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Productivity and Injectivity of Horizontal Wells

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Quarterly Report

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Summary of Technical Progress

A number of activities have been carried out in the last three months. A list outlining these efforts is presented below.

- Work on developing a three-dimensional Voronoi grid simulator is progressing. Extensive testing of the grid generation and visualization modules of the simulator is continuing while modifications and improvements are being made to these capabilities.

- The recently developed semi-analytical method for calculating critical cresting rates is being extended for the case of simultaneous gas and water coning toward a horizontal well.

- The accuracy of available correlations and analytical models for breakthrough times of horizontal wells is being investigated through simulations of a field case.

- Work on developing methods for coupling between reservoir and the wellbore through a network modeling approach is progressing. The current stage of the study involves evaluation of available analytical methods.

- The necessary modifications have been made to the rig at the Marathon facility and the high rate two-phase flow experiments are about to commence.

- New correlations for wall friction and interfacial friction factors have been developed for the stratified flow in horizontal and inclined pipes. After further testing this new approach will be used in our mechanistic model.

This quarterly report has been entirely devoted to the task listed in the last item above and we only present an abridged version of the Masters report of Mr. Liang-Biao Ouyang on which it is based. The complete study will be included in the next Annual Report of the Project.

Stratified Flow Model and Interfacial Friction Factor Correlations (Task 3)

Introduction

Gas-liquid flow in pipes is of practical importance in petroleum, chemical, nuclear and geothermal industries. Theoretical and experimental prediction of key factors, such as pressure drop, liquid holdup (or liquid volume fraction in the system), interfacial area, heat and mass transfer, is essential for proper design and operation of pipe systems.

Interfacial friction shear is an intrinsic characteristic of gas-liquid two-phase flow and it has a profound influence on the properties and the nature of the flow process. The relationship for the interfacial friction shear is an indispensable condition to complete any mechanistic model for gas-liquid flow in pipes. Notwithstanding many different correlations reported in the literature for calculating the interfacial friction factor (i.e., the dimensionless friction shear), this remains largely an unresolved area. Most, if not all, available correlations are deduced from specific range of experimental conditions, such as gas Reynolds number, liquid Reynolds number, pipe diameter, liquid holdup, inclination angle and flow patterns. Such correlations may only apply to a particular range of flow conditions. Significant errors may result when these correlations are used under flow conditions that are different from those used to develop them. Furthermore, existing mechanistic models typically exhibit discontinuities in pressure gradient and liquid holdup predictions across flow pattern boundaries. Those discontinuities may cause serious problems in full field simulations. One of the main reasons for the discontinuities is the inclusion of inappropriate interfacial friction factor correlation.

The main purpose for this study is to evaluate the existing interfacial friction factor correlations based on experimental observations. While, direct and accurate measurements of the wall friction and interfacial friction shears are the first choice for this evaluation, few experiments belonging to this category have been reported in the literature. Though we can also determine both the wall friction and interfacial friction shears by using any existing stratified flow model and thus evaluate different correlations, as we will find later in this report, the most widely-used stratified model is inconsistent with experimental observations.

Stratified Flow Model

Stratified flow in pipes refers to the flow pattern where the gas phase flows at the top of the pipe, while the liquid phase flows at the bottom (Fig. 1). It is divided further into stratified smooth flow and stratified wavy flow, depending on the shape of the interface.

The momentum balance equations for stratified flow in pipes can be derived for both gas and liquid parts (Govier & Aziz, 1972; Taitel & Dukler, 1976)

$$-A_L\left(\frac{dp}{dL}\right)-\tau_{wL}S_L+\tau_i S_i-\rho_L A_L\frac{g}{g_c}\sin\theta=0 \qquad (1)$$

$$-A_G\left(\frac{dp}{dL}\right)-\tau_{wG}S_g-\tau_i S_i-\rho_G A_G\frac{g}{g_c}\sin\theta=0 \qquad (2)$$

The friction shears are expressed in the form of the Fanning friction factor

$$\tau_{wL}=\frac{f_{wL}\rho_L V_L^2}{2g_c} \qquad (3a)$$

$$\tau_{wG}=\frac{f_{wG}\rho_G V_G^2}{2g_c} \qquad (3b)$$

$$\tau_i=\frac{f_i\rho_G(V_G-V_L)\left|V_G-V_L\right|}{2g_c} \qquad (3c)$$

The Fanning friction factors for the gas and liquid phases are usually evaluated from single phase equation, such as the Colebrook-White (1939), or the Blasius equation, based on the Reynolds number defined as a function of local velocities and hydraulic diameters (this method is termed as standard method in this report). The interfacial friction factor is obtained from empirical correlations. While there are relatively few methods available to calculate wall friction factors, dozens of correlations have been proposed for the determination of interfacial friction factor. However, predictions vary significantly among the correlations (Ouyang, 1995) and it is difficult to know which correlation to use for a particular case.

Consistency Check and Model Evaluation

Due to the presence of measurement errors, it is not easy to obtain experimental data which are completely consistent. Hence we should look into the degree of consistency in experimental data. Tables 1a and 1b show the comparison of the interfacial friction shears obtained from the two momentum balance equations (Eqs. 1 & 2) for all available data sets. The average absolute error (*AAE*) is used in assessing the order of magnitude of the difference, the average absolute relative error (*AARE*) is taken as the accuracy criterion which best expresses the average difference, while the standard deviation (*SDE* and *SRDE*) measures the scattering of results around the average value.

The high errors appearing in the consistency check for both stratified smooth and stratified wavy flows for most data sets (Tables 1a and 1b) suggest the need for further investigation. Two possibilities exist which may cause high error in the consistency check. One is measurement errors in the experimental data. The other is that the stratified flow model described above is inappropriate.

To check the influence of measurement error on the consistency study, errors are introduced artificially in the measured liquid holdup data and the measured pressure gradient data of data sets SU-101 and SU-205 for stratified smooth flow and of data sets SU-96 and SU-200 for stratified wavy flow. Six types of artificial errors are used, i.e., $\pm 10\%$ changes in measured liquid holdup data, $\pm 5\%$ and ± 0.0001 psi/ft changes in measured pressure gradient data. It is found that *AAE*s, *AARE*s and *SDE*s do not change significantly for data sets considered.

Therefore, it can be concluded that the influence of measurement errors in experimental data cannot be the main reason for the high error in consistency checks. In other words, the model used for the consistency check, though the most widely-used model for describing gas-liquid flow in pipes, may be inappropriate.

Recall the stratified flow model discussed above. The only parts in this model which may cause problems in the consistency check are the determination of the wall friction shears which are obtained through the calculation of the wall friction factors. The Colebrook-White (1939) equation or the Blasius-type equations are usually applied to calculate the wall friction factors for both gas and liquid phases in turbulent flow. As we know, the Colebrook-White equation and the Blasius-type equation were proposed to calculate the friction factor in single-phase flow and whether they can be used for two-phase or three-phase flow is unclear. Several researchers, such as Kowalski (1984), Kowalski (1987), Andritsos & Hanratty (1987), and Andreussi & Persen (1987), stated that the determination of the wall friction shear for gas phase (i.e., the wall friction factor calculation) is more reliable than the wall friction shear for the liquid phase. Direct measurements of the wall friction shears also verified this observation (Govier et al., 1957, Govier & Omer, 1962, Kowalski, 1984). So, on the assumption that most of the experimental data available are consistent, the liquid phase wall friction factor can be calculated from the pressure equation (Ouyang, 1995) such that the predicted liquid holdup and the predicted pressure gradients match the experimental results. The wall friction factor for the liquid phase obtained in this way is termed experimental f_{wL}.

Fig. 2 compares the experimental wall friction factors with the predicted values determined from the standard method. It can be easily seen that the standard method underestimates the wall friction factor for the liquid phase for both stratified smooth and stratified wavy flows. This is expected considering the fact that the Colebrook-White (1939) equation and the Blasius equation (or other equivalent forms) were proposed for single phase flow in pipes. A different mechanism dominates the fluid flow characteristics for multiphase flow in pipes. Hence the use of standard method to describe the wall friction is inappropriate and will lead to errors. Govier et al. (1957) and Govier & Omer (1962) determined the liquid phase wall friction factor from the measured pressure drop and liquid holdup data and found that, depending upon the relative volume of gas and liquid present, the liquid phase wall friction factor was 2.0 to 2,000 times larger than the value obtained from the single phase relationship. Unfortunately, enough attention has not been paid to their observations.

Comparison with Experimental Data

In this study, 18 different interfacial friction factor correlations, including all the widely-used correlations reported in the literature, have been incorporated in the stratified flow model to predict the liquid holdup and the pressure gradient. The predictions have been done separately for stratified smooth flow and stratified wavy flow data.

For stratified smooth flow, Table 2a shows that the modified Andreussi & Persen (1987) correlation gives the best prediction for liquid holdup, since the *AARE* (57.22%) is lower than those from other correlations and the *AAE* (0.065) only second to the lowest value (0.0632 for the Cheremisinoff & Davis correlation). The Hanratty & Andritsos (1984) and the Andritsos & Hanratty (1987) correlations rank as second and third best in the list. These three correlations are also the best ones for the prediction of pressure gradient. Their *AAE*s are 0.0038, 0.0035 and 0.0036 *psi/ft* respectively, which are much smaller than the corresponding results from other correlations. Unfortunately, even for these three correlations, the deviations of predicted liquid holdup and the pressure gradient from experiments are still quite large. The primary reason for this is that the predicted interfacial friction factors are different from those required for the correct prediction of experimental data. Fig. 3 displays an example of the deviations for the Andritsos & Hanratty (1987) correlation. It is instructive to note that the $f_i = f_{wG}$ correlation, even though it is commonly used by researchers for stratified smooth flow, doesn't predict pressure gradients and liquid holdups close enough to the measured values.

For stratified wavy flow, most correlations overestimate both the liquid holdup and the pressure gradient (Table 2b). Among the correlations considered, the modified Andreussi & Persen (1987) correlation predicts the closest liquid holdup to the measurements (*AAE* equals to 0.0607). The Andritsos & Hanratty (1987) correlation as well as the Cheremisinoff & Davis (1979) correlation also give good predictions of liquid holdup. But, for pressure gradient prediction, the modified Andreussi & Persen (1987) correlation does not predict good results, whereas the Andritsos & Hanratty (1987), Hanratty & Andritsos (1984) correlations provide best predicted pressure gradient results. The Baker et al. (1988) correlation yields fairly good results for pressure gradients. Comparisons of the predicted interfacial friction factor and the corresponding values obtained from experimental parameters are also shown in Fig. 3.

Hence, it can be concluded that none of the existing interfacial friction factor correlations can predict satisfactory results for the liquid holdup and the pressure gradient.

Development of New Correlations

From the experimental data available from the Stanford Multiphase Flow Database (SMFD), the experimental wall friction factor data for liquid phase have been computed and applied to develop a new correlation by means of regression. The regression was primarily done based on the dimensionless groups which affect gas-liquid two-phase flow in pipes. Two regression schemes were used for our investigation, one is the pseudo-linear regression (nonlinear regression which can be transformed into a linear one, it is also called general multiple linear regression), the other is the Polytope method (Gill et al., 1981).

Different forms of correlations which combine different dimensionless variables have been tested to get the best fit of experimental liquid phase wall friction factor. Regression leads to the following new correlation

$$f_{wL} = 1.6291\, R_{eL}^{-0.5161}\, R_v^{0.0926} \qquad (4)$$

where R_v is the gas-liquid volume ratio.

Fig. 4 shows the comparison between the experimental and predicted liquid phase wall friction factor by new correlation (Eq. 4). The figure indicates that the new correlation gives much closer results for the liquid phase wall friction factor to the experimental values than the standard method (Fig. 2), but it still predicts unsatisfactory friction factor for some of the data points. The number of data points falling into this category is small considering the fact that about 800 data points are shown in Fig. 4.

As shown by Fig. 3, the predicted interfacial friction factors are substantially different from experimental values even for the best available correlations, such as the Andritsos & Hanratty (1987), the modified Andreussi & Persen (1987). Furthermore, discontinuities in liquid holdup and pressure gradient often occur at the transition of different flow patterns when applying available interfacial friction factor correlations in the mechanistic models (Aziz & Petalas, 1994). Such discontinuities can cause problems for full field flow simulations. Hence, it is necessary to develop a new correlaton for interfacial friction factor which can hopefully predict satisfactory results for liquid holdup and pressure gradient, and provide smooth flow pattern transitions. The same regression approach, as used for the liquid phase wall friction factor case, was also applied here.

The choice of the functional form of the regression correlation is related to the selection of the independent variables or dimensionless groups. Sometimes, relevant theory may indicate the appropriate functional form. However, the functional form of the regression correlation for interfacial friction factor is not known in advance and must be decided upon once the data have been collected and analyzed. The functional form is determined by means of analyzing the existing correlations and considering the coefficient of multiple determination, the error mean square (*MSE*), and other statistical parameters for the trial correlation.

Following this procedure, a new correlation for the interfacial friction factor has been developed

$$f_i = 10^{-8.0942+4.2893 E_L \sin\theta} \frac{f_{wL}^{0.8732} N_{vL}^{0.3072} N_D^{1.0365}}{N_{\mu G}^{1.9140} H^{0.9783}} \qquad (5)$$

where E_L is the liquid holdup, θ the pipe inclination angle, f_{wL} the wall friction factor for liquid phase, N_{vL} the liquid velocity number, N_D the pipe diameter number, $N_{\mu G}$ the gas viscosity number, and H the holdup ratio.

It should be noted that there exist same problems with both the new liquid phase wall friction factor correlation and the interfacial friction factor correlation as for any regression models in that they are dependent upon the data available. When more data over a wider range of fluid properties, pipe sizes and inclination angles are considered, the results may change.

Test of New Correlations

No matter how strong the statistical relations, no cause-and-effect pattern is necessarily implied by a regression model. Even if the new correlations are developed on the basis of some underlying mechanisms, the new correlations still need to be examined with experimental data.

As expected, the new correlations can predict more satisfactory liquid holdup and pressure gradient for the experimental data used for developing the correlations than other correlations. Figs. 5a and 5b show the predicted liquid holdup and pressure gradient for stratified smooth and stratified wavy flow against experimental data. Notwithstanding the fact that large deviations from experimental values still exist for some data points, the number of data points falling into this category is small compared to the amount of data considered. But we should note that for some special data sets, predictions by the new correlations are still unsatisfactory.

A good test of the new correlations is to apply them to predict either liquid holdup or pressure gradient and compare with reliable measurements not used in developing the correlations. Minami & Brill (1987) experiment, in which only the liquid holdup data were measured, is selected for the test. This experiment consists of two types of fluid combinations. One is an air-water system where 54 measurements are provided and the other is an air-kerosene system where 57 measurements are reported.

Fig. 6 shows the comparison between measured and predicted liquid holdup by the new correlations for the liquid phase wall friction factor and for the interfacial friction factor. It is found that the new correlations provide satisfactory predictions of liquid holdup for the air-kerosene case but underpredict the liquid holdup for the air-water case.

Conclusions

Different interfacial friction factor correlations have been used to predict the liquid holdup and pressure gradient and compare them with experimental observations. The comparison results show that: (a) most existing correlations can lead to large deviations from measurements; (b) among available correlations, the Andritsos & Hanratty (1987) correlation, the modified Andreussi & Persen (1987) correlation, as well as the Hanratty & Andritsos (1984) correlation, are the best choices to determine the interfacial friction factor for stratified flow.

Consistency checks of experimental data indicate that the widely-used stratified flow model is inconsistent with experimental observations. It must be noted that this conclusion is independent of the interfacial friction factor correlation. On the basis of reported experiments with direct measurements of wall friction shear stress, we conclude that the liquid phase wall friction shear calculation should be reconsidered. The standard method (i.e., the single phase method) is found to underestimate the liquid phase wall friction factor.

New correlations for both the interfacial friction factor and the liquid phase wall friction factor have been developed based on experimental observations. Satisfactory coincidence is observed when new correlations are applied to predict the liquid holdup for the Minami & Brill (1987) experiments.

Selected References

Andreussi, P. and Persen, L. N. 1987 "Stratified Gas-Liquid Flow in Downwardly Inclined Pipes." Int. J Multiphase Flow, Vol. 13, No 4, 565-575

Andritsos, N. and Hanratty, T. J. 1987 "Influence of Interfacial Waves in Stratified Gas-Liquid Flows." AIChE J, Vol. 33, No 3, 444-454

Aziz, K. and Petalas, N. 1994 Multiphase Flow Technology for the Development of Oil and Gas Reservoirs. Course Notes, Stanford University, Stanford

Baker, A., Nielsen, K. and Gabb, A. 1988 "Pressure Loss, Liquid-Holdup Calculations Developed." Oil & Gas J, Mar 14, 1988, 55-59

Gill, P. E., Murray, W. and Wright, W. H. 1981 Practical Optimization. Academic Press, London, 401p

Govier, G. W. and Aziz, K. 1972 The Flow of Complex Mixtures in Pipes, Van Norstrand Reinhold, 792p

Govier, G. W. and Omer, M. M. 1962 "The Horizontal Pipeline Flow of Air-Water Mixtures." Can. J Chem. Eng., Vol 40, No 6, 93-104

Govier, G. W., Radford, B. A. and Dunn, J. S. C. 1957 "The Upwards Vertical Flow of Air-Water Mixtures." Can. J. Chem. Eng., Vol 35, No 8, 57-70

Kowalski, J. E. 1984 "Interfacial Shear Stress for Smooth and Wavy Stratified Flow in Pipes." AIChE Conference Paper 105a, Fundamental Research in Multiphase Flows, San Francisco, Nov 29, 1984

Kowalski, J. E. 1987 "Wall and Interfacial Shear Stress in Stratified Flow in a Horizontal Pipe." AIChE J, Vol 33, No 2, 274-281

Minami, K. and Brill, J. P. 1987 "Liquid Holdup in Wet-Gas Pipelines." SPE Production Engineering, Vol 2, No 1, 36-44

Ouyang, L. -B. 1995 Stratified Flow Model and Interfacial Friction Factor Correlations, M. S. Thesis, Stanford University, Stanford.

Taitel, Y. and Dukler, A. E. 1976 "A Model for Prediction of Flow Regime Transitions in Horizontal and near Horizontal Gas-Liquid Flow." AIChE J, Vol 22, 47-55

Table 1a Consistency Check of the Available Experimental Data (Stratified Smooth Flow)

Data Set	Number of Data	AE (psf)	AAE (psf)	RMS (psf)	SDE (psf)	ARE (%)	AARE (%)	RMSR (%)	SRDE (%)
SU-24	9	-0.0918	0.0918	0.0998	0.0416	-102.98	102.98	105.77	25.63
SU-25	11	-0.0366	0.0366	0.0476	0.0321	-112.66	112.66	117.58	35.31
SU-26	3	-0.0462	0.0462	0.0489	0.0196	-94.92	94.92	98.68	33.03
SU-28	1	-0.1323	0.1323	0.1323	—	-104.83	104.83	104.83	—
SU-29	1	-0.1349	0.1349	0.1349	—	-109.58	109.58	109.58	—
SU-96	29	-0.0124	0.0124	0.0192	0.0149	-136.73	136.73	139.83	29.77
SU-101	45	0.0005	0.0006	0.0009	0.0008	45.14	64.32	77.49	63.70
SU-109	2	0.0326	0.0875	0.0933	0.1237	-16.35	82.15	82.78	114.76
SU-110	9	-0.0476	0.0476	0.0495	0.0145	-102.40	102.40	106.06	29.28
SU-184	7	0.0378	0.0389	0.0458	0.0278	78.26	84.36	89.57	47.04
SU-188	8	0.6729	0.6729	1.0883	0.9144	88.15	88.15	103.15	57.26
SU-189	14	2.6010	2.6010	2.7356	0.8798	87.62	87.62	87.91	7.46
SU-190	9	0.2638	0.2638	0.3896	0.3041	105.09	105.09	105.57	10.64
SU-191	11	0.3461	0.4096	0.6016	0.5161	58.99	111.23	115.13	103.69
SU-192	9	0.8979	0.9322	1.2987	0.9952	83.93	120.94	126.73	100.71
SU-193	2	9.6615	9.6615	10.0383	3.8531	162.01	162.01	165.16	45.35
SU-194	19	4.5296	4.5296	5.0903	2.3862	113.49	113.49	114.74	17.34
SU-195	1	8.2426	8.2426	8.2426	—	118.93	118.93	118.93	—
SU-196	15	4.9025	4.9087	6.2529	4.0175	92.79	106.04	107.27	55.71
SU-197	11	-0.1188	0.4619	0.5799	0.5953	-42.30	103.06	104.50	100.22
SU-198	13	5.3311	5.3311	5.5865	1.7379	100.32	100.32	100.41	4.37
SU-199	74	-0.0340	0.0346	0.0588	0.0484	-64.66	88.95	93.49	67.99
SU-200	23	-0.0729	0.0729	0.1503	0.1344	-53.25	53.25	56.09	18.02
SU-201	5	-0.0179	0.0192	0.0260	0.0211	-13.08	14.69	17.49	12.98
SU-202	1	0.0118	0.0118	0.0118	—	5.48	5.48	5.48	—
SU-203	1	0.1031	0.1031	0.1031	—	48.43	48.43	48.43	—
SU-205	10	0.1098	0.1819	0.4635	0.4747	-113.28	153.89	164.24	125.36
SU-206	37	5.7107	5.8654	13.3760	12.2625	-56.99	119.67	122.52	109.95
SU-207	41	25.7271	25.8997	40.8723	32.1540	2.56	111.26	114.50	115.90
SU-208	38	9.1726	9.6558	29.7337	28.6632	-74.85	105.07	107.48	78.17

Table 1b Consistency Check of the Available Experimental Data (Stratified Wavy Flow)

Data Set	Number of Data	AE (psf)	AAE (psf)	RMS (psf)	SDE (psf)	ARE (%)	AARE (%)	RMSR (%)	SRDE (%)
SU-21	14	0.0018	0.2473	0.3581	0.3716	-17.46	52.01	55.54	54.71
SU-23	37	-0.0524	0.4103	0.5624	0.5677	-39.64	70.94	80.15	70.63
SU-24	61	-0.1312	0.1352	0.3286	0.3038	-63.10	65.79	76.54	43.69
SU-25	33	2.8126	3.0949	11.8744	11.7154	-47.09	64.68	69.85	52.39
SU-26	38	-0.2457	0.2484	0.4213	0.3469	-65.89	66.24	77.08	40.54
SU-28	4	-0.2313	0.2313	0.2723	0.1659	-71.49	71.49	85.66	54.49
SU-29	4	-0.2422	0.2422	0.2959	0.1963	-72.03	72.03	84.61	51.26
SU-53	5	-0.0478	0.0478	0.0519	0.0227	-47.72	47.72	48.31	8.46
SU-54	3	0.0059	0.0300	0.0346	0.0417	-8.17	67.19	68.87	83.76
SU-96	10	-0.0404	0.0404	0.0536	0.0371	-80.85	80.85	81.37	9.65
SU-109	2	0.7755	0.7755	1.0817	1.0665	75.28	75.28	92.88	76.94
SU-110	1	1.5209	1.5209	1.5209	—	141.57	141.57	141.57	—
SU-199	27	-0.2208	0.2213	0.3273	0.2463	-47.34	60.15	62.80	42.04
SU-200	29	-0.8053	0.8075	0.8877	0.3801	-66.41	66.66	68.79	18.23
SU-201	17	-0.6811	0.6831	0.9375	0.6641	-44.61	45.32	51.62	26.76
SU-202	11	-0.2962	0.2962	0.4000	0.2819	-29.44	29.44	32.58	14.63
SU-203	10	-0.3529	0.4078	0.7501	0.6978	-13.80	26.73	30.50	28.68
SU-204	50	-0.7828	0.8047	1.0664	0.7316	-33.81	36.30	40.47	22.48
SU-205	52	-0.1414	0.2079	0.3687	0.3439	-62.42	81.07	89.89	65.32
SU-206	39	1.4571	1.8597	5.3518	5.2170	-7.04	94.02	101.75	102.84
SU-207	18	8.8404	9.4962	17.4175	15.4424	3.8847	115.46	121.96	125.44
SU-208	5	26.1374	26.6737	41.7535	36.4039	-13.52	125.10	125.77	139.80
SU-209	63	50.9893	52.5793	251.825	248.590	-48.85	128.40	131.52	123.10
SU-213	16	-0.0524	0.0523	0.0586	0.0270	-139.17	139.17	142.87	33.35
SU-215	25	1.7081	1.9508	5.5383	5.3769	-66.78	125.95	129.54	113.28

Table 2a Comparison between the Measured and Predicted Liquid Holdup and Pressure Gradient (Stratified Smooth Flow)

	Liquid Holdup				Pressure Gradient			
Correlation	ARE (%)	AARE (%)	AE	AAE	ARE (%)	AARE (%)	AE	AAE
$f_i = 0.0142$	145.47	157.79	0.0718	0.0893	-10.94	167.01	0.0042	0.0052
Andritsos & Hanratty (1987)	58.28	74.11	0.0583	0.0759	-17.79	139.09	0.0027	0.0036
Andreussi & Persen (1987)	39.54	57.22	0.0436	0.0650	-42.71	186.77	0.0023	0.0038
Baker et al. (1988) ($V_i = V_G - V_L$)	166.53	177.88	0.0711	0.0890	-12.47	171.00	0.0044	0.0055
Baker et al. (1988) ($V_i = V_L$)	155.22	166.57	0.0694	0.0873	-15.92	162.52	0.0039	0.0051
Cheremisinoff & Davis (1979)	96.70	116.01	0.0403	0.0632	299.59	753.12	0.0057	0.0073
Cohen & Hanratty (1965)	101.33	120.10	0.0467	0.0689	268.29	688.78	0.0058	0.0072
$f_i = f_{wG}$	235.43	246.62	0.0879	0.1051	-3.61	182.93	0.0047	0.0059
Hanratty & Andritsos (1984)	49.42	67.42	0.0560	0.0743	-29.45	137.29	0.0026	0.0035
Kowalski (1984)	334.31	345.48	0.1119	0.1290	-3.56	187.68	0.0052	0.0064
Kowalski (1987)	379.64	390.66	0.1142	0.1309	38.91	245.56	0.0055	0.0067
Kaminaga et al. (1991)	173.77	186.09	0.0888	0.1059	-10.16	172.85	0.0043	0.0054
Kim et al. (1985)	99.36	113.51	0.0554	0.0750	12.15	200.54	0.0040	0.0049
Kokal & Stanislav (1989)	318.87	330.09	0.0939	0.1115	1.99	192.76	0.0051	0.0063
Laurinat et al. (1984)	204.84	216.36	0.0968	0.1138	10.54	200.85	0.0052	0.0063
Linehan (1968)	141.78	154.21	0.0669	0.0844	29.37	232.05	0.0045	0.0054
Spedding & Hand (1990)	281.18	292.36	0.0907	0.1079	3.90	195.07	0.0049	0.0061
Tsiklauri et al. (1979)	101.07	121.83	0.0453	0.0690	334.84	819.61	0.0062	0.0079

Table 2b Comparison between the Measured and Predicted Liquid Holdup and Pressure Gradient (Stratified Wavy Flow)

	Liquid Holdup				Pressure Gradient			
Correlation	ARE (%)	AARE (%)	AE	AAE	ARE (%)	AARE (%)	AE	AAE
$f_i = 0.0142$	248.66	254.06	0.1788	0.1897	82.17	188.42	0.0305	0.0507
Andritsos & Hanratty (1987)	76.98	94.50	0.0786	0.1010	97.29	203.49	0.0191	0.0286
Andreussi & Persen (1987)	15.32	60.31	0.0075	0.0607	240.96	405.78	0.0716	0.0770
Baker et al. (1988) ($V_i = V_G - V_L$)	286.12	291.28	0.1942	0.2050	88.39	197.12	0.0349	0.0558
Baker et al. (1988) ($V_i = V_L$)	242.93	248.10	0.1732	0.1840	73.79	181.88	0.0273	0.0484
Cheremisinoff & Davis (1979)	31.10	95.72	0.0263	0.1056	601.87	1098.12	0.0673	0.0723
Cohen & Hanratty (1965)	38.66	101.58	0.0353	0.1117	557.27	1021.80	0.0667	0.0718
$f_i = f_{wG}$	318.24	322.85	0.2226	0.2315	84.52	198.23	0.0361	0.0581
Hanratty & Andritsos (1984)	136.81	146.26	0.1198	0.1338	89.79	188.30	0.0240	0.0382
Kowalski (1984)	322.74	327.21	0.2331	0.2415	90.91	205.04	0.0381	0.0601
Kowalski (1987)	279.20	284.12	0.2161	0.2250	137.57	271.43	0.0389	0.0578
Kaminaga et al. (1991)	233.93	238.85	0.1828	0.1918	89.12	197.80	0.0298	0.0492
Kim et al. (1985)	152.74	163.59	0.1202	0.1382	168.77	306.88	0.0294	0.0425
Kokal & Stanislav (1989)	353.85	358.31	0.2441	0.2525	88.52	204.57	0.0393	0.0617
Laurinat et al. (1984)	330.04	334.73	0.2358	0.2444	109.46	225.61	0.0427	0.0637
Linehan (1968)	154.73	170.23	0.1230	0.1467	207.51	369.43	0.0331	0.0436
Spedding & Hand (1990)	254.39	259.44	0.1843	0.1957	87.57	205.03	0.0289	0.0495
Tsiklauri et al. (1979)	28.81	97.88	0.0258	0.1090	624.45	1155.10	0.0759	0.0810

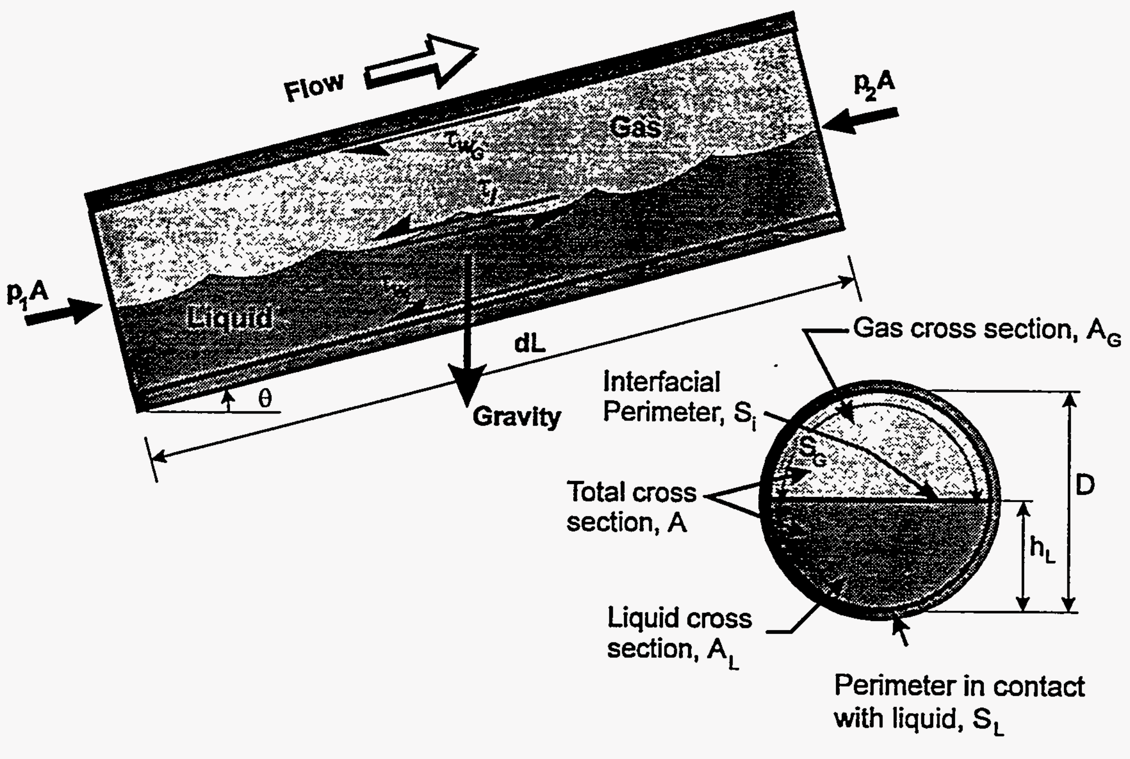
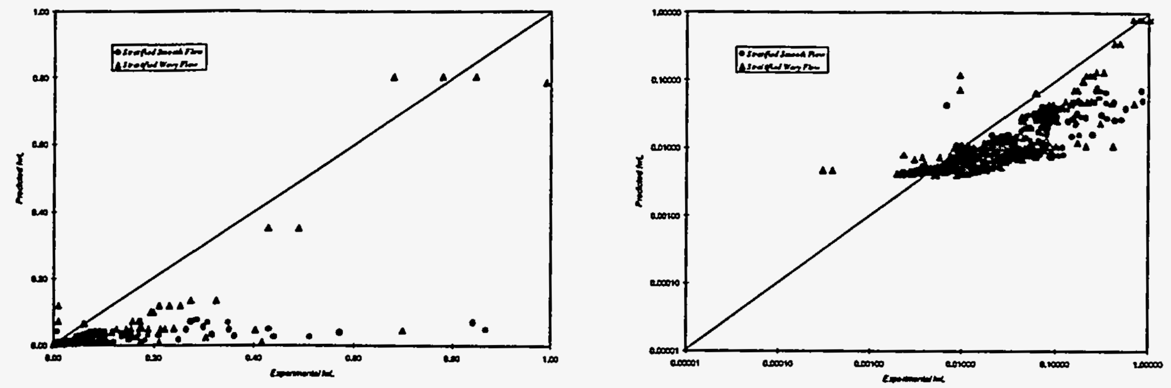
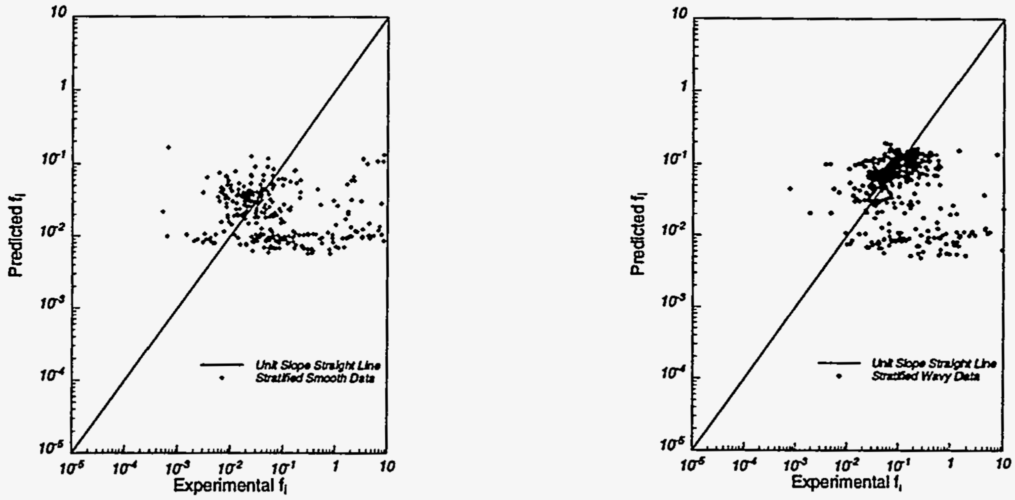


Figure 1 Schematic of Stratified Flow in Pipes



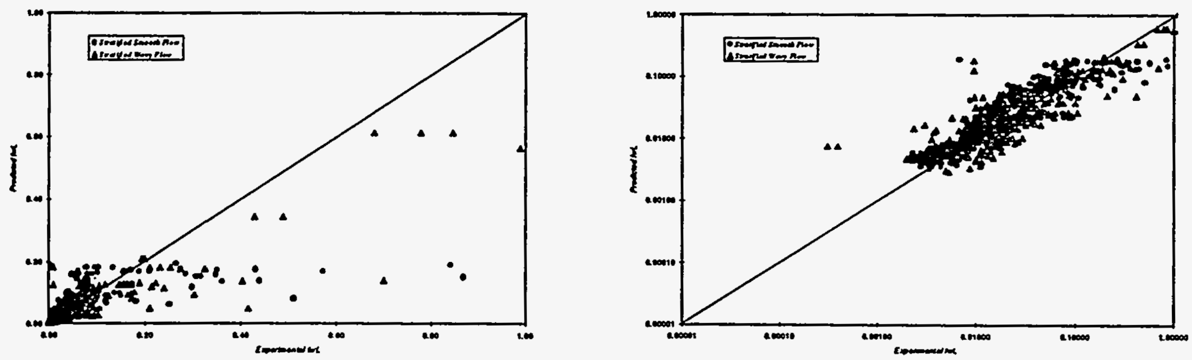
(a) Normal Scale (b) Logarithmic Scale

Figure 2 Comparison between the Experimental Liquid Phase Wall Friction Factor and the Predicted Value from Standard Method



(a) Stratified Smooth Flow (b) Stratified Wavy Flow

Figure 3 Comparison between Predictions and Experiments of the Interfacial Friction Factors for Andritsos & Hanratty (1987) Correlation



(a) Normal Scale (b) Logarithmic Scale

Figure 4 Comparison between the Experimental Liquid Phase Wall Friction Factor with the Predicted Value from New Correlation

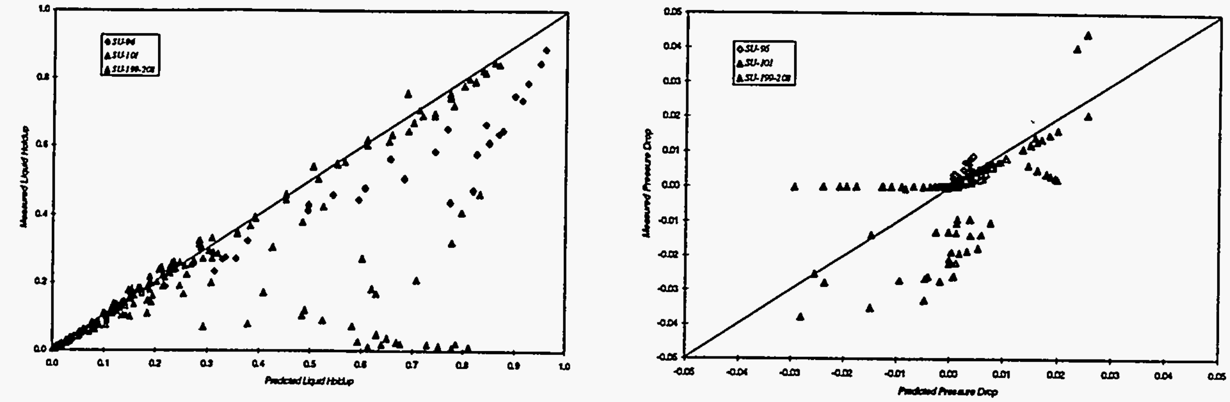


Figure 5a Liquid Holdup and Pressure Gradient Predicted from New Correlations (Stratified Smooth Flow)

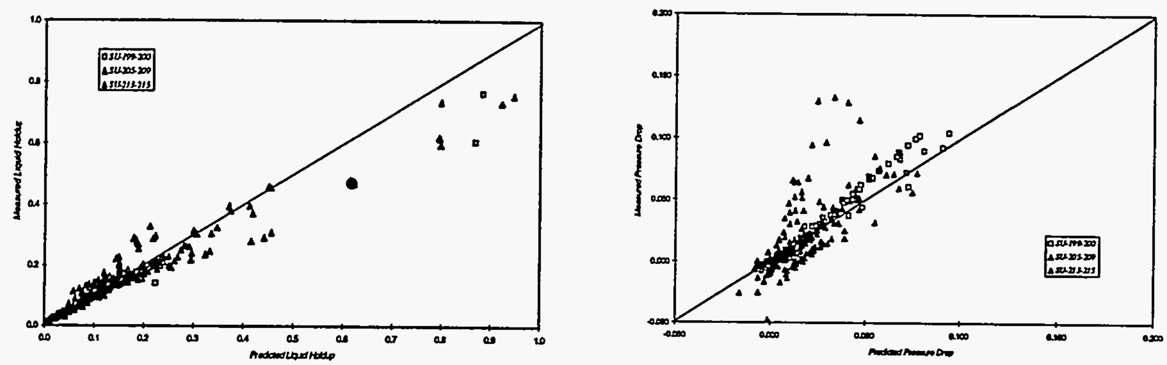
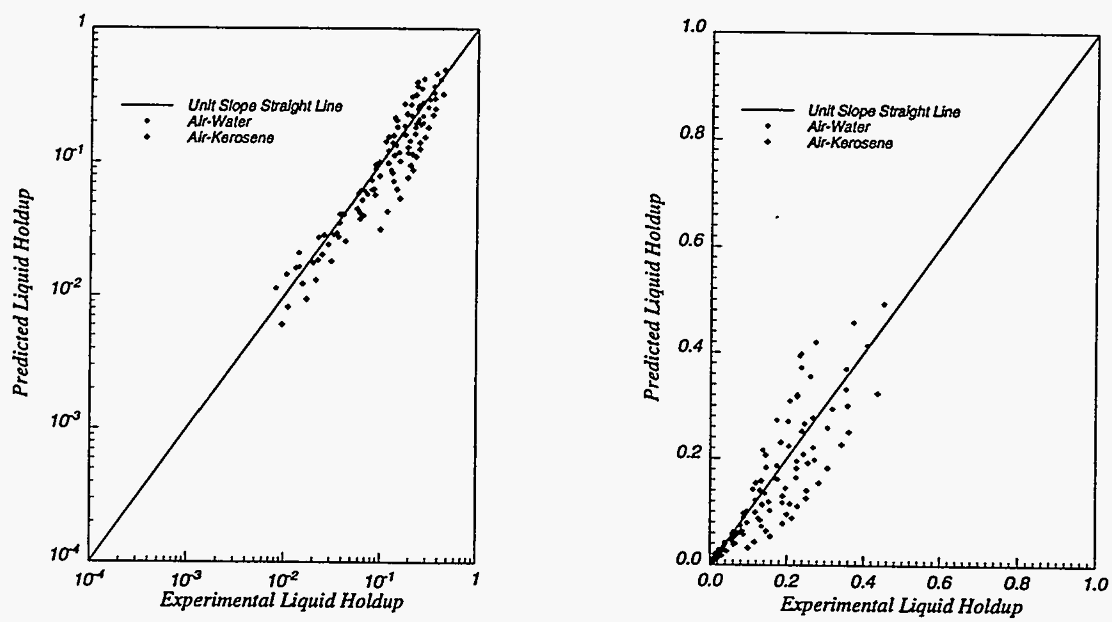


Figure 5b Liquid Holdup and Pressure Gradient Predicted from New Correlations (Stratified Wavy Flow)



(a) Logarithmic Scale *(b) Standard Scale*

Figure 6 Comaprison between Measured and Predicted Liquid Holdup by New Correlations