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FLOW REGIMES AND PRESSURE DROP MEASUREMENTS OF AIR-OIL TWO-PHASE FLOW IN HORIZONTAL PIPES

J.L. Pawloski, C.Y.Ching and M. Shoukri

Dept. of Mechanical Engineering, McMaster University, Hamilton, ON, CANADA L8S 4L7

ABSTRACT

An experimental study has been performed to investigate the flow regimes and pressure drop of air-oil two-phase flow in horizontal pipes. A new air-oil two-phase flow loop was designed and commissioned for this study. The flow regimes and pressure drop were obtained using a half-inch diameter pipe over a wide range of test conditions. The flow regimes were identified with the aid of a 1000 frames per second high-speed camera. The current flow regime data show significant differences in the transitional boundaries from the flow regime maps of Mandhane et al. (1974), Taitel and Dukler (1974) and Spedding and Nguyen (1980). The pressure drop measurements were compared to the predictions from four existing pressure drop models: Homogeneous, Martinelli (1948), Chisolm (1973) and Olujic (1985). The Chisolm and Martinelli models were found to be the most accurate, with an average error of about 35 percent.

INTRODUCTION

Accurate prediction of the flow regimes and pressure drop of air-oil flow is important in many industrial applications. For example, in aeroengines, air and lubrication oil are mixed in the bearing chamber, which is subsequently drained by a scavenging system comprising of a pump and piping system where the air and oil are separated. The accurate prediction of the pressure loss in the scavenge line is important to design the pressure limits of the bearing chamber to ensure no loss of lubricant with the air. The scavenge line can have several singularities such as sudden area changes, bends and junctions in addition to straight piping. Models to predict the pressure loss in each of these components are required for the proper design of the scavenge system. However, the complex nature of two-phase flow, characterized by turbulence, deformable phase interface, phase interaction, phase slip and compressibility of the gas phase has made it extremely difficult to obtain reliable flow models.

There have been numerous theories and correlations developed to predict pressure drop in two-phase flows in horizontal pipes. Among the more common models are the homogeneous model and the separated flow models. The homogeneous model assumes that the two-phase flow can be characterized as a single phase with one set of common properties. The homogeneous properties are determined from a weighted average of the mass flow rates of the gas and liquid. The separated flow models consider the two phases separately, with an inherent assumption that the two phases reach constant but not necessarily equal velocities. While several models of this type have been developed, the three most commonly used are the Friedel (1979), Martinelli (1948) and Chisholm (1973) models. Each of these separated flow models has been found to be acceptably accurate under certain flow conditions.

The pressure drop models are very likely to be dependent on the flow regime, as the flow regimes significantly affect the flow characteristics. Accurate identification of the flow regime under different flow conditions can greatly simplify the flow modeling by only dealing with the specific flow regime. The flow regimes are usually presented as flow regime maps, with the axes representing certain physical characteristics of the two phases. Among them, mass flow rate, superficial velocity and momentum flux have been the most widely used mapping parameters. The objective of this paper is to investigate the flow regimes and pressure drop for air-oil flow in horizontal pipes.

EXPERIMENTAL FACILITIES

The experiments were performed in a new versatile air/oil flow loop designed and constructed for the present research (Figure 1). It is designed to accommodate multiple test section geometries over a wide range of operating parameters. The facility operates at pressures up to 415 kPa, with maximum air and oil flow rates of 43.5 kg/hr and 1840 kg/hr, respectively. The oil is stored in the tank (1), which also acts as a separation chamber for the air and the oil. The oil passes through a fine mesh filter (2) before entering the rotary gear pump (3), which is driven by a three-phase, 1 HP electric motor. A programmable speed controller on the gear pump is used to

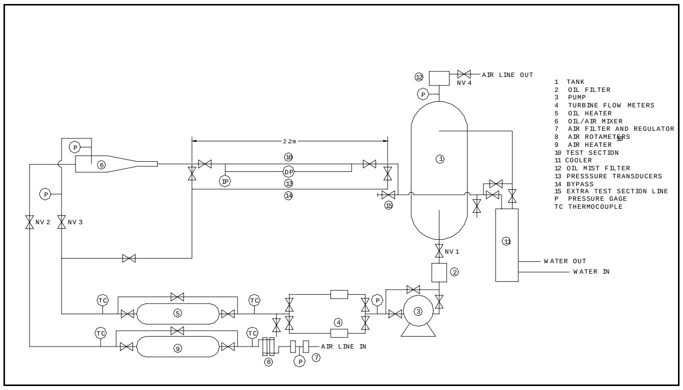

Figure 1 – Schematic of Air/Oil Flow Loop

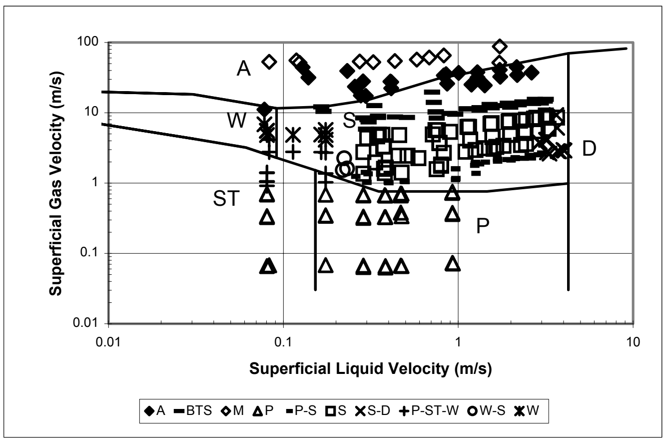

Figure 2 - Mandhane(1974) flow regime map

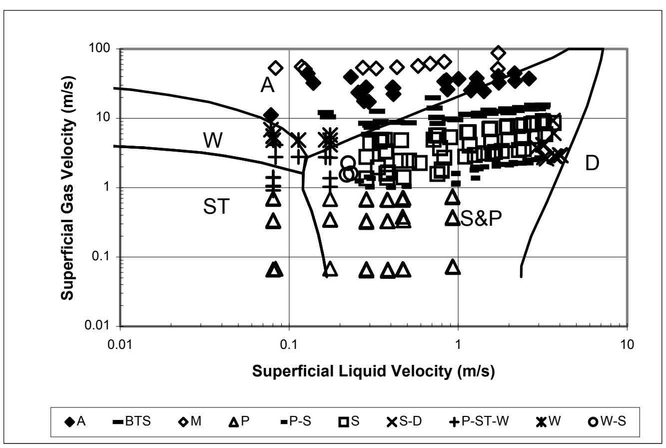

Figure 3 - Taitel & Dukler (1976) flow regime map

vary the oil flow rate. A 100-psi house line provides the air for the system. The air is filtered and regulated (7) before entering the air/oil mixer (6). Electric heaters are installed on both the air and oil lines to permit operation at temperatures up to 150°C. The air heater is a single-phase, 4 kW heater (9) and the oil heater is a three-phase, 18 kW heater (5). The air/oil mixer is annular in design, with oil flowing around an inner perforated pipe. Air flows in the inner pipe and enters the oil stream through 380 1/32-inch diameter perforations. Once the air/oil mixture has passed through the test section (10), it can either pass through a cooler (11) or flow directly to the phase separation and oil storage tank. An oil mist filter (12) removes any remaining oil in the air stream before it is vented to the outside. The air/oil mixture passes through a 0.9m long flow development section prior to entering the half-inch diameter, 1.0m long test section. A 0.6m long stabilization section follows immediately downstream of the test section. The entire test section is made of Lexan polycarbonate tubing to allow for complete flow visualization.

Two turbine flow meters (4) are used to measure the oil flow rate, with a range of 0.0036 – 0.51 kg/s (0.07-10.0 USGPM). Four rotameters (8) in a bank are used to measure the air flow rates, with a range 0-600 SCFH. Two Rosemount pressure transducers with an accuracy of ± 0.5% full scale are used to measure the system pressure and pressure drop along the pipe. Temperature is measured at various locations throughout the loop using type K thermocouples. Five standard liquid filled pressure gages are used to monitor pump pressure, inlet air pressure, inlet mixer conditions, and tank pressure. Flow regimes are identified by visual observation with the aid of a high-speed video camera (up to 1000 frames/s). The data is acquired using an AT-M10-16E-10DAQ board for the pressures and a PCI-6034E board with SCB-68 connection block for the temperatures. All data is processed using National Instrument's LabVIEW software in a program especially written for this research program.

RESULTS AND DISCUSSION

Flow Regime Maps

While as many as 31 different flow regimes have been identified for horizontal two phase flow (Hand and Spedding, 1993), only 6 main flow regimes are distinguished in this study. These are: Stratified (ST), Wavy (W), Annular (A), Mist (M), Plug (P), and Slug (S). Due to the existence of several sub regimes in slug flow, 3 additional slug sub regimes are identified: Slug Building Zone (SBZ), Foam Slug (FS) and Blow Through Slug (BTS).

The flow regime maps of Mandhane, Taitel and Dukler, and Spedding and Nguyen based on air-water properties were compared as a first step. This provides consistency between all three maps, as air-oil property corrections are not available for all three maps. The slug flow regime is well predicted by the flow map of Mandhane (Figure 2), with all data points falling within the suggested 'slug area' of the map. Transition between slug flow and annular flow is represented by the blow through slug data, which occurs at air superficial velocities in the range of 6 – 20 m/s. This transition is clearly over-predicted by the map, which suggests the transition occurs at higher air superficial velocities of 11 – 70 m/s (with increasing oil velocity). The map also poorly predicts the plug to slug transition, with the current data indicating the transition occurs at higher superficial gas velocities (1.2-2.5 m/s) over the range of liquid superficial velocities (0.25-4.3 m/s) than suggested by the map. All of the other transition boundaries are found to have transition data points on both sides of the predicted line. This does not necessarily indicate a problem with the transition boundary, as transition between flow regimes occurs more gradually than suggested by most flow regime maps (Barnea et. al., 1979).

The Taitel and Dukler (1976) flow regime map (for a 2.5 cm dia. pipe) is presented using superficial velocities (Figure 3). The transition boundaries between plug and slug flow, and annular and mist flow, were not developed by Taitel and Dukler and therefore cannot be evaluated. The transition between slug and annular flow, as represented by the blow through slug flow regime, is accurately predicted at oil velocities in the range of 0.3 – 0.7 m/s. At velocities greater than 0.7 m/s, the present data indicates transition occurs at lower gas velocities than those predicted by the map. Transition between wavy and annular flow regimes also appears to be well predicted at oil velocities below 0.1 m/s. All the other transitional boundaries require adjustment to better predict the transition between flow regimes. For example, the stratified to plug transition is predicted to occur at oil superficial velocities of 0.12 – 0.16 m/s, but plug flow was observed at an oil superficial velocity of 0.08 m/s. Similarly, the slug to dispersed flow regime transition range for the oil superficial velocity is over-predicted by 1.5 m/s.

The dimensionless plotting parameter map of Spedding and Nguyen (1980) is compared with the present data in Figure 4. In order to compare their flow map to other maps, Spedding and Nguyen (1980) used air and water two-phase flow results to obtain the transition boundaries. The definitions for the flow regions of this map are different than those of the previous two maps. For example, the blow through slug flow regime is represented as a flow region and not a transitional boundary. The same is true for the wavy to slug flow transition. The map predicts the blow through slug and annular flow regime data with a great deal of accuracy, however, the slug region is not well predicted by the flow regime map. Unlike the other two flow maps presented here, the dimensionless numbers used for the plotting parameters rely on the physical properties of the two phases indirectly. However, Spedding and Nguyen (1980) suggest that transitional boundary prediction errors are more likely to result from differences in test facilities than from use of different two-phase systems.

In order to evaluate the overall usefulness of the three flow regime maps, the maps were compared against one another. The ability of each map to correctly predict the flow regimes was calculated using the method suggested by Mandhane et. al. (1974). The number of correctly predicted points in an individual flow regime is divided by the number of total observed points in the flow regime and converted to a percentage. The total number of correctly predicted points and

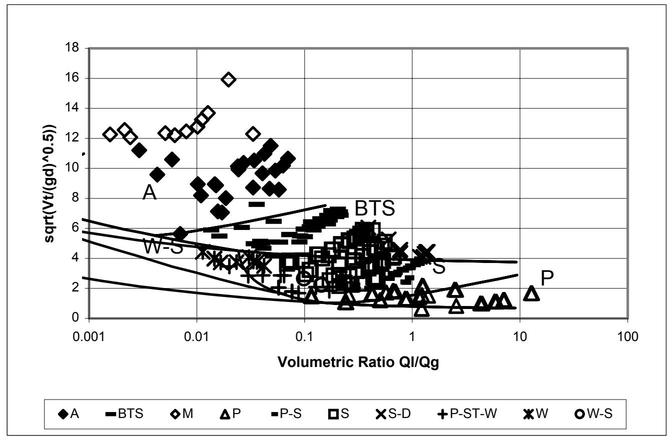

Figure 4 – Spedding & Nguyen (1980) flow regime map

the average accuracy of the whole map can then be determined (Table 1). The Mandhane et. al. (1974) and Taitel and Dukler (1976) flow regime maps predict the slug region with 100% accuracy. While Taitel and Dukler (1976) do not define a transition boundary between plug and slug flow, most of the plug points still lie within the defined "intermittent" region. In comparison the Spedding and Nguyen (1980) flow regime map performs poorly in the slug region but has a high accuracy in predicting the Blow Through Slug and Annular flow regimes. Overall the Taitel and Dukler (1976) flow regime map is found to have the highest prediction accuracy at 53%, which can be partly attributed to the high accuracy in predicting the flow regimes where the most data was collected.

Pressure Drop Measurements

Four frictional pressure drop models (Homogeneous, Martinelli, Chisholm, and Olujic) were compared against the measured pressure drop data over the entire range of flow regimes. Overall, the homogenous model was found to under-predict the pressure drop by an average of 41% (Figure 5). An analysis of the pressure drop results by flow regimes indicate that the mist flow and annular flow regimes are the best predicted by the homogeneous model. Figure 6 shows the pressure drop data for these two flow regimes, with an average under-prediction of about 26%. This is expected given the inherent assumptions in the homogeneous model.

The Martinelli model was found to consistently under-predict the pressure drop by an average of 47% across all flow regimes (Figure 7). The best prediction from the Martinelli model was for the slug-building zone, which averaged a 35% under-prediction (Figure 8). The annular flow regime was the most poorly predicted, with an average 56% under-prediction (Figure 8). The relatively small scatter in the data from the least squares line to the data from the Martinelli model allows for a simple single correction factor to be applied for all flow regimes. Taking the inverse of the slope of the trendline, the model is multiplied by a factor of 1.9, resulting in the data distribution shown in Figure 9.

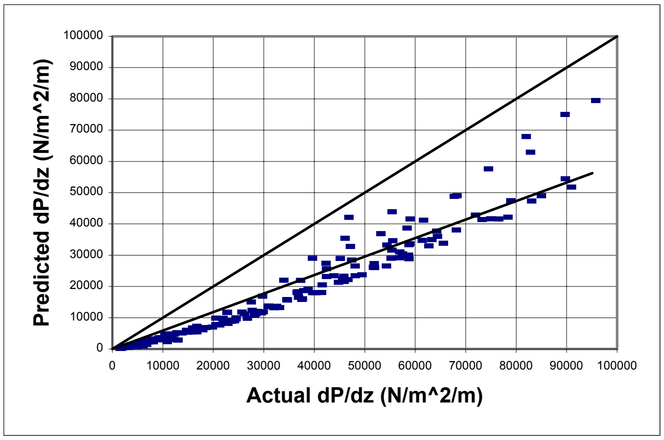

Figure 5 – Comparison with the Homogeneous Model

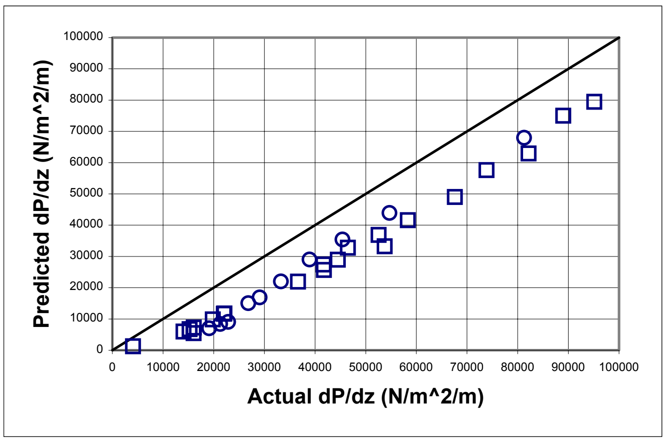

Figure 6 – Comparison of Mist and Annular Flow Regimes with the Homogeneous Model (□, Annular; ○, Mist)

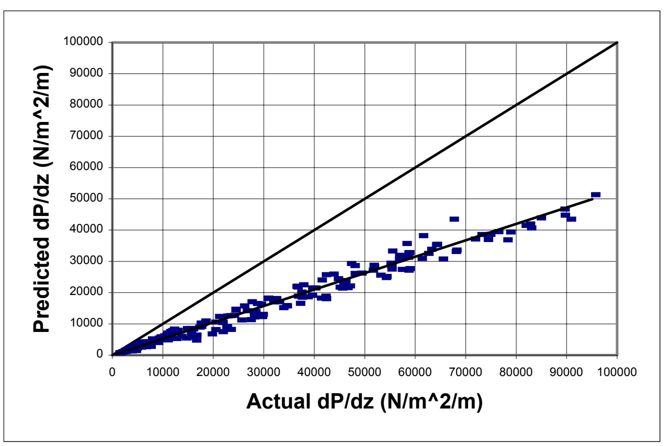

Figure 7 – Comparison with the Martinelli Model

The corrected model predicts the frictional pressure drop within ±30% of the measured pressure drop. The accuracy improves to ±15% for pressure drops above 15000 N/m^2/m.

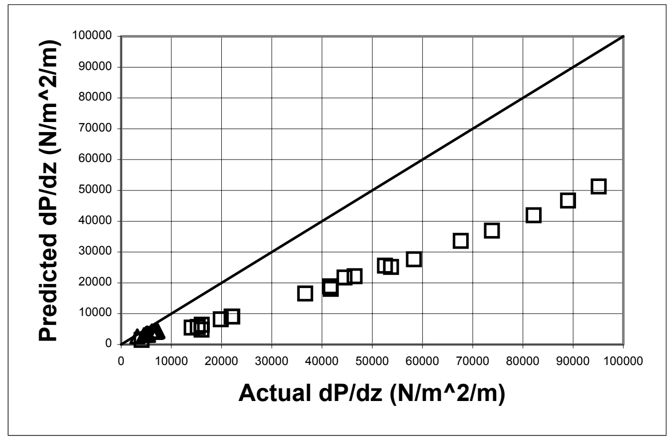

Figure 8 – Comparison of Annular and Slug Building Zone with the Martinelli Model (□, Annular; Δ, SBZ)

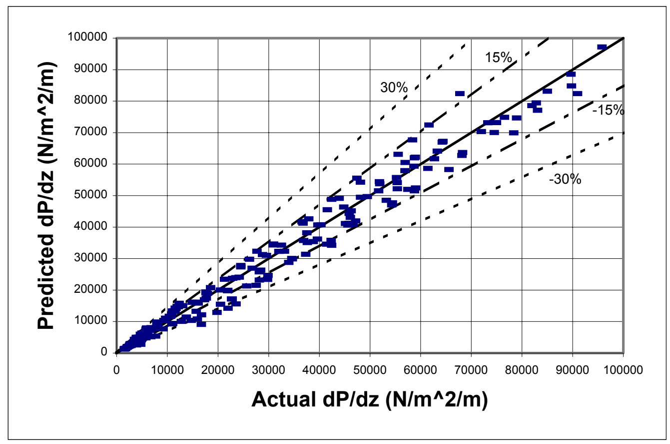

Figure 9 – Corrected Martinelli Model

The Chisholm model (Figure 10) predicted the pressure drop with an average of 43% under-prediction across all flow regimes. However, several of the flow regimes were predicted with a much higher accuracy (<30%). The flow regimes predicted with higher accuracy include plug, slug, slug building zone and the slug to plug transition. Figure 11 shows the data for these four regimes, with the slug building zone flow regime pressure drop predictions having almost no deviation from the measured values. Unlike the Martinelli frictional pressure drop model, the predictions from the Chisholm model do not closely follow one trendline, making a simple correction to the model difficult. The relatively accurate prediction (within 35%) of many of the flow regimes, however, indicates correction of the model may not be necessary. This model may be useful as a first step in developing a new model that predicts pressure drop based on flow regime.

Ferguson and Spedding (1995) examined the accuracy of 14 different frictional pressure drop models with respect to individual flow regimes, and found the Olujic model to perform

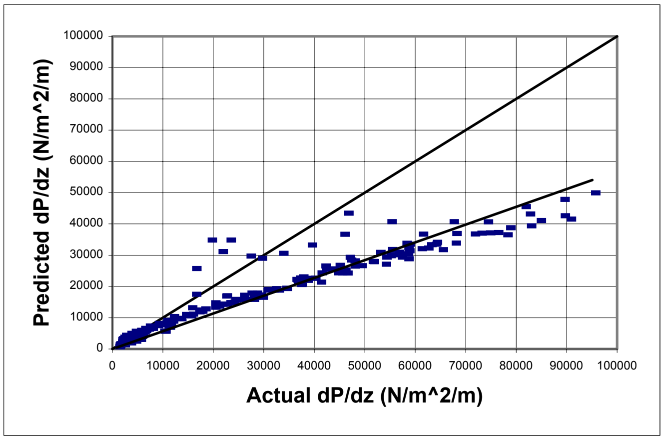

Figure 10 – Comparison with the Chisolm model

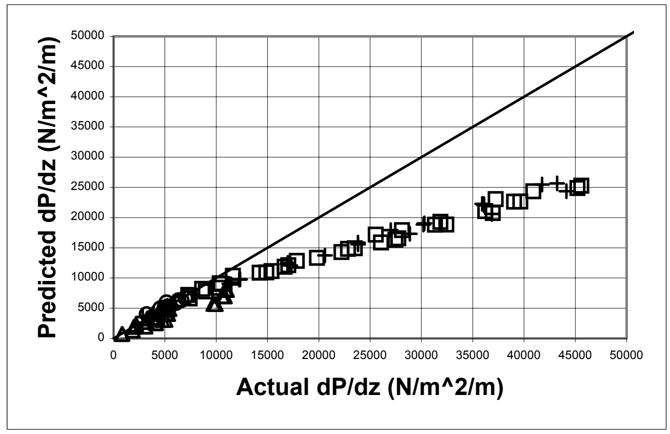

Figure 11 – Comparison with the Chisolm model (Δ, Plug; □, Slug; ○, SBZ; +, P-S)

the best over the largest number of identified flow regimes. The Olujic model was therefore investigated using the current air-oil data. The Olujic model attempts to separate the flow regimes into two regions, based on the Froude number and phase volume flow ratio, and uses different pressure drop models in the two different flow regions. When the gas phase velocity is much greater than the liquid phase velocity, the region is designated as alpha. When the velocities are approximately equal, the region is designated as beta. In terms of flow regimes, the beta region represents plug and dispersed flow, and the alpha region all others. In the beta region, the model under-predicted the data by an average of 45% (Figure 12). In the alpha region, the model produced reasonable results for pressure drops below 25000 $N/m^2/m$ (Figure 13). Above this value, the alpha region model greatly over-predicted the pressure drop (not shown in the figure), with all over-predicted points representing data in the blow through slug, annular, or mist flow regimes. It was determined that some flow regimes contained points falling in both the alpha and beta regions, suggesting that the model was not correctly identifying the specific flow regimes. Therefore, it is speculated that the criteria used to select the flow region model is not accurately separating the data by flow regimes. The Olujic model is, however, an useful example of a pressure drop model based on flow regimes.

In order to evaluate the different pressure drop models, the root mean square error of each model was computed and compared against the other models (Table 2). For each flow regime, the model that best predicts the pressure drop has been highlighted. The foam slug and slug-dispersed regimes are predicted to the same accuracy by the Homogeneous and Martinelli models, while the plug flow regime is predicted with almost the same accuracy by the Chisholm and Martinelli models. Of the eleven flow regimes evaluated in this study, the Chisholm model most accurately predicts seven. These include the intermittent (plug and slug) flow regimes, as well as the high-speed air flow rate (annular, mist and blow through slug) flow regimes. All regimes associated with high oil flow rates,

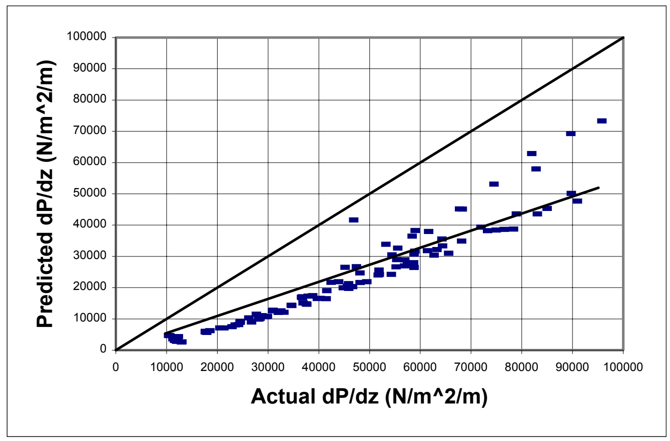

Figure 12 – Comparison with the Olujic model (Beta Region)

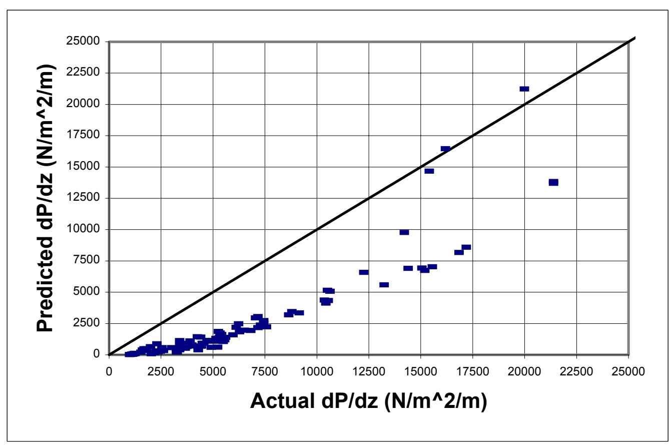

Figure 13 – Comparison with the Olujic model (Alpha Region)

including foam slug, dispersed flow, and the slug-dispersed transition, are well predicted by the Martinelli model. The Homogeneous model also predicted the foam slug and slug-dispersed transition well.

CONCLUDING REMARKS

Flow regime and pressure drop measurements for air-oil two-phase flow in a half-inch diameter horizontal pipe have been obtained. The current flow regime data are compared with the flow maps of Mandhane et al. (1974), Taitel & Dukler (1976), and Spedding and Nguyen (1980). While the current flow regime data exhibit the same trends of these flow maps, there are significant differences in the transition boundaries. For example, slug flow occurs over a narrower range of gas and liquid superficial velocities than that predicted by the maps. Overall, the Taitel & Dukler map is found to predict the flow regimes most accurately. The pressure drop data is compared against several existing models, including the homogeneous model, the separated flow models of Martinelli and Chisolm, and the Olujic model. The Martinelli model was found to consistently under predict the pressure drop by about 47% for all flow regimes. This suggests that a simple correction factor can be used to improve the model for the present air-oil flows. The Chisolm model predicts the pressure drop in several flow regimes with an accuracy of less than 30%, indicating it can be used accurately for a model based on flow regimes. The Olujic model attempts to differentiate the different flow regimes. However, it had the highest errors of the three models evaluated in this study. It is unlikely that a single model can predict the pressure drop over all flow regimes. A model that takes into account the flow regime is likely to provide the most accurate results.

ACKNOWLEDGEMENTS

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Table 1: Comparison of Flow Regime Maps

Flow Regime	Number of Points	Mandhane Correct (%)	T&D Correct(%)	S&N Correct(%)
A	24	54.2	66.7	**95.8**
M	11	**100.0**	90.9	0.0
S	60	**100.0**	**100.0**	48.3
W	9	33.3	33.3	44.4
P	35	**82.9**	**82.9**	54.3
BTS	38	2.6	15.8	**97.4**
P-S	34	0.0	0.0	0.0
P-ST-W	12	16.7	0.0	0.0
S-D	12	8.3	16.7	0.0
Total	235	50.4	**53.3**	47.5

Table 2: Pressure Drop Percentage Root Mean Square Error

Flow Regime	Homog.	Chisholm	Martinelli	Olujic
A	42	**38**	56	78
BTS	52	**40**	52	53
M	42	**39**	57	311
FS	**44**	45	**44**	49
P	65	**26**	**27**	84
P-S	64	**29**	36	67
P-ST-W	74	49	**31**	87
S	60	**33**	43	59
SBZ	70	**9**	35	72
S-D	**43**	45	**43**	47
W	59	76	**35**	72
Total	55	**35**	**40**	79

Defined Flow Regimes:

A – Annular	BTS – S to A Transition
D – Dispersed	FS – Foam Slug
M – Mist	P – Plug
S – Slug	SBZ – Slug Building Zone
ST – Stratified	W – Wavy