VERTICALLY UPWARD TWO PHASE FLOW IN AN ANNULUS

T.S.TORRENS[1] AND K.C.LEE[2]

[1]DesignPower New Zealand Ltd, Wellington, NZ

[2]Geothermal Institute, The University of Auckland, Auckland, NZ

SUMMARY - This paper describes an experimental study of pressure drop in vertically upward two phase flow in an annulus. An experimental rig was designed and built to measure pressure drop and observe flow regime for air water mixtures in a vertical 48.3 x 74.0 mm annulus. Measured pressure drop is compared to that predicted by the correlations of Duns & Ros (1963), Hagedorn & Brown (1965), Orkiszewski (1967), *Aziz* et al. (1972). Beggs & Brill (1973) and Caetano et al. (1992a,b). These correlations are also applied to the experimental results of Gaither et al. (1963) who measured pressure drop for water gas mixtures through a 1" x 2" (25 x 50 mm) annulus inside a 1000 ft (305m) deep test well.

1. INTRODUCTION

The annulus is one of the less common types of conduit which has been largely neglected in two phase flow research. Focus has been, and still is, strongly directed towards two phase flow in pipes. Indeed there are still significant problems to be resolved for two phase pipe flow, perhaps one of the reasons why interest in other conduit geometry has been neglected.

The principal aim of this study is to investigate methods which can be used to predict pressure gradient for vertically upward two phase flow in an annulus. The qualifier 'vertically upward' is necessary as the fluid mechanics of two phase flow changes considerable with inclination. Applications in the geothennal industry for this research can be found in aerated drilling and wells with calcite inhibitor pipes.

In liquid dominated geothermal reservoirs the use of aerated water or aerated mud drilling fluids has had some considerable success. The basic objective behind the use of aerated fluids is the better control of well bottom pressures while drilling. Bottom hole pressure depends on the weight or density of the drilling fluid above the drill bit. This can be controlled in aerated drilling by variation of the air-liquid ratio, giving a range of specific gravities from 0.05 to 1.1. Thus bottom hole pressures can be made to roughly balance reservoir pressures, avoiding excessive in-flows of reservoir fluid or outflows of drilling fluid.

Selection of the right air-liquid ratio to ensure that fonnation and well pressure are balanced relies on accurate prediction of down hole pressures (Russel, 1987). Downhole pressures are usually evaluated by calculating the pressure drop in the drill string-hole annulus, requiring a suitable correlation to predict pressure drop in vertically upward two phase flow in an annulus.

Calcite scaling in geothermal well bores is a persistent problem in a number of geothennal fields world wide. Calcite deposits on the walls of a well bore above the flash point depth, where the geothermal brine begins to flash as it flows up the well bore. The scaling causes a significant reduction in cross sectional area, leading to a decline in the well output. One way to overcome this is to inject a solution of calcite inhibitor down through a weighted tube inserted to below the depth of the flash point in the well. Calcite scaling is avoided and production remains steady. To gauge the effect of the calcite inhibitor tube on the wellbore flow requires a knowledge of two phase flow in vertical annuli.

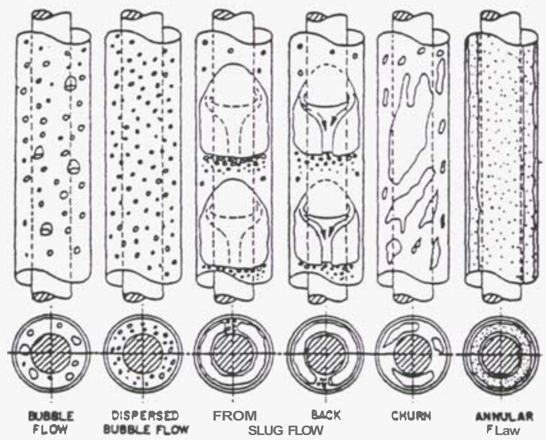

Figure 1.1- Flow Regimes for Upward Vertical Two Phase Flow in an Annulus (From Caetano et al., 1992a)

Methods used to predict pressure gradient in vertical two phase flow (regardless of the type of conduit) can generally be classified as either an empirical correlation or mechanistic model. Empirical Correlations usually consist of correlations for liquid holdup and friction factor. These two parameters are used to evaluate the elevation and friction components of the total pressure gradient respectively. Liquid holdup is defined as the fraction of conduit cross-sectional area occupied by the liquid phase. It is used to account for slippage between the two phases when calculating mixture density (and hence elevation pressure gradient).

Some empirical correlations may also consider flow regime. Flow regimes are the basic, geometrically distinct, shapes that the gas-liquid interface may assume. Flow regime depends on fluid properties, flow rates and conduit geometry. The set of flow regimes that exist for vertical two phase flow in an annulus are shown in Figure 1.1. Empirical correlations that are flow regime dependent will use different sets of liquid holdup and friction factor correlations for each flow regime. Flow regime is found by applying a series of empirically defined flow regime transition criteria.

Empirical correlations tend to over simplify the complex processes involved in two phase flow. The accuracy with which they can predict pressure gradient is therefore inherently limited. Brill (1987) suggests that over a wide range of conditions empirical correlations typically predict pressure gradient to within +/- 20%.

Mechanistic modelling has become increasingly important within the past decade. Mechanistic modelling attempts to improve pressure gradient predictions by closely considering the basic mechanisms and phenomena of two phase flow. It is a mixture of conservation equations (mass, momentum), observation and empirical correlations for such detail as bubble rise velocity and interfacial friction factor. A comprehensive mechanistic model (which can predict pressure gradient for any given set of conditions) must have models for pressure gradient for each flow regime and flow regime transition criteria.

Apart from a few outdated empirical correlations (for example Baxendell, 1958) Caetano et al. (1992b) is the only work that presents models to predict pressure gradient specifically for vertical two phase flow in an annulus. Using a mechanistic approach, Caetano et al. (1992b) have developed models for the bubble, dispersed bubble, slug and annular flow regimes. Sanchez (1972) and to a limited extent Langlineas et al. (1985) have examined the use of correlations developed for vertical two phase flow in pipes to predict pressure gradient in vertical annuli. The hydraulic diameter was used with varying degrees of success to adapt correlations to the annular geometry. Neither investigators considered any mechanistic type models.

2. EXPERIMENTAL EQUIPMENT

A laboratory rig was designed and built to measure pressure gradient and observe flow regime for air-water mixtures in a vertical annulus. Data from the rig was used as a basis to compare the various pressure gradient prediction methods considered. The rig was installed in the Aerodynamics & Fluid Mechanics Lab, Engineering School, University of Auckland.

The laboratory rig is shown in Figure 2.1. Air was supplied to the rig by a 15 kW Roots Blower, with a maximum discharge of 0.25 kg/s and maximum back pressure of 42 kPa. Water was supplied by a 0.55 kW centrifugal pump with a maximum flow rate of 180 l/min at 220 kPa. The air flow rate was measured using an orifice plate while the water flow rate was measured using two rotameters. The air and water were mixed before entering the annular test section.

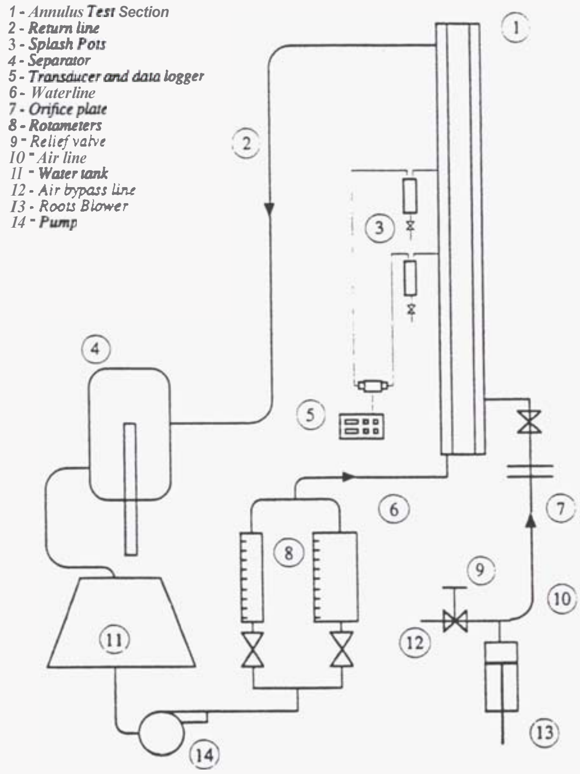

Figure 2.1- Schematic of Laboratory Test Rig

The annular test section was 6 m tall. The outer tube was made of 74.0 mm internal diameter transparent polycarbonate pipe and the inner tube was made up of 48.3 mm external diameter µPVC pressure pipe. To ensure that the inner pipe was concentric with respect to the outer pipe, four sets of three 2 mm diameter threaded steel rods were used as spacers, screwed into the inner tube. To measure pressure drop two pressure tapping points, 1.623 m (65 hydraulic diameters) apart, were inserted into the outer tube of the annulus. The upstream pressure tapping was located 2.220 m (86 hydraulic diameters) from the entry to the test section. Each pressure tapping was connected to a splash pot which separated the air and water. The air was then used to transmit the test section pressure to a pressure transducer. The pressure drop was recorded by a data logger every 2 seconds and averaged over 40 minutes to eliminate pressure fluctuations. Test section static pressure was measured from the upstream pressure tapping using a mercury manometer. Test section temperature was estimated by measuring the temperature of the water discharge from the separator using a mercury thermometer.

On exit from the test section the mixture flowed down through a return line to a Weber (inverted) separator. The separator discharged the air to atmosphere and the water was returned to a water storage tank.

3. PRESSURE GRADIENT CORRELATIONS CONSIDERED

The following correlations were selected to analyse the pressure gradient data collected from the laboratory rig;

- Duns & Ros (1963)
- Hagedorn & Brown (1965)
- Orkiszewski (1967)
- *Aziz* et al. (1972)
- Beggs & Brill (1973)
- Caetano et al. (1992b)

These correlations are reviewed as they have been implemented in the study by Torrens (1993). The first five correlations are in the main empirical, and have been developed for vertical two phase flow in pipes. The correlations of Duns & Ros (1963), Orkiszewski (1967) and *Aziz* at el. (1972) are flow regime dependent. All correlations, except Hagedorn & Brown (1965) are based on experiments from small scale laboratory rigs. The Hagedorn & Brown correlation was based on pressure drop data measured from small diameter tubing installed in a 1500 ft. (457 m) test well.

The Duns & Ros (1967) correlation is a modified form of the Ros (1961) correlation. Ros (1961) suggested modification to his conelation if it were to be applied to an annulus. The effect of these modifications on the Duns & Ros (1963) correlations are also considered.

Modifications to adapt the first five correlations above to the annular geometry were kept to a minimum. They included the following;

- Where appropriate the pipe diameter was replaced by the hydraulic diameter. As usual the actual flow area was used to calculate superficial velocities, not the area based on the hydraulic diameter.
- Acceleration was ignored for all correlations, regardless of observed or predicted flow regime.
- Where a single phase friction factor was required the smooth wall correlation of Caetano et al. (1992a) was used. This was developed specifically for turbulent flow in annuli.

As discussed above the Caetano et al. (1992a,b) correlation is a set of mechanistic models, developed specifically for two phase flow in vertical annuli. The experimental pressure gradient for those tests observed to be in churn flow was compared to the predictions from the slug flow model. Likewise the experimental pressure gradient for those tests observed to be in annular flow was compared to the predictions from the annular flow model. In comparison to the other correlations both of the Caetano et al. (1992b) models are significantly more complex.

4. STATISTICAL PARAMETERS

The error E between the predicted and experimental pressure gradient is defined as;

$$E = \left(\frac{dp}{dz}\right)_p - \left(\frac{dp}{dz}\right)_e \qquad (4.1)$$

where $(dp/dz)_p$ and $(dp/dz)_e$ are the predicted and experimental pressure gradient respectively. The average absolute error (ABS) and average relative error (ARE) are defined respectively as;

$$ABS = \sum_1^N \frac{|E|}{N} \qquad (4.2)$$

$$ARE = \sum_1^N \frac{E}{N} \qquad (4.3)$$

where N is the number of tests. The standard deviation (SD) of the absolute error is;

$$SD = \sqrt{\frac{\sum_1^N \left(|E| - AAE\right)^2}{N-1}} \qquad (4.4)$$

5. RESULTS & DISCUSSION

Using the laboratory rig described in Section 2.0 pressure gradient, flow rates, test section pressure and test section temperature, were measured for 89 tests. Of these tests 46 were observed to be in annular flow and 37 were observed to be in chum flow. The experimental results are presented in detail in Torrens (1993). The range of the various test parameters is shown in Table 5.1.

Table 5.1 - Range of Test Parameters

Parameter	Maximum	Minimum
Superficial Gas Velocity (m/s)	34.77	3.28
Superficial Liquid Velocity (m/s)	0.419	0.067
Pressure (kPa)	120.8	107.7
Temperature (°C)	27.2	18.0
Pressure Gradient (Pa/m)	4219	1083

The experimental pressure gradient was compared to that predicted using the correlations described in Section 3.0. A statistical analysis of this comparison for all 89 tests is shown in Table 5.2. The Caetano et al. (1992b) slug flow and annular flow models are not included as they were only analysed for those tests observed to be in churn flow or annular flow respectively. For the flow regime dependent empirical correlations the pressure gradient was evaluated based on the predicted flow regime, not the observed flow regime. The Duns & Ros (1963) correlation was the best overall correlation in terms of accuracy and consistency. However it is closely followed by the correlation of Beggs & Brill (1973). Needless to say the modifications to the

Duns & Ros (1963) correlation by Ros (1961) were of little effect.

The performance of the Aziz et al. (1972) and Orkiszewski (1967) correlations are far from satisfactory. Obviously the hydraulic diameter is not a suitable equivalent pipe diameter when calculating pressure gradient using the Orkiszewski method.

Table 5.2- Overall Performance of Pressure Gradient Correlations (89 Tests)

Correlation	% ARE	% ABS	% SD
Duns & Ros	4.06	14.19	10.78
Duns & Ros (Mod. by Ros)	5.31	14.54	11.38
Beggs & Brill	3.88	14.14	12.55
Hagedorn & Brown	10.47	18.93	13.60
Aziz et al.	-6.10	34.45	25.62
Orkiszewski	93.29	95.41	60.79

If annular flow is predicted the Aziz et al. (1972) correlation uses the Duns & Ross (1963) annular flow pressure gradient correlation. The Aziz et al. (1972) correlation predicts annular flow for much lower superficial gas velocities than the Duns & Ros (1963) correlation. It was found at these lower superficial gas velocities the Duns & Ros annular flow pressure gradient correlation was not very satisfactory. This, of course, lead to the poor performance of the Aziz et al. (1972) correlation.

5.1 Analysis of Test Observed to be in Churn Flow

A statistical analysis comparing predicted and experimental pressure gradients for those tests observed to be in churn flow is shown in Table 5.3. Again the Duns & Ros (1963) model performs the best. Caetano et al. (1992b) did not specifically develop a model for chum flow but the tests were analysed using the slug flow model. The model predicted pressure gradient reasonably well. However the performance with respect to the other auxiliary parameters predicted by the model was on the whole unrealistic. For example Taylor bubble length was predicted to be significantly larger than the total length of the test section, which is clearly unrealistic.

Currently there are no known mechanistic models for predicting pressure gradient in chum flow (for any type of conduit). For the purposes of predicting pressure gradient chum flow may be treated as a part of slug flow (as was done in this study) or as a transition zone between slug flow and annular flow. If the latter option is followed chum flow pressure gradient is calculated by averaging the pressure gradients calculated for the Same conditions, assuming slug flow and annular flow. Weighting factors may also be applied which depend on how far conditions are away from slug flow or annular flow. This method cannot be applied using the Caetano et al. (1992b) set of mechanistic models for two reasons. Firstly no slug-chum transition criteria has been developed for flow in annuli. Secondly the Caetano et al. (1992b) annular flow model will not converge to a solution for gas flow rates much below the chum-annular transition.

Table 5.3- Performance of Pressure Gradient Correlations - Churn Flow Observed (37 Tests)

Correlation	% ARE	% ABS	% SD
Duns & Ros	4.70	10.68	10.00
Duns & Ros (Mod. by Ros)	7.21	11.19	11.46
Beggs & Brill	-11.10	12.07	12.03
Caetano et al. (Slug Flow Model	-8.03	19.62	15.37
Hagedorn & Brown	23.90	24.36	16.59
Aziz et al.	28.11	36.14	34.91
Orkiszewski	109.35	109.35	70.15

5.2 Analysis of Test Observed to be in Annular Flow

Table 5.4 shows a statistical analysis comparing predicted and experimental pressure gradients for those tests observed to be in annular flow. The Caetano et al. (1992b) annular flow model is clearly the best overall correlation. The Hagedorn & Brown (1965) correlation also performs well. While the results in Tables 5.3 and 5.4 cannot be strictly compared on a statistical basis it is interesting to note that the correlations perform quite differently with respect to flows observed to be in churn or annular flow. This even applies to the non-flow regime dependent models of Hagedom & Brown (1965) and Beggs & Brill (1973).

Table 5.4- Performance of Pressure Gradient Correlations - Annular Flow Observed (46 Tests)

Correlation	% ARE	%ABS	%SD
Caetano et al. (Slug Flow Model	10.64	12.68	9.05
Hagedorn & Brown	-1.49	14.50	9.09
Duns & Ros	2.21	17.00	11.07
Beggs & Brill	16.65	17.01	12.98
Duns & Ros (Mod. by Ros)	2.51	17.17	11.18
Aziz et al.	-28.90	32.07	16.94
Orkiszewski	77.26	81.36	52.75

6. ANALYSIS OF THE GAITHER et al. (1963) RESULTS

Gaither et al. (1963) presented pressure drop data for water-gas mixtures through a 1" x 2" (25 x 50 mm) annulus inside a 1000 ft. (305 m) deep test well. Conditions for the Gaither et al. (1963) experiments come closer to approximating those in the field (particularly with respect to aerated drilling) than the preceding laboratory experiments. Superficial velocities in the well annulus were slightly lower than those in the laboratory rig and the flow regime ranged from slug to annular as predicted by the Caetano et al. (1992a) correlation. The measured pressure drop was compared to that predicted by the same correlations used to analyse the laboratory experiments. However this time acceleration and wall roughness were taken into account. The set of flow regime transition criteria and pressure gradient models of Caetano et al. (1992a,b) were integrated into a comprehensive model to predict pressure gradient for all conditions.

Using conventional well simulator technique, well annulus pressure drop was evaluated taking into account variation of fluid properties with depth. In brief the well was divided into a number of length intervals. The pressure gradient was then progressively calculated for each interval at the average interval temperature and pressure. Integrating the pressure gradient over each length interval gave the well annulus pressure drop. Note that the well annulus was made from two tubing strings. Pressure losses from the couplings on the inner tubing string were also estimated. Further details of the analysis of the Gaither et al. (1963) experiments are given in Torrens (1993).

The overall statistical results of the analysis are presented in Table 6.1. The Beggs & Brill (1973) correlation performed the best, followed closely by Caetano et al. (1992a,b). As with the analysis of the laboratory results the Orkiszewski correlation performed the worst by some considerable margin. For some of the tests analysed the error for this correlation was in excess of 80%.

Table 6.1- Performance of Pressure Gradient Correlations - Gaither et al. (1963) Results

Correlation	%ARE	%ABS	%SD
Beggs & Brill	3.35	10.48	7.03
Caetano et al. (Slug Flow Model	-1.41	13.58	8.95
Hagedorn & Brown	13.38	15.72	8.55
Duns & Ros (Mod. by Ros)	-15.94	16.08	7.11
Aziz et al.	-15.05	16.80	14.07
Duns & Ros	-17.36	17.36	7.01
Orkiszewski	20.17	34.35	25.60

7. CONCLUSIONS

With respect to predicting pressure gradient in vertically upward two phase flow in an annulus;

1. The Duns & Ros (1963), Hagedorn & Brown (1965) and Beggs & Brill (1973) empirical correlations are satisfactory. The best empirical correlation with respect to the laboratory experiments was that of Duns & Ros (1963). The best empirical correlation with respect to the Gaither et al. (1963) experiments was that of Beggs & Brill (1973).

2. The Orkiszewski (1967) and Aziz et al. (1972) correlations are unsatisfactory and should be used with caution.

3. For the' laboratory experiments the Caetano et al. (1992b) annular flow mechanistic model was the best correlation for those tests observed to be in annular flow. The slug flow model as applied to those tests observed to be in churn flow only performed moderately well. For the Gaither et al. (1963) experiments an integrated version of the Caetano et al. (1992a,b) set of models was the second best performing correlation.

   Overall the Caetano et al. (1992a,b) correlation performs well though at the expense of a significant increase in complexity.

The above comments apply to water-gas mixtures at both low and moderate pressure over the churn and annular flow regimes.

8. REFERENCES

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