MULTIPHASE FLOW

(ISMF '97)

Edited by CHEN Xuejun
GE Manchu

International Academic Publishers

MULTIPHASE FLOW

Proceedings of the International Symposium on Multiphase Flow

(ISMF '97)

October 7-11, 1997 Beijing, China

Edited by CHEN Xuejun
GE Manchu

Sponsors: Chinese Society of Engineering Thermophysics
Chinese Society of Theoretical and Applied Mechanics
Chinese Society of Petroleum Engineering
Chinese Society of Chemical Engineering
National Natural Science Foundation of China

Organizer: Chinese Society of Engineering Thermophysics

International Academic Publishers

图书在版编目(CIP)数据

多相流 ：国际多相流会议论文集 ：英文/陈学俊，葛满初编. –北京 ：万国学术出版社, 1997.9
ISBN 7-80003-405-4

I.多… II.①陈… ②葛… III.多相流动-国际学术会议-文集-英文 IV.O351-53

中国版本图书馆 CIP 数据核字 (97) 第 17618 号

Published and Distributed by
International Academic Publishers
137 Chaonei Dajie, Beijing 100010
The People's Republic of China

The book has been photographically reproduced from the best available copy. The papers were not refereed but were reviewed for their technical contents. Editing was restricted to matters of format, general organization and retyping.

The editors assume no responsibility for the accuracy, completeness or usefulness of the information disclosed in this volume. Unauthorized use might infringe on privately owned patents of publication right. Please contact the individual authors for permission to reprint or otherwise use information from their papers.

First edition 1997

Chen Xuejun and Ge Manchu
Proceedings of the International Symposium on Multiphase Flow

ISBN 7-80003-405-4/O · 60

ORGANIZATION

SPONSORS: Chinese Society of Engineering Thermophysics
Chinese Society of Theoretical and Applied Mechanics
Chinese Society of Petroleum Engineering
Chinese Society of Chemical Engineering

SCIENTIFIC COMMITTEE
Chairman: Professor Xuejun Chen (China)
Co-chairman: Professor C. L. Tien (USA)
Co-chairman: Professor G. F. Hewitt (UK)

Members:

Prof. S.G. Bankoff	(USA)	Prof. A.S. Mujumdar	(Canada)
Prof. Jean Bataille	(France)	Prof. M.S. Kwauk	(China)
Dr. Arthur E. Bergles	(USA)	Prof. R.I. Nigmatulin	(France)
Dr. Gian Piero Celata	(Italy)	Prof. A. Serizawa	(Japan)
Prof. R.X. Cai	(China)	Dr. William T. Sha	(USA)
Prof. J.M. Delhaye	(France)	Prof. M.X. Shi	(China)
Prof. A. Drew	(USA)	Prof. M. Sommerfeld	(Germany)
Prof. M.P. Dudukovic	(USA)	Prof. S.L. Soo	(USA)
Prof. L.S. Fan	(USA)	Prof. D.B. Spalding	(England)
Prof. Michel Giot	(Belgium)	Prof. Y. Tsuji	(Japan)
Prof. D.-H. Hellmann	(Germany)	Prof. T. Nejat Veziroglu	(USA)
Prof. G. Hetsroni	(Israel)	Dr. Regis Vilagines	(France)
Prof. Dr. H. Hofmann	(Germany)	Prof. J.Z. Xu	(China)
Prof. Sadik Kakac	(USA)	Dr. S. T. Yin	(Canada)
Prof. Y. Lee	(Canada)	Prof. H.R. Yu	(China)
Prof. F. Mayinger	(Germany)	Prof. L.X. Zhou	(China)

ORGANIZING COMMITTEE
Chairman: Prof. J. Z. Xu (China)
Co-chairman: Prof. M. C. Ge (China)
Co-chairman: Prof. T. K. Chen (China)

Members:

Prof. J.Y. Chen	(China)	Prof. M.J. Lu	(China)
Prof. Y.L. Chen	(China)	Prof. Z.Q. Lu	(China)
Prof. Zh.H. Chen	(China)	Prof. C.F. Ma	(China)
Prof. J.R. Fan	(China)	Prof. Y.Q. Pan	(China)
Prof. L.J. Guo	(China)	Prof. L.T. Shi	(China)
Prof. W.F. Han	(China)	Prof. C.J. Xiao	(China)
Prof. Y. Jin	(China)	Prof. Y.Q. Xu	(China)
Prof. X.F. Li	(China)	Prof. D.S. Xue	(China)
Prof. Z.H. Lin	(China)	Prof. B.Z. Zhang	(China)
Prof. Z.G. Ling	(China)	Prof. Z. Zhang	(China)
Prof. D.Y. Liu	(China)	Prof. Z.G. Zhang	(China)
Prof. H.Y. Liu	(China)	Prof. F. D. Zhou	(China)
Dr. Z.W. Liu	(China)		

Conference Secretariats:

Prof. M.C. Ge	Prof. D.S. Xue
Prof. L.T. Shi	Dr. D.G. Zhao
Prof. B.Z. Zhao	

FOREWORD

Multiphase flow phenomena are found in a wide range of engineering systems, such as in the field of chemical, petroleum, mechanical, power and nuclear engineering. Simultaneous Flow of gases and liquids or solids occurs in large number of engineering equipment, for example, boilers, evaporators, condensers, boiling water reactors, particle separators, filters, and oil and gas in pipelines.

Owing to the recent energy and environmental crises, many other multiphase flow problems have become important, such as the safety of nuclear reactors, the scaling up of fluidized bed reactors for converting coal to gaseous and liquid fuels, the design of heat exchangers for liquefied natural gas and liquefied petroleum gas, and the control of microcontamination and air pollution.

Thermal and hydrodynamic instabilities exist in multiphase flow which cause flow oscillations. There is a pressing need for the examination of multiphase systems under oscillating conditions and to be able to predict the conditions under which a multiphase system will perform reliability. Gas-Solid measurement techniques and gas particle systems, liquid-liquid extraction and direct contact heat exchange, gas-solid fluidized beds, and heat and mass transfer problem in multiphase flow system have lately become important research topics for many applications. There is also an increasing interest to take further research work in the basic mechanisms of the phenomena of multiphase flow to meet the requirement of industrial development.

Problems in multiphase flow have challenged many investigators as these phenomena affect not only the efficient and economical design of equipment, but also its safety in operation. Furthermore, multiphase flow researches may contribute much more to advance engineering science and environment protection, and to improve high technologies in the power field and information system.

The symposium provided a high level international platform in pleasant surroundings for the presentation of the latest results and for the exchange of ideas by the representatives of universities, research establishments and industries.

We would like to express our gratitude and warm thanks to the members of Scientific Committee and Organizing Committee, to the authors, and to all the person who had contributed to the symposium.

X. J. CHEN

J. Z. XU

M. C. GE

CONTENTS

Application

Numerical Simulation

Experiment, Measurement Techniques and Others

Three-phase Gas-Liquid-Liquid Flow : Flow Patterns, Holdups and Pressure Drop

[1] Geoffery F. Hewitt, [2]Lei Pan† and [3]Siew H. Khor
Department of Chemical Engineering and Chemical Technology,
Imperial College of Science, Technology and Medicine,
London SW7 2BY, England
Tel : +44 171 5945562, Fax : +44 171 594 5564
E-Mail : [1] g.hewitt@ic.ac.uk, [2]leipan@uiuc.edu, [3] s.khor@ic.ac.uk

ABSTRACT

This paper reviews the experimental and analytical studies of three-phase gas-liquid-liquid flow carried out at Imperial College. The studies carried out on flow patterns, phase holdup and pressure gradient are described and recent work on measurements of phase inter-entrainment using an isokinetic sampling technique is presented. All the experiments work described was conducted on the Imperial College WASP facility which has a 77.92 mm (nominal 3 inch) diameter test section. The analytical studies described include evaluations of closure relationships for the three-fluid model for three-phase stratified flow and the development if more generic empirical correlations approaches covering all flow regimes.

1. INTRODUCTION

Three-phase gas-oil-water flows occur widely in both on-shore and off-shore crude oil production since reservoirs of gas and oil almost always contain water, and water is often injected into gas and oil reservoirs to boost production at the later stages of reservoir life. To decrease production cost, gas-oil-water mixtures from some small off-shore oil fields are often transported to existing platforms or even to the shore. The transportation distance may be up to 200 km along the sea bed and the gas-oil-water mixtures flowing in the pipelines are usually under high pressure due to either oil well pressure or the pump pressure required for the transportation.

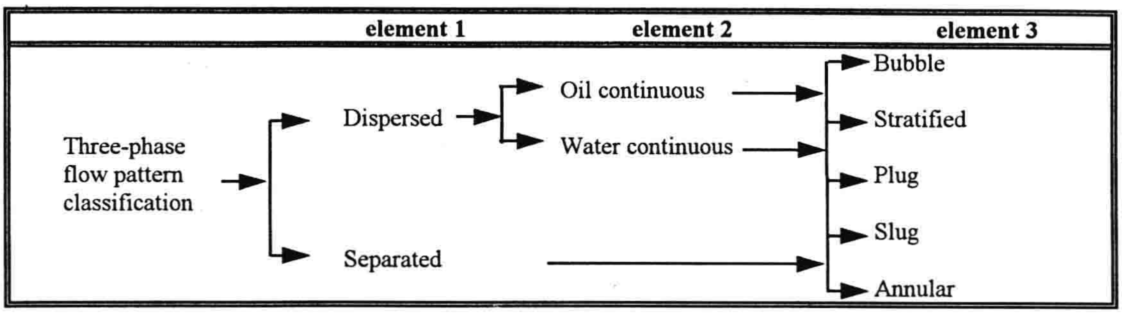
The two features of subsea operation and high operating pressure in transporting gas-oil-water mixtures undoubtedly mean that the cost for constructing the pipelines is high and the maintenance of them is difficult. Therefore, correct design and operation of the pipelines is crucially important for minimising the cost and guaranteeing operational safety, and this can only be realised on the basis of good understanding of gas-oil-water flow characteristics. Despite the growing importance of three-phase gas-liquid-liquid flows, the extent of research on them has been surprisingly limited. A number of preliminary studies was carried out in the 1950's but it was not until rather recently that a renewed emphasis began to be placed on the area. Perhaps the reason was that two-phase gas-liquid flows already presented a formidable challenge and the inclusion of a third phase seemed impossibly complex ! However, in view of the growing importance of such flows, a research programme was initiated at Imperial College in 1987 to investigate three-phase flow phenomenon experimentally and theoretically. Some results from this programme are briefly summarised in this paper.

A brief description of the WASP facility is given in Section 2 and results obtained for flow patterns in gas-liquid-liquid flow are described in Section 3. In Section 4, studies of phase holdups are described and methods of predicting phase holdup are discussed. Section 5 and 6 discuss pressure drop and phase inter-entrainment respectively and Section 7 summaries the main conclusion from the work.

2. THE EXPERIMENTAL FACILITY

A high pressure multiphase flow facility named WASP (water, air, sand and petroleum) was built at Imperial College, London in 1987 to investigate three-phase flow phenomena (Fig. 1). It has a 40 m long, horizontal, stainless steel test section of 77.92 mm (nominal 3") internal diameter, the facility has a design pressure of 50 bars (though the rig has so far been operated up to 30 bars). The air comes from high pressurised tanks and the oil and water are pumped by centrifugal pumps from their respective high pressure tanks, the fluids entering the test section via a mixer. This mixer is a pipe section of 0.5 m long axially divided into three parts (Fig. 2) which allows the smooth introduction of the three fluids into the test section in separate layers according to their densities. After passing through the

TABLE 1 THE WASP THREE-PHASE FLOW PATTERN CLASSIFICATION



test section, the air-oil-water mixture goes into the slug catcher (separator) for the separation of the air from the liquids. The air is vented from the top of the slug catcher to the atmosphere through a silencer and the two liquids are drained from the bottom into a dump tank where oil and water are separated by gravity. After sufficient separation time (a minimum of two hours), the oil and water are pumped back into their respective tanks for recirculation. All operations are implemented through a control PC.

Air and oil flowrates are measured by orifice plates, water flowrate by an electromagnetic flowmeter (*MAGFLO 381*) and the temperature of each of the three fluids by a thermocouple before it enters the mixer. The system pressure is measured at a point 1.5 m upstream of the exit of the test section with a *ROSEMOUNT* Gauge Pressure Transmitter Smart Model 1151. A *ROSEMOUNT* differential pressure transducer is used to measure the pressure drop over a distance of 2.5 m with the two measurement points being 3.5 m and 6.0 m upstream of the exit respectively. The two points are flush-mounted at the bottom of the test section and the two connection lines are Silicone-filled and sealed so that it is impossible for air bubbles to get into the lines which is a problem with conventional liquid-filled connection lines. A transparent visualisation section of 0.8 m length is installed 3 m upstream of the exit and allows visual identification of flow patterns. Video recordings are taken for later analysis. The data acquisition of pressure, pressure drop, temperature and flowrates is automatically done by a second PC using a sampling frequency of about 0.7 Hz. Approximately 80 readings for each parameter are recorded during each run. Therefore, every parameter value finally obtained is an average over 80 readings which effectively reduces the uncertainty in measuring the parameter due to the natural random fluctuations occurring in multiphase flows. A dual-energy gamma densitometer was used to measure three-phase holdups, the average measurement error being found to be no more than 5% (Pan *et al.*, 1995a).

3. FLOW PATTERNS

Definition, Classification and Identification

Based on the experimental observations, a methodology has been proposed of defining three-phase flow patterns with a 3-element (or 2-element) term as shown in Table 1. The first element is used to describe the configuration relationship between the oil and water phases, namely "dispersed" and "separated". The second classification element exists only if the first element is "dispersed" and has the two categories "oil continuous" and "water continuous" which are used to indicate which of the two liquid phases flows in a continuous state and hence is mainly in contact with the pipe wall; the third element is used to describe the configuration relationship between the gas and the total liquid phase using exactly the same terms as those for two-phase gas-liquid flow patterns. Table 1 shows that a total number of fifteen flow pattern descriptions are available based on the present definition and classification and it is believed that these are sufficient to cover the most important basic flow patterns for three-phase horizontal flow. However, it is possible to increase the number of the three-phase flow patterns defined if one is interested in distinguishing the flow in more detail.

To actually identify a flow pattern in experiments, the following methodology was employed. Element 1 of a flow pattern term is determined as follows : if an obvious and continuous water layer can be seen in the flow, the flow is termed "separated"; if no such layer is observed, the flow is described as "dispersed". To distinguish in the dispersed case, between "oil-continuous" and "water-continuous" flows (Element 2 of the flow pattern classification), a judgement is made based on the visual appearance of the flow; "oil-continuous" and "water-continuous" flows have very different visual appearance. Although this criterion seems rather quantitative (and a more objective method is needed for future work), there are many hints that can be used to assist the judgement. In the case of slug flow, for example, if after a slug passes, the liquid film remaining on the upper wall of the visualisation section looks milky, sticky and non-transparent and drains down slowly, it is oil-continuous flow. Otherwise, if the liquid film remaining on the upper wall looks and behaves like water, it is water-continuous flow. Element 3 of the present classification is familiar to every two-phase flow researcher because refers to flow patterns also encountered in two-phase gas-liquid flow and which have been extensively discussed in the literature (see for example, Hewitt, 1982). Based on the classifications above, eight three-phase flow patterns were experimentally identified by the present authors and are summarised in Table 2.

TABLE 2 FLOW PATTERN IDENTIFICATION IN THE WASP AIR-OIL-WATER EXPERIMENTS

	Flow Pattern			
No.	Element 1 : Oil-water relation	Element 2 : The continuos liquid phase	Element 3 : Air-liquid relation	Abbreviation
1	Separated		Slug Flow	SSl
2	Dispersed	Water continuous	Slug Flow	DWSl
3	Dispersed	Oil continuous	Slug Flow	DOSl
4	Separated		Stratified	SSt
5	Dispersed	Oil continuous	Stratified	DOSt
6	Dispersed	Oil continuous	Annular	DOA
7	Dispersed	Water continuous	Stratified	DWSt
8	Dispersed	Water continuous	Annular	DWA

Three-phase Flow Pattern Maps

Figs. 3, 4 and 5 show three-phase flow pattern maps obtained in this study for horizontal flow at 0, 5 and 10 barg, respectively. It is seen that the flow pattern map at 5 barg is the most complete (Fig. 4) and includes all the eight flow patterns given in Table 3 while the maps at 0 and 10 barg include only six and five flow patterns, respectively (Figs. 3 and 5). By comparing the flow regime maps, it is found that the region for stratified flow increases as the operating pressure increases.

Evaluation of Existing Flow Pattern Maps

In the (rather limited) literature on flow patterns in gas-liquid-liquid flow, two main approaches have been followed for the classifications of flow regimes :

1) Plotting the data on the basis of existing gas-liquid two-phase flow maps (Malinowsky, 1975; Laflin *et al.*, 1976; Stapelberg and Mewes, 1994). Many of the maps for two-phase flow include physical property effects and it has occasionally been suggested (see Stapelberg and Mewes, 1994, for instance) that the three-phase transition lines (based on mean physical properties) should lie between the transitions predicted for oil/gas and water/gas two-phase flows respectively.
2) Developing new regime maps for the three-phase flow case. This was done by Sobocinski [1958] and later by Acikgoz *et al.* [1992]. Note that such maps need to be three-dimensional if variations of the flowrates of all three phases are taken into account.

The data obtained at Imperial College are compared with the Acikgoz *et al.* [1992] three-phase flow maps in Fig. 6 and with the two-phase flow maps of Baker *et al.* [1954], Beggs and Brill [1993], Mandhane *et al.* [1974], Taitel and Dukler [1976], and Weisman *et al.* [1976] in Figs 7 to 11 respectively. In the two-phase flow maps, the predicted transition lines for oil-gas flow are shown as dotted lines whereas for water-gas flows are shown as solid lines.

The results obtained in the work summarised in the present paper show some of the same qualitative trends as those observed by Acikgoz *et al.* [1992] (Fig. 6) but they differ greatly in quantitative sense. This is perhaps not too surprising since the Acikgoz *et al.* Data were for a small diameter tube at low pressure and using a different oil. The map produced by Acikgoz *et al.* is, therefore, not of any general applicability.

The two-phase flow regime maps (Figs. 7 – 11) which the pressure data are compared are all claimed to be generally applicable to any gas/liquid combinations. The fact they differ substantially from one another, even for two-phase flows, perhaps reduces the credibility of such claims ! The map of Taitel and Dukler [1976] has become one of the most popular and has a firmer claim to generality since it is based (though with a number of approximations) on ideas about the physics of the transitions. However, even the map cannot be regarded as giving reliable predictions for two-phase flows; work in the WASP facility has shown, for instance, that the effect of pressure on the liquid flowrates for transitions to slug flow is opposite to that predicted by the model. As will be seen from the comparisons shown in Figs. 7 – 11, the three-phase flow data are certainly not predicted by the two-phase flow regime maps. In view of the additional complexities involved and of the uncertainties in the predictive capacity of such maps even for two-phase flows, this result is also unsurprising.

The prediction of flow pattern is an essential precursor to more accurate predictions of multiphase flow behaviour. Thus, there is a priority requirement for the development of more generalised three-phase flow regime maps and this is a priority for the current work at Imperial College.

4. HOLDUP

General Observation

In three-phase flows, the holdups (in situ phase fractions of the liquid phases) show some peculiar trends. Figs. 12-13 show some typical three-phase holdup data obtained in 1 upward inclined flow for fixed superficial air and total liquid velocities, where the input water fraction in the liquid is defined as :

$$\lambda_w = \frac{U_{ws}}{U_{os} + U_{ws}} \qquad (1)$$

where U_{ws} and U_{os} are the superficial velocities of the water and oil phases respectively. Based on a number of plots like those in Figs. 12-13, the following observations can be made :

(a) With increasing input water (volume) fraction in the liquid, the total liquid holdup increases to a maximum and then decreases sharply before becoming approximately constant. Experimental observations indicated that the peak occurs in the oil-continuous flow region and the flat part is in the water-continuous flow region. The region between the oil-continuous and water-continuous regions is called the phase inversion region and occurs between the maximum and the minimum points on the total liquid holdup curve. The peak in the total liquid holdup is caused mainly by the increasing effective viscosity of the liquid mixture. The sudden decline of the total liquid holdup between the maximum and the minimum points is caused by the sudden change in the effective viscosity of the liquid mixture accompanying the phase inversion. The holdup data seem to indicate that, in the oil-continuous flow region, the effective liquid viscosity changes dramatically, but it changes very little in the water-continuous flow region.

(b) With decreasing oil fraction in the total liquid (and hence increasing water fraction), the oil holdup decreases accordingly. However, with increasing water fraction the water holdup does not increase monotonically, but increases initially, then slightly decreases in the phase inversion region and increases again.

(c) The position of the peak on the total liquid holdup curve moves slightly towards higher water fraction position with increasing air flowrate.

(d) The holdups of oil, water and total liquid generally decrease with increasing air flowrate as expected theoretically.

One-Dimensional Modelling for Prediction of Holdup in Stratified Flow

One-dimensional modelling (the so-called "multi-fluid model") has become a popular framework for the calculations of both steady state and transient multiphase flows. In this framework, a single averaged velocity is assigned to each respective phases and the continuity, momentum and energy equations are written taking account of the inter-phase transfers of the concerned quantities. For the simplest stratified flow (in horizontal pipes), we may write the momentum equations for each phase as :

$$-A_g\left(\frac{dp}{dz}\right)-\tau_g S_g-\tau_{go} S_{go}=0 \qquad (2)$$

$$-A_o\left(\frac{dp}{dz}\right)-\tau_o S_o+\tau_{go} S_{go}-\tau_{ow} S_{ow}=0 \qquad (3)$$

$$-A_w\left(\frac{dp}{dz}\right)-\tau_w S_w+\tau_{ow} S_{ow}=0 \qquad (4)$$

where the subscripts o and w refer to the oil and water phases respectively, and the subscripts go and ow refer to the gas-oil and oil-water interfaces respectively. A_g, A_o, A_w, S_g, S_o, S_w, S_{go} and S_{ow} may be related by purely geometric relationships to the oil, water and gas holdups (volume fractions) ε_o, ε_w and ε_g respectively, with the assumption of the interfaces are flat. It is possible to reduce Eqns. 2 – 4 to two equations by elimination of the pressure gradient. Adopting the procedure developed by Taitel and Dukler [1976] for the gas-liquid flow case, a relationship can be produced between the water, oil and total dimensionless liquid heights (actual liquid height divided by tube diameter) and the dimensionless Lockhart-Martinelli parameters :

$$X_{go}=\left[\frac{(dp/dz)_o}{(dp/dz)_g}\right]^{1/2} \qquad (5)$$

$$X_{gw}=\left[\frac{(dp/dz)_w}{(dp/dz)_g}\right]^{1/2} \qquad (6)$$

where $(dp/dz)_o$, $(dp/dz)_g$ and $(dp/dz)_w$ are the pressure gradients for the oil, gas and water phases flowing alone in the channel respectively. If it is assumed that τ_o, τ_w and τ_g may be calculated from the standard Blasius equations and that $\tau_{go}=\tau_g$ and $\tau_{ow}=\tau_w$, then a generic relationship may be developed for dimensionless liquid heights as a function of X_{go} and X_{gw}.. Fig. 14 shows values calculated for dimensionless total liquid height using this procedure (which was also used by Hall, 1992 and Taitel *et al.*, 1995).

Roberts [1996] solved Eqns. 2 – 4 in the framework of a commercial two-fluid model code (PLAC) which allowed him to use more complex relationships for the shear stresses. In the recent work at Imperial College (Khor *et al.*, 1997) a computer code (*PRESBAL*) has been developed which allows solutions of Eqns. 2 – 4 with any arbitrary relationships for the shear stresses. The framework is somewhat similar to the other methodologies described above. The wall shear stresses are determined from the general friction factor relationship :

$$\tau_k=\frac{1}{2} f_k\, \rho_k\, u_k^2 \qquad (7)$$

where the subscript k indicates gas, oil or water, and, f_k is evaluated from standard single phase friction factor relationships. Following Taitel *et al.* [1995], allowance is made for the velocities of the contacting phases and the interfacial shear stresses (τ_{go} and τ_{ow}) are calculated from the friction factors using the expressions as shown below :

$$\tau_{go}=\frac{1}{2} f_{go}\, \rho_g\left(u_g-u_o\right)\left|u_g-u_o\right| \qquad (8)$$

$$\tau_{ow}=\frac{1}{2} f_{ow}\, \rho_o\left(u_o-u_w\right)\left|u_o-u_w\right| \qquad (9)$$

PRESBAL has adopted a solution approach in which, using selected correlations for shear stresses, the water and oil levels were systematically adjusted until the pressure gradients for the three phases were equal. This methodology has the advantage of being able to easily accommodate a whole variety of shear stress relationships and problems of convergence which encountered in other methodologies are by-passed (Khor *et al.*, 1997). The correlations which were included in *PRESBAL* are as follows :

- **Gas-wall friction** : The simple Blasius [1913] expression (for smooth pipes) and the more complex Colebrook [1939] expression (for rough pipes).
- **Oil-wall and water-wall friction** : Blasius [1913]; Colebrook [1939]; Andritsos and Hanratty [1987], Kowalski [1987], Hart *et al.* [1989], Hand [1991] and Srichai [1994].
- **Gas-oil interfacial friction** : Linehan [1968], Tsiklauri *et al.*[1979], Cheremisinoff and Davies [1979], Sinai [1983], Lee and Bankoff [1983], Laurinat *et al.*[1985], Kim *et al.*[1985], Andritsos and Hanratty [1987], Kowalski [1987], Baker *et al.*[1988], Hart *et al.*[1989], Hamersma and Hart [1989], Hand [1991], Xiao [1991], Hall [1992], Srichai [1994], Taitel *et al.*[1995].
- **Oil-water interfacial friction** : Baker *et al.* [1988] (i.e. the gas-liquid correlation applied to a liquid-liquid interface); Hall [1992] (i.e. correction to Blasius value on basis of parallel plate calculations); Taitel *et al.*[1995] (i.e. a fixed friction factor of f_{ow} = 0.014).

The definitions of D_g and D_w used were identical to that used by Hall [1991] and Taitel *et al.* [1995] which are $D_g = 4A_g/(S_g + S_{go})$ and $D_w = 4A_w/S_w$ respectively. For the definition of D_o, it was found that unphysical high values were resulted when the oil phase was considered as an opened channel flow. The oil layer is often quite thin in a three-phase stratified flow, hence the very low value of S_o causes D_o to be large. For this reason, a modified definition in a form of $D_o = 4A_o/(S_o + S_{ow})$ was proposed.

To verify the applicability of the code and to select the choice of friction factor relationships to provide the best representation of the data, experimental data for oil-water-air stratified flow obtained from the high pressure multiphase flow WASP facility, at Imperial College [Khor *et al.*, 1996a], and the data published by Sobocinski [1955] have been chosen. The procedure for the comparison was to select specific correlations for three of the four shear stress terms and then to calculate the values of ε_w and ε_o for each data point for the range of relationships incorporated in *PRESBAL* for the remaining shear stress term. By comparing the average ratio of the predicted holdup to the measured holdup and the standard deviation of the ratios, there emerged a series of "*best*" relationships for the shear stresses :

- **Gas-wall shear stress** : The Blasius equation is preferred as it requires less computational time than the Colebrook [1939] relationship, and it needs no information about the pipe roughness. However, this relationship is not recommended for flow systems in a very rough pipe.
- **Oil-wall and water-wall shear stresses** : It is recommended to use the Srichai [1994] relationships which relate the friction factors to their individual actual Reynolds numbers and their respective holdups.
- **Gas-oil interfacial shear stress** : The relationship of Hart *et al.* [1989] is recommended here, as suggested by Spedding *et al.* [1986] in their gas-liquid flow study. This model was originally developed for two-phase flow but it has been modified for three-phase flow case in the present study.
- **Oil-water interfacial shear stress** : The straightforward approach which uses a fixed value of f_{ow} of 0.014 as recommended by Taitel *et al.* [1995] is found to give the best prediction.

With this *best* choice of relationships, generally, good prediction is achieved for Sobocinski's low pressure data, but there is over-prediction in water holdup for the WASP high pressure case (see Fig. 15). Such comparisons for the two sets of experimental data are also presented graphically in Fig. 16 and 17, respectively. The considerable prediction errors in the latter show the assumptions made in the one-dimensional analysis that the fluids are separated and that the interfaces are (on average) flat are not applicable for the high pressure case, where inter-entrainment between the fluid layers becomes significant. This problem is now being investigated on the Imperial College WASP facility using an isokinetic sampling technique (Khor *et al.*, 1996b); more details of this work are given in Section 6.

Prediction Tool For All Flow Regimes

Despite its industrial significance, there is no general method available in the literature to predict three-phase holdup in all flow regimes. The authors hence tried to extend some well-known two-phase methods to three-phase flow, by considering the oil-water mixture as a single liquid phase and then estimate the properties of this '*pseudo*' liquid mixture.

The ten two-phase holdup prediction methods proposed by Lockhart & Martinelli [1949], Hoogendoorn [1959], Hughmark [15], Eaton *et al.* [1967], Guzhov *et al.* [1967], Premoli *et al.* [1971], Beggs & Brill [1973], Brill *et al.* [1981], Mukherjee & Brill [1983] and Minami & Brill [1987] were selected to predict 720 WASP three-phase holdup data. If a volume averaged liquid viscosity is used, then rather poor predictions are obtained; comparisons with the Beggs & Brill method is a typical example (Fig. 18). It was also found that none of these methods tested could give consistent prediction accuracy for the oil-continuous and water-continuous flow data in this study, implying that liquid viscosity effect is poorly represented in these methods because the major difference between oil-continuous and water-continuous flows lies in their viscosities. Therefore, it is not surprising that the method of Premoli *et al* was found to give the least inaccurate predictions for oil-continuous flow data while that of Hughmark was found to give the least inaccurate predictions for water-continuous flow data.

It was clear from the comparisons described above that an improved model was required for the effective viscosity of the liquid phase. The development of such a model is presented by Hewitt *et al* [1995] and Pan *et al* [1995 b]; in this model, the mixture effective viscosity, η_m was evaluated using an equations of the form :

$$\eta_m = (1 - C_m)\left[(1 - \lambda_o)\eta_w + \lambda_o\eta_o\right] + C_m \frac{\eta_{cont}}{(1 - \lambda_{cont})^k} \quad (10)$$

where η_w and η_o are the oil and water viscosities, η_{cont} is the viscosity of whichever phase is continuous, λ_o and λ_{cont} are the (input) volume fractions of the oil and continuos phases; and k is a constant whose value is around 2.5. C_m is a "*mixing degree coefficient*" whose values is between 0 and 1 and it is correlated against a three-phase flow Reynolds number. Eqn. 10 is an interpolation between the linear viscosity model and that of Brinkman [1952] using the Premoli *et al.* method for oil-continuous flow and Hughmark method for water-continuous flow. This approach was found to give excellent prediction accuracy to the WASP three-phase holdup data with an average error of 0.43% and a standard deviation of 4.72% (relative to the full span of holdup of 1.0). Figs. 19-20 show comparisons between the WASP three-phase holdup data and predictions made by using this approach.

5. PRESSURE DROP

Three-phase flow pressure drop was also found to behave in a quite different way than that for two-phase flow. Fig. 21 shows some measured three-phase total pressure drop data obtained in 1° upward inclined flow. The following observations can be drawn :

(a) With increasing input water fraction in the total liquid, the pressure drop increases to a maximum and then falls sharply leading to a region where the pressure gradient is approximately constant. This peak is caused by phase inversion.

(b) The larger the air flowrate, the larger the pressure gradient for given oil and water flowrates.

(c) The position of the pressure gradient peak moves slightly towards higher water fraction with increasing air flowrate, agreeing with the observation made earlier for the holdup curves.

As in the case of holdup prediction, pressure gradient calculation methods for two-phase flow were extended to three-phase flow in the work summarised in this paper. Thus, nine selected methods proposed by McAdams *et al.* [1942], Lockhart & Martinelli [1949], Dukler *et al.* [1964], Baroczy [1966], Schlichting [1970], Beggs & Brill [1973], Beattie & Whalley [1982], Friedel [1979] and Olujic [1985] were tested against 720 WASP three-phase pressure drop data. It was found that none of these methods tested could give consistent prediction accuracy for the oil-continuous and water-continuous flow data in this study, implying that liquid viscosity effect is poorly represented in these methods. The method of Beggs & Brill was found to give the best prediction accuracy for oil-continuous flow data while that of McAdams *et al.* was best for water-continuous flow data.

By combining the viscosity model described in Section 4 (see Eqn. 10) with the Beggs & Brill method for the oil-continuous flow case and McAdams *et al.* method for the water-continuous flow case, it gave predictions to the WASP three-phase pressure data with an average error of 4.85% but a standard deviation of 77.02%. Figs. 22-23 show comparisons between the WASP three-phase pressure drop data and predictions made by using this approach. Although reasonable agreement between the measured and the predicted pressure drops can be seen in Figs. 22-23, an improved method is certainly needed to enhance the prediction accuracy over a wider range.

6. INTER-ENTRAINMENT AT INTERFACES

An isokinetic sampling probe has been developed with the objective of investigating inter-entrainment between the fluid layers in three-phase gas-liquid-liquid stratified flows. The designed probe (see Fig. 24) is able to give information on local fluid flow rates and phase flow fractions of the respective liquids (oil and water) within the flow. From these measured parameters, the velocity profiles of the flow system can also be studied. The isokinetic sampling method requires great attention to detail and is extremely time-consuming; for instance, each measurement or sampling point requires approximately 10–15 minutes, depending on the flow conditions (i.e. fluctuations). However, the use of alternative technologies such as LDA or hot wire anemometry were unfeasible in such a complex three-phase flow.

A preliminary series of experiments on local oil and water superficial velocities in three-phase air-oil-water stratified flows has been conducted and demonstrated the successful operation of the isokinetic sampling probe in stratified multiphase flows, covering both the liquid and the gas phases. The results obtained showed the inter-entrainment near both the liquid-liquid and gas-liquid interfaces (see Fig. 25) which is particularly important as an understanding of such phenomena can provide us a better view of the flow behaviour at the interfaces and in each separate fluid layer.

At high pressures (i.e. at 5.0 barg), the inter-mixing between the liquid phases (oil and water) becomes more significant until one liquid phase is dispersed in the other liquid phase and vice versa, i.e. dispersions or emulsions are formed. The growing dispersed layer between the two separate liquid layers is often thin but can be observed through the transparent perspex section. The sampled liquids drawn near the interfaces using the isokinetic probe exhibit a more dispersed and viscous appearance and this '*pseudo*' oil-water emulsion which has a much higher viscosity and hence affects the velocity profiles of the liquid phases. As shown in Fig. 5, the peak of the water phase velocity profile is shifted towards the liquid-liquid interface. Likewise, the oil phase (between the liquid-liquid and gas-liquid interfaces) travels faster near the gas-liquid interface. These phenomena support the previous findings (Nädler & Mewes [1995] and Pan *et al.* [1995]) that the formation of emulsions affects the flow characteristics and pressure drop of the pipe flow of multiphase mixtures. Consequently, it is insufficient to consider only the viscosities of the individual fluids to estimate the phase holdup. The existence of these complex interfacial phenomena may also explain the discrepancies obtained when comparing the measured phase holdups and those predicted using *PRESBAL*.

7. CONCLUSION

The following conclusions can be drawn from the work summarised in this paper :

(1) The flow patterns in three-phase flow differ considerably from those in two-phase, therefore, the definitions and classifications proposed for two-phase flow are not adequate for three-phase flow. Hence, a new terminology was proposed in this study to define three-phase flow patterns which uses a three-element or two-element term for each three-phase flow pattern and this leads to a classification of 15 major three-phase flow patterns.
(2) Several widely used two-phase flow pattern maps were tested against the WASP three-phase flow pattern data and none of them were found to be adequate for three-phase flow situation.
(3) Phase holdups in three-phase flow were found to behave in a quite different way to that observed in two-phase flow. However, carefully selected two-phase prediction methods were found being able to give adequate prediction accuracy to the total liquid holdup of three-phase flow provided the oil-water mixture viscosity was estimated using a model taking account of phase inversion and mixing.
(4) Three-phase pressure drop was also found behave in a characteristic way, very different to two-phase pressure drop. However, carefully selected two-phase prediction methods were found being able to give reasonable prediction accuracy to three-phase pressure drop provided the oil-water mixture viscosity was estimated by a model taking account of phase inversion and mixing.
(5) The mixing of the liquid phases seems to be a crucial issue on three-phase flow and a better understanding of these processes is needed. The use of the isokinetic sampling method may provide an useful way forward in developing this understanding.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the WASP consortium for the financial support for the work reported in this paper.

REFERENCES

Acikgoz, M., Lahey, Jr., R. T. and Franca, F., 1992, "An Experimental Study of Three-Phase Flow Regimes," *Int. J. Multiphase Flow*, **18**, 327

Andritsos, N. and Hanratty, T. J., 1987 a, "Influence of interfacial waves in stratified gas-liquid flow," *AIChE J.* **33**, 444-454 ;

Andritsos, N. and Hanratty, T. J., 1987 b, "Interfacial instability for horizontal gas-liquid flows in pipes," *Int. J. Multiphase Flow* **13**, 583-603

Baker, O., 1954, "Designing for Simultaneous Flow of Oil and Gas," *O & G Jl.*, **53**, 185.

Baroczy, C. J., 1966, "A systematic correlation for two-phase pressure drop," *CEP Symp. Ser.*, **62**, 232

Beattie, D. R. H. and Whalley, P. B., 1982, "A simple two-phase frictional pressure drop calculation method," *Int. J. Multiphase Flow*, **8**, 83

Beggs, H. D. and Brill, J. P., 1973, "A Study of Two-Phase Flow in Inclined Pipes," *Jl. of Petroleum Tech., Trans.*, **255**, 607-617

Blasius, H., 1913, *Mitt. Forschungsard* **131** ; also refer to Govier and Aziz, 1972.

Brill, J. P., Schmidt, Z., Coberly, W. A., Herring, J. D. and Moore, D. W., 1981, "Analysis of two-phase tests in large-diameter flow pipes in Prudhoe bay field," *Society of Petroleum Engineers Jl.*, June, 363.

Brinkman, H. C., 1952, "The viscosity if concentrated suspensions and solutions," *Jl. of Chemical Physics,* **20**, 571.

Cheremisinoff, N. P. and Davis, E. J., 1979, "Stratified turbulent-turbulent gas-liquid flow," *AIChE Jl* **25**, 48-56

Colebrook, C. F., 1939, "Turbulent flow in pipes, with particular reference to the transition region between smooth and rough pipe laws," *J. Inst. Civil Engrs., London* **11**, 133-156

Dukler, A. E., Moye Wicks, III and Cleveland, R. G., 1964, "Frictional pressure drop in two-phase flow : A. a comparison of existing correlations for pressure loss and holdup," *AIChE Jl.*, **10**, 38

Eaton, B. A., Andrews, D. E., Knowles, C. R., Silberberg, I. H. and Brown, K. E., 1967, "The prediction of flow patterns, liquid holdup and pressure losses occurring during continuous two-phase flow in horizontal pipelines," *Jl. of Petrolem Tech.* (June)

Eck, B., 1973, *Technische Stromunglehre*. Springer, New York

Friedel, L., 1979, "Improved friction pressure drop correlations for horizontal and vertical two-phase pipe flow," *European Two Phase Flow Group Meeting*, No. **E2**, Ispra, Italy, June

Guzhov, A. I., Mamayev, V. A. and Odishariya, G. E., 1967, "A study of transportation in gas-liquid systems," *Proc. 10th Int. Gas Union Conference*, June 6-10, Hamburg, Germany

Hall, A. R. W., 1992, "Multiphase flow of oil, water and gas in horizontal pipe," *Ph.D. Thesis*, Imperial College, University of London, United Kingdom

Hamersma, P. J. and Hart, J., 1987, "A pressure drop correlation for gas/liquid pipe flow with a small liquid holdup," *Chem. Eng. Sci.* **42**, No. 5, 1187-1196

Hand, N. P., 1991, "Gas liquid cocurrent flow in a horizontal pipe," *Ph.D. Thesis*, The Queen's University of Belfast, United Kingdom

Hart, J., Hamersma, P. J. and Fortuin, J. M., 1989, "Correlations predicting frictional pressure drop and liquid holdup during horizontal gas-liquid pipe flow with a small liquid holdup," *Int. J. Multiphase Flow* **15**, 947-964

Hewitt, G. F., 1982, "Gas-liquid two-phase flow," *Chap. 2, Handbook of Multiphase Systems*, edited by G. Hetsroni, Hemisphere Publishing Corp.

Hewitt, G. F., Hall, A. and Pan, L., 1995, "Three-phase gas-liquid-liquid flow, a new challenge," *First International Symposium on Two-Phase Flow Modelling and Experimentation*, Rome, Italy, October 9-11

Hoogendoorn, C. J., 1959, "Gas-liquid flow in horizontal pipes," *Chem. Eng. Sci.*, **9**, 205

Hughmark, G. A., 1962, "Pressure drop in horizontal and vertical cocurrent gas-liquid flow," *IEC Fund.*, **2**, 315

Khor, S. H., Mendes-Tatsis, M. A. and Hewitt, G. F., 1996 a, "Experimental study of air-oil-water stratified flows at different pressures in a horizontal pipe," *MPS* Report No. **83**, *WASP* Report No. **24**, Imperial College, University of London, United Kingdom.

Khor, S. H., Mendes-Tatsis, M. A. & Hewitt, G. F., 1996 b, "Application of isokinetic sampling technique in stratified multiphase flows," *Proceedings of the ASME Heat Transfer* **3**, The 1996 International Mechanical Engineering Congress & Exposition (*IMECE*), Nov. 17-22, Atlanta, Georgia, U. S. A., 101-107

Khor, S. H., Mendes-Tatsis, M. A. and Hewitt, G. F., 1997, "One-dimensional modelling of phase holdups in three-phase stratified flow," *Paper submitted for Int. Jl. Multiphase Flow (CHISA special issue) publication*, February.

Kim, H. J., Lee, S. C. and Bankoff, S. G., 1985, "Heat transfer and interfacial drag in counter-current steam-water stratified flow," *Int. J. Multiphase Flow* **11**, 593-606

Kowalski, J. E., 1987, "Wall and interfacial shear stress in stratified flow in a horizontal pipe," *AIChE Jl* **33**, 274-281

Laflin, G. C. and Oglesby, K. D., 1976, "An Experimental Study on the Effects of Flow Rate, Water Fraction and Gas-Liquid Ratio on Air-Oil-Water Flow in Horizontal Pipes," *Bachelor's Thesis*, University of Tulsa

Laurinat, J. E., Hanratty, T. J. and Jepson, W. P., 1985, "Film thickness distribution for gas-liquid annular flow in a horizontal pipe," *Int. J. Multiphase Flow* **6**, No. 1/2, 179-195

Lee, S. C. & Bankoff, S. G., 1983, "Stability of steam-water counter-current flow in an inclined channel : Flooding," *J. Heat Transfer* **105**, 713-718

Linehan, J. H., 1968, "The interaction of two-dimensional, stratified, turbulent air-water and steam-water flows," *Ph.D. Dissertation*, Dept. of Mech. Eng., University of Wisconsin.

Lockhart, R. W. and Martinelli, R. C., 1949, "Proposed correlation of data for isothermal two-phase, two-component flow in pipes," *Chem. Eng. Prog.*, **45**, 39

Malinowsky, M. S., 1975, "An Experimental Study of Oil-Water and Air-Oil-Water Flowing Mixtures in Horizontal Pipes," *M.Sc. Thesis*, University of Tulsa

Mandhane, J. M., Gregory, G. A. and Aziz, K., 1974, "A flow pattern map for gas-liquid flow in horizontal pipes," *Int. J. Multiphase Flow*, **1**, 537

McAdams, W. H., Woods, W. K. and Heroman, L. C., 1942, "Vaporization inside horizontal tubes II benzene-oil mixtures," *Trans. ASME*, **64**, 193.

Minami, K. and Brill, J. P., 1987, "Liquid holdup in wet-gas pipelines," *SPE* Production Eng. (Feb.)

Mukherjee, H. and Brill, J. P., 1983, "Liquid holdup correlations for inclined two-phase flow," *Jl. of Petroleum Tech.* (May), 1003

Olujic, Z., 1985, "Predicting two-phase flow friction loss in horizontal pipes," *Chem. Eng.* (June 24), 45

Pan, L., 1996, "High Pressure Three-Phase (Gas/Liquid/Liquid) Flow," *Ph.D.* Thesis, Imperial College, University of London, UK

Pan, L. and Hewitt, G. F., 1995 a, "Precise measurement of cross sectional phase fractions in three-phase flow using a dual-energy gamma densitometer," *Session on Experimental Techniques in Two-Phase Flow, 30th ASME/AIChE/ANS/AIAA*, National Heat Transfer Conference, Portland, Oregon, USA, August 5-9

Pan, L., Jayanti, S. and Hewitt, G. F., 1995 b, "Flow patterns, phase inversion and pressure gradient in air-oil-water flow in a horizontal pipe," *2nd International Conference on Multiphase Flow*, Kyoto, Japan, April 3-7.

Pleshko, A. & Sharma, M. P., 1990, "An Experimental Study of Vertical Three-Phase (Oil-Water-Air) Upward Flows," *Advances in Gas-Liquid Flows*, presented at The Winter Annual Meeting of the American Society of Mechanical Engineers, Dallas, Texas, Nov. 25-30

Premoli, A., Francesco, D. and Prina, A., 1971, "A dimensionless correlation for determining the density of two-phase mixtures," *Thermotecnica*, **25**, 17

Roberts, I., 1996, "Modelling and experimental studies of transient stratified multiphase flows," *Ph.D.* Thesis, Imperial College, University of London, United Kingdom

Schlichting, P., 1970, "The transport of oil-water-gas mixtures in oil field gathering systems," *Erdol-Erdgas-Zeitschrift*, **86**, 235 (in German).

Sinai, Y. L., 1983, "A Charnock-based estimate of interfacial resistance and roughness for internal fully developed stratified two-phase horizontal flow," *Int. J. Multiphase Flow* **9**, 13-19

Sobocinski, D. P., 1955, "Horizontal co-current flow at water, gas-oil and air," *Master Thesis*, University of Oklahoma

Sobocinski, D. P. and Huntington, R. L., 1958, "Cocurrent Flow of Air, Gas-Oil and Water in a Horizontal Pipe," *Transactions of the ASME*, 252-256

Spedding, P. L., Hand, N. P. and Ferguson, M. E. G., 1986, "The effect of pipe diameter on prediction of holdup," *Encyclopaedia of Fluid Mechanics* (Gulf Publishing Group), Supplement 3 : Advances in flow dynamics, 31-50

Srichai, S., 1994, "High pressure separated two-phase flow," *Ph.D.* Thesis, Imperial College, University of London, UK

Stapelberg, H. H. & Mewes, D., 1994, "The pressure loss and slug frequency of liquid-liquid-gas flow in horizontal pipes," *Int. J. Multiphase Flow* , **20**, 285

Taitel, Y. & Dukler, A. E., 1976, "A model for predicting flow regime transitions in horizontal and near horizontal gas liquid flow," *AIChE Jl* **22**, 47-55

Taitel, Y., Barnea, D. and Brill, J. P., 1995, "Stratified three-phase flow in pipes," *Int. J. Multiphase Flow* **21**, 53-60

Tsiklauri, G. V., Besfamiliny, P. V. and Baryshev, Y. V., 1979, "Experimental study of hydrodynamic processes for wavy water film in a co-current air flow," *Two-Phase Momentum, Heat and Mass Transfer* **1**, 357-372, (edited by Durst F, Tsiklauri G. V. and Afgan N. H) Hemisphere, New York

Weisman, J., Duncan, D., Gibson, J. and Crawford, T., 1979, "Effects of fluid properties and pipe diameter on two-phase flow patterns in horizontal lines," *Int. J. Multiphase Flow*, **5**, 437-462

Xiao, J., 1990, "A comprehensive mechanistic model for two-phase flow in pipelines," *MSc. Thesis*, University of Tulsa, USA.