11th Australasian Fluid Mechanics Conference
University of Tasmania, Hobart, Australia
14-18 December 1992

EFFECTS OF PIPE DIAMETER ON PRESSURE DROP CALCULATIONS IN HORIZONTAL TWO-PHASE FLOW

C.H. NEWTON, M. BHARDWAJ and M. BEHNIA

School of Mechanical and Manufacturing Engineering
University of New South Wales
PO Box 1, Kensington, NSW 2033, AUSTRALIA

ABSTRACT

Several common pressure drop correlations are tested to determine the effect of the pipe diameter on the accuracy of their predictions in horizontal two-phase flow. Experiments have been performed using two different small size pipe diameters for a range of air and water flow rates. Existing data from the literature has also been included in the calculations. The data set included some 506 data points and it was observed that the average error in Lockhart-Martinelli predictions were lowest. There was a significant ordering of the pressure drop data with respect to both Reynolds and Froude numbers for each diameter.

NOTATION

D = Diameter
g = Gravitational Acceleration
L = Length
ΔP = Measured Pressure Drop
V_{SG}, V_{SL} = Superficial Gas and Liquid Velocity
λ_L = No-Slip Liquid Holdup
μ_G, μ_L = Gas and Liquid Viscosity
ρ_G, ρ_L = Gas and Liquid Density

INTRODUCTION

The design of two-phase pipelines requires an accurate assessment of both pressure drop and liquid holdup in order to size diameters and construct separation and pumping facilities. Due to the complexity of the problem, in spite of several decades of research, the approach is still primarily empirical. There are a number of correlations reported in the literature which are used for these calculations. In general, these have been based on experiments conducted in the laboratory, where data can be obtained systematically and accurately. Unfortunately, in the field application (especially in the oil and gas industry) the pipe diameter may be up to an order of magnitude larger than the diameters on which the majority of these correlations were based, and the range of pressures, temperatures and flowrates are also generally far removed from experimental conditions.

Several evaluation studies have been performed to gauge the effectiveness of the various frictional pressure gradient correlations available (e.g. Mandhane et al., 1977, Gregory & Fogarasi, 1985, Simpson et al., 1987). The general conclusions of these studies have been that the majority of correlations : (i) perform best on the data upon which they were based, (ii) perform poorly (with relative errors of up to several hundred percent) outside the ranges of data on which they were constructed, and (iii) diverge rapidly in accuracy as the diameter of the pipe is increased.

In this paper we examine the effect of pipe diameter on the accuracy of several well known frictional pressure drop correlations commonly used in industry. The correlations are tested against experimental data obtained from two different sources : our horizontal two-phase flow rig with 32 and 50mm internal diameter pipes, and some other experimental data available in the open literature for larger pipe sizes (102 and 153mm).

EXPERIMENTS

The experimental rig shown in Fig. 1 consists of two closed-loop unheated horizontal pipes. The internal diameters are 32 and 50mm, with lengths of 12.5 and 13m respectively. Settling lengths of 2m were installed in the inlet of each test section to dampen the entrance effects. In our experiments reported here, these pipelines transported various mixtures of air and water, although the rig is equipped to handle multicomponent liquid mixtures (e.g. oil/water/air). The pipes are made of clear acrylic in order to enable visual observation of flow patterns. At the test section inlet a mixing chamber consisting of a manifold-nozzle arrangement was used to produce the two phase mixture. At the outlet a separator removed the air and vented it to the atmosphere, leaving the water to be recirculated through the system via a centrifugal pump. The water tank was equipped with a heat exchanger to regulate its temperature.

Liquid and Gas flowrates were measured using differential pressure transducers connected to orifice meters with standard D and D/2 pressure tappings. Test section pressure drop was measured by a differential pressure transducer connected to single static pressure tappings placed horizontally at both ends of the test section. The transducers were interfaced to a personal computer equipped with an analog to digital card. Special software was developed for sampling and averaging the readings. A sampling frequency of 20 Hz and an averaging period of 15 seconds were used.

The testing procedure for both pipe diameters was as follows: the pump was set to a particular speed via a frequency drive and measurements for increasing gas flowrates were taken until this parameter reached the limit of the transducer. The pump speed was then increased and

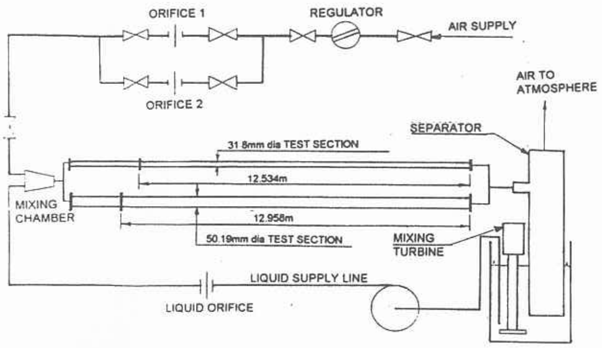


Figure 1. Schematic Diagram Of Experimental Rig

the procedure was repeated. For each data point several readings were recorded to ensure repeatability. Sufficient time was allowed for the flow to settle and the transducer readings to become stable.

A total of 122 acceptable data points for the smaller pipe and 321 points for the larger pipe were recorded. A summary of the data flow regimes is presented in Figure 2.

The predominance of data in the slug and plug flow regimes is readily explained. When testing at low flowrates of both liquid and gas (where stratification of the flow would be expected) it was discovered that the test section pressure transducer was not sensitive enough to detect the small pressure drop that occurred. Also, limitations on the pumping capacity and separation equipment prevented the generation of data in the annular and dispersed regimes.

LARGE DIAMETER PIPELINE DATA

In order to extend the range of our analysis past small pipeline diameters the experimental data of Reid et al. (1957) was chosen as a basis for comparison. Several recent large diameter data sets exist in the literature, e.g. Gregory (1980), Brill et al. (1981), but these are based on gas–oil measurements under field conditions, with variable elevation profiles and significant heat transfer effects. The data of Reid et al. was collected for air–water mixtures under horizontal adiabatic conditions, similar to those encountered in our experiments.

They performed 15 two–phase pressure drop measurements for a 102mm pipeline and 28 measurements for a 152mm line. The length of their test section was 17.1m and data was collected under standard atmospheric temperatures and pressures.

PRESSURE DROP CALCULATIONS

In this study five correlations commonly used in industry (primarily oil and gas) were tested against the experimental data bank. These were:

(a) Beggs and Brill (1973)
(b) Dukler et al. (1967) (with Eaton et al. (1967) holdup correlation)
(c) Duns and Ros (1963)
(d) Lockhart and Martinelli (1949)
(e) Orkiszewski (1967)

Correlations (c) and (e) were developed using data from vertical oil wells, however, for the purpose of this study we extracted the frictional pressure drop component from them for analysis.

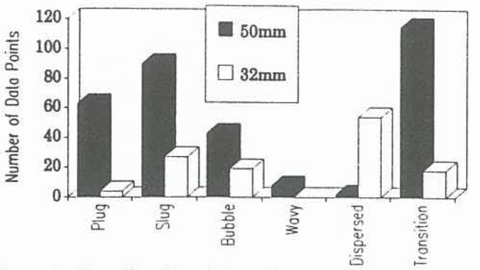


Figure 2. Classification of Data Points By Flow Regime

In a previous study Behnia and Ilic (1990) found a significant ordering of data between pressure drop and mixture Reynolds and Froude numbers, for high velocity field measurements. To gain some understanding of the effect of pipe diameter on our experimental data we used a similar approach. Figures 3 and 4 show plots of the average non–dimensional pressure gradient, defined as

$$\Delta P^* = \Delta P/\rho_m g L \tag{1}$$

versus both the mixture Reynolds number

$$Re_m = \rho_m V_m D / \mu_m \tag{2}$$

and mixture Froude number

$$Fr_m = (V_m)^2 / gL \tag{3}$$

where

$$\rho_m = \lambda_L \rho_L + (1 - \lambda_L) \rho_G \tag{4}$$

$$\mu_m = \lambda_L \mu_L + (1 - \lambda_L) \mu_G \tag{5}$$

and

$$V_m = V_{SL} + V_{SG} \tag{6}$$

Figures 3 and 4 are plotted in terms of the four pipe sizes. A clear grouping for each pipe diameter is observed in both cases, with an almost linear relationship between pressure drop and Froude number. Behnia and Ilic found a sixth order Froude number relationship for their data but made no attempt to isolate the effects of pipe diameter. Both figures clearly show a significant increase in pressure drop as the diameter is decreased for a given mixture velocity.

Figure 5 shows the predictive performance of the Lockhart–Martinelli correlation for a range of pipe sizes. At first glance it appears that the accuracy of this method is not significantly affected by the pipeline diameter, although

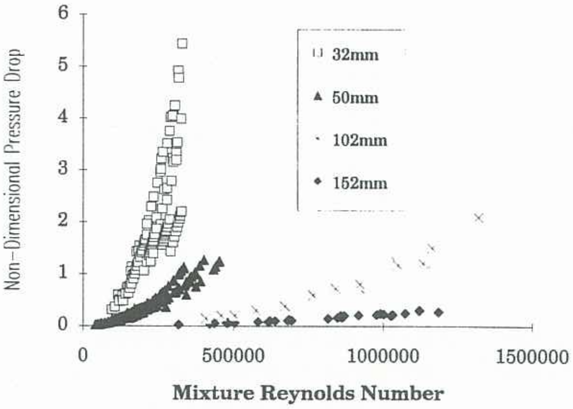


Figure 3. Pressure Drop – Reynolds Number Relationship for Four Pipe Sizes

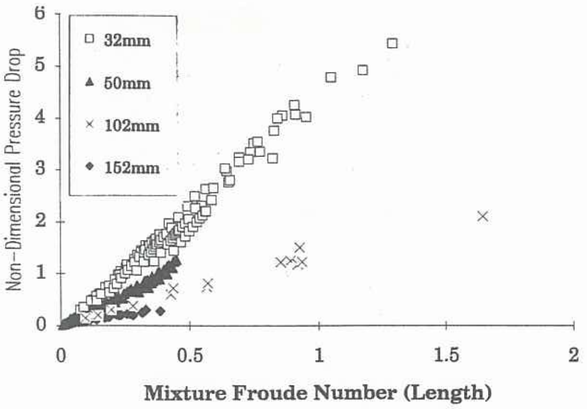


Figure 4. Pressure Drop – Froude Number Relationship for Four Pipe Sizes

this may not be a valid observation since the range of measured pressure drops decreased with increasing diameter. Indeed, the errors are observed to increase with pipe diameter at diminishing flow rates, and since the data sets are biased towards more readings at lower flow rates, calculation of average errors may not be a justifiable basis for comparison.

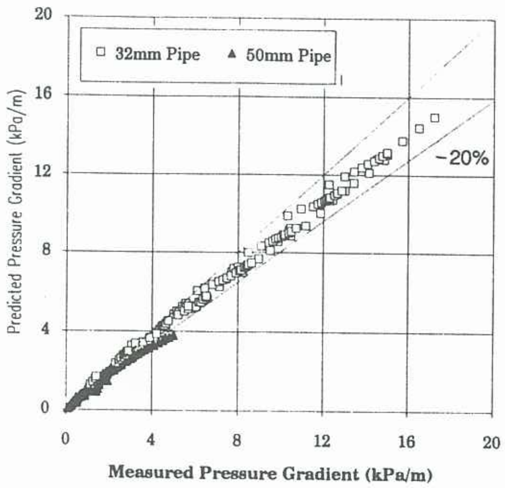


Figure 5(a). Accuracy of Lockhart and Martinelli Correlation for Experimental Data

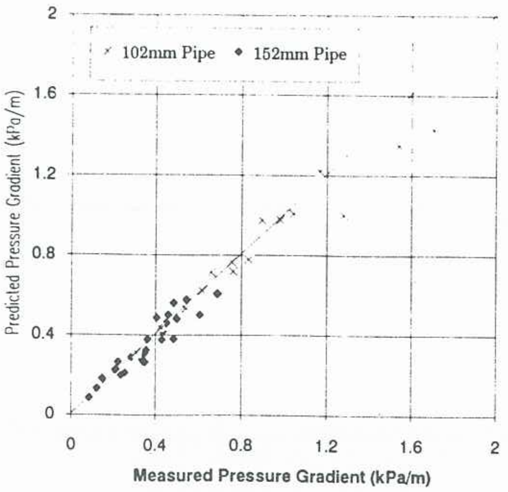


Figure 5(b). Accuracy of Lockhart and Martinelli Correlation for Large Pipe Data

Figure 6 shows the performance of the Dukler et al. correlation for the range of pipe sizes. In this case no significant error increase due to diameter is observed although, again this may be due to the lack of data at high velocities for the larger pipe sizes.

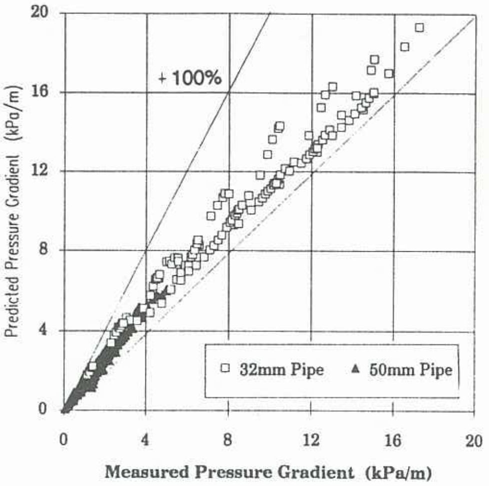


Figure 6(a). Accuracy of Dukler et al Correlation for Experimental Data

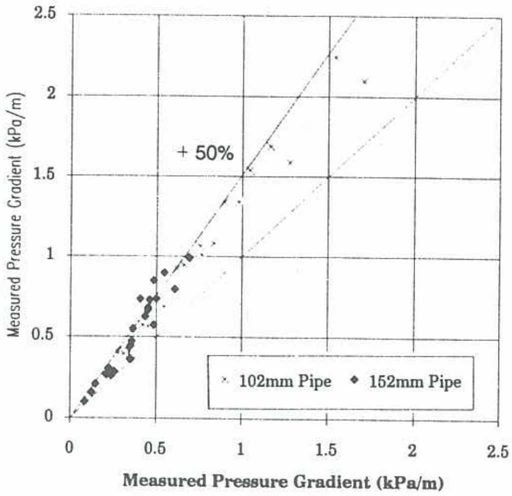


Figure 6(b). Accuracy of Dukler et al Correlation for Large Pipe Data

ERROR ANALYSIS

The measure of accuracy of a correlation in predicting pressure drops is usually based on an average of the errors of all data points considered. There are a number of different ways this average can be represented (Behnia, 1991). For each data the percentage error in pressure drop prediction is determined by:

$$c_i = (\Delta P' - \Delta P) \times 100 / \Delta P \qquad (7)$$

where $\Delta P'$ is the calculated pressure drop for the i^{th} data point. An average percentage error E, for the N data points in the set is:

$$E = \left(\sum_{i=1}^{N} c_i \right) / N \qquad (8)$$

This averaging technique can be misleading because positive and negative errors can cancel one another. Another measure of accuracy can be calculated as standard deviation (σ) of all data points, defined as:

$$\sigma = \sqrt{\left[\sum_{i=1}^{N}\left(e_i - E\right)^2\right]\Big/(N-1)} \qquad (9)$$

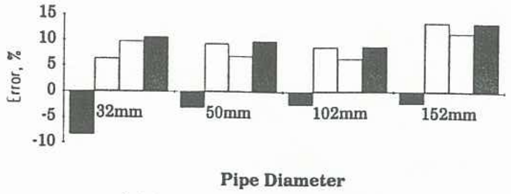
Alternatively, it is also possible to calculate an absolute average error to overcome the deficiency of the average error (Eq. 8) or a root mean square given by:

$$E^* = \sum_{i=1}^{N}\left|e_i\right|\Big/N \qquad (10)$$

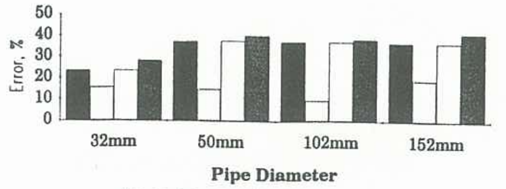
$$\text{RMS Error} = \sqrt{\sum_{i=1}^{N}\left(e_i\right)^2\Big/N} \qquad (11)$$

With the help of an error analysis computer program, the above error values have been computed for each of the pipe diameters using the previously discussed correlations. Results are presented in a graphical form in Fig. 7. It is noted that Lockhart-Martinelli correlation has the lowest overall average error for the data examined. The Orkiszewski correlation performs well for the smaller diameters, but has a relatively high underprediction at higher diameters. Both Beggs-Brill and Duns-Ros methods show an increasing trend in error with pipe diameter. Errors in Dukler correlation predictions seem to be in general higher than Lockhart-Martinelli but nonetheless not sensitive to the pipe diameter. However, more large diameter data at higher mass flowrates is required for a further validation of these observations.

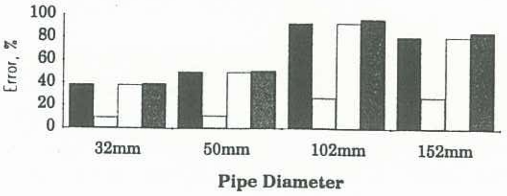
It is interesting to note that for very large pipe diameters carrying oil and gas, Behnia (1991) has shown that actual high flowrate pipeline field data is best represented by Beggs-Brill correlation.



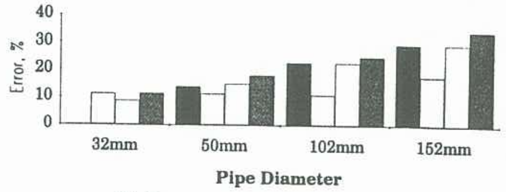
(a) Lockhart and Martinelli



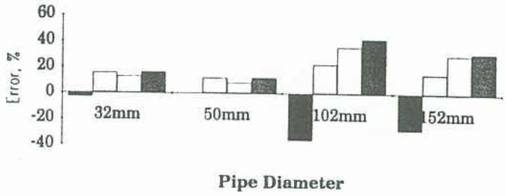
(b) Dukler et al



(c) Beggs and Brill



(d) Duns and Ros



(e) Orkiszewski

■ Average Error ☐ Standard Deviation ☐ Absolute Average Error ▨ RMS Error

Figure 7. Error Distribution Versus Pipe Diameter

REFERENCES

BEGGS, H D & BRILL, J P (1973) A Study of Two-Phase Flow in Inclined Pipes.Journal Petroleum Technology, 25, 607-617.

BEHNIA, M & ILIC, V (1990) A Simple Correlation for Estimation of Multiphase Pressure Drop in an Oil Pipeline.SPE Prod.Eng,5, 370-372.

BEHNIA, M (1991) Most Accurate Two-Phase Pressure-Drop Correlation Identified.Oil & Gas Journal,89, 90-95.

BRILL, J P, SCHMIDT, Z, COBERLY, W A, HERRING, G D & MOORE, D W (1981) Analysis of Two-Phase Tests in Large Diameter Flowlines in Prudhoe Bay Field.SPE Journal, 363-378.

DUKLER, A E, WICKS, M & CLEVELAND, R G (1964) Frictional Pressure Drop in Two-Phase Flow : An Approach Through Similarity Analysis.AIChE Journal,10, 44-51.

DUNS, H & ROS, N C J (1963) Vertical Flow of Gas and Liquid Mixtures in Wells.Proc. 6th World Petroleum Congress, 451-456.

EATON, B A, ANDREWS, D E, KNOWLES, C R, SILBERBERG, I H & BROWN, K E (1967) The Prediction of Flow Pattern, Liquid Holdup and Pressure Losses Occuring During Continous Two-Phase Flow in Horizontal Pipelines.J. Petroleum Technology,19, 815.

GREGORY, G A (1980) AGA Gas Liquid Pipeline Data Bank. University of Calgary, Project PR-148-110.

GREGORY, G A & FOGARASI, M (1985) A Critical Evaluation of Multiphase Gas-Liquid Pipeline Calculation Methods.Proc. 2nd Int. Conf. Multiphase Flow, London, 93-108.

LOCKHART, R W & MARTINELLI, R C (1949) Proposed Correlation of Data for Isothermal Two-Phase Two Component Flow in Pipes.Chem. Eng. Progress,45, 39-48.

MANDHANE, J M, GREGORY, G A & AZIZ, K (1977) Critical Evaluation of Friction Pressure Drop Prediction Methods for Gas-Liquid Flow in Horizontal Pipes.J. Petroleum Technology,29, 1348-1358.

ORKISZEWSKI, J (1967) Predicting Two-Phase Pressure Drops in Vertical Pipe.J. Petroleum Technology, 829-838.

REID, R C, REYNOLDS, A B, DIGLIO, A J, SPIEWAK, I & KLIPSTEIN, D H (1957) Two-Phase Pressure Drops in Large Diameter Pipes.AIChE Journal,3, 321-324.

SIMPSON, H C, ROONEY, D H, GILCHRIST, A, GRATTAN, E & CALLANDER, T M S (1987) An Assessment of Some Two-Phase Pressure Gradient, Holdup, and Flow Pattern Prediction Methods in Current Use.Proc 3rd Int Conf. Multiphase Flow,The Hague, 23-36.