COMPARISONS OF EXPERIMENTAL DATA OF TWO PHASE FLOW IN LARGE DIAMETER HORIZONTAL PIPE WITH SOME PRESSURE DROP PREDICTION MODELS

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الملخص

تم في هذا البحث اختبار بعض نماذج حساب الانخفاض في الضغط للسريان ثنائي الطور لتحديد مدى تأثير قطر الانبوب على دقة التنبؤ لهذه النماذج في حالة السريان ثنائي الطور الأفقي الكاظم للحرارة. نتائج تجريبية من أنبوب ذو قطر كبير (0.203 m) في مجال من التغيرات في معدل تدفق الماء ومعدل تدفق الهواء تم استعمالها. 385 نقطة بيانات تجريبية تم استخدامها في هذه المقارنة وقد لوحظ أن كل النماذج التي تم اختبارها أعطت نسبة خطأ عالية (>50%) باستعمال RMS مقارنة مع البيانات التجريبية الفعلية للقطر الكبير. المقارنة كذلك أوضحت أن نمط التدفق له بعض التأثير على عملية التنبؤ لانخفاض الضغط للسريان ثنائي الطور الأمر الذي جعل معظم النماذج تعطي قيم تنبؤ لانخفاض الضغط أكبر في حالة نمط التدفق الطبقي (stratified flow) ونمط التدفق المتموج (wavy flow) بينما أعطت قيم تنبؤ لانخفاض الضغط أقل لبقية أنماط التدفق الأخرى.

ABSTRACT

In this investigation, several two-phase flow pressure drop prediction models are tested to determine the effect of pipe diameter on the accuracy of their predictions in horizontal adiabatic two-phase flow setup. Experimental results from a large diameter (0.203 m) pipe for a range of air and water flow rates were used. The data set included 385 data points and it was observed that all the tested models gave high (>50%) RMS error compared to the actual large diameter experimental data. The comparisons also revealed that the flow pattern type has some influence on the two-phase pressure drop predictions, due to this; most of the predictions tend to overpredict the two-phase pressure gradient of the stratified and wavy flow patterns and under predict the rest of the experimental data for other flow patterns.

KEYWORDS: Two-phase; Large Diameter Tube; Stratified Flow; Pressure Drop.

INTRODUCTION

Two-phase flow phenomenon is found in a wide range of engineering systems, such as conventional power plants, boiling water reactors and evaporators of refrigeration systems, as well as, in variety of evaporative and condensate heat exchangers in the chemical and petroleum industries. Over the past decades, problems in two-phase flow have challenged many investigators, as this phenomenon affect not only the efficient and economical design of equipment, but also its safety in operation.

Two phase flows obey all the basic laws of fluid mechanics; the equations, however, are more numerous and more complex than in single-phase flow with the result that the solution of many problems is difficult and cannot be set out in a neat mathematical manner. In many instances, solutions are dependent on modelling techniques and experimental results or the setting up of a simplified analytical model of the problem. There are many theories presented in the two-phase flow literature, but the bulk of information, available is empirical, based on the experimental results and correlations derived from researches.

Two-phase flow is a difficult subject principally because of the complexity of the form in which the two fluids exist inside the pipe, known as the flow regime (flow pattern). Due to the difficulty in constructing a model from basic principles in all but the most elementary situations, dimensional analysis is used to establish the relevant groups to aid in designing suitable experiments. Most available empirical results are applicable only to gas-liquid two-phase flow. In two-phase flow, the concept of hold-up is important. It is the relative fraction of liquid phase in the pipe. This is not necessarily equal to the relative fraction of that phase in the entering fluid mixture.

The two-phase flow behaviour in pipes is very complex; Phases tend to separate because of the differences in their densities. Expansion of the highly compressible gas phase with decreasing pressure increases the in-situ, volumetric flow rate of the gas, as a result, the gas and the liquid phases normally do not travel at the same velocity in the pipe, upward flow the less dense, more compressible, less viscous phase tends to flow at a higher velocity than the liquid phase, causing a phenomenon known as slippage.

The usual question for the engineer is that of calculating the pressure drop required to achieve specified flow rates of the gas and the liquid through a pipe. To make design calculations involving two-phase flow, this may also, affect heat and mass transfer characteristics during the change of phase. It is not possible to understand the two-phase flow phenomenon without a clear understanding of the flow patterns encountered. It is expected that the flow patterns will influence the two-phase pressure drop, hold up, system stability, exchange rates of momentum, heat and mass transfer during the phase change heat transfer processes. It is thus critically important to be able to predict the conditions (flow patterns, pressure drop, void fraction…etc.) under which a two-phase flow system will perform reliably and safely. Such understanding is central to the design, control, and performance prediction of these systems.

The ability to accurately predict the type of flow is necessary before relevant calculation techniques can be developed. Therefore, the need for reliable design models, and the importance of two-phase flow in many industrial applications, especially in the energy related industries have been the driving force behind a very large research effort over the past decades and for this investigation. It is hoped that this investigation will provide a better insight into the subject of two-phase flow in large diameter pipes.

There are a number of correlations reported in the literature, which are used for these calculations. In general, these have been based on experimental work conducted in the laboratory (< 50 mm diameter), where data can be obtained systematically and accurately. Unfortunately, in the field application (oil and gas industry), the pipe diameter may be much larger in order of magnitude than the diameter on which the majority of these correlations were based, and the range of pressures, temperatures, and flow rates, are also generally far removed from experimental conditions

PRESSURE DROP PREDICTIVE MODELS

The prediction of design parameters such as pressure drop during gas-liquid flow is achieved by one of the three approaches: empirical correlations, analytical models or phenomenological models. Empirical approaches are the most common in modeling of two-phase pressure drop due to their acceptable accuracy in the range of the database used for the development of the correlation, and the minimum knowledge of the flow characteristics is required. The frictional pressure drop for two phase, two component, isothermal flow in horizontal tube was initially developed by (Lockhart and Martinelli, 1949, [1]; Bankoff, S.G.,1960, [2]; Cicchitti et al, 1960, [3]; Thom, 1964, [4]; Pierre, 1964, [5]; Baroczy, C.J.,1965, [6]; Chawla, J.M.,1967, [7]; Chisholm, D.,1973, [8]; Friedel, L.,1979, [9]; Gro¨nnerud, R.,1979, [10]; Muller-Steinhagen and Heck, 1986, [11]).

These models result in errors in predictions that are often too large for that required in engineering calculations. Tribbe and Mu¨ller-Steinhagen [12] presented an extensive comparison of 35 two-phase pressure drop predictive models compared to a large database for the following fluid combinations: air-oil, cryogenics, steam-water, air-water and several refrigerants. They ran a statistical comparison for this large database, also segregating the data by flow regime. They found that statistically the model of Muller-Steinhagen and Heck [11] gave the best and most reliable results.

A work published by Ould-Didi et al. [13] showed a comparison between seven of the most common and leading predictive models and experimental data obtained for five different refrigerants over a wide range of experimental conditions. Overall, they found that Gronnernd (1979) [10] and Muller-Steinhagen and Heck [11] models to be equally the best, while the Friedal (1979) [9] model was the third best. Segregating the data by flow regimes using the flow pattern map by Kattan [14], the authors found that predictive models work differently varying the flow regime. Later, Moreno Quiben and Thome [15-16] published a work in which they made an extensive comparison to predictive models (Friedel, [9], Quiben and Thome [16], Muller-Steinhagen and Heck [11], Gronnerud [10], Jung and Rademacher [17]. The database used is for seven refrigerants (R22, R134a, R404A, R407C, R410A, R417A, and R507A) over a wide range of operating conditions. The statistical analysis showed that the models by Gronnerud and by Moreno Quiben and Thome are equally the best of the five models analyzed.

Benbella A. Shannak, (2008) [18] tested ten of the most common models found in the open literature including his own, using Friedel`s Data-Bank containing of about 16000 measured data. He proposed his own model, and concluded that an acceptable result was obtained from Friedel`s, [9], and Muller-Steinhagen and Heck [10] models. Several other statistical comparisons of the most reliable predictive models were published.

PRESENT WORK

In this paper the effect of pipe diameter on the prediction accuracy of several well-known frictional pressure drop models (correlations) commonly used were studied. The models were tested against 385 data points obtained from experimental work on a horizontal two-phase flow in 203 mm internal diameter, and 34 m long test section [19]. The data obtained cover the *Stratified flow* (smooth and wavy), and *Intermittent flow* (plug and slug) only, but did not include any *Annular flow*, due to the vast amount of air flow required which was in access of air supply available [19].

The six models chosen from the numerous studies found in the open literature are:

(1) (Lockhart and Martinelli, 1949, [1]; widely used in the industry, and due to its continued historical references.

(2) Bankoff, S.G., 1960, [2]; an extension of the homogeneous model (simplest to use).

(3) Chisholm, D., 1973, [8]; an extension of Lockhart and Martinelli and Baroczy, model which allows for mass velocity effects.

(4) Muller-Steinhagen and Heck [11], (5) Gronnernd (1979) [10], (6) Friedal (1979) [9]; were recommended by many previous researchers, and statistical comparison studies, as the most reliable predictive models, for horizontal two-phase flow pressure drop.

EXPERIMENTAL TEST RIG AND MEASUREMENT METHODS

A test rig shown in Figure (1) was constructed and used by Ali E.M [19]. The data which were collected in the study contain 385 test points, covering; stratified (smooth), stratified (wavy), plug, and slug flow patterns. The test rig consists of 34 m long pipe as test section, the pipe was made from PVC except 2.55 m clear Perspex (observation section, used for flow patterns recording). The test section was completely horizontal, and the water flow rate was measured in terms of the pressure difference across sharp edged orifice plates (50.57 mm or 88.90 mm diameter depending on the flow rate) inserted to the pipe line. Mixing device was located at a distance of 35 diameters downstream of the water flow orifice plate as shown in Figure (1) [19]. The purpose of the mixer was to promote mixing of the air and the water before the entrance to the test section. Air flow rates were measured using two orifice plates (17.525 mm and 41.328 mm), depending on the air flow rate needed in a particular test run, inserted into two air pipeline systems of diameter 25.4 mm and 50.8mm respectively. A set of four rotameters were used, which cover the lower 20% of the airflow range [19]. The temperature of air and water in different stations along the pipeline were measured using copper-constantan thermocouples. Seven temperature measuring station were used; two at air supply lines (25.40 mm diameter pipeline, and 50.8 mm pipeline) located downstream of the orifice plate, and four in the test section, two (one on top and one on the bottom), at distance of 9.074 m from the inlet to the test section, and the other two at a distance of 28.429 m from the inlet. All the thermocouples were connected to a calibrated multi-channel digital thermometer, to give a direct temperature reading in ^{O}C [19].

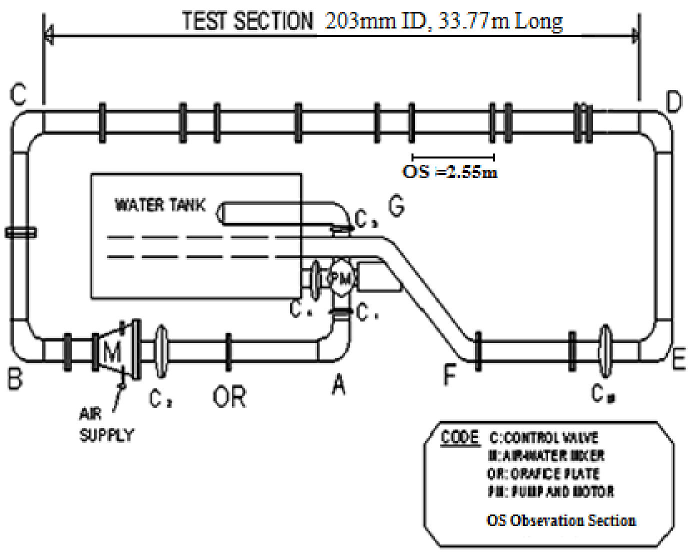

Figure 1: Layout of test rig [1].

A total of 36 tapping point were used to measure the pressure distributed along the test section (34-meter-long), 23 on the bottom of tube and 13 on the top, distributed initially at 2 m and later at 1m intervals, diametrically opposite each other. These are all connected by means of flexible tubes to two boards of multi-tube, manometer piezometer systems, one for the top tapings and the other for the bottom tapings. The first step in the conversion of the pressure drop raw data into useful information was to plot static pressure distribution along the test section. The slope of the linear part of the graph determined the pressure gradient, whilst deviations from linearity were considered, as unsettled flows due to the effects of the inlet and outlet bends. The total pressure gradient was taken as the friction pressure gradient, since the momentum component constitute a very small part of the total pressure drop.

COMPARISON OF THE PREDICTIVE MODELS TO THE EXPERIMENTAL DATA

The data of flow patterns and pressure drop used in this investigation are for 203 mm diameter, and 34 m long horizontal test section Figure (1), reported by Ali, E.M. [19]. All the 385 experimental data points reported were for air-water combination.

Six pressure drop prediction models were included in this investigation to compare with the experimental data. These models are that of Lockhart and Martinelli [23], Friedel [9], Gronnerud [10], Chisholm [8], Bankoff [2], Muller-Steinhagen and Heck [11]. All these models are empirical, and often provide good accuracy in the range of data base available for the development of each of them. The pressure drop data used in this comparisons only the linear part of the pressure distribution along the test section determined the pressure gradient, whilst deviations from linearity were considered as unsettled flows due to the effects of the inlet and outlet bends, and the total pressure gradient was taken as the friction pressure gradient, since the momentum component constitute a very small part of the total pressure drop.

The experimental data were grouped into four groups as follows:

Group1: Four flow patterns observed during the collection of the data, namely; plug, slug, stratified, and wavy. The experimental data did not cover any annular flow patterns. The comparisons of the experimental two-phase pressure gradient values against that obtained from the six correlations considered for comparisons are shown in Figures (2) to (7).

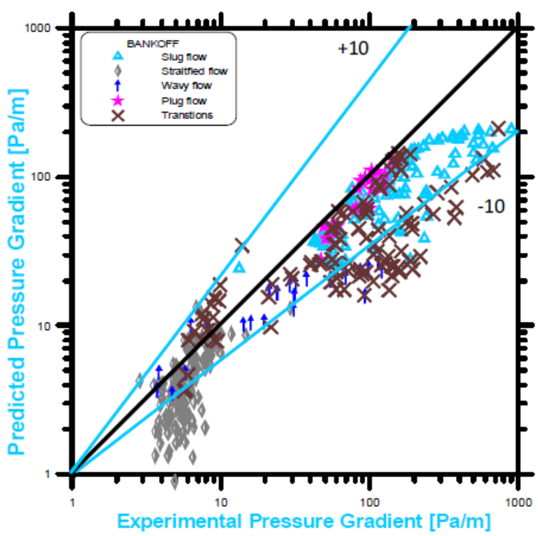

Figure 2: Comparison between Experimental and Bankoff Predictions (ALL DATA)

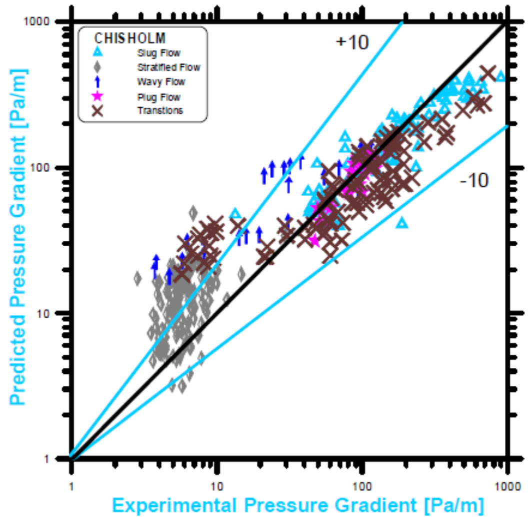

Figure 3: Comparison between Experimental and Chisholm Predictions (ALL DATA)

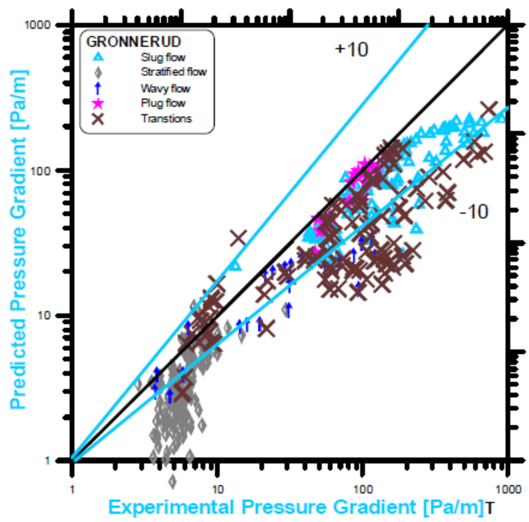

Figure 4: Comparison between Experimental and Gronnerud Predictions (all data)

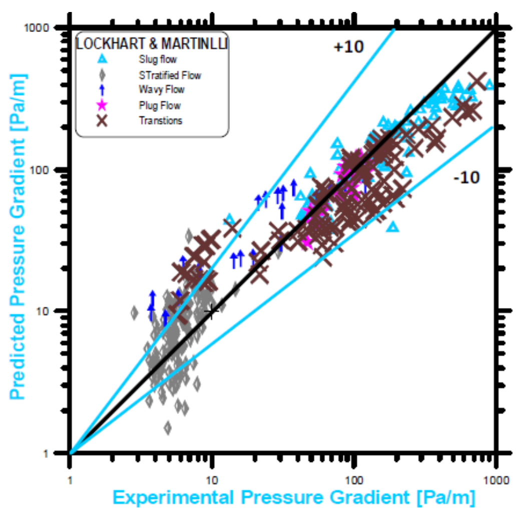

Figure 5: Comparison between Experimental and Lockhart and Martinelli Predictions (all data)

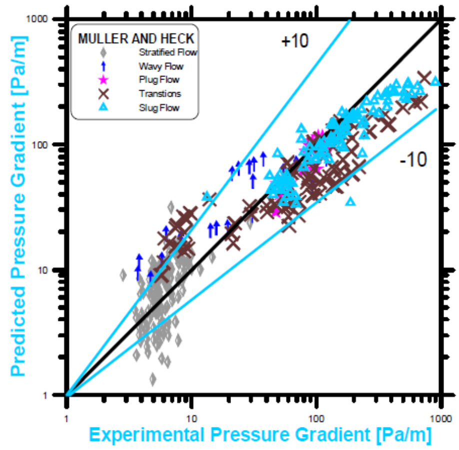

Figure 6: Comparison between Experimental and Muller-Steinhagen and Heck Predictions (all data)

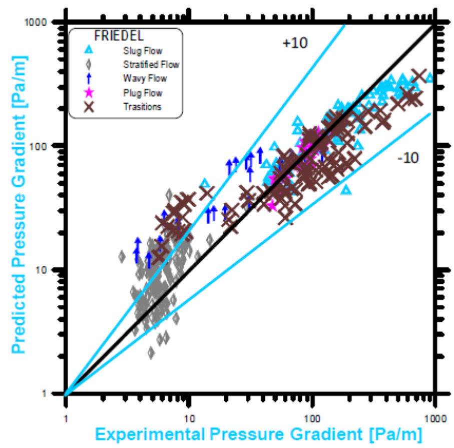

Figure 7: Comparison between Experimental and Friedel Predictions (all data)

Group 2: Experimental data (176 data point), for stratified, wavy and the stratified-wavy transitions. The comparisons of experimental two-phase pressure gradient values against that obtained from the six correlations considered for comparisons are shown in Figures (8) to (13).

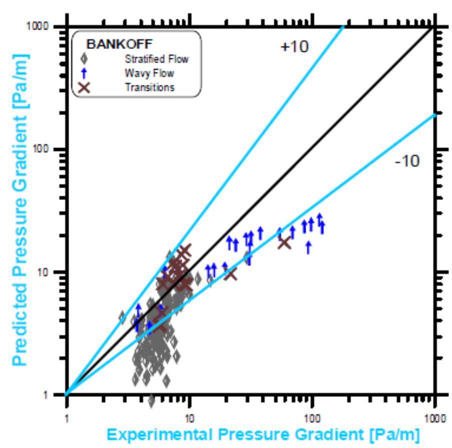

Figure 8: Comparison between Experimental and Bankoff Predictions (Stratified, Wavy and Transition)

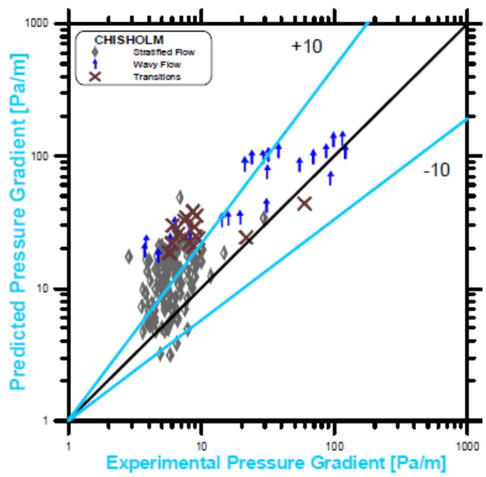

Figure 9: Comparison between Experimental and Chisholm Predictions (Stratified, Wavy and Transition)

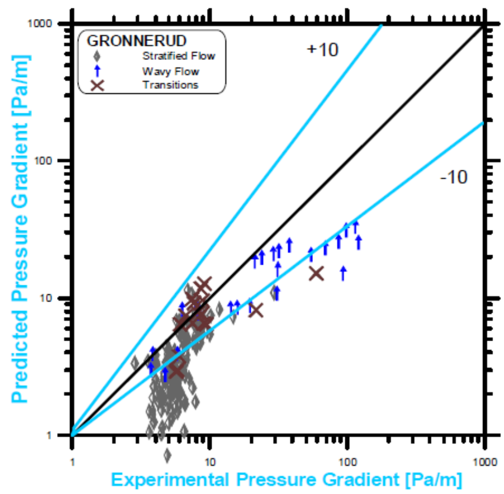

Figure 10: Comparison between Experimental and Gronnerud Predictions (Stratified, Wavy and Transition)

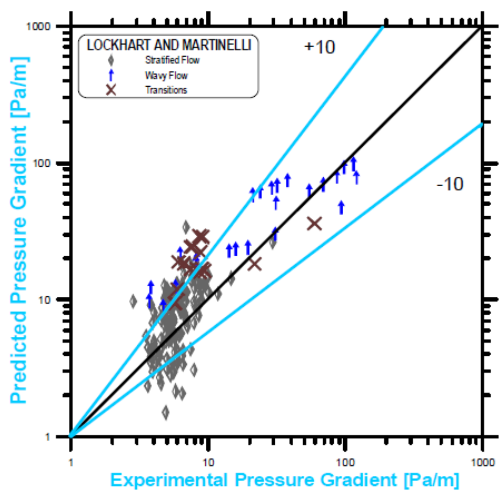

Figure 11: Comparison between Experimental and Lockhart and Martinelli Predictions (Stratified, Wavy and Transition)

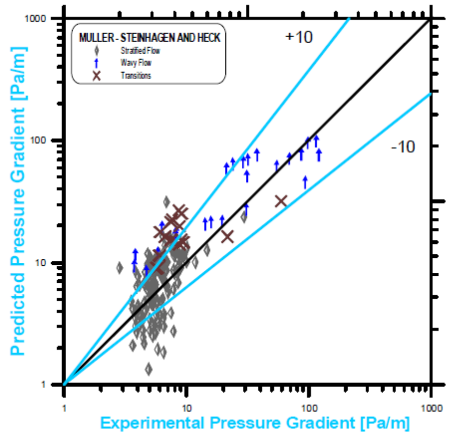

Figure 12: Comparison between Experimental and Muller-Steinhagen and Heck Predictions (Stratified, Wavy and Transition)

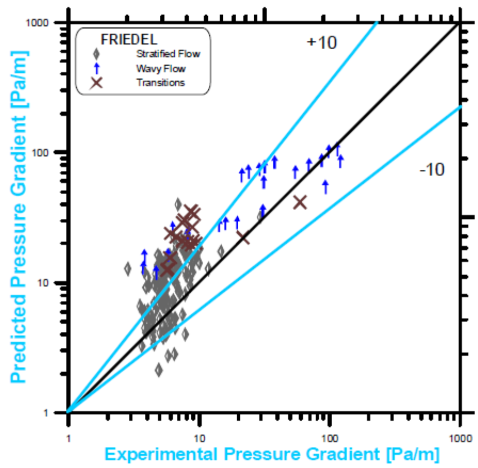

Figure 13: Comparison between Experimental and Friedel Predictions (Stratified, Wavy and Transition)

Group 3: Stratified flow pattern pressure gradient data (138 data point) are presented in this group, and comparisons of this pressure gradient data are plotted against that obtained from the six correlations considered for comparisons are shown in Figures (14) to (19).

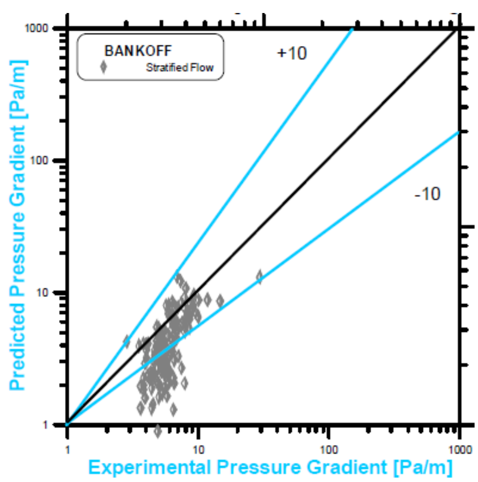

Figure 14: Comparison between Experimental and Bankoff Predictions (stratified flow)

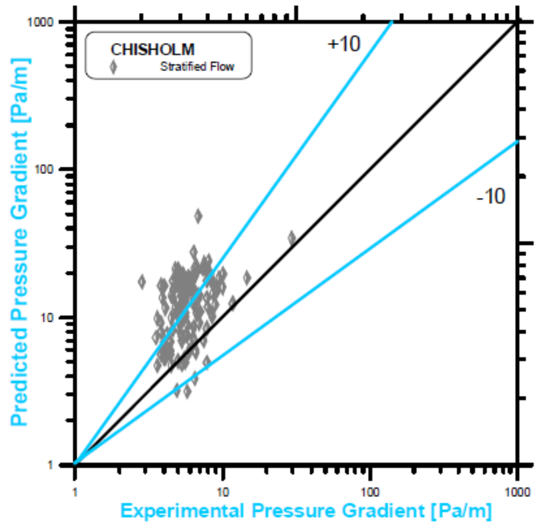

Figure 15: Comparison between Experimental and Chisholm Predictions (stratified flow)

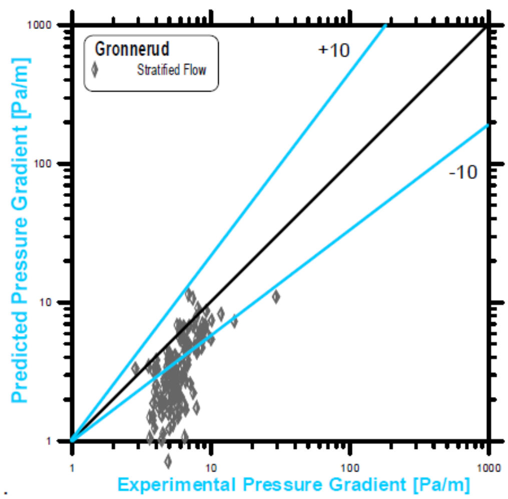

Figure 16: Comparison between Experimental and Gronnerud Predictions (stratified flow)

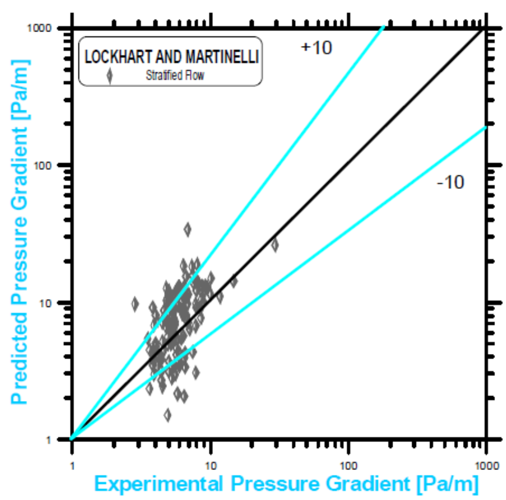

Figure 17: Comparison between Experimental and Lockhart and Martinelli Predictions (stratified flow)

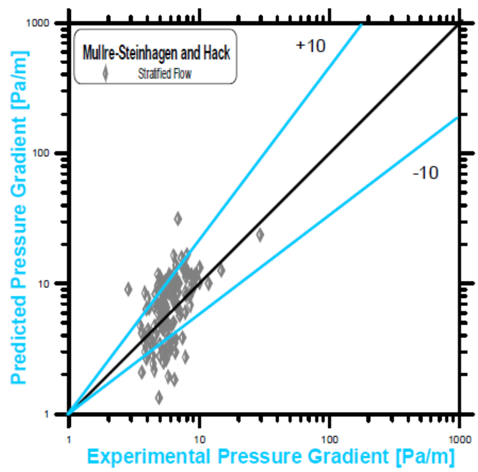

Figure 18: Comparison between Experimental and Muller-Steinhagen and Heck Predictions (stratified flow)

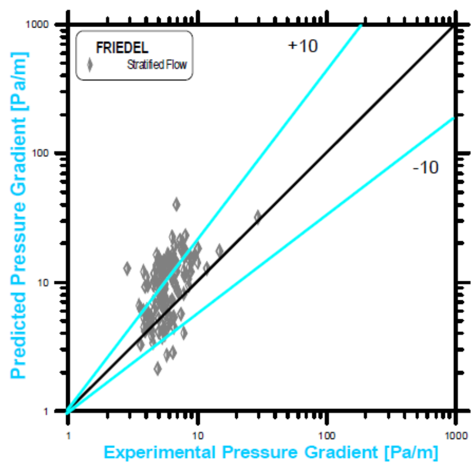

Figure 19: Comparison between Experimental and Friedel Predictions (stratified flow)

Group 4: The slug flow pattern pressure gradient experimental data (95 data point) are presented in this group, and comparisons of this pressure gradient data are plotted against the predicted values that obtained from the six correlations considered for comparisons, and are shown in Figures (20) to (25).

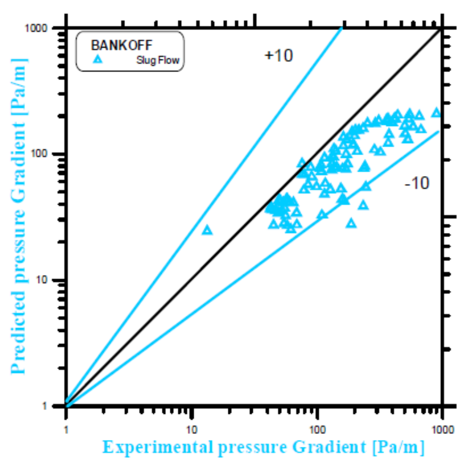

Figure 20: Comparison between Experimental and Bankoff Predictions (slug flow)

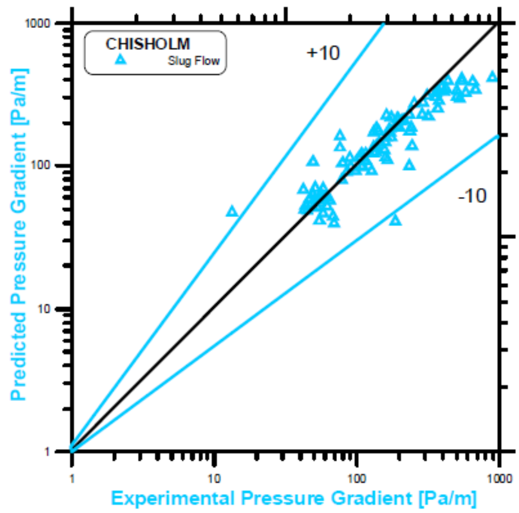

Figure 21: Comparison between Experimental and Chisholm Predictions (slug flow)

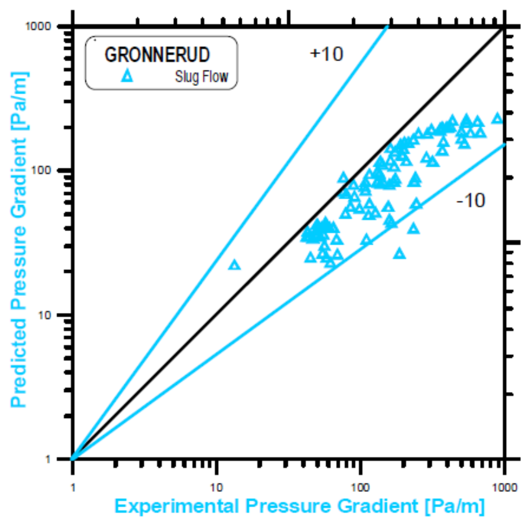

Figure 22: Comparison between Experimental and Gronnerud Predictions (slug flow)

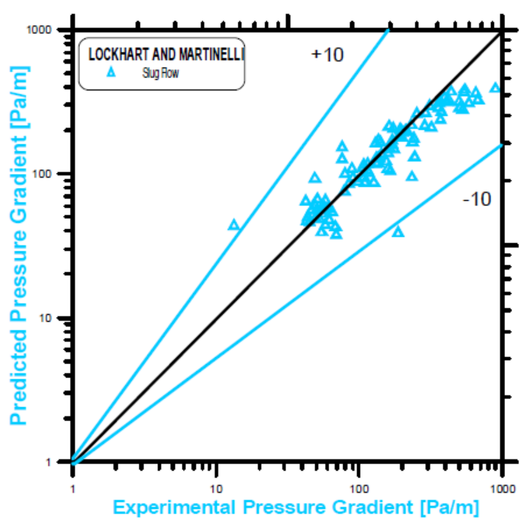

Figure 23: Comparison between Experimental and Lockhart and Martinelli Predictions (slug flow)

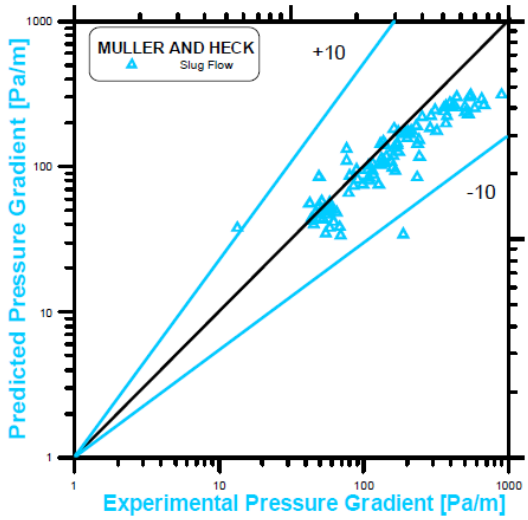

Figure 24: Comparison between Experimental and Muller-Steinhagen and Heck Predictions (slug flow)

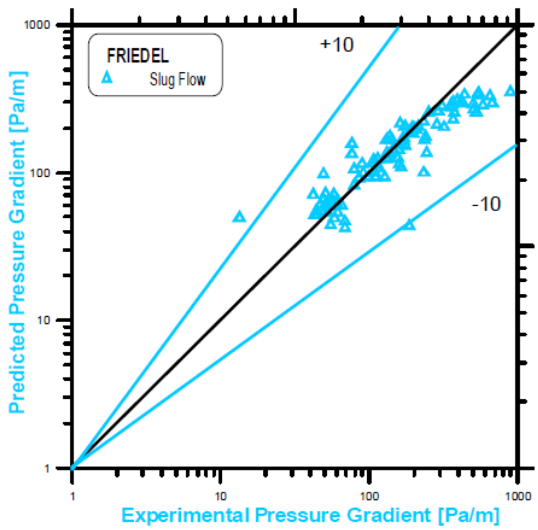

Figure 25: Comparison between Experimental and Friedel Predictions (slug flow)

The root mean square error values percentage (RMS%) and the average error values percentage (AVE%) based on the experimental values, were calculated for the six models, and tabulated along with the ranking of each model, and are shown in Table (1).

In the light of the Figures (2 to 7) and Table (1) it is worth noting that:

- None of the models tested gave overall pressure drop predictions with RMS% error less than 48% over the experimental data range.
- Chisholm model gave poor performance with a very high RMS% error associated with the prediction i.e. > 100%, for all sets of experimental data except that of slug flow.
- Bankoff and Gronnerud models gave a better predictions of the pressure drop of all experimental data with RMS% < 50%.
- In spite of the big differences in the values of RMS% between the models, most of them tend to over predict the two-phase pressure gradient of the stratified and wavy

flows and under predict the rest of the experimental data, which may be due to stratification affects. Therefore, in general, flow pattern has a noticeable effect on the accuracy of the prediction.

In the view of the RMS% and AVE% values; the best models predicted the whole experimental data, is that of Bankoff [2], with rankings of [1/1] and for which the deviations are 48% and 41%. The second-best model is that of Gronnerud [10], with ranking of [2/2]. The model of Muller-Steinhagen and Heck [11], came third with ranking of [3/3]. The Lockhart and Martinelli [1], Friedel [9], Chisholm [8], gained the rankings of [4/4], [5/5], and [6/6] respectively. The deviations of the worst model are 131% and 83%.

For further analysis of the predicted pressure drop results given by all the six models, against the experimental pressure drop data for large diameter test section, the data were segregated by the flow pattern to three groups, which are discussed below.

Given the plots (8) to (25), along with the information presented in Table (1), the following notes are drawn:

The ranking of the used models for the data groups; G2 and G3 did not differ from that of the whole data (G1). For G4, however, the model of Lockhart and Martinelli [1], came first with rankings [1/2] and deviations of 37% and 26%.

The second and third places were taken by Muller-Steinhagen and Heck [11], and Friedel [9], with deviations of 41% and 114%, and 42% and 26% respectively. Gronnerud [10], moved to the fourth place.

In general, in spite of the big differences in the values of RMS% between some models, most of them tend to be consistent in predicting the four sets of the experimental data shown in Table (1), this indicates that each correlation is better suited to specific flows, certain pipe diameters and for specific range of application. The results of the comparison cannot be considered satisfactory. The scatter sometimes is appreciable and suggests that either the tested models are inadequate for predicting the friction pressure drop in large diameter tubes, due to the possible interfacial level gradient [19] or that the comparison is unfair, or perhaps both. However, this conclusion is perhaps not too surprising if one remembers that:

(i) Many of the models compared were developed from data taken in small diameter tubes and for other fluid combinations and sometimes did not include mass velocity effects.

(ii) For a given mass or volume flow rate, the friction pressure drop in large tubes is much less than in smaller tubes, hence large differences do not necessarily constitute large pressure drops in absolute terms, and hence small uncertainties in the model could be amplified.

(iii) There is more scope in large diameter tubes for flow separation and stratification, and hence for variations in liquid level along the tube. This mostly applies to stratified and wavy type flows. This stratification effect however, could also affect other flow patterns e.g. annular (was not encountered during this study), where the film thickness at the bottom of the tube is so thick as to give the effect of stratified type flow superimposed on the symmetrical annular flow.

Table 1: Tabulated values of RMS% and AVE% of the six models tested for the four groups of experimental data.

Groups & / Number of data	G1 All data	G2 Stratified + wavy + Transition	G3 Stratified Flow only	G4 Slug Flow only
Number of data	385	176	138	95
Bankoff method [2].				
Ranking	[1/1]	[1/1]	[1/1]	[5/5]
RMS%	48.023	43.21	40.63	48.10
AVE%	41.28	39.56	34.76	43.31
Lockhart & Martinelli method [1].				
Ranking	[4/4]	[4/4]	[4/4]	[1/2]
RMS%	70.48	91.66	76.11	37.40
AVE%	46.68	69.72	55.07	25.51
Friedel method [9].				
Ranking	[5/5]	[5/5]	[5/5]	[3/3]
RMS%	95.53	129.99	112.17	41.90
AVE%	62.25	102.06	85.29	25.92
Gronnerud method [10].				
Ranking	[2/2]	[2/2]	[2/2]	[4/4]
RMS%	49.72	48.17	48.06	47.11
AVE%	43.81	45.31	43.18	42.95
Chisholm method [8].				
Ranking	[6/6]	[6l6]	[6/6]	[6/1]
RMS%	130.55	185.04	164.83	52.78
AVE%	82.80	148.54	128.33	23.58
Muller-Steinhagen and Heck method [11]				
Ranking	[3/3]	[3/3]	[3/3]	[2/6]
RMS%	63.39	80.52	65.91	40.84
AVE%	44.51	61.60	47.60	114.14

CONCLUSIONS

The experimental data of the large diameter test section, were compared with six recommended two-phase frictional pressure drop models; Friedel, Bankoff, Gronnerud, Muller – Steinhagen and Heck, Chisholm, and Lockhart and Martinelli. In general, most of the models under predicted the experimental data. The RMS errors are over 50% for most of them. Segregation of the experimental data by flow regime show some improvement on the slug regime. Hence, flow pattern has a noticeable effect on the accuracy of the prediction, and need to be accounted for in the development of models used in two-phase flow pressure drop prediction. Bankoff and Gronnerud models were consistent in their predictions of the experimental pressure drop data for the four sets, with RMS% error less than 50%. Muller–Steinhagen models gained third place in this comparison. All the models tested were developed from small diameters (<50 mm) data, this indicates that each correlation is better suited to specific flows, certain pipe diameters and for specific range of application. In large diameter tubes, where stratification affects all flow regimes, particularly in the case of stratified type flow, the assumption that the total pressure drop is given only by frictional pressure drop does not seem to be accurate. The visual identification of the flow regimes near transitions can also be easily wrongly predicted.

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