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Pressure Differential Devices for Measuring Total Mass Flow Rate and Enthalpy in Two-phase Geothermal Pipelines

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ABSTRACT

Mass flow rate and enthalpy are critical parameters that need to be measured on a real-time basis during production from two-phase geothermal systems as well output can significantly change with time, due to a host of reservoir and wellbore events. Existing field measuring techniques are not capable of accurately determining in real-time the enthalpy and mass flow rate from individual geothermal wells in production without using wellhead separators. A new method for the real-time measurement of both enthalpy and mass flow rate using pressure differential devices (such as orifice plates, nozzles and Venturi meters) has been developed using data from multiple geothermal fields in Indonesia and New Zealand. This measurement technique can be applied cost-effectively with high accuracy (1-2%) and repeatability for a wide range of geothermal two-phase flow conditions. Furthermore, the new technique can be coupled with other enthalpy measurement devices including the micro-lip pressure testing techniques.

1. INTRODUCTION

Measurement of geothermal fluid output from geothermal wells is mandatory in the geothermal industry for day-to-day field management, and required by law for meeting resource consent obligations. 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 in real time.

Most 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, University, & Programme, 2010). Consequently, the monitoring of mass flow rate and enthalpy from each production well is difficult because two-phase pipelines from production wells are connected directly to other wells to deliver the geothermal fluid to a central separator. Thus, the mass flow rate and enthalpy in the central separator is the total from several wells.

There are four established two-phase flow measurement techniques used by the geothermal industry: total flow calorimeters (Bixley, Dench, & Wilson, 1998); the lip pressure method (James, 1962; Mubarok, Cahyono, Patangke, & Siahaan, 2015); the separator method (Grant & Bixley, 2011; Mubarok et al., 2015) and tracer flow testing (Broaddus, Katz, Hirtz, & Kunzman, 2010; Lovelock, 2001). Several other methods have been investigated by different authors over the years, including an ultrasonic meter (Liu, Wang, Cui, & Wang, 2015; Zheng, Zhao, & Mei, 2015), Coriolis flow meter (Anklin, Drahm, & Rieder, 2006; O'Banion, 2013), radio frequency (Sisler & Zarrouk, 2015), resistivity meter (Spielman, 2003) and compression load cells (Sisler et al., 2016). Nevertheless, none of these methods have moved to mainstream industrial use due to an inability to measure both real-time mass flow rate and enthalpy, the complexity of installation, high cost, and unproven accuracy. However, pressure differential devices have been widely used since the 1980's for measuring single-phase flow rate can be also used to measure mass flow rate from two-phase wells with relatively low accuracy.

A correlation for measuring two-phase fluid from a geothermal well has been developed by Helbig and Zarrouk (2012) using a separated flow model combining empirical and phenomenological approaches. However, the Helbig and Zarrouk (2012) correlation is relatively complex and requires several empirical parameters. A new correlation from Mubarok et al. (2019) was developed to increase the measurement accuracy with 1% mean relative error. The Mubarok et al. (2019) correlation introduces enthalpy (h) which is more appropriate for the geothermal applications and allows other enthalpy measurement devices to work together as a coupled measurement technique.

In this work, the results of extensive geothermal field testing of pressure differential devices both in New Zealand and Indonesia were used to develop a novel two-phase flow measurement technique. This implementation allows the real-time measurement of both mass flow rate and enthalpy at low cost in geothermal pipelines with high accuracy and reliability.

2. PRESSURE DIFFERENTIAL PRESSURE DEVICES

The most commonly used fluid flow measurement device is a differential flow meter, due to several advantages: they are simple, inexpensive, have a wide range of capacity, easy maintenance and high accuracy (Upp & LaNasa, 2002). Differential flow meters consist of two elements; a primary and a secondary element. The primary element is installed in the flow path to increase the velocity and restrict the fluid flow producing a pressure difference between upstream and downstream of the restriction. The secondary element is the instrumentation to measure required fluid flow variables, such as pressure and temperature. Both primary and secondary elements are usually installed into the differential flow meter unit. In general, there are seven types of differential flow meter, including orifice plates, Venturi tubes, nozzles, Venturi nozzles, low-loss devices (e.g. Dall tubes), inlet flow meters (e.g. Borda inlets) and cone meters (Reader-Harris, Wolfgang Merkirch Germany, Donald Rockwell USA, & Cameron Tropea Germany, 2015).

The physical principle of differential pressure flow meter uses mass and energy conservation for fluid flow through a pipeline. The pressure difference from the flow meter is used to determine the fluid flow rate by application of Bernoulli's theorem (Reader-Harris et al., 2015). A typical restriction of the compressible flow by the primary element in the pipeline is shown in Figure 1.

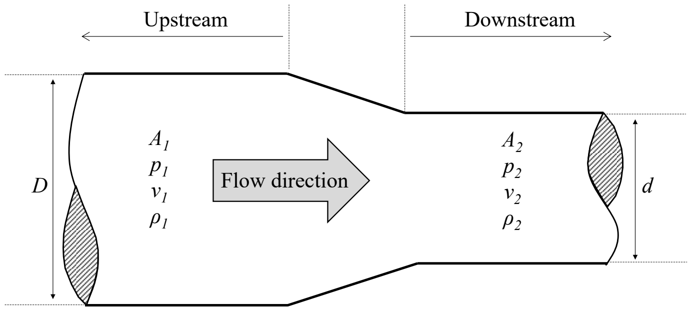

Figure 1: Typical of pipe section with primary element as fluid flow restriction of the pressure differential flow meters.

Energy (Equation 1) and mass conservation (Equation 2) can be expressed as:

$$\frac{1}{2}\rho_1 v_1^2 + p_1 = \frac{1}{2}\rho_2 v_2^2 + p_2, \tag{1}$$

$$\dot{m} = \rho_1 v_1 A_1 = \rho_2 v_2 A_2, \tag{2}$$

where $\dot{m}$ is the mass flow rate (kg/s), ρ_1 is the upstream fluid density (kg/m^3), v_1 is the upstream fluid velocity (m/s), p_1 is the upstream pressure (Pa), A_1 is the upstream cross sectional area (m^2), ρ_2 is the downstream fluid density (kg/m^3), v_2 is the downstream fluid velocity (m/s), p_2 is the downstream pressure (Pa) and A_2 is the downstream cross sectional area (m^2). The relationship between cross sectional area (A) and the diameter ratio ($\beta = d/D$) can be defined as:

$$\frac{A_2}{A_1} = \left(\frac{d}{D}\right)^2 = \beta^2. \tag{3}$$

From the substitution of equations (1-3) with pressure differential ($\Delta p = p_1 - p_2$), the expansion factor (ε) and the coefficient that relates the flow rate to the theoretical mass flow rate through a device called the discharge coefficient (C), the equation for mass flow rate becomes:

$$\dot{m} = \frac{C\varepsilon}{\sqrt{1-\beta^4}}\frac{\pi d^2}{4}\sqrt{2\rho\Delta p}. \tag{4}$$

The value of the expansion factor is unity ($\varepsilon = 1$) for incompressible flow. For compressible flow, the expansion factor (ε) can be expressed as:

$$\varepsilon = \sqrt{\left(\frac{\kappa\tau^{\frac{2}{\kappa}}}{\kappa-1}\right)\left(\frac{1-\beta^4}{1-\beta^4\tau^{\frac{2}{\kappa}}}\right)\left(\frac{1-\tau^{\frac{\kappa-1}{\kappa}}}{1-\tau}\right)}, \tag{5}$$

where κ is the isentropic exponent and τ is the pressure ratio ($\tau = {p_2}/{p_1}$).

The discharge coefficient (C) depends on the type of pressure differential flow meter (BS, 1997). The Venturi discharge coefficient (C) value is 0.984 for a Venturi tube with an "as cast" convergent section, 0.995 for Venturi tube with a machined convergent section and 0.985 for Venturi tube with a rough-welded sheet-iron convergent section. The orifice (Equation 7) and nozzle (Equation 8) discharge coefficients (C) are (BS, 1997):

$$C = [0.5961 + 0.0261\beta^2 - 0.216\beta^8] + \left[0.00521\left(\frac{10^6\beta}{Re_D}\right)^{0.7}\right] + \left[0.0188 + 0.0063\left(\frac{19000\beta}{Re_D}\right)^{0.8}\left(\frac{10^6}{Re_D}\right)^{0.3}\beta^{3.5}\right]$$
$$+\left[(0.043 + 0.08e^{10L_1} - 0.123e^{-7L_1})\left(1 - 0.11\left(\frac{19000\beta}{Re_D}\right)^{0.8}\right)\left(\frac{\beta^4}{1-\beta^4}\right)\right] - \left[0.031\left(\frac{2L_2}{1-\beta} - 0.8\left(\frac{2L_2}{1-\beta}\right)^{1.1}\right)\beta^{1.3}\right], \tag{7}$$

$$C = 0.9965 - 0.00653\sqrt{\beta}\sqrt{\frac{10^6}{Re_D}}, \tag{8}$$

where Re_D is the Reynolds number. The Reynolds number (Re_D) is a function of fluid density (ρ), velocity (v), dynamic viscosity (μ) and internal pipe diameter (D):

$$Re_D = \frac{\rho v D}{\mu}. \tag{9}$$

In this work, six types of pressure differential flow meters for measuring the mass flow rate and enthalpy of geothermal two-phase fluid are considered and discussed; a sharp-edge concentric orifice, sharp-edge top eccentric orifice, sharp-edge bottom eccentric orifice, segmental orifice, nozzle and Venturi as shown in Figure 2. These pressure differential flow meters have been selected by considering the initial and running costs, installation flexibility and the manufacturing complexity for geothermal applications.

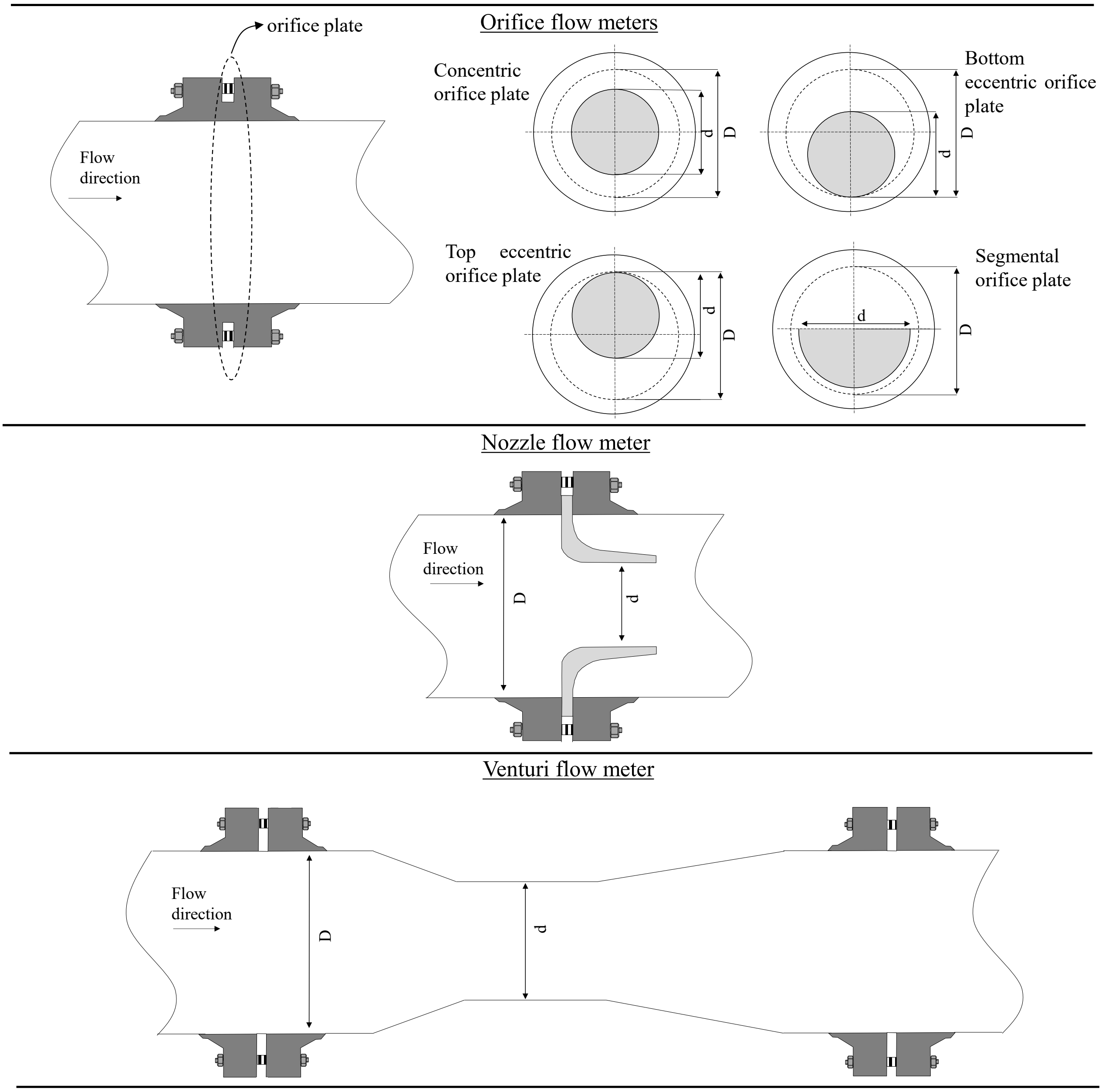

Figure 2: Pressure differential pressure devices type used for measuring mass flow rate and enthalpy.

3. NEW TECHNIQUE FOR MEASURING REAL-TIME MASS FLOW RATE AND ENTHALPY

Since 2007 research and field implementations of two-phase differential pressure devices (orifice plate, Venturi tube and nozzle) have focused on measuring both mass flow rate and enthalpy of the geothermal fluids in large diameter (8”, 10”, 12”, 14” and 20”) geothermal pipelines in real-time (Mubarok et al., 2019; Zarrouk et al., 2019).

Real-time measurement of both h and $\dot{m}$ for all production wells gives the field operator up-to-date knowledge of the available power output of all geothermal wells. It also allows prompt response when problems occur in any well (thermal breakthrough, Casing damage, scale build-up etc.). The data is also very valuable when building numerical reservoir models and history matching well performance accurately.

The flow meter operating principle is similar to other differential pressure flow meter (Reader-Harris et al., 2015). However, multiple pressure tappings are installed in this new flow meter. When the two-phase fluid approaches the multiple tapping flow meter, it will have pressure upstream (p_1). The fluid velocity increases at the constricted area of the primary element of flow meter, the pressure downstream will drop to p_2. The difference between p_1 and p_2 is known as differential pressure (Δp) and it is measured using differential pressure transducers (Upp & LaNasa, 2002). The values of Δp from multiple tappings are correlated and are used to calculate the real-time of enthalpy and mass flow rate. The differential pressure signal is measured by a differential pressure transmitter from the primary element. The signal from transmitter is then processed and interpreted in the computing device to define an initial dryness and enthalpy coefficient; the enthalpy coefficient is constant for one set of measurements. The enthalpy coefficient and real-time differential pressure data are used to calculate the predicted enthalpy and mass flow rate simultaneously. The process is summarised in a flow chart shown in Figure 3.

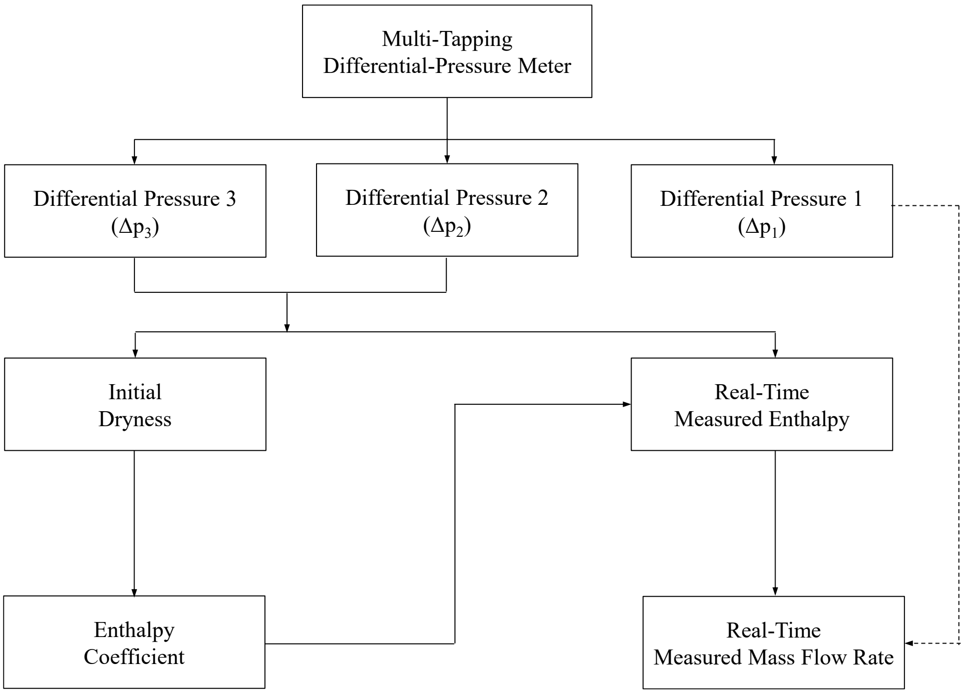

Figure 3: Flowchart of process for measuring real-time geothermal two-phase mass flow rate and enthalpy using differential pressure devices.

The measured enthalpy (h) is determined from the second and the third pressure differences ($\Delta p_2, \Delta p_3$), while the mass flow rate ($\dot{m}$) is calculated using h and the first pressure difference (Δp_1) (Mubarok et al., 2019). In mathematical notation, h and $\dot{m}$ can be written as:

$$h = f(\Delta p_2, \Delta p_3), \tag{10}$$

$$\dot{m} = [9.7 \times 10^5 \times \ (h)^{-1.72}] \left[\left(\frac{p_1}{p_2} \right)^{D\sqrt{\frac{\Delta p}{D}}} \right] \left[\frac{\left(\frac{\pi d^2}{4} \right) \sqrt{2\Delta p_1}}{\left(\sqrt{1-\beta^4} \right)} \right]. \tag{11}$$

4. RESULTS AND DISCUSSION

Fieldwork has been carried out in a several wells in different geothermal fields in Indonesia and New Zealand. The differential pressure flow meter was installed in a two-phase pipeline of a geothermal well and tested during operation conditions. The flow meter has been tested in wide range of nominal pipe size (NPS), h and $\dot{m}$. In the validation process, the field testing results were compared to h and $\dot{m}$ data from production testing. The installation of differential pressure flow meters (orifice type) on the two-phase pipeline with NPS 20 inch of well 1 (Wairakei, New Zealand) and 12 inch of well 2 (Ulubelu, Indonesia) are shown in Figure 4.

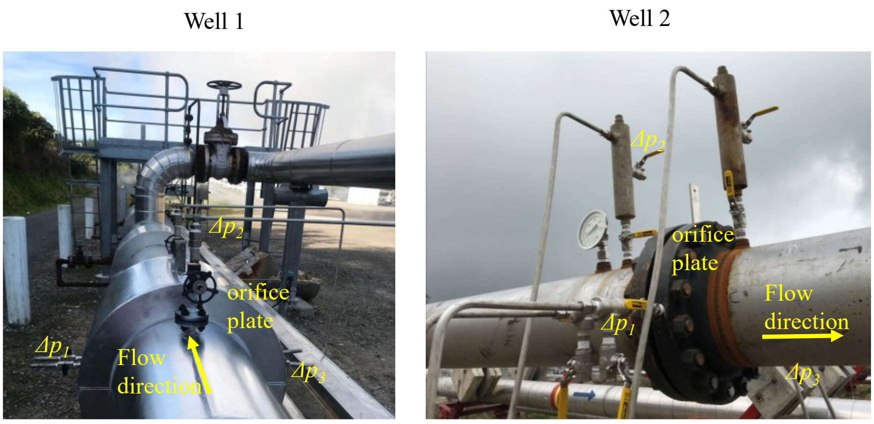

Figure 4: Two-phase orifice differential pressure flow meter installation at well 1 and well 2 (Pictures by the author).

Figure 5 shows some results of field testing in two different geothermal fields, with accurate real time measurement of both the two-phase mass flow rate and enthalpy are compared to field test data using horizontal discharge method. The horizontal discharge facility and measurement device position in a field testing is shown in Figure 6. From Figure 5, both measured h and $\dot{m}$ which are calculated using Equation (10 and (12) have a good match to the field data with relative error is 0.09% for h and 1.28% for $\dot{m}$. The value for h is helpful to achieve the good match for the measured $\dot{m}$ even for the well with large fluctuations, as seen for well 2 because h is one of the parameters for measuring $\dot{m}$ in Equation (11).

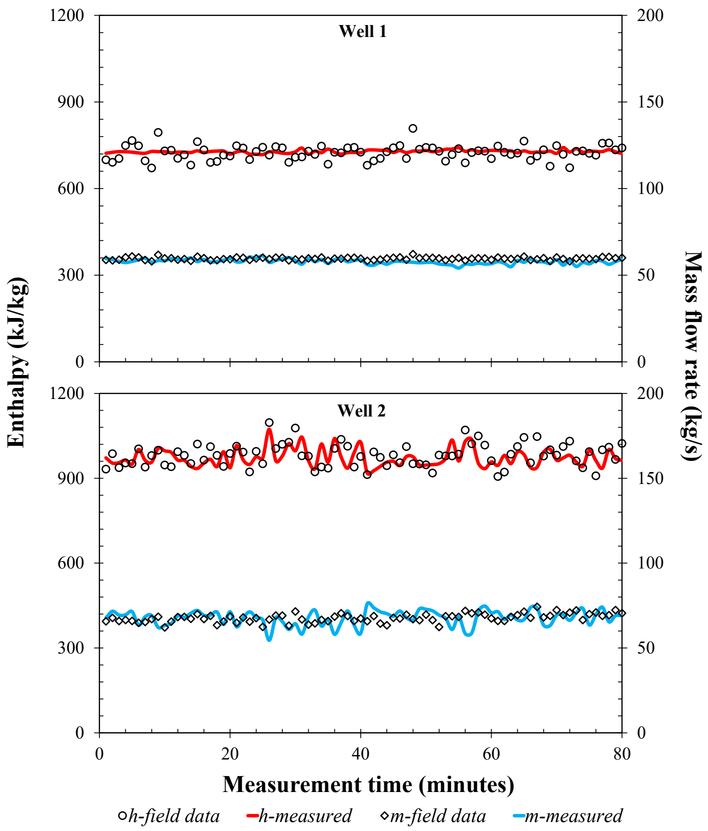

Figure 5: Real time measurement of total mass flow rate and enthalpy from two wells in different geothermal fields, New Zealand (well 1) and Indonesia (well 2).

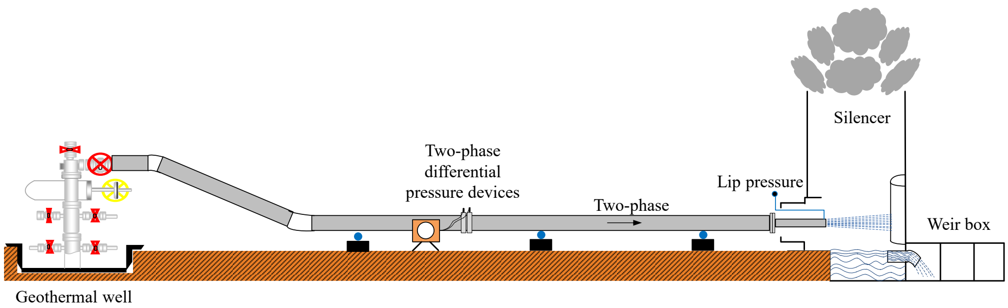

Figure 6: Schematic diagram of horizontal lip pressure facility.

Table 1 gives a summary of the comparison between existing two-phase flow measurement techniques used in the geothermal industry and the two-phase differential pressure devices. The data demonstrates that the two-phase differential pressure is providing real time accurate measurement of mass flow rate and enthalpy while the well is in production. From the field testing result, it is shown that a new technique for two-phase flow measurement using a multi-tapping differential flow meter has good accuracy and can be implemented successfully for measuring real-time geothermal two-phase enthalpy and mass flow rate.

Table 1. Comparison of geothermal two-phase flow mass flow rate and enthalpy measurement methods.

Method	Measurement		Enthalpy error (kJ/kg)	Mass flow rate relative error (%)
	Online	Real-time		
Total flow calorimeter	No	No	10-30	3-5
Lip pressure	No	Yes	20-50	4-8
Separator	Yes	Yes	10-30	3-5
Tracer dilution	Yes	No	20-50	7-10
Differential pressure	Yes	Yes	10-20	1-2

5. CONCLUSIONS

Geothermal two-phase flow measurement technique using pressure differential flow meter are presented with field testing data at geothermal wells in Indonesia and New Zealand. New advancement in the implementation of pressure differential techniques offer accurate real-time measurement of enthalpy and mass flow rate while the well is online. This new technology will help the geothermal industries to get a real-time monitor of well capacity and performance during production at low cost.

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NOMENCLATURE

A	Cross-sectional area (m^2)	*Greek letters*	
C	Discharge coefficient	β	Ratio of the orifice diameter to the inside pipe diameter ($\beta = d/D$)
D	Inside pipe diameter (m)	Δ	Differential
d	Pressure differential device diameter (m)	ε	Expansion factor
h	Enthalpy (kJ/kg)	μ	Dynamic viscosity (kg/m.s)
$\dot{m}$	The total mass flow rate of the fluid (kg/s)	ρ	Density (kg/m^3)
NPS	Nominal pipe size	τ	Pressure ratio ($\tau = {}^{p_2}/_{p_1}$)
p	Pressure (Pa)	*Subscripts*	
p_1	Pressure upstream of the device (Pa)	1	Upstream
p_2	Pressure downstream of the device (Pa)	2	Downstream
Re_D	Reynolds number using inner pipe diameter		
v	Velocity (m/s)		

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. *Proceedings 20th Geothermal Workshop*. Auckland, New Zealand: Geothermal International Association.

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. *Geothermal Resources Council*. USA: GRC Transactions.

BS. (1997). Measurement of fluid flow by means of pressure differential devices. *Part 1: Orifice Plates, Nozzles and Venturi Tubes Inserted in Circular Cross-Section Conduits Running Full*. United Kingdom: British Standard Institute.

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

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

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

Liu, J.-N., Wang, B.-X., Cui, Y.-Y., & Wang, H.-Y. (2015). Ultrasonic tomographic velocimeter for visualization of axial flow fields in pipes. *Flow Measurement and Instrumentation*, *41*, 57–66.

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. In *World Geothermal Congress* (pp. 1–7). Melbourne, Australia: International Geothermal Association.

Mubarok, M. H., & Zarrouk, S. J. (2016). Steam-field design overview of the Ulubelu geothermal project, Indonesia. In *New Zealand Geothermal Workshop*. Auckland, New Zealand: Geothermal International Association.

Mubarok, M. H., Zarrouk, S. J., & Cater, J. E. (2019). Two-phase flow measurement of geothermal fluid using orifice plate: Field testing and CFD validation. *Renewable Energy*, *134*, 927–946.

O'Banion, T. (2013). Coriolis: The direct approach to mass flow measurement. *American Institute of Chemical Engineers*. USA: AIChE.

Purwono, A. N., University, U. N., & Programme, G. T. (2010). *Comparison and selection of a steam gathering system Ulubelu geothermal project, Sumatera, Indonesia* (Vol. 26). Reykjavík. Iceland: United Nations University.

Reader-Harris, M., Wolfgang Merkirch Germany, B., Donald Rockwell USA, B., & Cameron Tropea Germany, D. (2015). Orifice plates and venturi tubes. Springer New York, USA.

Sisler, J. R., & Zarrouk, S. J. (2015). Measurement of two phase flows in geothermal pipelines using radio frequency (RF) power measurements: Experimental results. In *Proceedings 37th New Zealand Geothermal Worksop* (pp. 1–7). Taupo, New Zealand: International Geothermal Association.

Sisler, J. R., Zarrouk, S. J., Urgel, A., Lim, Y. W., Adams, R., & Martin, S. (2016). Measurement of two phase flows in geothermal pipelines using load-cells: Field trial results. In *Proceedings 41st Workshop on Geothermal Reservoir Engineering* (pp. 1–10). California, USA: Stanford University.

Spielman, P. (2003). Continuous enthalpy measurement of two-phase flow from a geothermal well. *Geothermal Resources Council*. USA.

Upp, E. L., & LaNasa, P. J. (2002). *Fluid flow measurement: A practical guide to accurate flow measurement* (Second). Woburn, US: Gulf Professional Publishing.

Zarrouk, S. J., Mubarok, M. H., & Cater, J. E. (2019). The Geothermal Two-Phase Orifice. In *ULUSAL TESISAT MHENDISLIGI KONGRESI, Izmir, Turkey*.

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.