PRESSURE DROP IN LARGE DIAMETER GEOTHERMAL TWO-PHASE PIPELINES

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Keywords: *Geothermal, two phase flow, pressure drop correlations, Harrison-Freeston, Homogenous, Friedel.*

ABSTRACT

Most conventional geothermal wells produce two-phase flow of water, steam and gas at the well head. This fluid normally travels at the surface in the geothermal fluid transmission system toward the separator where steam and water are separated. Early transmission system used short runs of small diameter pipelines to avoid the slug flow regime, which caused significant problems of increased pressure drop and water hammer effects to the pipelines. However, significant work was been dedicated over the years to develop and use empirical, theoretical and phenomenological correlations to calculate pressure drop in the two-phase pipelines. However, most of these correlations were developed from work on relatively small diameter pipelines. As most of the new geothermal development uses large diameter pipelines carrying fluid from several wells to centralized separation stations, problems have been encountered in many fields.

This work evaluates some of the existing correlations for estimating pressure drop in two-phase geothermal pipelines applied to field data from the Lahendong geothermal field, Indonesia. Actual two-phase pressure drop data were measured from a range of horizontal pipes (10-22“) to be compared with the existing correlations. The result shows that the annular flow is the most common flow regime in the pipelines. Generally, Friedel’s correlation is the best suited for large diameter (>18“) pipelines, with 5–15% average deviation. The homogenous and Harrison-Freeston methods better suit smaller pipe sizes (10”–18”), with an average deviation of 5–28%. The Lockhart-Martinelli, Zhao-Freeston and Brill-Mukherjee correlations were found to be less accurate in predicting the two-phase pressure drop in the same range of pipe sizes. Based on the results, a correction factors chart is proposed to reduce discrepancies in the estimated pressure drops for the given range of pipe sizes.

1. INTRODUCTION

Most conventional geothermal wells produce a two-phase flow of water, steam and gas at the well head. This fluid normally travels at the surface in the geothermal fluid transmission system towards the separator or flash plant where steam and water are separated. The pipeline network should be designed considering two-phase flow behaviour and the pressure drop in the system. This subject has been intensely studied over the years with many correlations proposed to calculate (predict) the two-phase pressure drop in pipelines. However, most of these correlations resulted from experimental work using relatively small-sized pipes (4“–5“) that are largely inapplicable to modern geothermal fluid transmission systems (Freeston, 1987).

Two-phase pressure drop predictions have been made using empirical, theoretical and phenomenological correlations. However, there is still no agreed method that can satisfactorily calculate the pressure drop in all two-phase conditions.

This paper will present the analyses of two-phase flow conditions from the geothermal fluid transmission lines of Units 1 & 2 of the Lahendong geothermal field in Indonesia. Field data were used to make pressure drop predictions using six existing correlations/methods; Harrison-Freeston Method (Freeston & Lee, 1979), Homogenous Method (Wolverine Tube Inc., 2006), Lockhart-Martinelli Method (Lockhart & Martinelli, 1949), Friedel Method (Friedel, 1979), Zhao-Freeston Method (2000), and Brill-Mukherjee Method (Mukherjee & Brill, 1985). The results are presented and compared with actual pressure drop measurements for a range of pipe sizes (10“–22”) to find out which correlations best suits such conditions.

1.1 Two-phase flow regimes

There are many types of flow patterns/regimes that can occur in two-phase flow, depending on the flow parameters that include pipe diameter, flow rate and velocity. For flow regime analysis, several flow pattern maps have been proposed. *Mandhane et al., 1974* evaluated existing flow pattern maps for two-phase flow in horizontal pipes against many flow pattern observations contained in the multiphase pipe flow data bank (Figure1).

Madhane’s Flow Pattern Map (Figure 1) is an improvement on previous maps because the effect of pipe diameter is taken into account by using the superficial gas and liquid velocities (V_{SG} and V_{SL}) as the coordinate axes.

The superficial velocitie are required to determine the flow regime. Therefore, the superficial liquid velocities are:

$$V_{SL} = \frac{\dot{m}_l(1-x)}{\rho_l \times A} \tag{1}$$

$$V_{SG} = \frac{\dot{m}_g(1-x)}{\rho_g \times A} \tag{2}$$

where V_{SL} is the superficial liquid velocity (m/s), V_{SG} is the superficial gas velocity (m/s), $\dot{m}_l$ is the liquid mass flow rate, $\dot{m}_g$ is the steam mass flow rate, ρ_l is the liquid density, ρ_g is the steam density, A is the pipe cross sectional area, and x is the steam dryness.

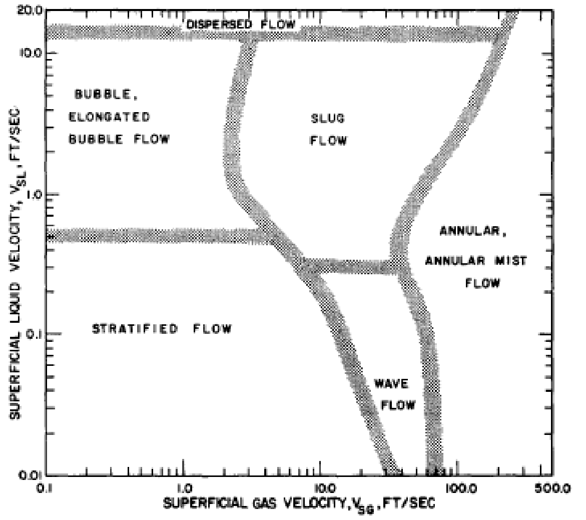

Figure 1: Madhane's Flow Pattern Map (from Mandhane, et al., 1974).

Figure 1 shows that the major patterns that can occur in two-phase conditions. The characteristics of horizontal two-phase flow regimes can be described in Figure 2.

1.1.1. Bubble Flow

Occurs at very low gas/liquid ratios where the gas forms bubbles at that the top of the pipe. However, when shear forces are dominant, uniform distribution of bubbles might occur in the pipe.

1.1.2. Plug Flow

This flow regime has liquid plugs that are separated by elongated gas bubbles. Bullet shape bubbles occur, but they tend to move along in a position closer to the top of the tube.

1.1.3. Stratified Flow

The gas and liquid phases flow separately one on top of the other at low gas and liquid velocity. The liquid flows along the bottom of the pipe while the gas flows in the top section of the pipe.

1.1.4. Wavy Flow

Increased gas velocity in stratified flow creates wave on the interface in the flow direction. The amplitude of the wave depends on the relative velocity (slip ratio) but it normally does not touch the upper side of the pipe wall.

1.1.5. Slug Flow

Large amplitude wave or splashes of liquid occasionally pass through the upper side of the pipe when there is a high gas velocity than the average liquid velocity. Slug flow can cause sudden pressure pulses and vibrations in the pipelines.

1.1.6. Annular Flow

The liquid phase forms a continuous film around the inside wall of the pipe and the gas flows in the central core with higher velocity. Due to effect of gravity, usually the liquid film is thicker at the bottom of the pipe in horizontal flows.

Geothermal transmission pipelines can be very long and equipped with many components, fittings, valves and instruments. Thus the flow regime might change due to disturbances along the pipe. In addition, the production parameters, flow rate and enthalpy from the wells might change with time and affect the flow regime transition.

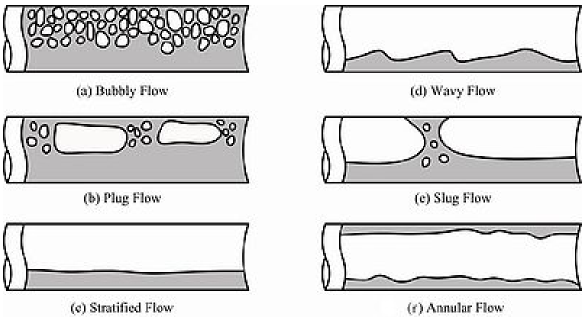

Figure 2: Flow Regimes in Horizontal Two-Phase Flow (Hewitt, 1998).

At certain points, the flow regime transition can create unfavorable flow conditions when a slug of water travels at the high velocity of the gas stream. Slug flow should be avoided in the fluid transmission lines since it negatively impacts both the equipment and pipeline integrity. Slug flow may cause fatigue that can reduce pipe strength and cause severe damage in pipe support structures. Two-phase pipelines should be designed for annular flow regime conditions to minimize the possibility of encountering slug flow (Freeston & Lee, 1979).

2. TWO-PHASE PRESSURE DROP EVALUATION

A set of experimental data was collected from Units 1 & 2 of the Lahendong geothermal field in Indonesia for pressure drop predictions in the transmission pipelines. The transmission lines consist of a range of pipe sizes from 10” to 22” in diameter. Six existing pressure drop estimation methods (Harrison-Freeston, Homogenous, Lockhart-Martinelli, Friedel, Zhao-Freeston Method (Zhao et al, , and Brill-Mukherjee) were compared with the actual field data. Figure 3 shows the simplified Pipe Flow Diagram (PFD) of the transmission line data was taken from.

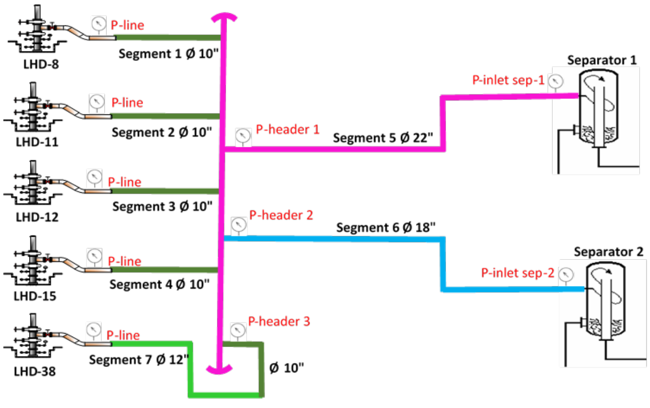

Figure 3: Simplified PFD of Lahendong Units 1 & 2 Transmission Line.

There are five production wells in the production cluster which produce two-phase fluid to the flash plant (separators 1 and 2). Well LHD-38 (Figure 3) is a new well that was introduced in the system for production make-up purposes. In this work, the pressure drop in the transmission pipelines was calculated before and after the new well was introduced to the system. This is to get a feel of how the production parameter changes have affected the flow regimes and the pressure drop. The calculations also consider the effect of valves and fittings, which should be taken into account in two-phase pressure drop predictions.

The actual pressure drop of the pipeline segments (Figure 3) in the two-phase transmission lines is shown in Table 1, while the flow regime changes can be seen in Figures 4–6 below.

Table 1: Actual Pressure Drop Measurements.

Segment	Actual Pressure Drop (bar)	
	Before Additional Well	After Additional Well
1	0.20	0.30
2	0.60	0.40
3	5.10	4.60
4	1.70	1.00
5	1.40	2.25
6	1.80	1.70
7	N/A	1.40

The calculation results show that annular flow is the most common flow regime in the pipelines. This means the pipeline is suitable enough to flow the water and steam. However, the production parameters changed due to the introduction of the new make-up well. This is when the flow regime changed slightly to wave flow in some segments. The flow regime changes can be observed in the flow pattern map below (Figure 4). Pink dots are the flow regimes before the introduction of the new make-up well in the system, while the green dots are the flow regimes after the inclusion of the new well.

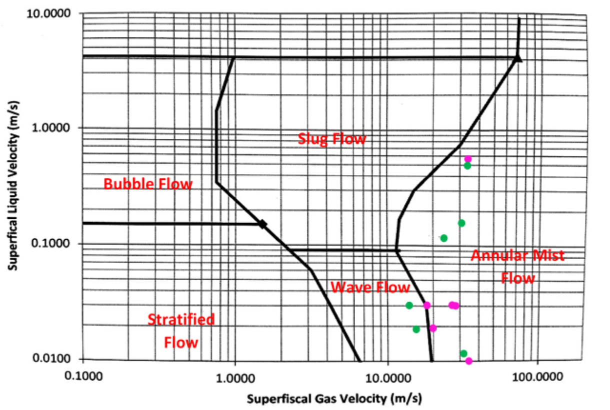

Figure 4: Flow Regime Changes Due to the Inclusion of Make-up Well.

The results also show the discrepancies in pressure drop prediction between the different correlations. Generally the existing models do not match the actual pressure drop measurement and show fairly high deviation (>30%).

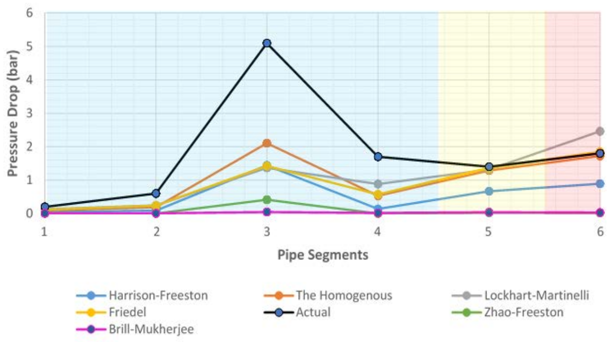

Figure 5: Pressure Drop Calculation before the Additional Well.

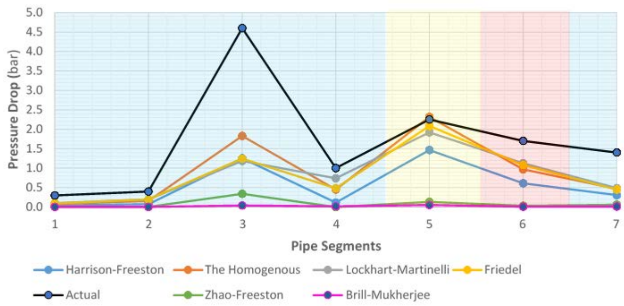

Figure 6: Pressure Drop Calculation after the Additional Well

Nevertheless based on the observation of the matches, it seems that the Friedel method predicts two-phase pressure drop in 18” and 22” diameter pipes better than methods. On the other hand, the Homogenous method seems suitable for all pipe sizes (10”–22” diameter), though the deviation is still high.

3. ANALYSIS AND DISCUSSION

The results trend from 6 existing methods shows similar trend to the actual pressure drop in each segment, however some results show larger deviation compared to the actual data. For most of the data, the pressure drop correlations showed poor performance, with a deviation index of >30%, although all correlations were in good agreement with the data on which they were developed. This may be due to the fact that some parameters was determined experimentally under controlled labratory conditions, making the correlations more or less empirical, while the field data used in this work was based on measurement under dynamic operational conditions.

The performance of all correlations generally improved as the percentage error index was relaxed. But no correlation predicted all the data accurately within the ±15% deviation band. Instead, results show that for the dataset given some correlations are better suited to specific flows and certain pipe diameters. This indicates that each correlation is suitable for specific range of application. Although the dataset could not be predicted well by a single correlation, some correlations predicted better than others.

The high error in the two-phase pressure drop predictions might be caused by the pipe surface roughness data, which was not well defined. The existing pipes had been in operation for few years, hence the surface roughness might be significantly changed from the initial condition due to mineral deposition (scaling) and internal corrosion. Furthermore, the change in surface roughness will eventually increase the friction factor of the flow in the pipelines and ultimately increase the actual pressure drop.

In addition, the existing two-phase pressure drop correlations account for the pipe surface roughness using single-phase pressure drop calculations. This would mean that the accuracy of single-phase friction factor correlation that is used for the two-phase pressure drop calculation has to be investigated further so that the pipe surface roughness can be better accounted for in a wider range of flow conditions.

Based on the results, correction factors are proposed for each correlation to reduce the discrepancy in the estimated two-phase pressure drop for the given range of pipe sizes (Table 2). The correction factor is essentially the multipliers or a corrected friction factor in the existing correlations. The values were obtained by optimization as a procedure to obtain the smallest average calculation errors.

A correction factor chart can then be derived from these results to be used in predicting two-phase pressure drop for the range of pipe sizes given (10"–22" diameter). It is important to note that the correction factors presented here might not solve the problems for every flow condition. The charts should be used for particular pipe conditions that have undergone changes in the surface roughness parameter. The correction factors in the existing correlations and the correction factor chart are shown in Table 2 and Figure 7, respectively.

Table 2: Correction Factors for Two-Phase Pressure Drop Prediction

Methods / Models	Initial Correlation	Correction factor
Harrison-Freeston	$\Delta P_{TP} = f\frac{L}{D}\frac{\rho_{TP} \times v_{TP}^2}{2}$	$\Delta P_{TP} = cf\frac{L}{D}\frac{\rho_{TP} \times v_{TP}^2}{2}$
The Homogenous	$\tau_l = \frac{f \times \rho_l \times v_l^2}{8}$	$\tau_l = c\frac{f \times \rho_l \times v_l^2}{8}$
Lockhart & Martinelli	$\frac{dP}{dx_l} = \frac{f \times \rho_l \times v_{sl}^2}{2D}$ $\frac{dP}{dx_g} = \frac{f \times \rho_g \times v_{sg}^2}{2D}$	$\frac{dP}{dx_l} = c\frac{f \times \rho_l \times v_{sl}^2}{2D}$ $\frac{dP}{dx_g} = c\frac{f \times \rho_g \times v_{sg}^2}{2D}$
Friedel	$\frac{dP}{dx_{TP}} = 2f_{lo} \times (\frac{m}{A})^2\frac{\phi_l^2}{\rho_l \times D}$	$\frac{dP}{dx_{TP}} = c \times f_{lo} \times (\frac{m}{A})^2\frac{\phi_l^2}{\rho_l \times D}$
Brill-Mukherjee	$\frac{dP}{dx} = \frac{f \times \rho_M \times v_M^2}{2D}$	$\frac{dP}{dx} = c\frac{f \times \rho_M \times v_M^2}{2D}$
Zhao-Freeston	$\frac{dP}{dx_{friction}} = \frac{f \times \rho_L \times v_L^2}{2D}$	$\frac{dP}{dx_{friction}} = c\frac{f \times \rho_L \times v_L^2}{2D}$

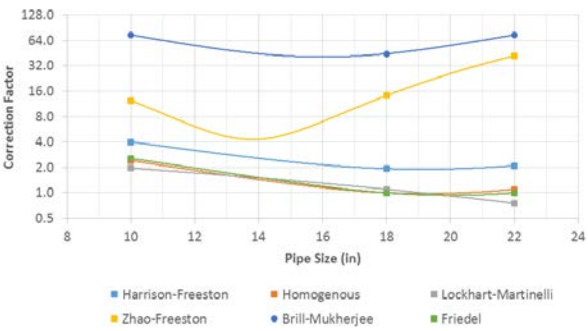

Figure 7: Correction factor chart for two-phase pressure drop predictions.

Table 3: Correction Factor Functions

Method	Correction Factor Function
Harrison-Freeston	$y = 0.0251 X^2 - 0.9617 X + 11.106$
The Homogenous	$y = 0.0167 X^2 - 0.6417 X + 7.15$
Lockhart & Martinelli	$y = 0.0017 X^2 - 0.1542 X + 3.335$
Zhao-Freeston	$y = 0.5625 X^2 - 15.525 X + 111.4$
Brill-Mukherjee	$y = 0.9375 X^2 - 30 X + 280.75$
Friedel	$y = 0.0161 X^2 - 0.6458 X + 7.3938$

These calculation results show better predictions of the two-phase pressure drop compared to the uncorrected calculations. The average deviation ranges between 5% and 30% (Table 4). We can still see that some correlations predict better for certain pipe sizes. Friedel's and the Harrison-Freeston correlations are best suited for large diameter (>18") pipelines with 5–16% average deviation. The Homogenous method is better suited to smaller pipe sizes (10"–18") with an average deviation of 5–15%. The Lockhart-Martinelli, Zhao-Freeston and Brill-Mukherjee correlations are found to be less accurate in predicting the two-phase pressure-drop in the current range of pipe diameters. A comparison of the results from all correlations can be seen in Figures 8 and 9 below.

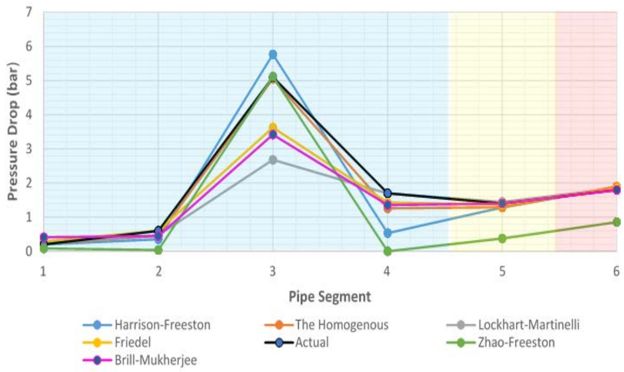

Figure 8: Pressure Drop Calculation with Correction Factor (before Additional Well).

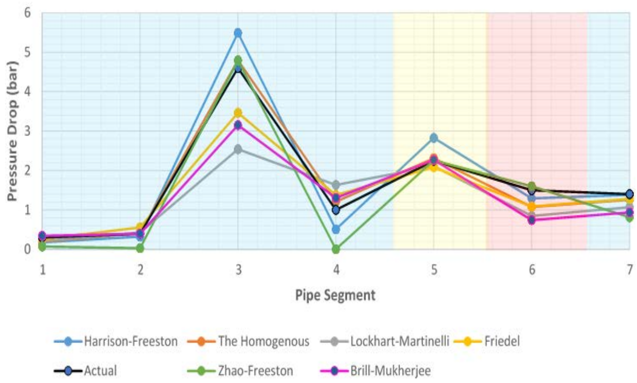

Figure 9: Pressure Drop Calculation with Correction Factor (after Additional Well).

Table 4 gives the average deviation of the different two-phase pressure drop calculation methods for both before and after the addition of the make-up well by considering correction factor in the calculation.

Table 4: Average Deviation of Two-Phase Pressure Drop Prediction

Methods	Average Error (%)		
	D = 10"	D = 18"	D = 22"
Harrison-Freeston	28.34	16.83	8.95
Homogenous	15.03	5.40	16.88
Lockhart & Martinelli	28.21	4.83	23.02
Zhao-Freeston	62.63	36.73	29.59
Brill-Mukherjee	34.15	0.43	25.30
Friedel	23.68	4.70	15.09

4. CONCLUSION

A comparison of six two-phase pressure drop correlations was made against actual field pressure drop data collected from two-phase fluid transmission lines in the Lahendong geothermal field, Indonesia. The performance of each dataset was determined using a deviation percentage. The results of this work can be summarized as follows:

- Comparison of two-phase pressure drop calculations using six existing correlations with actual pressure drop data revealed that the existing correlations had a high (>30%) deviation compared to the actual field data.
- Correction factors were used in the two-phase pressure drop calculations for pipe diameters of 10”–22” which accounts for the deviation in the estimation of the surface roughness of the pipes.
- Friedel’s and the Harrison-Freeston correlations are best suited for large diameter (>18“) pipelines, with an average deviation of 5–16%.
- The Homogenous methods better suited smaller pipe sizes (10”–18”), with an average deviation of 5–15%.
- The Lockhart-Martinelli, Zhao-Freeston and Brill-Mukherjee correlations were found to be less accurate in predicting the two-phase pressure drop in all pipe sizes. These correlations were inconsistent in predicting the two-phase pressure drop in both small- and large-diameter pipelines.

ACKNOWLEDGEMENTS

The authors would like to thank the New Zealand Government for the NZAID Scholarship and PT Pertamina Geothermal Energy (PGE) for the support to this research and the permission to publish this paper.

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