al. (2010) shows that the tracer dilution method can be used for online flow rate and enthalpy measurement using a new liquid-phase tracer and an automated analysis technique. However, it is difficult to find appropriate instrumentation for chemical tracer analysis with the required sensitivity and accuracy due to limitations in current sensor technology.

3. TWO-PHASE FLOW CORRELATIONS FOR ORIFICE PLATE TECHNIQUE

The sharp-edge orifice plate is a simple, flexible and economical method to measure two-phase flow from production wells (Figure 1). Two-phase flow correlations for sharp-edge orifice plates have been developed by Murdock (1962), James (1965), Lin (1982), Zhang et al. (1992) and Helbig and Zarrouk (2012). The accuracy of the Helbig and Zarrouk (2012) correlation is higher than the other methods. However, it requires an estimated enthalpy, thus on-going validation of measurement is required in order to avoid increasing error.

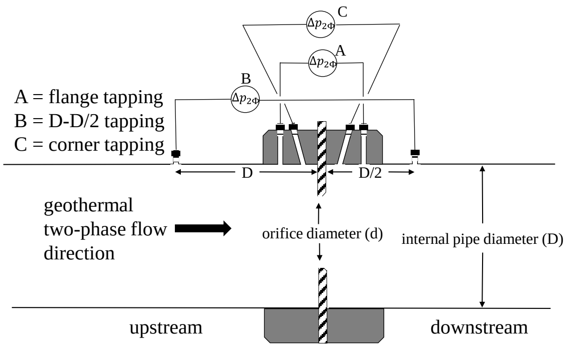

Figure 1: A simple diagram of the sharp-edge orifice plate.

The development of the five existing correlations is based on either homogenous flow and separated models. These correlations need an estimate of enthalpy, which is taken from a horizontal discharge or separator testing data (Mubarok et al., 2015). In conclusion, the five correlations of two-phase orifice plate are:

Murdock correlation

$$\dot{m}_{2\Phi} = \left[\frac{\left(\frac{F_a Y_G C_G \pi d^2}{4}\right)}{\left(\sqrt{1-\beta^4}\right)\left(x + 1.26(1-x)\left(\frac{C_G Y_G}{C_L}\right)\right)\left(\sqrt{\frac{\rho_G}{\rho_L}}\right)}\right] \sqrt{2\Delta p_{2\Phi}\rho_G}. \quad (1)$$

James correlation

$$\dot{m}_{2\Phi} = \left[\frac{\left(\frac{F_a Y_G C_G \pi d^2}{4}\right)}{\left(\sqrt{1-\beta^4}\right)\left(\sqrt{x^{1.5}\left(1-\frac{\rho_G}{\rho_L}\right)+\left(\frac{\rho_G}{\rho_L}\right)}\right)}\right]\sqrt{2\Delta p_{2\Phi}\rho_G}. \quad (2)$$

Lin correlation

$$\dot{m}_{2\Phi} = \left[\frac{\left(\frac{F_a Y_G C_G \pi d^2}{4}\right)}{\left(\sqrt{1-\beta^4}\right)\left((1-x)(\theta) + x\sqrt{\frac{\rho_L}{\rho_G}}\right)}\right]\sqrt{2\Delta p_{2\Phi}\rho_L}, \quad (3)$$

where θ is:

$$\theta = 1.48625 - \left(9.26541\left(\frac{\rho_G}{\rho_L}\right)\right) + \left(44.6954\left(\frac{\rho_G}{\rho_L}\right)^2\right) - \left(60.6150\gamma\left(\frac{\rho_G}{\rho_L}\right)^3\right) - \left(5.12966\gamma\left(\frac{\rho_G}{\rho_L}\right)^4\right) - \left(26.5743\left(\frac{\rho_G}{\rho_L}\right)^5\right), \quad (4)$$

Zhang correlation

$$\dot{m}_{2\Phi} = \left[\frac{\left(\frac{F_a\left((1-\varepsilon) + (\varepsilon Y_G)\right) C_L \pi d^2}{4} \right)}{\left(\sqrt{1-\beta^4}\right)\left(x^n \left(\frac{\rho_L}{\rho_G} - 1\right) + 1\right)} \right] \sqrt{2\Delta p_{2\Phi} \rho_L}, \tag{5}$$

The exponent of the corrected orifice dryness fraction (n) is:

$$n = 1.25 + 0.26\sqrt[3]{x}. \tag{6}$$

<u>Helbig and Zarrouk correlation</u>

$$\dot{m}_{2\Phi} = \left[\left(\frac{p_1}{11.5 \times 10^5} \right)^{\sqrt[D]{\frac{10^{-5}\Delta p_{2\Phi}}{D}}} \right] \left[\frac{\left(\frac{F_a \pi d^2}{4}\right)}{\left(\sqrt{1-\beta^4}\right)} \sqrt{2\Delta p_{2\Phi}} \right]$$

$$\left[\frac{(1 - 0.9x - 0.1x^2)\left(C_L\sqrt{\rho_L} - Y_G C_G \sqrt{\rho_G}\right)}{(1+15x)} + \left(Y_G C_G \sqrt{\rho_G}\right) \right]. \tag{7}$$

To use the correlations (1), (2), (3), (5) and (7), the orifice thermal expansion factor (F_a), compressibility coefficient of the fluid (Y_G) and orifice discharge coefficient of the fluid ($C_{L/G}$) can be calculated by:

$$F_a = 1 + \frac{2(\alpha_{OP} - \beta^4 \alpha_P)(T_F - 293.15)}{1-\beta^4}, \tag{8}$$

$$Y_G = 1 - \frac{(0.41 + 0.35\beta^4)\Delta p_{2\Phi}}{p_1 \kappa}, \tag{9}$$

$$C_{L/G} = U + V + W + X, \tag{10}$$

where β is the ratio of pipe inside diameter and orifice bore diameter. To calculate an orifice discharge coefficient ($C_{L/G}$), the equations for parameters U, V, W and X are:

$$U = 0.5961 + 0.0261\beta^2 - 0.216\beta^8, \tag{11}$$

$$V = 0.00521\left(\frac{10^6 \beta}{Re_{D,L/G}}\right)^{0.7} + \left(0.0188 + 0.0063\left(\frac{19000\beta}{Re_{D,L/G}}\right)^{0.8}\right)$$

$$\times \left(\left(\frac{10^6}{Re_{D,\frac{L}{G}}} \right)^{0.3} \beta^{3.5} \right), \tag{12}$$

$$W = (0.043 + 0.08e^{10L_1} - 0.123e^{-7L_1})$$

$$\times \left(1 - 0.11\left(\frac{19000\beta}{Re_{D,L/G}}\right)^{0.8}\right)\left(\frac{\beta^4}{1-\beta^4}\right), \tag{13}$$

$$X = -0.031\left(\frac{2L_2}{1-\beta} - 0.8\left(\frac{2L_2}{1-\beta}\right)^{1.1}\right)\beta^{1.3}. \tag{14}$$

Based on the above equations, the Reynolds number ($Re_{D,L/G}$), fluid velocity ($v_{L/G}$) and pipe cross sectional area (A_p) can be calculated using equations (15) to (17).

$$Re_{D,L/G} = \frac{\rho_{L/G} v_{L/G} D}{\mu_{L/G}}, \tag{15}$$

$$v_{L/G} = \frac{A_{OP}}{\sqrt{1-\beta^4}} \sqrt{\frac{2\Delta p_{2\Phi}}{\rho_{L/G}}} A_p^{-1}, \tag{16}$$

$$A_p = \frac{\pi d^2}{4}. \tag{17}$$

From the BS 1042: Section 1.1 (1992) standard, the coefficients for L_1 and L_2 are shown in Table 1.

Table 1: Coefficient values of L_1 and L_2 (BS 1042: Section 1.1, 1992).

Tapping type	L_1	L_2
Corner tapping	0	0
D-D/2 tapping	1	0.47
Flange tapping	0.0254/D	0.0254/D

4. MODIFICATION OF CORRELATIONS

Two-phase orifice plate data was provided by Helbig and Zarrouk (2012). The data were taken from different geothermal fields including New Zealand, Indonesia, the Philippines with additional data from the James (1965) experiment. The trend of calculated and field data (1600 field data points) for the five different correlations is shown in Figure 2.

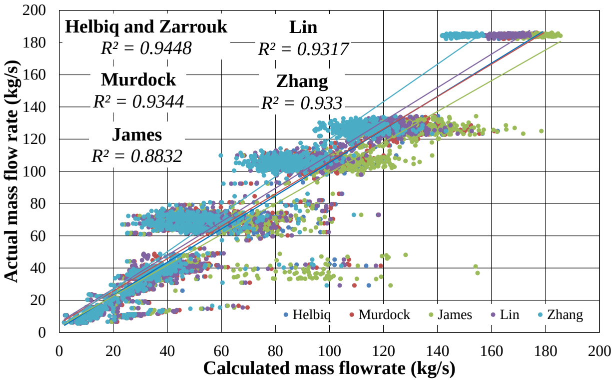

Figure 2: The trend in calculated and field data for the five correlations.

Figure 2 shows that Helbig and Zarrouk's (2012) correlation achieves the highest R^2 value, followed by the correlations of Murdock (1962), Lin (1982), Zhang et al. (1992) and James (1965). A higher R^2 represents a better match (i.e. better accuracy) of the calculated relative to the actual measured two-phase mass flow rate. Furthermore, Helbig and Zarrouk (2012) correlation is the most accurate for a wider range of steam dryness fractions than the other correlations.

In this work, a systematic approaches was used to simplify and reduce the complexity of the Helbig and Zarrouk (2012) correlation.

The first step is examining the pressure coefficient of 11.5 (bar a) as given in equation (7). Helbig and Zarrouk (2012) determined the coefficient from the p_1 versus variance graph. In this work, the same approach was used. However, the downstream pressure (p_2) was added to Figure 3.

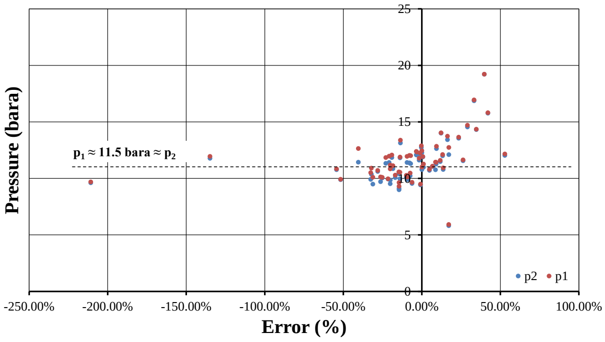

Figure 3: Upstream and downstream pressure versus the mass flow rate error (difference).

The spread for p_1 and p_2 is slightly different to the coefficient as determined by Helbig and Zarrouk (2012), therefore we substituted the coefficient 11.5 (bara) with p_2.

The second step is examining the thermal expansion factor (F_a). From the data provided, we found that the calculated F_a (from equation 8) varied from 1.00486 to 1.00808 with an average value of 1.00666, which did not significantly affect the mass flow rate result. The parameter F_a could be replaced with 1.

The last stage of modification involved simplification of the parameters x, C_L, ρ_L, Y_G, C_G and ρ_G in the Helbig and Zarrouk (2012) correlation (Table 1). All parameters are related to the enthalpy of the fluid (h) and to check the correlation between the parameters and h, the enthalpy coefficient (C_h) is used:

$$C_h = \left[\frac{(1-0.9x-0.1x^2)\left(C_L\sqrt{\rho_L}-Y_G C_G\sqrt{\rho_G}\right)}{(1+15x)} + \left(Y_G C_G\sqrt{\rho_G}\right)\right]. \quad (18)$$

A correlation graph between C_h and h is shown in Figure 4.

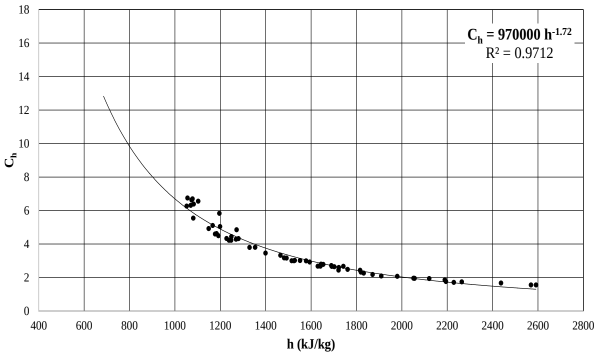

Figure 4: Correlation between C_h and h.

From Figure 4, the revised correlation for C_h is:

$$C_h = [970000h^{-1.72}] \quad (19)$$

Considering to the modifications above, the modified correlation becomes:

$$\dot{m}_{2\Phi} = \left[\left(\frac{p_1}{p_2}\right)^{D\sqrt{\frac{\Delta p_{2\Phi}}{D}}}\right]\left[\frac{\left(\frac{\pi d^2}{4}\right)\sqrt{2\Delta p_{2\Phi}}}{\left(\sqrt{1-\beta^4}\right)}\right][C_h]. \quad (20)$$

The coefficient a is used to change the first term in equation (20):

$$a = \left[\left(\frac{p_1}{p_2}\right)^{D\sqrt{\frac{\Delta p_{2\Phi}}{D}}}\right]. \quad (21)$$

If equations (17), (19) and (21) are substituted into equation (7), the final equation for calculating the orifice two-phase mass flow rate using the modified correlation is:

$$\dot{m}_{2\Phi} = \frac{aA_p\sqrt{2\Delta p_{2\Phi}}C_h}{\left(\sqrt{1-\beta^4}\right)}. \quad (22)$$

To test the modified correlation, the mass flow rate was calculated using equation (22) and then compared to the field data and Helbig and Zarrouk (2012) correlations (Figure 5 and Figure 6).

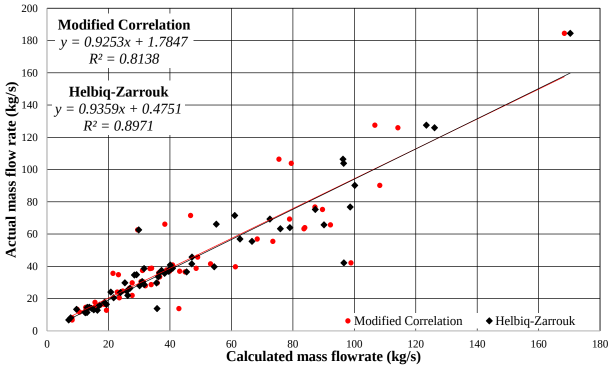

Figure 5: Modified correlation vs Helbig and Zarrouk (2012) correlation with comparison to the field data.

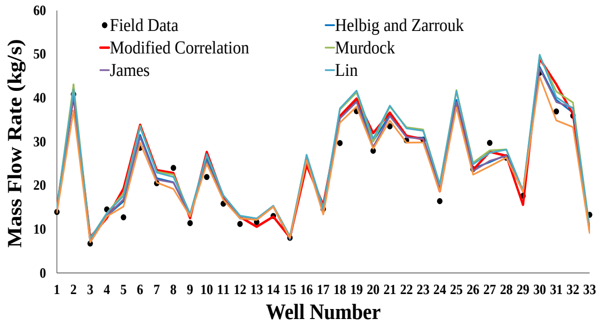

Figure 6: The comparison of six different correlations and field data from 33 Indonesian geothermal wells.

Figure 5 shows that the R^2 for the modified correlation is similar to that of the Helbig and Zarrouk (2012) correlation. In addition, the calculated mass flow rate for the modified correlation (solid red line) has a good match with the experimental data and Helbig and Zarrouk (2012) correlation (Figure 6). The error for different correlations is summarized in Table 2, which shows the performance and accuracy of each correlation.

Table 2: Summary of mean error for different correlations

Correlation	Mean Error (%)
Helbig and Zarrouk (2012)	9
Murdock (1962)	13
James (1962)	11
Lin (1982)	11
Zhang (1992)	19
Modified Correlation	9

The percentage of mean error (9%) is produced by both the modified new correlation and the Helbig and Zarrouk (2012) correlation (Table 2). This indicates that the modified correlation can be used as an alternative to calculate the two-phase mass flow rate of geothermal fluid with the same accuracy and performance as the Helbig and Zarrouk (2012) correlation. The new modified correlation is simpler to use than the previous correlations (Helbig and Zarrouk, Murdock, James, Lin and Zhang).

5. FUTURE WORK

The limitation for all the correlations discussed above is their accuracy when estimating the dryness fraction of the geothermal fluid. Currently, the dryness fraction (hence enthalpy) cannot be measured directly by the orifice plate. It can be measured using additional equipment. Future research is required to develop the capability to measure real-time mass flow rate and enthalpy simultaneously. A coupled two-phase orifice plate and load cell may provide accurate and independents measurement of both mass flow rate and enthalpy.

All the correlations discussed in this work were developed for the standard concentric sharp-edge orifice plate. New research and field testing will focus on developing two-phase flow correlations using a sharp-edge orifice plate with an eccentric hole (Figure 7). This should result in lower pressure drop across the orifice plate and less potential trapping of solids (rocks or scaling products) by the orifice plate.

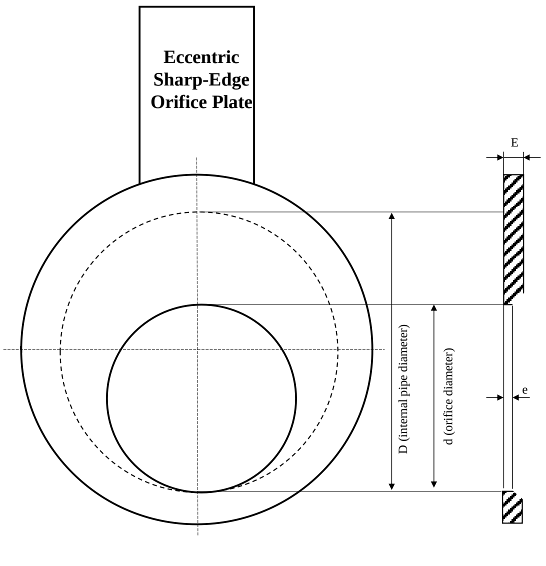

Figure 7: Schematic diagram of a sharp-edge orifice plate with an eccentric hole.

6. CONCLUSIONS

The objective of this study was to test and simplify existing two-phase orifice plate correlations to generate and cover a wide range of fluid enthalpy.

A new modified correlation was developed and calibrated using several field data sets. The modified correlation was compared with the Helbig and Zarrouk (2012) correlation, which is the most accurate to date, covering a wider range of dryness fractions than the other available four correlations (Murdock, James, Lind and Zhang). The new modified correlation is recommended for use in geothermal two-phase flow measurement.

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REFERENCES

Anklin, M., Drahm, W., & Rieder, A. (2006). Coriolis mass flowmeters: Overview of the current state of the art and latest research. *Flow Measurement and Instrumentation, 17*, 317-323.

Bixley, P., Dench, N., & Wilson, D. (1998). *Development of well testing methods at Wairakei 1950-1980*. Paper presented at the 20th Geothermal Workshop, Auckland, New Zealand.

Broaddus, M., Katz, J. I., Hirtz, P., & Kunzman, R. (2010). *Advancements in tracer flow testing: Development of real-time technology for flow and enthalpy measurement*. Paper presented at the Geothermal Resources Council, Los Angeles, CA.

BS 1042: Section 1.1. (1992). Measurement of fluid flow in closed conduits *Part 1. Pressure differential devices, Section 1.1 Specification for square-edged orifice plates, nozzles, and venturi tubes inserted in circular cross-section conduits running full*, pp. 1-62. United Kingdom: British Standard Institution.

Grant, M. A., & Bixley, P. F. (2011). *Geothermal reservoir engineering* (2nd ed.). Cambridge, UK: Elsevier.

Helbig, S., & Zarrouk, S. J. (2012). Measuring two-phase flow in geothermal pipelines using sharp edge orifice plates. *Geothermics, 44*, 52-64.

Hirtz, P. N., Kunzman, R. J., Broaddus, M. L., & Barbitta, J. A. (2001). Developments in tracer flow testing for geothermal production engineering. *Geothermics, 30*, 727-745.

James, R. (1962). Steam-water critical flow through pipes. *Proceedings of the Institution of Mechanical Engineers, 176*(26), 741-748.

James, R. (1965). Metering of steam-water two-phase flow by sharp-edged orifices. *Proceedings of the Institution of Mechanical Engineers, 180*(23), 549-572.

Lin, Z. H. (1982). Two-phase flow measurements with sharp-edged orifices. *International Journal of Multiphase Flow, 8*(6), 681-693.

Lovelock, B. G. (2001). Steam flow measurement using alcohol tracers. *Geothermics, 30*, 641-645.

Mubarok, M. H., Cahyono, Y. D., Patangke, S., & Siahaan, E. E. (2015). *A statistical analysis for comparison between lip pressure and separator in production well testing at Lahendong and Ulubelu field.* Paper presented at the World Geothermal Congress, Melbourne, Australia, 19-25 April, 2015.

Mubarok, M. H., & Zarrouk, S. J. (2016). *Steam-field design overview of the Ulubelu geothermal project, Indonesia*. Paper presented at the 38th New Zealand Geothermal Workshop, 23–25 November 2016, Auckland, New Zealand.

Murdock, J. W. (1962). Two-phase flow measurement with orifices. *Journal of Basic Engineering, 84*(4), 419-432. 10.1115/1.3658657

O'Banion, T. (2013). Coriolis: The direct approach to mass flow measurement. *Chemical Engineering Progress, 109*(3), 41–46.

Purwono, A. N. (2010). Comparison and selection of a steam gathering system Ulubelu geothermal project, Sumatra, Indonesia. In *Geothermal Training in Iceland 2010: Reports of the United Nations University Geothermal Training Programme* (pp.525–562). Reykjavík, Iceland: United Nations University.

Zhang, H. J., Lu, S. J., & Yu, G. Z. (1992). An investigation of two-phase flow measurement with orifices for low-quality mixtures. *International Journal of Multiphase Flow, 18*(1), 149-155.

Zheng, D., Zhao, D., & Mei, J. (2015). Improved numerical integration method for flowrate of ultrasonic flowmeter based on Gauss quadrature for non-ideal flow fields. *Flow Measurement and Instrumentation, 41*, 28-35.