THE GEOTHERMAL TWO-PHASE ORIFICE PLATE

Mohamad Husni Mubarok1,2,*, Sadiq J. Zarrouk3 and John E. Cater4
1 Department of Engineering Science, The University of Auckland, Private Bag 92019, Auckland, New Zealand
2 Pertamina Geothermal Energy, Jakarta, 10340, Indonesia
*mmub714@aucklanduni.ac.nz ; husnimubarok@pertamina.com

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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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cross sectional area (m²)</td>
</tr>
<tr>
<td>a</td>
<td>Pressure coefficient of modified correlation</td>
</tr>
<tr>
<td>C</td>
<td>Orifice discharge coefficient</td>
</tr>
<tr>
<td>Δh</td>
<td>Enthalpy coefficient</td>
</tr>
<tr>
<td>D</td>
<td>Inside pipe diameter (m)</td>
</tr>
<tr>
<td>d</td>
<td>Orifice diameter (m)</td>
</tr>
<tr>
<td>F_A</td>
<td>Orifice thermal expansion factor</td>
</tr>
<tr>
<td>F_C</td>
<td>Correlation factor</td>
</tr>
<tr>
<td>F_T</td>
<td>Time ratio correction factor</td>
</tr>
<tr>
<td>h</td>
<td>Enthalpy (kJ/kg)</td>
</tr>
<tr>
<td>K</td>
<td>Two-phase coefficient</td>
</tr>
<tr>
<td>K_C</td>
<td>Correction factor</td>
</tr>
<tr>
<td>m</td>
<td>Mass flow rate of the fluid (kg/s)</td>
</tr>
<tr>
<td>p</td>
<td>Pressure (Pa)</td>
</tr>
<tr>
<td>p_A</td>
<td>Pressure upstream of the orifice plate (Pa)</td>
</tr>
<tr>
<td>p_C</td>
<td>Pressure downstream of the orifice plate (Pa)</td>
</tr>
<tr>
<td>R_e_D</td>
<td>Reynolds number for inner pipe diameter</td>
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<tr>
<td>T_F</td>
<td>Fluid temperature (K)</td>
</tr>
<tr>
<td>U,V</td>
<td>Substitution factors to calculate orifice design coefficient</td>
</tr>
<tr>
<td>v</td>
<td>Fluid velocity (m/s)</td>
</tr>
<tr>
<td>W</td>
<td>Substitution factor to calculate orifice design coefficient</td>
</tr>
<tr>
<td>X,Y</td>
<td>Substitution factor to calculate orifice design coefficient</td>
</tr>
<tr>
<td>x</td>
<td>Dryness fraction of the fluid</td>
</tr>
<tr>
<td>x_m</td>
<td>Corrected orifice dryness fraction of the fluid</td>
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</tbody>
</table>

Greek letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td>α</td>
<td>Thermal expansion coefficient (m/mK)</td>
</tr>
<tr>
<td>β</td>
<td>Rate of the orifice diameter to the inside pipe diameter (β = d/D)</td>
</tr>
<tr>
<td>ε</td>
<td>Void fraction</td>
</tr>
<tr>
<td>Θ</td>
<td>Corrective coefficient</td>
</tr>
<tr>
<td>κ</td>
<td>Isentropic coefficient</td>
</tr>
<tr>
<td>μ</td>
<td>Dynamic viscosity (kg/ms)</td>
</tr>
<tr>
<td>ρ</td>
<td>Density (kg/m³)</td>
</tr>
<tr>
<td>σ</td>
<td>Time ratio coefficient</td>
</tr>
<tr>
<td>τ</td>
<td>Passing time of the liquid phase (s)</td>
</tr>
<tr>
<td>Δp</td>
<td>Differential pressure (Pa)</td>
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</table>

Subscripts

<table>
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<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>1Φ</td>
<td>Single-phase</td>
</tr>
<tr>
<td>2Φ</td>
<td>Two-phase</td>
</tr>
<tr>
<td>G</td>
<td>Gaseous/steam phase</td>
</tr>
<tr>
<td>H</td>
<td>Homogenous</td>
</tr>
<tr>
<td>L</td>
<td>Liquid phase</td>
</tr>
<tr>
<td>OP</td>
<td>Orifice plate</td>
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Superscripts

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>n</td>
<td>Exponent of the corrected orifice dryness fraction</td>
</tr>
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</table>

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.

Murdock correlation

\[ n_{2φ} = \frac{F \cdot Y \cdot C \cdot \pi \cdot d^2}{4 \left( \frac{1}{x} - \frac{\rho}{\rho_c} \right)} \sqrt{2 \cdot \Delta p_{2φ} \rho_c} \]  

James correlation

\[ n_{2φ} = \frac{F \cdot Y \cdot C \cdot \pi \cdot d^2}{4 \left( \frac{1}{x} - \frac{\rho}{\rho_c} \right) \left[ 1 - x \cdot \frac{\rho_c}{\rho} - \frac{\rho_c}{\rho} \right]} \sqrt{2 \cdot \Delta p_{2φ} \rho_c} \]  

Lin correlation

\[ n_{2φ} = \frac{F \cdot Y \cdot C \cdot \pi \cdot d^2}{4 \left( \frac{1}{x} - \frac{\rho}{\rho_c} \right) \left[ 1 - \frac{\rho_c}{\rho} \right] \left[ 1 - x \cdot \frac{\rho_c}{\rho} \right]} \sqrt{2 \cdot \Delta p_{2φ} \rho_c} \]  

where \( \theta \) is:

\[ \theta = 1.48625 - \left( 9.26541 \left( \frac{\rho_c}{\rho} \right)^3 \right) + \left( 44.6954 \left( \frac{\rho_c}{\rho} \right)^3 \right) \\
- \left( 6.06150 \left( \frac{\rho_c}{\rho} \right)^3 \right) - \left( 5.12966 \left( \frac{\rho_c}{\rho} \right)^3 \right) \\
- 26.5743 \left( \frac{\rho_c}{\rho} \right)^3 \]  

Zhang correlation

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:

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\[
\dot{m}_{2b} = \left[ \frac{F_p ((1 - \varepsilon) + (s Y_C)) C_s \pi d^2}{4} \right] \sqrt{\Delta p_{2b} \rho_L} \left( \frac{1}{\sqrt{1 - \beta^2}} \right)^n \left( \frac{(1 - 0.9x - 0.1x^2)}{(1 + 15x)} \right) (C_{L/G} p_1 - Y_C C_{G/L} p_2) + (Y_C C_{G/L} p_2) \right],
\]

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

\[n = 1.25 + 0.26 \sqrt{\varepsilon}.\]

Helbig and Zarrouk correlation

\[
\dot{m}_{2b} = \left[ \frac{P_1}{115 \times 10^6} \left( \frac{1}{\sqrt{1 - \beta^2}} \right)^n \left( \frac{(1 - 0.9x - 0.1x^2)}{(1 + 15x)} \right) \left( C_{L/G} p_1 - Y_C C_{G/L} p_2 \right) \right] \left( \frac{1}{\sqrt{1 - \beta^2}} \right)^n \left( \frac{(1 - 0.9x - 0.1x^2)}{(1 + 15x)} \right) (C_{L/G} p_1 - Y_C C_{G/L} p_2) + (Y_C C_{G/L} p_2) \right].
\]

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

\[F_p = 1 + \frac{2 (\rho_\varepsilon - \beta^4 \rho_g)}{1 - \beta^4},\]

\[Y_C = 1 - \frac{(0.41 + 0.35 \beta^6) \Delta p_{2b}}{p_L^K},\]

\[C_{L/G} = U + V + W + X,\]

where \(\beta\) 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:

\[U = 0.5961 + 0.0261 \beta^2 - 0.2169 \beta^4,\]

\[V = 0.00521 \left( \frac{10^6}{R_{D_{L/G}}} \right)^{0.7} + 0.0188 + 0.0063 \left( \frac{19000 \beta^6}{R_{D_{L/G}}} \right)^{0.8},\]

\[\times \left( \frac{10^6}{R_{D_{L/G}}} \right)^{0.3} \beta^{3.5},\]

\[W = 0.043 + 0.086 e^{10x} - 0.123 e^{-7x},\]

\[\times \left( 1 - 0.11 \left( \frac{19000 \beta^6}{R_{D_{L/G}}} \right)^{0.8} \right) \left( \frac{\beta^4}{1 - \beta^4} \right),\]

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

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).

<table>
<thead>
<tr>
<th>Tapping type</th>
<th>(L_1)</th>
<th>(L_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corner tapping</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>D/D2 tapping</td>
<td>1</td>
<td>0.47</td>
</tr>
<tr>
<td>Flange tapping</td>
<td>0.0254/D</td>
<td>0.0254/D</td>
</tr>
</tbody>
</table>

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 and 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 approach 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.
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 ($E_a$). From the data provided, we found that the calculated $E_a$ (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 $E_a$ could be replaced with 1.

The last stage of modification involved simplification of the parameters $x$, $C_a$, $p_1$, $Y_C$, $C_T$, and $p_2$ 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:

$$C_h = \left[\frac{1 - 0.9x - 0.1x^2}{(1 + 15x)}\right] \left(C_e\sqrt{\frac{p_1}{p_0}} - Y_C\sqrt{\frac{p_0}{p_2}} + (Y_C\sqrt{\frac{p_0}{p_2}})\right).$$

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

$$C_h = 970000 \text{ h}^{-1.72}$$

From Figure 4, the revised correlation for $C_h$ is:

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

Considering the modifications above, the modified correlation becomes:

$$m_{2\phi} = \left(\frac{p_1}{p_2}\right)^{0.5\frac{\Delta h_{2\phi}}{h_{2\phi}}} \left[\frac{\left(m\frac{\Delta h_{2\phi}}{h_{2\phi}}\right)^2}{2\beta^2} \left(\frac{\Delta h_{2\phi}}{h_{2\phi}}\right) C_h\right].$$

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

$$a = \left(\frac{p_1}{p_2}\right)^{0.5\frac{\Delta h_{2\phi}}{h_{2\phi}}}.$$

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:

$$m_{2\phi} = a\frac{\Delta h_{2\phi}}{h_{2\phi}} \left(\frac{\Delta h_{2\phi}}{h_{2\phi}}\right) C_h$$

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).
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


