The Hydrodynamics of Liquid-Liquid Two Phase Flow Through Horizontal Pipeline

THESIS

Submitted in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy in Engineering By DHURJATI PRASAD CHAKRABARTI

Under the supervision of

Dr. Gargi Das



DEPARTMENT OF CHEMICAL ENGINEERING INDIAN INSTITUTE OF TECHNOLOGY KHARAGPUR- 721 302, INDIA 2006

to my father



INDIAN INSTITUTE OF TECHNOLOGY, KHARAGPUR PIN CODE: 721 302 INDIA

DEPARTMENT OF CHEMICAL ENGINEERING

CERTIFICATE

This is to certify that the thesis entitled *The Hydrodynamics of Liquid-Liquid Two Phase Flow Through Horizontal Pipeline* submitted by **Dhurjati Prasad Chakrabarti** in fulfillment of the requirements of the degree of *Doctor of Philosophy in Engineering*, is a bonafide record of the investigations carried out by him, in the Department of Chemical Engineering, Indian Institute of Technology, Kharagpur under my guidance and supervision. In my opinion, the thesis has reached the standard fulfilling the requirements of the Ph. D. degree as prescribed in the regulations of this institute.

ljang: Da, (Dr. Gargi Das) 24 |07 | 2006

Department of Chemical Engineering Indian Institute of Technology Kharagpur 721302 Dr. Gargi Das Charagpur 721302 Dr. Gargi Das Professor Engg.

i

Acknowledgement

Words fail to express my sincere gratitude to my thesis supervisor Dr. Gargi Das for her encouragement, patience, insightful advice, guidance and sustained interest in successful completion of my dissertation. In addition, her philosophical guidance has built up a momentum inside me. I also thank almighty for making me to feel fortunate to work under her great stewardship.

I am grateful to Prof. P. K. Das, Department of Mechanical Engineering for providing useful suggestions and showing the right direction among the jungle of roads during the work.

I wish to acknowledge my respectful thanks to Prof. A. K. Biswas, former-HOD, Prof. R. K. Saha, former-HOD and Prof. D. Mukherjee, present-HOD for extending all the necessary facilities for carrying-out my research work.

I am thankful to Prof. S. Ray for providing necessary advice during the work. I am also grateful to all the professors in the department for their sincere cooperation.

I am always thankful to Mr. G. Chanda, Mr. P. Guha, Mr. T. Bera, Mr. D. Mallik, Mr. S. Guha and Mr. P. Dua for their great help and sincere cooperation during fabrication of the experimental setup and its runs. I acknowledge the help I have received from all other non teaching staffs of our department.

I would like to thank my co-researchers and friends Mr. Tapas Mondal, Mr. Arun Kumar Jana, Ms. Parama Ghoshal and Dr. A. Roy for their enormous help and encouragement during research work. If I forget to mention the help render by my friends Vaibhav, Kaustubha, Souvik, Chiku, Pinak, Ujjal, Sunil, Srikanto and Goldy I will be doing a great injustice.

I am thankful to my mother for her support and encouragement during the course of my research work. She transformed all the odds into reality.

I am indebted to my wife Surja, whose constant encouragement, suggestion, patience in looking after the whole family problems and motivation, made me to achieve this endeavor in a peaceful and cheerful manner.

Last but not the least, I am grateful to my three-year-old Urbi. Her constant smile irrespective of situation (dilapidated or smooth) is a source of inspiration for me.

Date: 24,07,2006 Place: IIT, Kharagpur

Shugih han autentorf

(Dhurjati Prasad Chakrabarti)

ii

Abstract

The present study has investigated the hydrodynamics of liquid-liquid two phase flow through a horizontal pipe. An indigenously developed optical probe has been used for the identification of the different flow patterns. The presence of different phase contents and various interfacial features along the optical path gives rise to attenuation and scattering and makes the identification possible. The probability density function (PDF) analysis and the wavelet multiresolution technique have been adopted for development of an objective flow pattern indicator. Attempts have been made to identify the interfacial configurations in the oil continuous regime where not much could be revealed through visualization or photography related techniques. The information obtained from the probe signals at low phase flow rates has been exploited for this purpose. In addition, a sampling technique has been devised to understand the distribution of water in the continuous oil phase. A flow pattern map has been constructed from the information thus obtained. It represents the regions of existence of pure stratification, mixed stratification as well as fully dispersed flows in the water continuous regime and the presence of inverted plug flow and inverted dispersed flow in the oil continuous regime. The close agreement of the present flow pattern map with the maps available in literature reveals the effectiveness of the objective flow pattern indicator for liquid-liquid horizontal flows.

The influence of the mixer design on the downstream distribution of the two liquids has been studied and it has revealed that a slight change in the mixer design does not influence the downstream patterns. However, a completely different design may ensure the disappearance or a prolonged existence of a particular flow distribution.

Extensive experiments have been carried out to estimate water holdup and pressure drop during liquid-liquid flows through horizontal pipes. The deviation of the insitu composition from the input fraction is noted to understand the effect of slip between the phases. Further efforts have been directed to identify the flow patterns from the time dependent pressure signals and the statistical analysis of the random signals. An analysis of the holdup and pressure drop characteristics have been performed in the different flow patterns. A separated flow model has been considered for stratified flow while the homogeneous flow model has been adopted for dispersed and oil continuous flow. Both the separated and homogeneous models are used to analyse the stratified mixed pattern as it combines the characteristics of stratification with dispersion. The models have been validated with the present experimental data as well as the data reported in literature.

The effectiveness of an orifice meter as an online metering device has been tested in the present study. Prior to testing the effectiveness of an orifice as an online mass flow metering device, studies have been directed to observe the influence of the orifice on the phase distribution of the two liquids in the pipe. The optical probe along with the photographic technique has been used for the identification of the flow patterns both at the upstream and downstream of the orifice. The studies have revealed that the orifice can be used as an effective homogenizer/emulsifier to disperse liquid-liquid flows.

Contents

Su	bject	Page no.
Cer	rtificate	i
Ack	knowledgement	ii
Abs	stract	iii
Cor	ntents	v
Nor	nenclature	ix
List	of Figures	xi
List	t of Tables	xiv
Ch	apter 1 Introduction	1
Chapter 2 Literature survey		5
	2.1 Introduction	5
	2.2 Gas-liquid flows	5
	2.3 Liquid-Liquid flows	9
	2.3.1 Through horizontal conduit	11
	2.3.2 Oil-water flow in Inclined and vertical pipes	29
	2.4 Flow through an orifice	36
,	2.5 Lacunae in the past literature	41
	2.6 Objective of the present study	41
Cha	apter 3 Experimental facility and procedure	43
	3.1 Introduction	43
	3.2 Fluid handling systems	43
	3.3 Liquid supply system	44
	3.3.1 Rotameters	44
	3.4 Experimental setup	44
	3.4.1 Entry section	47
	3.4.2 Mixer	47

v

3.4.3 Test section	49
3.4.4 Exit section	49
3.4.5 Separator	49
3.5 Instrumentation scheme	49
3.5.1 Photography	50
3.5.2 Optical probe	51
3.5.2.1 Selection of optical probe	51
3.5.3 Pressure sensor	55
3.6 Experimental procedure	55
3.6.1 Estimation of flow pattern	56
3.6.2 Holdup Measurement	56
3.6.3 Estimation of pressure drop	57
3.7 Liquid-liquid two phase flow through an orifice	57
3.7.1 Experimental setup	57
3.7.2 Instrumentation scheme	58
3.7.3 Pressure measurement	59
3.7.4 Experimental procedure	59
Chapter 4 Identification of flow patterns	60
4.1 Introduction	60
4.2 Method of analysis of the random signals obtained	
from the optical probe	61
4.2.1 Probability Density Function analysis	62
4.2.2 The wavelet multiresolution technique	63
4.3 Estimation of flow patterns from visual and photography	65
4.4 Characterization of the flow patterns from probe signals	
and their PDF analysis	67
4.4.1 At low kerosene velocities	67
4.4.2 At moderate kerosene velocities	69
4.4.3 At high kerosene velocities	73
4.5 The wavelet analysis to identify the transition boundaries	75
4.6 The Sampling Technique to understand the distribution	

.

of water in oil at high kerosene velocities	80
4.7 The flow pattern map from the objective indicator	82
4.7.1 Comparison with data from literature	84
4.8 Identification of phase inversion	88
4.8.1 The Flow pattern map to denote phase inversion	92
4.8.2 Comparison of the predicted phase	
inversion with results from literature	93
4.9 Effect of mixer geometry	95
4.10 Conclusion	97
Chapter 5 Estimation of pressure drop and holdup	99
5.1 Introduction	99
5.2 Experimental measurement	102
5.3 Holdup results	103
5.4 Pressure gradient results	105
5.4.1 Identification of flow patterns from time dependent	
pressure signals	109
5.4.1.1 The PDF analysis	109
5.4.1.2 The Wavelet analysis	111
5.5 Analysis of pressure drop and holdup	117
5.5.1 The stratified flow pattern	117
5.5.2 The analysis by Brauner et al. (1996)	121
5.5.3 The dispersed and oil continuous flow pattern	123
5.5.4 The Stratified mixed flow pattern	125
5.6 Comparison of the theoretical analyses with experimental data	125
5.7 Experimental data reported in literature	130
5.8 Conclusion	131
Chapter 6 Liquid-liquid two phase flow through an orifice	132
6.1 Introduction	132
6.2 Measurement technique	134
6.3 Method of analysis	134
6.3.1 Cross correlation function	134

•

vii

6.4 Experimental measurement	135
6.5 Flow patterns at the upstream	135
6.6 Flow patterns downstream of the orifice	136
6.6.1 At low oil velocities	136
6.6.2 At moderate oil velocities	138
6.4 Analysis of cross correlation function	142
6.5 Flow pattern map at the downstream of the orifice	146
6.6 Comparison with the upstream flow pattern map	147
6.7 Pressure drop	148
6.8 Conclusion	152
Chapter 7 Conclusions and Recommendations	
7.1 Conclusions	154
7.2 Recommendations for future work	156
References	157
Appendix-1	
Outcome of the dissertation	170

Nomenclature

- A Cross sectional area (m²)
- B_o Bond number
- C Constant in friction factor and Reynolds number correlation
- D Pipe diameter and hydraulic diameter (m)
- d Drop diameter (m)
- ΔE Summation of the change in potential and surface energies with respect to plane interface (dimensionless)
- f Friction factor
- g Acceleration due to gravity (m s^{-2})
- H Holdup
- h Height of the centroid (m)
- KE Kinetic energy/unit length
- N_{Re} Reynolds number
- n Constant in friction factor and Reynolds number correlation
- PE Potential energy/unit length
- p Pressure (kPa)
- Δp Change in pressure (kPa) or pressure gradient (kPa/m)
- Q Flow rate of a phase $(m^3 s^{-1})$
- S Perimeter of the tube (m)
- SE Surface energy/unit length
- R Radius of the pipe (m)
- U Velocity of a phase $(m s^{-1})$
- V Volume occupied by a phase (m^3)
- z Length of the tube (m)

Greek letters

- α Fluid/wall contact angle
- β Input volume fraction of the heavier phase
- β_0 Orifice to diameter ratio
- ε void fraction
- ε_v Eötvös Number
- ϕ^* Interface curvature
- ϕ_0 View angle of interface from the center of the pipe
- ϕ_o^p View angle for plane interface
- μ Viscosity (kg m⁻¹s⁻¹)
- ρ Density of a phase (kg m⁻³).

- $\frac{1}{\rho}$ Density ratio of two phases
- θ Angle subtended by the interface at the center
- σ Surface tension (N m⁻¹)
- τ Shear stress (kg m⁻¹ s⁻²)
- v Kinematic viscosity (m²s⁻¹)

Subscripts and Superscripts

- 1, A Lighter phase
- 2, B Heavier phase
- O Oil
- KW Water-kerosene interface
- K Kerosene
- L Liquid
- m Mixture
- G Gas
- S Superficial velocity
- P Perspex
- W Water

List of Figures

3.1	a) Schematic diagram of the experimental setup	45
	b) Photograph of the experimental setup	46
3.2	Schematic diagram of the mixers: a) mixer 1; b) mixer 2; c) mixer 3	48
3.3	Schematic diagram of water kerosene separator	50
3.4	a) Optical instrumentation to detect flow regime	53
	b) Circuit diagram of the amplifier	53
3.5	a) Probe signal for "Smooth stratified" pattern at U _{SK} 0.06 m/s and U _{SK} 0.07 m/s	54
	b) Probe signal for "Oil disported in water" nothern at U. O. ()	
	and How 1.3 m/s	54
36	Schematic diagram of the orifice	60
5.0	Schematic diagram of the office	58
4.1	A full scale decomposed signal using Daubachies4 wavelet with level	64
	S at U_{SK} 0.06 m/s and U_{SW} 0.7 m/s	
4.2	Schematic description of the flow regimes	66
4.3	Schematic & photograph, probe signal and PDF of different flow patterns at U_{SK} 0.06 m/s	69
4.4	Schematic & photograph, probe signal and PDF of different flow	71
	patterns at U_{SK} 0.3 m/s	
4.5	Schematic & photograph, probe signal and PDF of different flow	72
	patterns at U_{SK} 0.5 m/s	
4.6	Schematic diagram, probe signal, PDF and PDF-moments of the	74
	different flow patterns at $U_{SK} = 1.78 \text{ m/s}$	
4.7	d_1 and a_5 of the probe signal at U_{SK} 0.06 m/s	76
4.8	d_1 and a_5 of the probe signal at U_{SK} 0.3 m/s	77
4.9	d_1 and a_5 of the probe signal at U_{SK} 0.5 m/s	78
4.10	d_1 and a_2 of the probe signal at U_{SK} 1.78 m/s	79
4.11	Change of variance with different levels of the decomposed signal at	80
	U_{sr} a) 0.06 m/s; b) 0.3 m/s; c) 0.5 m/s; d) 1.78 m/s.	00
4.12	Sampling technique in the pipe	81
4.13	Flow pattern map with transitions	83
4.14	a) Comparison of the present flow pattern map with the map	86
	proposed by Angeli-Hewitt (2000)	00
	b) Comparison of the present flow pattern map with the map	87
	proposed by Lovick-Angeli (2004)	0,
	c) Comparison of the present flow pattern map with the experimental	87
	data of Trallero (1995)	07
4 15	Comparison of the present transitions with the theoretical curves	88
7.15	proposed by Brauper and Moalem Maron (1991 1992 1993)	00
4 16	Visual and photographic observation probe signal and PDF curve	۵۵
J.IU	for the different natterns at $U_{au} = 1.3 \text{ m/s}$	20
1 17	The approach of the different levels of the decomposed signal for U_{1}	02
4.1/	1.2 m/s	72
	1.3 III/S	

4.18	Flow pattern map for the transition from the water continuous to the oil continuous regime	93
4.19	A comparison of the present map with results of literature	05
4.20	Flow nattern of 0.025 m diameter nine with mixer 1.2 and 2	93
1.20	The patient of 0.023 in channeler pipe with mixer 1, 2, and 3	96
5.1	Holdup as a function of superficial water velocity at constant oil flow	103
	rate	
5.2	Holdup as a function of input phase fraction for different flow patterns	104
5.3	Pressure gradient as a function of superficial water velocity at constant oil flow rate	105
5.4	Variation of pressure gradient with U_{SW} at constant a) $U_{SK} = 0.06$ m/s, b) $U_{SK} = 0.5$ m/s, c) $U_{SK} = 0.7$ m/s	107
5.5	Variation of pressure gradient with U_{SK} at constant a) $U_{SW} = 0.07$ m/s, b) $U_{SK} = 0.18$ m/s	108
5.6	Cross sectional view of the two phases under stratified flow for	118
	prediction of the geometric parameters in the present analysis	
5.7	Cross sectional view of the two phases as represented by Brauner et al. (1996)	123
5.8	a) Experimental holdup vs. predicted holdup for stratified flow	126
	b) Experimental pressure drop vs. predicted pressure drop for stratified flow	
5.9	a) Experimental holdup vs. predicted holdup for stratified mixed flow	127
	b) Experimental pressure drop vs. predicted pressure drop for stratified mixed flow	
5.10	a) Experimental holdup vs. predicted holdup for dispersed flow	127
	b) Experimental pressure drop vs. predicted pressure drop for	
	dispersed flow	
5.11	a) Experimental holdup vs. predicted holdup for the oil continuous	128
	flow pattern	
	continuous flow pattern	
5.12	Pressure drop prediction with different viscosity equations for the oil	129
	continuous flow pattern	
5.13	Prediction of Lovick and Angeli' 2004 experimental data a) Holdup,	130
	b) Pressure drop	
6.1	Flow patterns at low kerosene velocities (U_{SK} 0.06 m/s)	139
6.2	Flow patterns at moderate kerosene velocities (U_{SK} 0.3 m/s)	140
6.3	Flow patterns at higher kerosene velocities (U_{SK} 0.5 m/s)	141
6.4	Cross correlation of the optical probe signals. Upstream flow pattern:	143
	stratified smooth ($U_{SK}=0.06 \text{ m/s}$; $U_{SW}=0.07 \text{ m/s}$)	

.

xii

6.5	Cross correlation of the optical probe signals. Upstream flow pattern: dispersed ($U_{sx}=0.06$ m/s; $U_{sw}=1.3$ m/s)	144
6.6	Cross correlation of the optical probe signals. Upstream flow pattern: three layer ($U_{SK}=0.5 \text{ m/s}$; $U_{SW}=1.0 \text{ m/s}$)	145
6.7	a) Flow pattern map at the downstream section of the orifice	147
	b) A comparison of the maps at the upstream and downstream section of the orifice	148
6.8	Pressure profile before and after the orifice for different velocities of the two liquids	149
6.9	Variation of C_d with N_{Re} for pure water	151
6.10	C_d for different flow regimes of oil water flow a) variation with mixture velocity, b) variation with N_{Re}	151
6.11	Comparison of predicted flow rate with the actual one ($C_d = 0.78$)	152

xiii

List of Tables

Page no.

3.1	Physical properties of Water and Kerosene (at 298K and atmospheric pressure)	43
4.1	Composition of two phase mixture as obtained from the sampling probe	82
5.1	Pressure signal, PDF and a5-d1 of wavelet with varying U_{SW} at U_{SK} =0.06 m/s	113
5.2	Pressure signal, PDF and a5-d1 of wavelet with varying U_{SW} at U_{SK} =0.5 m/s	114
5.3	Pressure signal, PDF and a5-d1 of wavelet with varying U_{SW} at U_{SK} =0.7 m/s	115
5.4	Pressure signal, PDF and a5-d1 of wavelet with varying U_{SK} at U_{SW} =0.07 m/s	116

Chapter 1

Introduction

Multiphase flow or simultaneous flow of several phases is commonly encountered in numerous engineering processes. The simultaneous flow of as many as four phases namely, water, crude oil, gas and sand is not uncommon during oil exploration. Two-phase flow is the simplest case of multiphase flow. There are many common examples of two-phase flows. Fog, smog, rain, clouds, snow, icebergs, quick sands, dust storms, mud etc. are some of the examples of naturally occurring two-phase flow. In industries the different variations of two-phase flow commonly observed include gas-liquid flow, gas-solid flow, liquid-solid flow and liquid-liquid flow. Among these, gas-liquid and liquid-liquid flows are similar in many respects as both of them are characterized by a deformable interface.

The majority of the past studies are primarily confined to gas-liquid flows. The literatures on liquid-liquid systems are much less. There is no guarantee that the information available for gas-liquid flows can be extended to liquid-liquid systems since there are intrinsic differences in the physics of two flow situations. The density ratio is usually larger for oil/water flow as compared to the gas-liquid systems. As a result, gravitational separation of dispersed drops is much less rapid and this leads to a greater propensity (of liquid-liquid systems) to form dispersions. The viscosity ratio between the oil and water also varies over a larger range as compared to gas-liquid cases. As a consequence the dispersion of drops, drag between the phases and the slip velocities between the phases is not expected to obey the formulations or characters representing gas-liquid flows. Further, the interfacial chemistry is more complex for liquid-liquid two phase systems. Combined with the consequences related to the density and the viscosity ratios, the interfacial chemistry is far more important for oil-water flow as compared to gas-liquid flows. Moreover, for liquid-liquid systems the dispersed phase can invert to form a continuous phase and vice versa under certain operating conditions. This has been reported for liquids in stirred vessels as well as under flow conditions. The unique phenomena termed as phase inversion has never been reported for gas-liquid systems.

On the other hand, liquid-liquid two-phase flows are encountered in a wide variety of applications, such as in solvent extraction equipment like column contractors and mixersettlers. Two-phase liquid-liquid reactions, offering numerous advantages over homogeneous reaction, are in vogue nowadays in the field of crop science and medicinal science. Nuclear reactors, film coolers and oil gas pipelines are the examples of processes involving liquid-liquid two-phase flow. Liquid-liquid flow has been proposed as a cooling system in a controlled fusion reactor. The importance of such flows has been increased in recent years due to the increased occurrence of such flows in oil industries. Two-phase oil-water flows are important in production wells and in sub sea pipelines where production of oil from offshore reservoirs also implies the simultaneous production of free water. For many years the amount of free water produced was small and hence given little attention. However, in recent years water production has increased due to reservoir aging and more complex reservoirs. Offshore production includes long horizontal wells and multiphase transport over long distances. The pressure required for transporting the fluids over long distances is highly influenced by the frictional pressure drop, which can be significantly affected by the distribution of oil and water phases. Understanding the complex nature of oil/water flow is important to build predictive design models with high accuracy.

With these considerations, the present study has been undertaken to understand the hydrodynamics of liquid-liquid flows through horizontal pipes. The horizontal configuration is chosen since gravity adds greater complexity to the flow configurations. The work is primarily experimental in nature in order to understand the relatively unknown physics of the flow situation. It has been noted that the starting point for any investigations in gas-liquid flow involves an estimation of the different configurations of the two phases inside the conduit. Accordingly the present study is also directed to the prediction of the different flow patterns, which occur under a wide range of flow

conditions. A novel optical probe has been designed for this purpose. The statistical analysis of the random probe signals has provided an objective flow pattern indicator to estimate the transitions between the different regimes. Attention has next been focused to predict the in situ holdup and pressure drop during the flow of the two phases through the conduit. Further attempts have been made to estimate the total mass flow of the two liquids inside the conduit by an orificemeter. Prior to testing the effectiveness of an orifice as an online mass flow metering device, studies have been directed to observe the influence of the orifice on the phase distribution of the two liquids in the pipe.

The present work is organized in seven chapters. The results of the study have been elaborated from fourth to sixth chapters.

The first chapter presents the general introduction and scope of the present work.

The second chapter deals with a thorough survey of the relevant work in liquid-liquid systems. A short review on relevant gas-liquid system has also been presented to understand the idea behind the present research.

The experimental setup designed and fabricated to investigate some hydrodynamic aspects of simultaneous flow of oil and water through a horizontal pipes is described in the third chapter. The associated instrumentation techniques for the hydrodynamic study have also been described here. The description of an additional test rig fabricated to study oil-water flow through an orifice has also been given in this chapter.

The fourth chapter reports the flow patterns occurring in the present system for a wide range of phase flow rates. The development of an objective flow pattern indicator from the random signals and its statistical analysis has been described. The results have been represented in the form of a flow pattern map. The map has been compared with the existing experimental and theoretical analysis of the past researchers. The fifth chapter presents the experimental measurements and analysis of water hold up and pressure drop during liquid-liquid flow through the horizontal pipe. The results are compared with the existing theories.

The use of an orifice as a flow-measuring device for liquid-liquid system is described in the sixth chapter. Prior to the study additional light on the change in flow pattern due to the presence of an orifice has been discussed.

The salient conclusions drawn in the fourth, fifth and sixth chapters have been highlighted in the seventh and final chapter. Some recommendations have also been made for further investigation.

4

Chapter 2

Literature survey

2.1 Introduction

The increasing importance of liquid-liquid two phase flow has been the driving force for extensive research in this field. The studies have been carried out to understand the liquid-liquid flows through circular conduits of different dimensions and orientations. However, it is noted that the works are primarily influenced by the results available for gas-liquid flow. Therefore, a short review on the relevant studies of gas-liquid flow has been presented prior to a detailed literature on liquid-liquid flows. The main attention has been given to liquid-liquid horizontal flows. However, the literature on liquid-liquid flows through inclined and vertical pipes have also been presented to have a comprehensive idea of the studies carried out on oil-water systems. This review brings out the lacunae of the literatures and focuses on the need of the present study.

2.2 Gas-liquid flows

The earlier studies on gas-liquid flows through a horizontal conduit were associated with the identification of the flow pattern to understand the hydrodynamics and heat and mass transfer characteristics (Wallis, 1969). Several methods have been proposed for the identification of flow patterns. The simplest method for determining flow pattern was by visual observation and photographic technique (Raissan 1965; Hsu & Graham, 1963; Bergles & Suo, 1966; Hewitt and Roberts, 1969). Due to the lack of precision in visual observations other methods based on pressure measurement or spectral distribution of wall pressure fluctuations (Govier et al., 1957; Isbin et al.,1959; Chaudry et al.,1965; Hubbard & Dukler, 1966), photon attenuation (Jones & Zuber, 1975; Hawkes et al., 2000, Mouza et al., 2000), impedance probe (Solomon, 1962; Barnea et al., 1980), nuclear magnetic Resonance (Lynch & Segel, 1977), ultrasonic imaging (Kamei & Serizawa, 1998) etc. have gradually become popular.

A conventional way to represent the flow pattern is in the form of a map. The earliest and perhaps the most reliable flow pattern map for gas-liquid flow was proposed by Baker (1954), although other researchers suggested (White and Huntington, 1955; Govier and Omer, 1962; Kosterin, 1949), with different coordinates. Al-Sheikh et al. (1970) defined a variety of dimensionless groups and used the Dukler-two phase flow data bank to evaluate the suitability of the various pairs of variables for mapping the flow regimes. They concluded that no two groups could characterize all the transitions. Mapping based on superficial velocities of liquid and gas ($U_{LS} \& U_{GS}$) had been proposed by Madhane et al. (1974) and this has till date been most popular way till date to represent a flow pattern map.

Subsequently prediction of the flow pattern-transitions and the stability analysis have gained importance. In gas-liquid flows, the two-fluid model (Taitel and Dukler, 1976) is the workhorse of prediction schemes. In this analysis momentum equations are written for each of the respective phases and are closed using single-phase flow based friction relationships. Therefore, the evaluation of pressure drop and in situ phase fraction becomes a required criterion.

Taitel and Dukler (1976) proposed a mechanistic model for the gas-liquid stratified flow in horizontal and near horizontal pipes. This model is widely used to predict liquid holdup and pressure drop in the entire stratified flow region. In this model, the gas-liquid interface is assumed to be smooth and flat, and the interfacial friction factor is assumed to be equal to the gas-wall friction factor. Based on the physical concepts flow regime transitions were predicted and a flow regime map based on the theory was presented by them.

The model of Taitel and Dukler (1976) for horizontal flow does not take into account the effect of surface tension on stratified and non stratified boundary. The transition to slug

flow caused by surface tension forces at low liquid and gas flow rates has been modeled by Barnea et al. (1983) by comparing gravity and surface tension forces. They have validated the analysis with their experimental data on seven different diameter glass pipes ranging from 4 mm to 12.3 mm..

Hamersma and Hart (1987) and Hart et al (1989) reported their experimental studies of gas-liquid flow for small amount of liquid holdup (for the range below 0.06) in the horizontal pipe. In this, apparent rough surface (ARS) model is introduced by assuming that the film-wetted wall is covered by a liquid layer of equal thickness. Correlations for predicting liquid holdup and frictional pressure drop were proposed. They had shown that in the domain of 38 and 72 m Pa interfacial tension of the gas liquid there was no significant effect on liquid holdup. The pressure gradient was observed to increase slightly with decreasing surface tension values.

Chen et al (1997) proposed a double Circle model to describe the situation, where gasliquid interface present a curved configuration. They have considered the interface as a portion of a circle eccentric to that of the pipe to account the liquid layer (for liquid loading conditions). The layer is bounded between the pipe wall circle and the eccentric circle. They reported this to be applicable for a stratified wavy flows. They have also presented a correlation to predict interfacial friction factor. The model was applied to the experimental results from a 7.9 mm, conduit where air and kerosene were the test fluids. It was found that four interfacial structures exist for the stratified wavy pattern, namely two dimensional wave, three dimensional wave, roll wave and entrained droplet flow.

The phenomenological models (McAdams et al., 1942; Lockhart and Martinelli, 1949; Hart et al., 1989; Chen et al., 1997; Vlachos et al., 1999) have been developed based on the interpretation of the dominant physical mechanisms of the process. However, these models generally rely on gross simplifying assumptions and empirical closure models, which tend to reduce their predictive capabilities. Major factors hindering modelling attempts include the inadequate representation of the interfacial interaction between the liquid film and the gas core region and an inability to determine the fraction of the liquid phase, which is entrained as droplets.

Badie et al. (2000) presented pressure gradient and holdup data for air-water and air-oil flows in 0.079 m horizontal pipe for low liquid loading condition. Addition of a very small liquid flow was found to result in a considerable increase in the pressure gradient compared with single phase gas flow. The pressure gradient and the holdup data were compared with predictions of the 'apparent rough surface' (ARS) and the 'double-circle' models. The ARS model was reported to give better predictions for the holdup over the experimental range. Both models were reported to predict the pressure gradient for air-water flows at high gas flow rates reasonably well. However, the predictions were reported not to be in close agreement for air-water experiments at low gas flow rates and for air-oil experiments.

Ng et al. (2001) investigated the behavior of gas-liquid flow in horizontal pipe for low liquid loading condition. They had carried out an axial view studies using an inline axial view system. In this entrainment and deposition of liquid phase to the upper part of the pipe wall was observed. They have described the possible interface shapes as the proportions of a family curves and a single parameter b, defined as B/κ_o^2

Where B is the Bond no designated by $B = \frac{\Delta \rho g R^2}{\sigma_{AB}}$ ($\Delta \rho$: density difference between the

two fluids; g: gravitational constant; R: radius of the pipe and σ_{AB} : interfacial tension between fluid A & B) and κ_0 is the reference curvature at the center of the interface. They have calculated the appropriate value of b (hence κ_0) as a part of the solution along with the portion of the curve to use. The solution is concluded to be important in prediction of the system performance and flow characteristics including the limiting conditions of both annular and stratified flow.

The stratified/nonstratified transition in gas-liquid flows has been traditionally tackled via stability analyses, resulting in a transitional boundary, which relates mainly to stratified/slug transition. The early studies employed classical Kelvin-Helmholtz (K-H)

theory for two inviscid layers (Kordyban, and Ranov, 1970; Kordyban, 1977, Wallis and Dobson, 1973). While considering gas-liquid flows, ($\rho_G/\rho_L \ge 1$), and assuming that the interfacial disturbance velocity equals the (slower) liquid layer velocity, the liquid destabilizing contribution has been neglected. This results in rather simple Bernoulli-type transitional criteria, whereby the forces in the flowing gas phase over the ("stationary") liquid interfacial disturbance exceeds the restoring gravity forces. Such criteria, required the insertion of empirical constants to match the experimental data along the stratified/slug transitional boundary (Kordyban, 1977, Wallis and Dobson, 1973, Mishima, and Ishii., 1980). Lin and Hanratty (1986) and Andritsos et al. (1987) extended in subsequent studies the classical K-H instability theory for ideal fluids, to account for the various viscous shear stresses due to the mobility of both phases. They described that this "viscid" analysis yielded an interfacial disturbance velocity, which was different from the liquid velocity, and consequently a nonnegligible destabilizing effect of the liquid phase inertia. The application of the "viscous K-H" instability for the onset of slugging in gas-liquid horizontal flows, has been shown to be in better agreement with the experimental findings for various liquid phase viscosities. The above and other related studies associated the departure from stratified pattern with a marginal instability boundary and the stability criteria so obtained have been proposed to be applied mainly for stratified/slug transition.

Brauner et al (1989, 1990, 1991) attempted to study the stability and transitions in gasliquid and liquid-liquid two-phase flows and analyses on the well-posedness of the hyperbolic equations which govern the stratified flow has been done. It had been shown, that the combined conditions for stability and reality of characteristics defined a buffer zone, which was bearing a potential for stratified/nonstratified transition. Brauner et al (1991) inferred that the departure from stratified to other bounding flow patterns was not always located along the marginal stability boundary.

2.3 Liquid-Liquid flows

The general observations of the past literatures indicating different distributions of liquidliquid systems are described below. The survey has been listed chronologically.

As in gas-liquid systems, the interfacial distribution and other hydrdynamic properties depend on the liquids flow rates and physical properties, tube diameter and inclination. However, due to the relatively low density differential between the two-fluids, the role of gravity in liquid-liquid systems diminishes. Therefore, wall-wetting properties of the liquids and surface tension forces become important and may have a significant effect on the flow pattern. Stratified flow with a complete separation of the liquids may prevail for some limited range of relatively low flow rates where the stabilizing gravity force due to a finite density difference is dominant. With increasing flow rates, the interface displays a wavy character with possible entrainment of drops at the interface. The entrainment process increases with increasing flow rates. When the lighter and heavier phases are still continuous at the top and bottom of the pipe, but there is a concentrated layer of drops at the interface, a three layer structure is formed. Eventually, for sufficiently high water flow rate, the entire oil phase becomes discontinuous in a continuous water phase resulting in an oil-in-water dispersion or emulsion. An emulsion is a stable dispersion. Vice versa, for sufficiently high oil flow rate, the water phase may be completely dispersed in oil phase resulting in a water-in-oil dispersion or emulsion. It is also possible for oil-in-water and water-in-oil dispersions to coexist. There are operating conditions under which an oil-in-water dispersion will change to water-in-oil dispersion. This phenomenon is referred in the literature as phase inversion and is associated with an abrupt change in the frictional pressure drop. The flow of viscous oil in a core, which is lubricated by a water film in the annulus (core flow), is most attractive from the viewpoint of pressure drop reduction in transportation of highly viscous oils. The occurrence of annular flow is frequently encountered in oil-water systems of low-density differential, $\Delta \rho$ and small diameter (D) tubes. These systems are characterized by a

small non-dimensional Eotvos number $[E_{OD} = \frac{\Delta \rho g D^2}{8\sigma}$ (σ : interfacial tension)]. In systems where $E_{OD} \ll 1$, an annulus of the wetting phase (surrounding a core of the non-wetting phase) is a natural configuration which complies with surface tension forces and wall-adhesion forces.

.

2.3.1 Through horizontal conduit

The history of the subject as it is presently understood starts with the application of Clark & Shapiro 1949 of Socony Vacuum Oil Company who used additives to reduce the density differences between the oil and water and anionic surfactants to reduce emulsification of water into oil. In this study, injection of 24% water have reported to reduce a pressure gradient by a factor from 7.8 to 10.5 and optimum pressure reduction occurred when 8-10% water was injected with the crude oil. The viscosity of the crude oil used was 800- 1000 cP. Unfortunately they could not give the idea about flow pattern.

Russell et al (1959) observed primarily three types of flow patterns visually for two phase liquid-liquid flow in a one inch horizontal pipe. They classified the flow patterns as bubbly, stratified and mixed and it was shown that the patterns occurred in laminar, transitional and turbulent conditions. Flow conditions were investigated by them over a range of input oil-water volume ratios from 0.1 to 10 at thirteen superficial water velocities ranging from 0.116 ft/sec to 3.55 ft/sec. They accounted the prediction of holdup as the function of liquid input ratio. A correlation for pressure drop was proposed by plotting a Fanning type friction factor based on water properties versus a superficial water velocity.

Russell and Charles (1959) presented equations for two layers flowing between wide parallel plates and for concentric flow in a horizontal circular pipe for the theoretical prediction of reduction in pressure gradient. They proposed that the power requirement could be obtained when less viscous liquid B was introduced between the more viscous liquid A and the stationary boundaries of the flow area. The maximum reduction were described to be obtained in the pipe system with concentric flow was considerably greater than that in the parallel plate system. They said that for concentric flow system the

pressure gradient could be reduced by a factor of $\frac{\mu_A^2}{(2\mu_A - \mu_B)\mu_B}$ or

$$\frac{(dp/dx)_{A}}{(dp/dx)_{AB}} = \frac{\mu_{A}^{2}}{(2\mu_{A} - \mu_{B})\mu_{B}}$$
(2.1)

(μ designates viscosity) and the power requirement could be reduced by a factor of $\frac{0.36\mu_A}{\mu_B}$ (if μ_A is large compared to μ_B).

Charles et al. (1961) investigated the horizontal flow of equal density oil-water mixture through 1-inch diameter pipe. Oil of viscosities 6.29, 16.8 and 65.0 cP were used in the experiment. The flow patterns noted were water drops in oil, concentric oil-in-water (annular flow), oil slugs in water, oil bubbles in water and oil drops in water. Holdup ratios were found to be greater than unity when water was the continuous phase and less than unity when the oil became continuous. The addition of water to oil, in the laminar regime (Nre \leq 1500) was found to lower the pressure gradient to a minimum, after which they described that the addition of water increased the pressure gradient.

Shinnar (1961) considered that drop coalescence, like drop break-up, also happens in the inertial sub range of turbulence in oil water two phase flow. It was described that when two drops collide with each other then coalescence will not happen if their kinetic energy, which will take them apart again, is larger than their adhesion energy and there will therefore be a minimum drop diameter d_{\min} for which separation after collision can still happen (Shinnar, 1961) and for drops with diameters larger than d_{\min} coalescence is not possible. Thomas (1981) considered a minimum contact time to be necessary for the drops to coalesce. He also reached a similar to Shinnar's conclusion, that coalescence will occur when the diameters of the colliding drops are smaller than a diameter d_1 , which depends on the critical film thickness necessary for the film rupture.

Charles and Redberger (1962) reported the reduction of pressure drop in transporting heavy viscous oil, by adding the less viscous fluid (water). They concluded that the reduction factors were considerably lower than experimental values and this appeared to indicate the wave motion and mixing at the oil-water interface. They tried results for the velocity distribution in viscous flow between non-coaxial circular cylinders.

Redberger and Charles (1962) revived the problem in order to obtain information on the rate of mass flow. They transformed to bi-polar co-ordinates and solved the transformed equation by the finite difference technique of successive over relaxation.

Therefore, in 60's people had been undertaken rigorous (theoretical and experimental) studies of laminar two-phase flows of viscous liquids in channels (Charles & Redberger 1962, Gemmel & Epstein 1962, Yu & Sparrow 1969), although the problem of single-phase flow was classical. It was then established that maximum pressure gradient reduction is obtained with concentric-layered (oil in water) flows, and for this reason this particular pattern had received rather wider coverage than the stratified regime.

Howarth (1964) suggested that the coalescence frequency, v_{coal} , of the drops in a oilwater dispersed flow should be given by the product of the collision frequency, v_{coal} , and of the fraction of collisions that result in coalescence, f_{coal} . He defined the coalescence frequency in terms of a critical velocity of approach between the two colliding drops. He reported that the work on drop coalescence may give some insight on the phenomenon but they also stressed that the different proposed relationships cannot be readily used in practical situations, since there are no expressions available for the necessary parameters (e.g. critical film thickness between the drops where coalescence will occur).

Yeh et al., (1964) suggested a model to predict the change in phase continuity (phase inversion) for oil-water flow.

$$\varepsilon_{w} = 1/(1 + (\mu_{o} / \mu_{w})^{0.5})$$
(2.2)

Where ε_{w} , μ_{o} and μ_{w} are the water holdup, oil-viscosity and water-viscosity respectively. This was developed with reference to a configuration of laminar flow in stratified layer and however, its validity was tested against the critical holdup data obtained in a flask (dispersion prepared by manual vigorous shaking of specified volumes of an organic and water phases).

Charles and Lilleleht (1966) used the similarity methods developed by Lockhart and Matrinelli (1949) for gas/liquid flow, to present pressure gradient data in the stratified flow of two liquids. One fluid was in laminar and the other in turbulent flow. The parameters defined was

$$X^{2} = \frac{(dp / dx)_{A}}{(dp / dx)_{B}}$$
(2.3)

Which represents the ratio of the pressure for the more viscous oil phase (A) flowing alone in the pipe, to the pressure gradient for the less viscous water phase (B) flowing alone in the pipe. The multiplier is defined as

$$\phi^2 = \frac{(dp/dx)_{AB}}{(dp/dx)_A}$$
(2.4)

Empirical relation between the parameters ϕ and X were based on curve fitting experimental data. A shift from the gas/liquid flow condition was observed by them.

The velocities and the associated pressure gradients of infinitely long liquid-borne cylinders flowing freely in pipes were related analytically to their radial positions by Kruyer et al. (1967). These velocities and pressure gradients were compared by them with those of liquids in cylinder-free pipes and expressed as ratios. They evaluated the resultant equations for values of the cylinder/pipe diameter ratio between 0.25 and 0.97, with radial positions varying from the fully eccentric to the fully concentric position. As the clearance between the pipe and the bottom of the cylinder increases, they found that the pressure ratio (R_P) decreases and the velocity ratio (R_V) increases. The relationship between R_P and R_V was said to be independent of liquid viscosity and density, capsule density and pipe diameter, and was shown to be nearly linear for the larger diameter ratios. The relationships were compared with data from three experimental capsule pipelines with pipe diameters from $\frac{1}{2}$ to 4 in., involving a variety of diameter ratios, cylinder lengths and densities, and oil viscosities. The experimental results for single capsules of finite length were shown to be in close agreement with the predictions for infinitely long cylinders.

Sinclair (1970) presented core annular flow data for three different pipelines (1.9, 2.54 and 6.35 cm), but he did not perform holdup measurement and used one constant input

ratio throughout his experiments. The test fluids used in the experiments were humble fractol oil (viscosity 1000 cP, density 0.94 gm/cm3) and sea water.

A systematic study of annular flow of two immiscible liquids was performed by Hasson, Mann & Nir (1970 a, b). They tried to develop the mechanism of annular flow of two immiscible liquids as well as the breakup mechanism. In their experiment water was used as the core fluid whereas Kerosene-perchloroethylene as the annulus fluid. They have also tried to measure the annular film thickness.

Guzhov et al. (1973) performed experiments in a 39.4 mm Steel pipe with oil and water as test fluids. The oil was with a viscosity of 21.8 cP, specific gravity of 0.896 and interfacial tension of 44.8 dynes/cm. The mixture velocity was varied from 0.3 m/s to 1.6 m/s. They observed the flow patterns visually and the stress had been given to the patterns namely separated flow with dispersion at interface and water or oil/water bottom layer, emulsion of water/oil and oil/water. Pressure gradients were also measured for different flow patterns.

Malinowsky (1975) performed experiments in a 38.4 mm Steel pipe with an oil with a viscosity of 4.6 cP, specific gravity of 0.850 and interfacial tension of 22.3 dynes/cm. The mixture velocity varied from 0.6 m/s to 2 m/s. Dispersed oil in water and dispersed water in oil were the flow patterns observed by them. Pressure gradients were also measured for different flow patterns.

Oglesby (1979) had done experimental studies with oil and water where the oil had a viscosity of 41.32 cP, density 868 kg/m³ and 30.1 dynes/cm interfacial tension. The mixture velocity was maintained as 1.4 m/s and the oil percent was 74. Semi-segregated and Semi-mixed flow patterns were observed. Additionally the pressure drop studies were also performed.

The shift of the curve for the parameters ϕ and X (as defined by Lockhart and Matrinelli, 1949) in liquid-liquid system from the gas/liquid flow condition had been explained by

Theissing (1980). He attributed this difference to the density ratio difference that exist between a gas/liquid and an oil/water system. He proposed a general correlation for predicting the two phase flow pressure gradient and the correlation is found to take into account the density ratio and is not restricted to a specific flow pattern.

Ooms et al. (1984) predicted a theoretical model for core annular flow of a highly viscous oil in the core and water in the annulus through a horizontal pipe. It was termed as lubricating-film model. According to this model the movement of rippled oil core induces pressure variations in the water film. To check the validity of the model, oil (μ >500 cp) water Core annular flow experiments had been carried out in a 2 inch & 8 inch ID pipe. The model is found to predict the pressure drop poorly in the large pipe.

Cox (1985) had done experimental studies with an oil of viscosity 1.38 cP, density 754 kg/m³ in a 50.1 mm acrylic pipe. The mixture velocity was maintained between 0.7-1.0 m/s. Stratified, dispersed oil in water and dispersed oil in water & water are the flow patterns observed by him. In addition to that the holdup estimation for each flow pattern had been done. Scott (1985) described a similar kind of flow patterns resulted from the experiments done in a 5.08 cm acrylic pipe. There he found stratified, oil in water and dispersed oil in water & water type of flow patterns.

Tidhar et al. (1986) studied phase inversion in liquid-liquid systems flowing in a motionless mixer using the modified electroresistivity method (Sembira et al., 1986). The pairs of liquids used were: (a) water-kerosene, (b) water-CCl₄ and (c) water- (kerosene + CCl₄). Suizer SMV-4 mixing elements made of stainless steel (SS316) and identical elements coated with a film of Teflon were used. On the basis of the experimental results, the conclusions drawn were, "(a) the metastable or ambivalent zone is very narrow; (b) at low flow rates the nature of the surface of the mixing elements has a strong influence on the phase inversion phenomenon; (c) at high flow rates the nature of the surfaces has a weak influence on inversion. The inversion was described to occur when the volume fraction of the dispersed phase is close to 0.5". They also derived a predictive model for phase inversion based on free energy considerations.

Oliemans et al (1986) tried to overcome the draw back of lubricating film model introduced by Ooms et al (1984). Oliemans et al (1986) introduced a turbulent-lubricating-film model. An empirical correlation was established to measure the water holdup (H_w),

$$H_{w} = \beta \left[1 + (1 - \beta)^{5} \right]$$
(2.5)

Where β is the input water fraction. Experiments were carried out with fuel oil (μ = 3000 cP) in 5 cm pipe and it was inferred that the amplitude and the wavelength at the oil water interface vary with water fraction and oil velocity.

A model for predicting the pressure drop and in situ holdup associated with the annular flow of two immiscible liquids in a horizontal pipe was presented by Brauner (1988). Simple explicit expressions were derived for the pressure drop and hold-up associated with a laminar core (with either a laminar or turbulent annular layer). She described that the model converges to a solid capsule flow model, in the limit of a highly viscous core, $\mu_A/\mu_B \rightarrow \alpha$, in which case the *in situ* velocities of both phases approach the mixture velocity, while the hold-up equals the input volumetric ratio. The corresponding pressure drop was observed to be comparable to that which would have been obtained with the less viscous fluid (water) flowing alone in the pipe at the combined mixture velocity. The pressure drop ratio was found to be independent of the tube diameter as long as a turbulent annular layer is maintained.

Flow of two immiscible stratified layers were presented by Brauner and Moalem Marom (1989) using an "adjustable definition" of the hydraulic diameter of two layers. All possible flow situations resulted from laminar-laminar, turbulent-turbulent or mixed flow regimes for a wide variety ranges of density and viscosity ratios were covered by this formulation. According to them prediction of liquid-liquid system require two dimensionless parameters namely ϕ and χ^2 . Two phase pressure drop was discussed in terms of pressure drop reduction. The prediction was found to support the available experimental data.

Arirachakaran et al., (1989) have suggested an empirical model based on a number of experimental studies on oil-water dispersed flows covering a wide range of oil viscosities, to confirm the importance of viscosity on phase inversion. The model equation is given below:

$$\varepsilon_w = \left(\frac{U_{SW}}{U_m}\right) = 0.5 - 0.1108 \log_{10}\left(\frac{\mu_0}{\mu_r}\right)$$
(2.6)

In the above equation ε_w is the critical water cut for phase inversion, μ_r is the continuous phase viscosity m Pas, μ_0 is the oil viscosity, and U_{sw} and U_m are the water superficial and mixture velocities respectively.

The study by Brauner and Moalem Maron, (1993) attempted to propose a form of interfacial shear, which incorporates an explicit functional dependence on the interface slope due to interfacial waviness. The implementation of the proposed model as a closure law in the stability analysis of stratified flows were found to reveal the crucial role of the dynamic term in determining the stability characteristics. They had shown that the inclusion of the newly proposed dynamic term of interfacial shear can predict the stratified-smooth/stratified-wavy transitional boundary (Brauner and Moalem Maron, 1992) satisfactorily for a wide range of two-fluid systems.

Pal (1993) presented results concerning the laminar and turbulent flow behaviors of unstable (without any added surfactant) and surfactant-stabilized water-in-oil emulsions. The unstable emulsions is observed to exhibit drag reduction behavior in turbulent flow; the measured friction factors (f) were found to fall well below the values expected on the basis of the laminar flow properties.

$$f = 0.079 N_{\text{Re}}^{-0.25} \tag{2.7}$$

Where N_{Re} is the Reynolds number. Unstable water-in-oil emulsions were found to exhibit much stronger drag reduction activity than the unstable oil-in-water emulsions. He expressed that the drag reduction activity diminishes (in some cases vanishes completely) upon the addition of a surfactant to the system. Pal (1993) presented a critical review of the previous literatures (Baron et al., 1953; Cengel et al., 1962; Faruqui and Kundsen, 1962; Ward and Kundsen, 1967; Zakin et al., 1979; Pal, 1987) on pipeline emulsions but these works were restricted to *oil-in-water* type emulsion.

Arney et al (1993) presented holdup and pressure drop data of a horizontal core annular flow. Waxy crude oil ($\mu = 27$ P) was used as the core fluid. The experiment was done through a glass pipe of 15.9 mm to observe the flow pattern. The following empirical formula was used to predict the holdup,

$H_{W} = \beta \left[1 + 0.35 \left(1 - \beta \right) \right]$ (2.8)

Where H_W is the in situ water holdup and β is the input water fraction. In their study Reynolds number and friction factor were modified based on simple concentric cylindrical CAF (core annular flow) model.

Stapelberg and Mewes (1994) also used the parameters X and ϕ to represent the experimental pressure gradients taken in two pipes with different diameters. Although their data followed a similar trend to that of Charles and Lilleleht (1966), an obvious effect of the pipe diameter was found by them. They used two pipes of 2.38 and 5.9 cm diameter made of acrylic and glass respectively. They concluded that a single model is not sufficient to correlate the pressure gradient data in all the regimes of liquid-liquid flow.

Valle and Kvandal (1995) used 3.75 cm glass tube for a cocurrent flow study of oilwater. The oil was having a viscosity of 2.55 cP, density of 792 kg/m³ and interfacial tension of 37.3 dynes/cm. They presented a large number of pressure drop and holdup data in the experimental flow range. Apart from visual observation they have used conductivity probe and sampling probes to determine the flow pattern. They reported the flow patterns as stratified, stratified mixed, dispersed oil in water & water and dispersed oil in water & water in oil.

Stability analysis of eccentric CAF were done by Huang and Joseph (1995). In their analysis eccentric core flow steady solutions were described. They studied the linear stability analysis using finite element method to solve a group of PDEs. In their study the

large asymmetric eigenvalue problem generated by Finite element method is solved by Arnoldi's method. From the analysis they concluded that the eccentric flow would be stable when the stability of the concentric flow is established.

Trallereo (1995) presented a comprehensive review of the work done in this area. Based on experimental studies, several flow pattern maps for horizontal oil-water flow was proposed. In addition to the experimental studies, models for predicting the flow pattern transitions had also been developed. The following six flow patterns were identified for horizontal oil-water flow: Segregated flow (Stratified flow and Stratified flow with mixing at the interface). dispersed flow: (a) Water dominated (water-continuous flow) Dispersion of oil in water and water, and Oil in water emulsion. (b) Oil dominated (oilcontinuous flow) Dispersion of water in oil and oil in water, water in oil emulsion.

The flow of two immiscible liquids as well as the influence of an additional injected gas phase in horizontal pipes was investigated by Nädler and Mewes (1995). The experiments were carried out in a transparent horizontal pipe with an inner diameter of 59 mm. Experimental results were presented for the flow regimes of the two phase and three phase flow of oil, water and gas mixtures. The effect of phase inversion on the pressure drop was measured. The experimental results obtained for the three phase flow of oil, water and air indicated that drag reduction was possible by injecting gas in laminar flowing mixtures of oil and water. In the aerated slug flow regime of oil, water and air, a water dominated and an oil dominated flow system were distinguished by them.

Brauner et al. (1996) described that for a general two-fluid system, the basic in situ configuration of stratified layers was with a curved interface. Energy considerations were employed to predict the interface configuration. The effect of the fluid physical properties, *in situ* hold up, tube dimension, wall adhesion and gravitation on the characteristic interface curvature were explored. The prediction of interface curvature has been described to provide the closure relation required for a complete solution of stratified flows with curved interfaces for a variety of two-fluid systems.

20
The flow of two immiscible liquids in a horizontal pipe with an inner diameter of 59 mm and a total length of 48 m was experimentally investigated by Nädler and Mewes (1997). Results were presented for the effect of emulsification and phase inversion on the pressure drop for different flow regimes of two phase oil-water mixtures. The measurements were conducted for oil viscosities of 22, 27 and 35 mPas, which were obtained by changing the temperature of the liquids. Maximum pressure drops were obtained in the region of phase inversion. Inversion was observed for input water fractions between 10 and 2%. In order to detect the type of the emulsion formed in the pipeline and the occurrence of phase inversion, the electrical conductance of the flowing mixture was measured by means of an in-line conductance cell. Phase inversion and emulsification was identified by changes in the conductance of the oil-water mixture. They found that in the case of water-in-oil emulsions, maximum values of the pressure drop of the pipeline flow of water and oil were observed. In the flow region, where above the bottom of the pipe water layer and layers of water-in-oil and oil-in-water dispersions are flowing, drag reduction was observed. The minimum pressure drop of the flow of dispersions was found to be of the order of the pressure drop of the pure water phase flowing alone in the pipe. The occurrence of phase inversion and the total emulsification of one liquid phase within the other was observed by them for different input water fractions. In case of oil-in-water emulsions filling the whole crosssectional area of the pipe the pressure drop was observed to be in between the pressure drop of the pipeline flow of the pure oil phase and the flow of the pure water phase.

Vedapuri et al. (1997) had done experimental studies with an oil of viscosity 2 cP, in a 10.1 cm plexiglass pipe. The mixture velocity was maintained between 0.7-1.0 m/s. Isokinetic probes were used by him to detect the phase continuity. Stratified mixed and dispersed oil in water and water in oil are the flow patterns observed by him. In addition to that the holdup estimation for each flow pattern had been done.

An experimental-theoretical analysis of oil-water horizontal flow in a circular small diameter pipe (3 mm internal diameter) was presented by Beretta, (1997a). In particular, a comparison with available data of pressure drop with a theoretical model for a wide range

of oil to water viscosity ratio was reported by Beretta (1997a,b). The potential of the core flow configuration (Beretta, 1997a) for achieving pressure loss reduction and power saving in the transportation of viscous oils was discussed. A sensible pressure drop reduction, in comparison with the pressure loss required by a single phase viscous flow (at the same flow rate of viscous flow) has been observed in a liquid-liquid (oil/water) flow. It was resolved from their study that the viscous fluid (oil) occupies always the central core flow and the less viscous flow (water) flows around it. Brauner (1988) theoretical model is found to predict satisfactorily in their investigated range of oil-towater viscosity ratios. By the analysis of experimental data, an empirical coefficient was proposed in order to estimate pressure drop with more accuracy for the investigated oil-to water viscosity ratios.

Valle and Utvik (1997) used 7.62 cm steel tube for a cocurrent oil-water flow study. The oil was having a viscosity of nearly 1 cP and density of 741 kg/m³. They presented a large no of pressure drop and holdup data in the experimental flow range. Apart from visual observation they have used conductivity probe to determine the flow pattern. They reported flow patterns as stratified, dispersed oil in water and dispersed water in oil.

A two-fluid model was used by Brauner et al (1998) to solve the momentum equations for a variable interface curvature. Energy considerations are proposed to provide a closure relation for the interface curvature. The analysis identified all the input dimensionless parameters which determine the solution for the stratified flow pattern. They obtained a complete solution of the problem, including the interface shape, in situ hold-up and pressure drop. The validity of the two-fluid model was evaluated by comparing its prediction with available experimental data and with the results of exact analytical solutions for laminar flows with curved interfaces.

Pressure gradients were measured by Angeli and Hewitt (1998) during the cocurrent flow of a low viscosity oil (1.6 mPa s viscosity and 801 kg/m³ density) and water in two 1-inch nominal bore horizontal test sections made from stainless steel and acrylic resin, respectively. Measurements were made for mixture velocities ranging from 0.3 to 3.9 m/s

and for water volume fractions from 0 to 100%. The main finding was the large difference between the results due to the different wettability characteristics of the two pipe materials. Furthermore, it was found that at high mixture velocities, where dispersed flow patterns prevail, there is a peak in pressure gradient during phase inversion and an apparent drag reduction effect when oil is the continuous phase.

A theoretical approach of two instability criteria from the stratified to nonstratified flow in horizontal pipes at cocurrent flow conditions was presented by Sung (1999). The theoretical instability criteria for the stratified and nonstratified flow transition in horizontal pipe had been developed by hyperbolic equations in two-phase flow. These criteria, onset of slugging criterion and critical flow condition criterion, at cocurrent flow condition were designed to correspond to imaginary and zero characteristics which occur when the hyperbolicity of a stratified two-phase flow are broken, respectively.

Data on drop size distributions formed during oil-water flows was presented by Angeli and Hewitt (2000a) using a video recording technique, which employed an endoscope. It was observed that the drop size would depend on the competing phenomena of break up and coalescence. There were extensive works on drop size in stirred vessels concerning mainly the maximum drop size, d_{max} , that could exist in a turbulent system (a comprehensive review is given by Zhou and Kresta, 1998). Most of the models are based on the theory developed by Hinze (1955) for drop break up in isotropic turbulence with improvements to account for increased dispersed phase fraction. Coalescence studies focused mainly on the probabilities of collision and coalescence between two drops that contact in a turbulent field and it was reported that a minimum drop size, d_{min} , that could resist coalescence (Shinnar, 1961; Liu and Li, 1999).

The experiments were performed by Angeli and Hewitt (2000b) with both the water and the oil (1.6 mPa s viscosity and 801 kg m~3 density) as continuous phases, in two 1-in nominal bore horizontal test sections, made from stainless-steel and acrylic resin, respectively. Continuous phase velocities varied from 1.1 to 1.7 m/s and dispersed phase volume fractions from 3.4 to 9% were used. The experimental drop size distributions

23

were reported to be represented satisfactorily by the Rosin-Rammler distribution, with the values of the parameter δ ranging from 2.1 to 2.8. The Rosin-Rammler distribution is described by the following relation (Mugele & Evans, 1951):

$$1 - V_{cum} = \exp\left(-\left(\frac{d}{\alpha}\right)^{\delta}\right)$$
(2.9)

where V_{cum} is the cumulative volume fraction of the drops that have diameters less than δ and α as well as d are the parameters of the distribution. The results showed that the drop size distributions were strongly influenced by the pipe material, with the drops being smaller in the steel than in the acrylic pipe for the same flow conditions. It was observed that they were also influenced by the nature and the velocity of the continuous phase. Both the maximum and the Sauter mean diameters were found to depend on the (-1.8) power of the continuous phase velocity. They reported that none of the theoretical correlations for the maximum drop size could represent accurately the experimental data, while the often used Hinze (1955) equation under predicted the experimental results in all cases.

Two methods were used by Angeli and Hewitt (2000c) for the flow pattern identification, namely high speed video recording and determination of the local phase fractions with a high frequency impedance probe, while the continuous phase in dispersed flows was recognized with a conductivity needle probe. Measurements were made for mixture velocities varying from 0.2 to 3.9 m/s and input water volume fractions from 6% to 86%. Over this range of conditions, different flow patterns were observed, ranging from stratified to fully mixed except annular flow. In general, the mixed flow pattern was reported to appear in the steel pipe at lower mixture velocities than in the acrylic pipe, where, also, oil was the continuous phase for a wider range of conditions. The visual observations were found to be consistent with the measurements using the high frequency impedance probe.

Full-scale experiments were conducted by Fairuzov et al. (2000) in order to investigate flow pattern transitions in horizontal pipelines carrying oil-water mixtures. In the experiments, a 16-inch. pipeline conveying light crude oil was used. The line was connected to a freshwater network to control the input water volume fraction. The transition from stratified flow to dispersed flow was determined by measuring the transversal water fraction profile. For this purpose, a special device, the multi-point sampling probe, was designed and installed into the pipeline. The probe had movable sampling tubes that allowed taking samples simultaneously at six points along the diameter of the pipe. Based on the water fraction obtained, a flow pattern map was constructed. The experimental stratified / nonstratified transition boundary was compared with two theoretical criteria obtained in the linear stability analysis of stratified two-phase liquid-liquid flow.

Simmons and Azzopardi (2001) utilized a laser diffraction technique (Malvern 2600) and laser back scatter technique (Par-Tec m300) for drop size study in liquid-liquid pipe flow, both for horizontal and vertical. The test fluids used are kerosene and aqueous potassium carbonate solution. They studied the drop size distribution in a 0.063 m pipe with mixture velocities ranging from 0.8-3.1 m/s. The Hinze theory were reported to agree well with their experimental data.

The transition to Dispersed oil in water and Dispersed water in oil patterns from the mixed stratified pattern is based on the postulation that a homogeneous dispersion can be maintained when the turbulence level in the continuous phase is sufficiently high (Brauner, 2001). The continuous phase is described to disperse the second phase into small and stable droplets of a maximum diameter, d_{max} which is less than the critical diameter, d_{crit} where d_{crit} is obtained from:

$$\frac{d_{crit}}{D} = Min\left(\frac{d_{c\sigma}}{D}, \frac{d_{cb}}{D}\right)$$
(2.10)

where $d_{c\sigma}$ represents the maximal drop diameter above which drops are deformed and d_{cb} represents the maximal drop diameter above which drops would go to the wall due to buoyancy.

Phenomena accompanying flow of water-oil mixture during droplet flow of water in oil had been described by Hapanowicz and Troniewski (2002). Aims used in the

determination of characteristic parameters in two-phase liquid-liquid flow were presented. The method for calculating the equivalent viscosity and pressure drop during flow of liquid-liquid mixture in the range of the water droplet pattern was given by them. In the study by Brauner and Ullmann (2002), the criterion of minimum of the system free energy was combined with a model for drop size in dense dispersions to predict the critical conditions for phase inversion. The model had been favorably compared with available data on the critical holdup for phase inversion. They tried to provide explanations of features of phase inversion phenomena in liquid-liquid pipe flows and in static mixers.

The Rotatable Coordinate Axis, was proposed by Hong be et al. (2004). It was used to study the hydraulic characters of two-phase stratified flow in pipe. Based on this method, the plane flow model for stratified turbulent flow in pipe was built. Then, the analytic formulas of velocity, discharge etc were obtained in wells and pipes by this model. To prove the theory of the plane flow model, experiments of aeration in stratified pipe was conducted with the aeration experiment device. It was concluded that aeration could effectively achieve the resistance reduction in pipeline, which could offer great theory support to the development of oil and natural gas mixed transportation technology.

Lovick and Angeli (2004a) studied the size and vertical distribution of drops experimentally in dispersed liquid–liquid pipeline flows. Under most conditions the pattern was described to be dual continuous where both phases retain their continuity and there was entrainment in the form of drops of one phase into the other. The investigations were carried out in a stainless steel test section with 38 mm ID with water and oil (density 828 kg/m³ and viscosity 6 mPa s) as test fluids. Mixture velocities from 1.5 to 2:5 m/s and input oil volume fractions from 20% to 80% were used. A dual sensor impedance probe were used for the measurement of drop chord length and drop velocity at different locations in a pipe cross section.

Subsequently the dual continuous flow pattern (both phases retain their continuity at the top and bottom of the pipe while there is interdispersion), which occurs during the pipe

flow of two immiscible liquid phases, was studied in detail by Lovick and Angeli (2004b). Pressure gradient, in situ volume fraction and phase distribution data were obtained. The identification of the dual continuous flow pattern boundaries was achieved with the use of an impedance and a conductivity probe. Measurements were made for mixture velocities from 0.8 to 3 m/s and input oil volume fractions from 10% to 90%. Dual continuous flow appeared at intermediate mixture velocities between stratified and dispersed flows was reported to result in pressure gradients less than those of single phase oil flow. The velocity ratio was observed to increase with increasing input oil fraction, and was above 1 at high oil fractions apart from the highest mixture velocities where it was reduced to values below 1. This behaviour was explained by the in situ phase distribution data and the shape of the oil–water interface. The standard two-fluid model was unable to predict the pressure gradient and hold-up during dual continuous flow.

Chesters and Issa (2004) discussed the fundamental physics behind phase inversion and they presented the fundamental transport equations necessary to describe the phenomenon. The model based on CFD required the formulation of closure relations, which feeded into the equations via the source terms. However, no validation of the overall model was carried out.

Bannwart et al. (2004) aimed at an experimental study on the flow patterns formed by heavy crude oil (initial viscosity and density 488 mPa s, 925.5 kg/m3 at 20°C) and water inside vertical and horizontal 2.84-cm-diameter pipes. The oil-water interfacial tension was 29 dyn/ cm. Effort was concentrated into flow pattern characterization, which was visually defined. The similarities with gas-liquid flow patterns were explored and the results were expressed in flow maps. In contrast with other studies, the annular flow pattern (core annular flow) was reported to be observed in both horizontal and vertical test sections.

Phase inversion and its effect on pressure gradient during dispersed flow of two immiscible liquids was studied in a horizontal stainless steel pipe with 38 mm ID by Ioannou et al. (2004). Water and oil (828 kg/m³ density and 5.5 cP viscosity) were used

as test liquids. Phase inversion point were monitored with a conductivity probe. Also volume fraction distribution in a pipe cross section was obtained with an impedance probe at phase fractions near the phase inversion point. Experiments were conducted under two different initial conditions; starting from oil and from water continuous dispersions, while mixture velocities varied from 3 m/s-4 m/s and input oil fractions from 20%-80%. It was reported that mixture velocity and dispersion initialization did not affect the phase inversion point significantly. They found that changes in the mixture conductivity close to phase inversion were reflected to changes in the pressure gradient. A good agreement was reported between the experimental phase inversion points and those predicted using a Population Balance Equations model for drop size distribution combined with the criterion of equal interfacial energy between the two possible dispersions (oil-in-water and water-in-oil) at phase inversion.

Ioannou et al. (2005) studied phase inversion and its effect on pressure gradient during the dispersed flow of two immiscible liquids for two pipe materials (steel and acrylic) and two pipe sizes (60 and 32 mm ID). Water and oil (796 kg/m³ density and 2.19 mm² s⁻¹ viscosity) were used as test fluids while the appearance of phase inversion in the acrylic pipes was confirmed with the use of impedance ring probes. In the large pipes (steel and acrylic with 60 mm ID) it was found that the phase inversion point (oil volume fraction where inversion appears) depended on whether the inversion was from oil to water continuous mixture or from water to oil (hysteresis). It was reported that phase inversion in all cases was preceded by a large increase in pressure gradient, which was sharply reduced immediately after the new continuous phase was established. The pressure gradient peak was found to be sharper and larger at high mixture velocities than at low ones and in the acrylic pipe compared to the steel one.

An attempt was made by Raj et al. (2005) for a detailed investigation of liquid-liquid stratified flow through horizontal conduits. In their study it was revealed that water-kerosene two phase flow showed distinct stratified patterns like three layer flow, oil dispersed in water and water flow, etc. They reported that the transition equations available for predicting the regimes in gas-liquid flow couldn't be extended for liquid-

liquid cases by merely substituting phase physical properties in the equations. Further efforts were made to estimate the in-situ liquid holdup from experiments and theory. The analysis considered the pronounced effect of surface tension and attempted to modify the Taitel-Dukler (1976) model to account for the curved interface observed in these cases. The curved interface model of Brauner (1996) was validated with their experimental data and those reported in literature.

An investigation of the pressure drop characteristics during the simultaneous flow of kerosene-water mixture through a horizontal pipe of 0.025 m diameter was made by Chakrabarti et al. (2005). Measurements of pressure gradient were made for different combinations of phase superficial velocities ranging from 0.03 to 2 m/s such that the regimes encountered were smooth stratified, wavy stratified, three layer flow, plug flow and oil dispersed in water and water flow patterns. Considering energy minimization and pressure equalization of both the phases, a model was developed to predict the actual situation.

The theory-based closure relations for the wall and interfacial shear stresses used for laminar stratified flow, were extended by Ullmann et al. (2004) and Ullmann and Brauner (2006) to apply it for turbulent flows in either or both of the phases. The closure relations were formulated in terms of the single-phase-based expressions, which were augmented by two-phase interaction factors, due to the flow of the two phases in the same channel. These closure relations, which were valid for smooth stratified flow in horizontal or inclined pipes, were used as a platform for introducing necessary empirical corrections required in the stratified wavy flow regime. Based on experimental data available from the literature, new empirical correlations for the wave effect on the interface curvature, on the interfacial shear and on the liquid wall shear were described (Ullmann and Brauner, 2006).

2.3.2 Oil-water flow in Inclined and vertical pipes

The effect of inclination on flow pattern for two phase flow have been studied thoroughly by different researchers. How inclination affects the in situ phase fraction and frictional pressure gradient, have also been discussed by them comprehensively, Scot and Kundsen (1972) used 1.89 cm brass tube with -90 deg inclination for a cocurrent oil-water flow study. Three types of oil having viscosities of 180,8.6,0.98 cP respectively were used for the experiment. They presented a large no of pressure drop and holdup data. From visual observation they determined the flow pattern. They worked in the flow regime of 'dispersed oil in water'.

Mukherjee et al. (1981) measured pressure loss and holdup for oil-water flow in 1.5 in dia inclined pipe with inclination angles from ± 30 deg to ± 90 deg from horizontal. Pressure losses were higher than calculated from available techniques, with maximum values near the phase inversion. Effects of input liquid fraction and inclination angle on friction ptressure gradient were presented by them. Correlations were given to predict in situ liquid fraction.

Hill and Oolman (1981) used three different diameter tubes with +30 to +90 deg inclination. The oil was having a viscosity of 1.6 cP. A large no of pressure drop and holdup data in the 'large oil bubble in water' and 'stratified' regime were presented.

Cox (1985), Scott (1985), Vedapuri (1997) etc. as described in the previous section along with their work on horizontal pipes, provided insitu phase distribution data for inclined oi-water flows. The inclination was varied from ± 2 to ± 30 . They encountered stratified, dispersed, semi segregated or semi dispersed flow patterns.

Vigneaux et al., (1988) did his experiments with an oil with sp. Gravity 0.741 in a 20 cm pipe. The inclination was maintained between +25 to +90 deg. He had used the high frequency (1 GHz) impedance probe consisting of 0.5 mm diameter tip to detect the flow pattern. The measurements are based on the difference between the impedance value when the probe tip is immersed in oil or water. Flores et al. (1997) by the help of a conductivity probe established different flow patterns at different pipe inclinations (45,60,75,90 deg) for oil (sp. gr 0.858) –water flow through a 5.08 cm acrylic pipe.

Dispersed, pseudo slug and Churn flow pattern were focused along with other patterns (Flores et al., 1998).

The effect of upward $(+5^{0}, +10^{0})$ and downward (-5^{0}) pipe inclinations on the flow patterns, hold up and pressure gradient during two-liquid phase flows was investigated by Lum et al. (2006), experimentally for mixture velocities between 0.7 and 2.5 m/s and phase fractions between 10% and 90%. High-speed video recording and local impedance and conductivity probes were used to precisely identify the different flow patterns. In both positive and negative inclinations the dispersed oil-in-water regime extended to lower mixture velocities and higher oil fractions compared to horizontal flow. Oil plug flow, appeared at both $+5^{0}$ and $+10^{0}$ inclination while the stratified wavy pattern disappeared at -5^{0} inclination. The oil to water velocity ratio was higher for the upward than for the downward flows but in the majority of cases and all inclinations oil was flowing faster than water. The increase in the velocity ratio became more significant as the degree of inclination increased.

At low mixture velocities, where the transition from stratified (S) to dual continuous (DC) flow occurs, a general agreement exists that in upward inclined flows dispersion appears at lower velocities than in the horizontal case (Oddie et al., 2003). The magnitude of the shift in this transition boundary has been observed to increase with inclination (Alkaya, 2000). There is no consensus on the effect of inclination at higher velocities, namely on the boundary of the dual continuous and fully dispersed flows mixing could be generally enhanced (Vedapuri et al., 1997), or either enhanced or retarded according to input composition and velocity (Scott, 1985). Alkaya (2000) observed that this transition boundary was not affected by slight inclination but that a new dispersed flow pattern, dispersed water-in-oil under an oil layer, appeared at $\pm 5^0$ at high oil fractions and low velocities. The data points of Oddie et al. (2003), while sparse, do indicate enhancement of mixing with increased inclination; interestingly, this transition was evident from 0⁰ to $\pm 2^0$, and from $\pm 10^0$ to $\pm 20^0$, but not from $\pm 2^0$ to $\pm 10^0$. Abduvayt et al. (2004) observed stratified and dual continuous flows while dispersed flow did not appear for the conditions investigated at $\pm 0.5^0$ and $\pm 3^0$. They also reported an enhancement of the

stratified region with inclination. In terms of the interface shape of stratified flow, Alkaya (2000) reported a very smooth interface between $+1^{0}$ and $+5^{0}$. In contrast Scott (1985) at $+15^{0}$ and $+30^{0}$ and Abduvayt et al. (2004) at +3- noted that the smooth interface of horizontal flow was completely replaced by large amplitude waves. Kurban's (1997) experimental work revealed that both smooth and wavy interfaces still exist when the pipe is inclined at $+1^{0}$.

The number of investigations on slightly declined oil-water flows is smaller than on slightly inclined ones. The works of interest are those of Cox (1985) at- 15° and -30° , which is complementary to that of Scott (1985) above, Vedapuri et al. (1997) at -2° , Alkaya (2000) at -0.5° , -1° , -2° and -5° , Oddie et al. (2003) at -2° and Abduvayt et al. (2004) at -0.5° and -3° . Cox (1985) and Alkaya (2000) observed that the transition from separated to dispersed flow occurs at lower velocities in downward inclined than in horizontal flow, but Oddie et al. (2003) observed a lesser degree of dispersion at -2° , such that the flow was less homogeneous than at 0-. The data of Cox (1985) reveal relatively little change from horizontal to -15° , but a more significant shift from -15° to -30° : dual continuous flow appears at a lower mixture velocity at -30° than at 0° and -15° .

For Alkaya (2000), downward inclination enhanced the dispersed water-in-oil pattern slightly so that it appears at lower mixture velocities at -5^{0} , but not at -1^{0} . There was little effect of downward inclination on the boundaries of the other patterns by Alkaya (2000) otherwise. According to Abduvayt et al. (2004) at -3^{0} the stratified smooth pattern disappears and is replaced by stratified wavy flow, which at low water fractions extends to a higher mixture velocity compared to horizontal flow. In addition they also found that at this inclination the dual continuous pattern diminishes and occurs only at intermediate and high input water fractions.

The behaviour of the frictional pressure drop $(\triangle P_f)$ with varying input velocities and compositions at low inclinations is not well documented. Alkaya (2000) reported pressure gradient data and compared it against various models available. In general, the total two-phase pressure gradient could be either higher or lower than the single-phase values,

depending on mixture velocity and input composition, while with increasing input oil fraction pressure gradient generally increased to a maximum before decreasing to the value of single-phase oil. The data of Alkaya (2000) in horizontal and inclined flow appeared similar, with the peaks and troughs in the inclined case being the lesser of the two. Lum et al. (2004) provides data on frictional pressure gradient at 0^{0} and $+5^{0}$. It was seen that the two-phase ΔP_{f} values generally decreased to a minimum at intermediate oil volume fractions for each mixture velocity. In terms of the values obtained, there is a marginal difference in the ΔP_{f} between 0^{0} and $+5^{0}$. The results of Abduvayt et al. (2004) showed an increase in the total pressure drop with inclination.

Experiments were conducted by Rodriguez and Oliemans (2006) in a 15 m long, 8.28 cm diameter, inclinable steel pipe using mineral oil (density of 830 kg/m₃ and viscosity of 7.5 mPa s) and brine (density of 1060 kg/m₃ and viscosity of 0.8 mPa s). Steady-state data on flow patterns, two-phase pressure gradient and holdup were obtained by them over the entire range of flow rates for pipe inclinations of -5, -2, -1.5, 0, 1, 2 and 5 deg. The characterization of flow patterns and identification of their boundaries was reported to be achieved via observation of recorded movies and by analysis of the relative deviation from the homogeneous behavior. A stratified wavy flow pattern with no mixing at the interface was identified in downward and upward flow by them. Two gamma-ray densitometers were used by them for accurate measurement of the absolute in situ volumetric fraction (holdup) of each phase for all flow patterns. Extensive results of holdup and two-phase pressure gradient as a function of the superficial velocities, flow pattern and inclinations were reported. The new experimental data were compared with the area-averaged steady-state two-fluid model for stratified flow and the homogeneous model for dispersed flow.

In vertical upward flow and low oil viscosities, the flow patterns as observed by different researchers typically include oil drops, bubbles or slugs in water, transitional flow (TF, churn), water drops in oil and oil-in-water or water-in-oil emulsions. For the detection of the flow patterns different probes were used. El-Hamouz et al. (1995), utilized a laser diffraction technique (Malvern 2600) and El-Hamouz and Stewart (1996) used a laser

back scatter technique (Par-Tec m300) for the detection of the flow pattern. Farrar and Bruun (1996) applied a hot film anemometer based technique in the study of kerosenewater two-phase flow in the bubbly, spherical cap bubble and churn flow regimes. The authors have presented radial bubble volume fraction profile, bubble cut chord length profile, bubble mean velocity profile and turbulent intensity profile. Hamad et al, (1997, 2000) developed an intrusive needle type optical probe to study kerosene-water twophase flow through a vertical pipe. The probe utilizes light emitted inside an optical guide. The intensity of the light reflected back from the probe tip depends on the surrounding medium and is used for phase detection. Jin et al, (2003) used wall mounted ring electrode probe and characterized the flow patterns in oil/water two-phase flow in vertical pipe. A limited number of efforts have been made to develop phase detection probe for liquid-liquid flow using techniques other than conductivity or impedance principle.

Bannwart et al. (2004) tried to characterize the flow patterns visually. In contrast with other studies, the annular flow pattern ("core annular flow") was observed in both horizontal and vertical test sections. These flow pattern was reported to occur in heavy oil-water flows at low water input fractions. In their experimental study they used a heavy crude oil (initial viscosity and density 488 mPa s, 925.5 kg/m3 at 20°C) and water inside vertical and horizontal 2.84 cm i.d. pipes. Before these study Bannwart (2001) studied the modeling aspect of a core annular flow and some conditions were suggested for a stable core annular flow. He also proposed an equation to determine the holdup, based on the measurement of interfacial wave speed. Similarly other equations were developed to predict the pressure gradient.

The flow patterns during two phase kerosene-water flow through a vertical conduit was identified by Jana et al. (2006a) using the conductivity probe method. The normalized time series data of parallel wire probe was analyzed by PDF and wavelet analysis. The analysis showed that at low flow rates of kerosene, kerosene flows as droplets in the continuous water phase. At high flow rates of kerosene, the analysis showed that there may exist a separated flow pattern like core annular flow. The continuity of the water

layer at the pipe wall was examined by applying wall mounted point probes. To examine the existence of kerosene in the center of the pipe at high flow rates of kerosene, a point probe has also been inserted in the center of the pipe. This probe data proved the existence of core annular flow with water as a thin layer or film at the pipe wall.

A novel optical technique was devised by (2006a) for identification of flow patterns during liquid-liquid two-phase upflow through a vertical pipe. It was based on the difference in optical properties of the two phases and estimates the flow patterns on the basis of the proportion of light attenuated and scattered by the two-phase mixture. The nonintrusive measurement system was having a laser source and a photodiode. Statistical analysis of the probe signals was adopted for a better understanding of the flow phenomena. The distribution was observed to be bubbly at low flow rates of both the liquids. They identified core annular flow at high kerosene velocities.

A non-intrusive dye tracing technique, laser-induced fluorescence (LIF), was applied by Liu et al. (2006a) to investigate the co-current flow of two immiscible organic-aqueous liquid flows in a vertical pipe. This technique was described to allow detailed visualization of the dynamic evolution of the flows. Flow structures in liquid-liquid flows at high-dispersed phase fraction were revealed which had not been seen before. It was depicted that in pipe flow, an unstable range was found in the flow pattern map in which oil-in-water (o/w) and water-in-oil (w/o) dispersions could co-exist.

As the flow velocity was increased, the flow went to a transition from annular to wavyannular to mixed (or transition) flow, and finally dispersed flow (Liu et al., 2006b). The results also indicated that secondary dispersions, such as w/o/w and o/w/o, occur in the dispersed core of a mixed flow. In transient flow (in which the flow velocity is decreased), the structure of the flow was reported to be very complex and the formation of 'slugs' could occur, which resemble the situation in gas-liquid flows.

2.4 Flow through an orifice

Except some works on oil-water emulsion flow, the literatures available are based on gas liquid two phase flow through an orifice. In this section some recent literatures of gasliquid flow through an orifice have been discussed to understand the liquid-liquid two phase flow.

Experiments of early 80's (Lin, 1982) confirmed that the quality or flow rate could be predicted with good accuracy by the pressure drop measurements across the orifices for a wide range of density ratio of the phases. On the basis of theoretical and experimental studies, Lin, 1982 presents a simple and practical relationship for calculating two-phase flow rate or quality whose mean square root error is about 12% when the quality ranges from 2-100%.

Chen et al. (1986) found that the results based on the basic model of local resistance of an orifice proposed by him are in good agreement with the experimental results of steamwater systems by Kofaezen (1976) and Janssen (1966).

Yan and Thrope, (1990) described the effect of cavitation on gas-liquid flow through orifices. They stated that the cavitation number $[\sigma = (P_3 - P_v)/(O.5\rho V^2)$; here P₃ is the downstream pressure, P_v is the vapour pressure of the liquid, ρ is the density of the liquid and V is the average liquid velocity at the orifice] at the choked condition is a function of the ratio of the orifice diameter to the pipe diameter only.

Aguta et al (1995) found that a significant amount of liquid will accumulate in the upstream of an orifice at low gas flow rates. The height of the accumulated layer has been found to decrease linearly with the square of the modified froude no., until the formation of a stratified liquid layer.

A theoretical model had been developed by Wenran and Yunxian (1995) for the measurement of two parameters namely mass flow rate and phase fraction (steam

quality). The model was proved in a set of orifice experiments for the two phase flow system at a pressure range of 5.8-12.1 MPa and steam quality of 0.05-0.95.

Pressure changes through sudden expansion and sudden contraction of thick and thinorifice plates were modeled by Kojasoy et al (1997). The modeling was based on the reversible and irreversible losses through contractions and expansions. The volumeaveraged momentum equation and the reversible mechanical energy equation were used to evaluate the irreversibilities. Local void fraction, a necessary input for the prediction of pressure drop, was correlated from a large number of experimental data.

Using an on line integrating RMS device for the measurement of differential pressure signal through orifice plate it was possible to correlate the liquid flow rate with the total two-phase flow by Ferreira, (997). The slotted orifice flow meter was shown to be insensitive to upstream flow conditioning and it responds to two phase flow in a well behaved manner which could be easily characterized (Morrison et al, 2001). This flow meter can be used in poorly designed metering runs, compact metering runs, and compact header configurations with rough pipe whose response to the presence of two phase flow is predictable. If the quality of the mixture is known, the product of the flow coefficient and expansion factor can easily be obtained since the product is only a function of the mixture quality. Then by using only the density of either the liquid or gas, the total mass flow rate through the slotted orifice meter can be determined.

Xu et al (2002) used U bottom orifice in a flash chamber and they found that the pressure drop is higher than that of the single-phase flow for lower temperature flash down, but lower for higher temperature flash down and the pressure drop is higher than the plain orifice.

The pressure profiles along horizontal pipes with a sudden contraction constituted by orifices of different thickness and area flow ratio allowed the local pressure drop to be evaluated during single and two-phase flows by Fossa et al (2002). The impedance method was adopted to measure the area void fraction in different locations upstream and

downstream of the singularity and the corresponding slip ratios were also discussed. They concluded that the time average void fraction generally increases across the singularity and just downstream of the restriction, the void fraction usually attains the maximum measured value along the pipe. This behavior has been observed irrespective of the orifice thickness for the higher values of the liquid flow rate.

The generalized correlations for two-phase and subcooled inlet conditions were separately derived by Choi et al (2004) from a power law in the form of dimensionless parameters generated by the Buckingham Pi theorem. The database for their correlation, includes extensive experimental data for R12, R22, R134a, R407C, R410A, and R502 refrigerant obtained from the open literature. For subcooled inlet conditions at the short tube entrance, the correlation yielded an average deviation of 0.3% and a standard deviation of 6.1% based on the present database, while for two-phase inlet conditions it predicted the database with an average deviation of 0.2% and a standard deviation of 5.0%.

Ten sharp-edged short tubes and three chamfered tubes with lengths between 8.02 and 25.42 mm and diameters between 0.83 and 1.53 mm were used to investigate the flowing characteristics of R744 and based on the large amount of experimental data, a correlation for mass flow rate prediction was developed by Liu et al. (2004).

Slotted orifice is observed to require a short straight pipeline for pressure recovery (Geng et al., 2006). Geng et al. (2006) observed that there was no accumulated liquid in the upstream and the downstream of the orifice plate for the air/water mixture. They concluded that with the help of CFD the optimum design of different slotted orifices with a high degree of confidence level is possible.

One-dimensional numerical simulation of the fluid-dynamic behaviour of short tube orifices working with trans-critical carbon dioxide (CO_2 or R744) has been developed by Garcı'a-Valladares (2006). The prediction is found to be in good agreement with the experimental data. In a nutshell we should discuss about short tube orifice.

38

A short tube orifice has been widely used as an expansion device in heat pumps and automotive and residential air-conditioners due to its simplicity, low cost, ease of installation and maintenance, high reliability and the elimination of additional check valves when the cycle is reversed in heat pumps. Short tube orifices generally are within a range of length to diameter (L/D) ratios ranging from 3 to 20 (Aaron, 1990). The two-phase flow through a short tube orifice is rather complicated although its geometries are simple. A choking phenomenon has been observed for refrigerants flowing through short tube orifices. When choking occurs, the mass flow rate was almost independent of the downstream pressure. This suggests that the mass flow through a short tube orifice under choked flow conditions generally corresponds to the critical mass flow.

Conventional chlorinated refrigerants are being phased out due to negative effects in the environment (UNF, 1997). The search, investigation and utilization of new refrigerants substitutes are an important goal for researchers. During the last decade investigations indicated that carbon dioxide should be considered as a natural refrigeration fluid for its non-negative environmental impact and because it is non-flammable and non-toxic (Lorentzen, 1994; Kruse, 1999; Fleming, 2003). To obtain optimum efficiency in these systems, short tube orifices should be precisely designed for a given set of system operating conditions. There are many uncertainties about the physics in two-phase critical flow, and it is difficult to find a general theoretical model to predict the mass flow rate accurately. Obtaining optimum performance in a system with a short tube orifice requires quantifying the critical flow rate that can be produced through the orifice. In the venacontracta of a short tube orifice the flow is accelerated to almost 20 times the free stream inlet velocity due to the sharp and abrupt contraction at the entrance to the orifice. This acceleration was accompanied by flow separation from the entrance edge of the short tube due to the sharp turn at the tube inlet. The cross section of the .ow was at a minimum and the centreline axial velocity was at a maximum at the vena-contracta. Hence, the minimum pressure (maximum pressure drop) could be observed at the vena-contracta. Downstream of the vena-contracta, the flow reattached itself to the wall of the tube and decreased in velocity (Kim, 1993). Most of the short tube flow models have been developed by empirically correcting the orifice constant and downstream pressure, in the general orifice equation (Kim, 1994; Payne and O Neal, 1998; Singh et al., 2001; Chen et al., 2004; Liu et al., 2004) through an adjusted downstream pressure.

In liquid-liquid two phase flow system the work on emulsion flow through metering devices is the only significant contribution Pal, (1993) Buhidma and Pal, (1996). Pal (1993) inferred that orifice and venturi meters are feasible flow metering devices for oil/water emulsions. Empirical expressions are given by him for the orifice and venturi discharge coefficients to predict the discharge coefficients for the emulsions (stable and unstable) when geometrically similar meters are employed. It is inferred that the correlations are accurate to within $\pm 5\%$ and the proposed correlations are based on experimental data from a single orifice and a single venturi.

Metering of two-phase liquid/liquid emulsion flow has been reviewed comprehensively by Pal (1994). A brief discussion about the industrial applications of emulsions, the working principles of various emulsion metering techniques available have been discussed briefly. They also point out the limitations of these techniques.

Buhidma and Pal (1996) used wedge meters and segmental orifice meters for feasible flow estimation of oil-water emulsions. The differential pressure produced across these meters follows the squared relationship of flow over a wide range of Reynolds number. They demonstrated that the discharge coefficients of the segmental orifice decrease with an increased opening.

Oddie and Pearson (2004) have described some of the commercially viable techniques for gas-liquid, gas-solid, liquid-solid, and liquid-liquid flows in a review article. They have stressed on the techniques involving differential pressure meter, Coriolis, electromagnetic, and cross-correlation flow meters, gamma-ray absorption and gradiomanometer densitometers, and local electrical and fiber-optic sensors.

2.5 Lacunae in the past literature

The aforementioned review shows that the flow regime during liquid-liquid two phase flow have been identified primarily by visual techniques. A few researchers (Angeli & Hewitt, 1998, Lovick & Angeli, 2004 etc.) have used a impedance/conductivity probe but the random signals have not been analyzed further for a better appraisal of flow. They have also reported several limitations of the conductivity/capacitance technique in liquidliquid flows due to its intrusive nature of detection. The literature further confirms that the information available for gas-liquid flows, cannot be extended directly to the liquidliquid cases. Moreover, much work has not been reported on the holdup, pressure drop and other aspects of liquid-liquid system over a wide range of flow rates and fluid properties. The previous studies have pointed out the need to account for the wettability properties of the phases. Although a number of literatures is available for gas-liquid flow except few works on oil-water emulsion flow to explore the orifice as a flow metering device.

2.6 Objective of the present study

Considering the immense applications of liquid-liquid flows and the lacunae in the past literature, the present study aims at

- The development of a non intrusive objective method for identification of flow patterns during liquid-liquid two phase flow through a horizontal conduit such
- that it is applicable both for the oil continuous and the water continuous distribution.
- Development of an objective flow pattern identifier from the random probe signals and their statistical analysis to estimate the range of existence of the different pattern as well as to predict the transition from a water continuous to an oil continuous distribution.
- Verification of the random probe signals with photography and visualization at low flow rates.
- Construction of a flow pattern map and its comparison with data of literature.

- Estimation and analysis of holdup and pressure drop for different patterns over a wide range of phase flow rate.
- Study of liquid-liquid flow through an orifice to understand the influence of an orifice on the flow patterns in a horizontal tube and the potential of an orifice as an on line flow metering device.

Chapter 3

Experimental facility and procedure

3.1 Introduction

The physics of liquid-liquid two phase flow through a horizontal conduit is not well known. Therefore extensive experimentation has been carried out for a comprehensive understanding of the flow phenomena. The experimental setup has been designed and fabricated to investigate some hydrodynamic aspects of simultaneous flow of oil and water through a horizontal pipe. An additional test rig has also been fabricated to study oil water flow through an orifice. The test facility and the measurement techniques of the various parameters have been described in this chapter. The test facility comprises of the fluid handling system and the experimental setup.

3.2 Fluid handling systems

The test liquids used are water and kerosene. Tap water is used for the experimental purpose. The kerosene has been procured from Hindustan Petroleum Corporation Limited, India. The kerosene is dyed with 5 ppm of 1,4 dialkyl anthraquenone (blue) for better visualization of the flow phenomena. The physical properties, namely density, viscosity and surface tension of the fluids are listed in Table 3.1. These have been checked from time to time for accuracy of estimation.

Table	3.1.	Physical	properties	of	Water	and	Kerosene	(at	298K	and	atmospheric
pressure)											

Fluid	Density kg/m ³	Viscosity kg/(m.s)	Surface tension (N/m)	Refractive index
Kerosene	787	0.00120	0.027	1.45
Water	1000	0.00084	0.072	1.33

Interfacial tension: 0.04 N/m

3.3 Liquid supply system

Water is stored in a PVC tank of 0.5 cubic meter capacity, whereas kerosene is kept in a cylindrical steel tank of 0.2 cubic meter capacity. Both of them are circulated from their respective storage tank by two separate centrifugal pumps (P1 and P2 in figure X1) of 1.5 hp each, to the test section. The suction and delivery head of the pumps are 10 and 50 m respectively. The simultaneous adjustment of the bypass valve BV1 and the online control valves V1 or V2 control the flow rate of water. A pair of precalibrated rotameters WR1 and WR2 connected in parallel measures the flow rate of water. Similarly kerosene flow rate is controlled by BV2, V2 or V3 and the flow rate is checked by precalibrated kerosene rotameters KR1 and KR2.

3.3.1 Rotameters

The liquid flow rates have been measured with rotameters of different ranges. The rotameters for both the liquids range from 0 to 0.001 m^3 /s with a least count of $1.66 \times 10^{-5} \text{ m}^3$ /s for R1 and 0 to $1.66 \times 10^{-4} \text{ m}^3$ /s where the least count is $3.33 \times 10^{-6} \text{ m}^3$ /s for R2. The rotameters have been calibrated by the standard method of noting the flow rates of the liquids collected in a measuring cylinder over a measured interval of time.

The flow rates are measured for a sufficiently long time to avoid personal error. The error for the flow rate measurement using the first kind of rotameter is within $\pm 5\%$ except for some data points at the lower flow rates where the error exceeds $\pm 15\%$. Therefore, for lower flow rates the rotameter ranging from 0 to 1.66 x 10^{-4} m³/s has been used and the error is restricted within $\pm 7\%$. The reproducibility of the data has been tested under identical inlet conditions.

3.4 Experimental setup

The experimental setup consists of a) entry section, b) test section and c) exit section in order in the direction of the flow along with a separator. The whole of the test section is made of Perspex to enable visualization of flow. A schematic diagram of the

experimental setup is presented in figure 3.1a and the photographic representation of the setup has been described in figure 3.1b.





45





Horizontal setup with orifice arrangement

Figure 3.1b: Photograph of the experimental setup

3.4.1 Entry section

The entry section consists of two parts, the mixer and a straight developing section.

3.4.2 Mixer

Three types of mixers have been designed to understand the effect of mixer geometry on the flow distribution. The schematic diagrams of the mixers are presented in figure 3.2.

Mixer 1 comprises of two concentric tubes of 0.025 m and 0.075 m diameter. The two fluids are introduced through the two tubes. Kerosene in the outer tube is introduced by a pipe A in figure 3.2a of 0.025 m diameter, while water is introduced through pipe B as shown in the figure. Both the inlet pipes as well as the direction of flow of both the fluids are indicated by arrows in the figure. The arrangement ensures no lateral mixing of the fluids at the entry. A reducer connects the mixer to the test rig of 0.025 m.

In mixer 2 the inner tube is perforated as shown in figure 3.2b. The perforations enable better mixing of the two phases. Mixer 3 also comprises of a cylindrical section followed by a reducer (figure 3.2c) of the same dimension as mixer 1. The cylindrical section is provided with an axial partition 0.30 m of length and breadth equal to inner diameter of cylinder to ensure stratification at the entry. The partition or baffle is made of a Perspex sheet of 0.0035 m thickness. The liquids are introduced through two inlets located diametrically opposite to each other on two sides of the partition as shown in figure 3.2c. The outlet of the mixer enters the straight developing section of length 2.5 m and diameter 0.025 m. This provides a L/D ratio of 100 to the test liquids prior to the test section.



Figure 3.2: Schematic diagram of the mixers: a) mixer 1; b) mixer 2; c) mixer 3

48

3.4.3 Test section

The test section (TS in figure 3.1a) is 0.025m in diameter and 2.2 m in length. Two quick closing valves (q1 and q2 in figure 3.1a) are connected at the two ends of the test section for measuring the volume average liquid holdup of the two phase mixture. By the quick closing valve technique.

A glass view box (VB) is attached to the test section for photography. It is located at a distance of 1.2 m from the starting point of the test section. The rectangular box, filled with water has been installed to eliminate the effects of reflection and refraction by the circular cross section of the pipe. This box has a length of 0.3 m, width of 0.1m and height of 0.1 m. The optical probe is installed at a distance of 1.7 meters from the entry (Region O1 in figure 3.1a). The optical probe is described in the section "Instrumentation scheme".

Two pairs of pressure transducers (DPT1 and DPT2 in Fig X1a) are used to measure the differential pressure across a distance of 2.1 m and 0.025 m respectively as described in the section "Instrumentation scheme".

3.4.4 Exit section

The liquids flow through an exit section of length 2.0 meter and 0.025 m diameter before entering the separator to reduce the effects of flow disturbance in the test section.

3.4.5 Separator

The separator has been fabricated from perspex sheet for visual observation of separation. It is a rectangular tank of 0.8 m^3 capacity (as shown in figure 3.3). The tank is provided with three baffles at intervals of 0.16 meter from each other and two outlets (C3 and C4), for the two fluids after gravity separation.

3.5 Instrumentation Scheme

A scheme of instrumentation have been included in the system for measurement of different parameters as described in the subsequent paragraphs.

3.5.1 Photography

A digital camera (SONY DSC-F717, Sony Electronics Inc. NJ, image device-11 mm (2/3 type), CCD primary color filter, with approximately 5240000/5020000 pixels, lens with focal length of 9.7- 48.5 mm, and more precisely 38 - 190 mm when converted to a 35 mm still camera) is used in still and video mode with proper lighting arrangement to visualize the nature of the two-phase flow. For still photography a shutter speed upto 1/1000 sec is used. The images are analyzed frame wise by an image processing software to visualize the interfacial configuration during the simultaneous flow of the two liquids through the pipe. The photographs are taken at the view box section to minimize the effect of reflection and refraction as mentioned above.







3.5.2 Optical probe

A novel optical probe has been designed and fabricated in the present study to understand the flow patterns during liquid-liquid two phase flow through the horizontal pipe.

3.5.2.1 Selection of the Optical probe

As mentioned in Chapter 2, several techniques are available for the identification of the flow patterns for gas liquid flows. The most widely used methods are those involving the measurement of conductance/capacitance of the two phase mixture. This method is particularly attractive because of its low cost, accuracy and instantaneous response. The main drawback with most of the popular processes is the intrusive nature of detection. This disturbs the flow phenomena and is particularly disadvantageous for liquid-liquid cases where the oil/organic phase often wets the probe and alters its response. Further the conductivity probe has been reported to be suitable for liquid-liquid flows (Angeli & Hewitt, 1998) when the water phase is continuous and fails for the oil continuous flow patterns. So it was felt necessary to devise a new, easy, instantaneous and non intrusive method for identification of flow patterns.

Accordingly the optical probe has been designed and fabricated in the present study. A schematic diagram of the probe is presented in figure 3.4a. As shown in the figure it comprises of

a) A point semiconductor laser source (~2 mW, ~660 nm wavelength and 2 mm beam diameter manufactured by Jain Lasertech Pvt. Ltd., Mumbai 400 031), which is being used as a source of monochromatic laser light.

b) A photo diode sensor (SD 3410, manufactured by Honeywell) located at the diametrically opposite point to detect the light after its passage through the test section.. Its test conditions are Vce=5V; H=2mW/cm² and the operating temperature range is – 55C to 125C. The detector is placed inside a dark box to omit the effect of external light source.

c) An amplifier arrangement (figure 3.4b) after the detector. The complete circuit is depicted in fig.1b. The Operational Amplifier (LM324N, OPAMP) is a key building block in analog integrated circuit design. The OPAMP is composed by several transistors and passive elements (resistors and capacitors) and arranged such that its low frequency voltage is very high. The LM324 OPAMP consists of four independent, high gain, internally frequency compensated operational amplifiers which were designed specifically to operate from a single power supply over a wide range of voltages. Operation from split power supplies is also possible and the low power supply current drain is independent of the magnitude of the power supply voltage. With this OPAMP and several resistors and capacitors the output has been amplified.

d) An Agilent 3970A data acquisition to transfer the signals to the computer. The 34970A 3-slot mainframe, which includes a built-in 6.5 digit DMM, can operate as a stand alone data logger with 50,000 readings of built-in memory It also includes both GPIB and RS-232 interfaces for connection to the computer. The Agilent BenchLink data logger software, which provides easy test configuration setup and real-time data display and analysis.

The light incident on the photodiode is converted to a voltage signal and recorded continuously in the PC via data acquisition system through the processing circuit. The signal depicts the variation in the intensity of light falling on the diode. Prior to the experiments, signals have been recorded for single phase water and kerosene flow through the pipe. A higher voltage is obtained for only water as compared to that of only kerosene due to the higher absorption coefficient of the latter. It has been noted that the same value of voltage has been obtained for all velocities of either phase, thus indicating that the amount of light attenuated by the individual liquids is independent of its velocity. All the signals obtained for two phase flow are normalized with respect to V_{max} , the voltage obtained for pure water flow, to facilitate a comparative study.



During two phase flow the amount of light incident on the photodiode depends on the fraction absorbed and scattered by the two phase mixture. The amount attenuated depends on the absorption coefficient of the fluids. Since it is higher for blue kerosene as compared to water, the amount attenuated increases with the increase in the kerosene fraction in the pipe. For a water-kerosene mixture apart from attenuation, scattering becomes predominant with the onset of the droplets and wavy interfaces. This is evident from the signals obtained for smooth stratified flow and dispersed droplets as shown in figure 3.5. In smooth stratified flow lack of disturbances at the interface gives a smooth response whereas in dispersion scattering of light causes a fluctuating lower voltage response. Thus the optical probe has been observed to be a very effective tool for flow indicator to identify the flow patterns and transitions. Its primary advantage arises from its non intrusive nature which ensures no obstruction of the flow passage and eliminates the problem associated with kerosene sticking to the probe and altering its response. Further it is not affected by the physical properties of the fluid namely its acidity, alkalinity, corrosiveness etc. It also ensures instantaneous response due to the high sensitivity of the photodiode and due to the monochromatic and coherence character of the laser light.



Figure 3.5: a) Probe signal for "Smooth stratified" pattern at U_{SK} 0.06 m/s and U_{SW} 0.07 m/s
b) Probe signal for "Oil dispersed in water" pattern at U_{SK} 0.06 m/s and U_{SW}

1.3 m/s

3.5.3 Pressure sensor

24PCB Honeywell Differential Pressure Transducers (DPT1 and DPT2 in figure 3.1a) with a full scale accuracy of \pm 0.25% has been adopted for the estimation of pressure differential during two phase flow. This sensor has been chosen for the following causes

- Miniature package.
- Variety of gage pressure port configurations easily and quickly modified for our special needs.
- Operable after exposure to any temperature condition (Storage Temperature 55⁰ to +100⁰C).
- Ideal for wet/wet differential applications.
- Choice of termination for gage sensors.
- 2 mA constant current excitation significantly reduces sensitivity shift over temperature.
- Can be used to measure positive pressure.
- Limited only to those media which will not attack polyetherimide, silicon, fluorosilicone, silicone, EPDM and neoprene seals. It has been used comfortably with water.

It has been calibrated with a U tube manometer filled with carbon tetra chloride and the error have been observed to lie within $\pm 5\%$ except some data points for the lower flow rates where the error reaches upto $\pm 9\%$.

3.6 Experimental procedure

Experiments have been carried out to estimate the flow patterns, the in situ fraction of the two phases inside the pipe and the pressure differential in the test section. Prior to experimentation, the rotameters are calibrated for both the water and the kerosene by comparing the rotameter reading with the amount of liquid collected for fixed interval of time. The two phase mixture is introduced at the entry section and flows through the test passage. From the test section it is passed to the separator through the exit section. In the separator, the mixture is allowed to settle for some time. The fluids are separated by gravity. The baffles also facilitate the separation. After separation, kerosene, the top layer

55

is recycled back to the storage tank by opening the valve C4 and water is taken back to the water tank from C3.

3.6.1 Estimation of flow pattern

In order to predict the flow regimes during the simultaneous flow of the two fluids, experiments have been carried out for different combinations of two fluids. The superficial velocities of the test liquids are varied from 0.03-2.5 m/s. The experiments are carried out by increasing the water velocity at a constant value of kerosene velocity. The velocity of kerosene is then changed and the readings are repeated over the entire range of water velocity. The flow patterns occurred in the liquid-liquid system are characterized by the optical probe. In order to obtain reliable values of PDF and wavelet for a particular set of operating condition, the signals have been recorded for a sufficiently long time. The initial test results have revealed that a period of 2 minutes is sufficient for this purpose. The reproducibility of the results was checked by recording the signals for longer time periods under different combinations of phase velocities in the different flow patterns. Different windows of time span 2 minutes have been selected from the same continuous signal and the PDFs have been constructed from them. The moments exhibit high repeatability and agree within $\pm 5\%$ for all the cases with a time span of 2 minutes or more. So a time period of 2 minutes is selected for recording the probe signals.

3.6.2 Holdup Measurement

When the system reaches steady state, the holdup is measured, by instantaneously arresting the flow between the two quick closing valves in the test section. The two liquids are drained through the outlet H in figure 3.1a and collected in a measuring flask. In order to ensure complete drainage of the liquids from the test rig, compressed air is passed through the test section. The collected mixture is allowed to settle for some time, and the volume of both the fluids is noted. The water holdup (H_W) is calculated as,

$$H_{W} = \frac{V_{W}}{V_{W} + V_{K}}$$

Where V_W =Volume of Water; V_K = Volume of Kerosene
3.6.3 Estimation of pressure drop

A pressure transducer connected to the tappings at a distance of 2.1 m is used to measure the pressure drop. The pressure drop has been measured over the entire range of phase velocities (U_{SW} =0.03 to 2.5 m/s and U_{SK} =0.03 to 2.48 m/s). An additional interest was felt to identify the flow patterns from the random pressure signals. In order to note the effect of tapping distance on the characteristics of the random signals, the differential pressure signals have also been recorded at distances of 0.025 m from the two tappings. The distance has been selected according to the observation of Matsui (1984) who has stated that a spherical cap bubble or a cluster of small bubbles of same order of magnitude as the pipe radius can be recognized if the distance between the tappings connecting a pressure transducer is selected to be equal to the inside radius of the pipe. Thus, the test section has recorded differential pressure signals across two different distances namely 2.1 m and 0.025 m. The signals of the transient pressure fluctuation is recorded continuously in a PC via a data acquisition system, described in the optical probe section, with a sampling frequency of 23Hz for 2 minutes. It has been noted that apart from the average value of the signal, no other differences between the two signals were evident.

3.7 Liquid-liquid two phase flow through an orifice

Next, experiments are carried out to investigate the influence of an orifice on the flow phenomenon for the kerosene-water flow in a horizontal conduit. The test facility and the measurement techniques of the various parameters have been described below.

3.7.1 Experimental setup

The schematic diagram of the experimental setup, fabricated to investigate the flow through an orifice is shown in Fig 3.1a. The set up comprises of five parts namely, mixer, upstream section (US), orifice (Or), downstream section (DS) and exit section.

Mixer 1 described in the previous section is used to introduce water and kerosene into the test rig. A straight horizontal upstream section of 0.025 m diameter before the orifice is

constructed. The orifice is located at a distance of 2.8 m from the mixer. The entire tube is made of perspex to enable visualization of the flow phenomenon.

The orifice, as described in Figure 3.6, is sharp edged. It is fitted to the conduit with two perspex flanges with a bolt hole center diameter of 0.065 m. The orifice is made of copper with 1 mm thickness. Its internal diameter is 0.012 m. and the orifice has a divergence of 45° towards the downstream.

The downstream section is of 0.025 m diameter. It is extended upto a distance of 2.5 m.

The exit section, separator and fluid handling systems are common with the previously described horizontal setup.



Figure 3.6: Schematic diagram of the orifice

3.7.2 Instrumentation scheme

The instrumentation techniques used in the system are described below.

Optical probe: The optical probe described above along with the photographic technique (described in Section 3.5.2) has been used here for a better understanding of the flow

phenomenon. Four optical probes are installed at distances of 0.8D (O3), 32D (O2) from the orifice at the upstream and 0.8D (O4), 70D (O5) from the orifice in the downstream section respectively as shown in **figure 3.1a**. The signals from the four optical probes are recorded simultaneously to observe the changes in the flow phenomenon along the length of the test section.

3.7.3 Pressure measurement

The pressure drop along the length is measured by U tube manometers. Carbon tetra chloride and mercury are used as the manometric fluid. Six pressure taps are located at distances of 1D, 2D, 3D, 5D, 10D and 30D from the orifice in the upstream section and seven pressure taps at 0.8D, 2D, 3D, 5D, 10D, 30D and 60 D from the orifice in the downstream region as shown in figure 3.1a. The pressure differentials are measured with respect to the first pressure tap located 30D upstream from the orifice.

3.7.4 Experimental procedure

The superficial velocities of both the test fluids are varied from 0.03–1.5 m/s. The experiments are carried out by increasing the water velocity at a constant value of kerosene velocity. Then the velocity of kerosene is changed and the readings are repeated.

The flow patterns have been observed visually and photographed both in the upstream as well as in the downstream section. Four probes as described in the section "Experimental setup" are used in the upstream and downstream section to identify flow patterns for a particular flow condition. The optical responses are recorded in the PC via a data acquisition system as described in section "Optical probe". The statistical analyses of the signals have provided quantitative identification of flow pattern in the upstream as well as in the downstream end of the orifice. The pressure differentials are measured with respect to the first pressure tap at 30D upstream position.

Chapter 4

Identification of flow patterns

4.1 Introduction

During liquid-liquid horizontal flow through a conduit, the important hydrodynamic parameters and the different transport processes are influenced by the geometric distribution or topology of the components within the flow. The interfacial configurations are not under the control of the experimenter or designer and vary with physical properties and velocities of the two fluids, the conduit geometry, its inclination and many other operating conditions. The different phase distributions can broadly be classified into several flow regimes or patterns. Two extreme cases of phase distribution in a liquidliquid horizontal system can be thought of as fully separated and well dispersed flows. However, in reality the flow patterns possesses combined features of these two ideal cases and are characterized by varying degrees of component separation. As a result, several unique flow patterns are observed during the flow of two immiscible liquids through a horizontal pipe.

A survey of the past literature shows that several studies described in Chapter 2, have been carried out to identify the interfacial configurations during such flows. The common methods adopted for flow pattern estimation are based on the techniques (Hewitt, 1978), which have been noted to be effective for gas-liquid systems. Accordingly, the majority of the researchers (Russell and Charles, 1959; Charles et al., 1961 etc) have adopted visualization and photography related techniques. These techniques are very effective under low phase velocities but fail to identify the distribution at high flow rates of one or both the liquids. Several studies have also adopted different designs of conductivity / impedance probes (Jana et. al., 2006a, Angeli & Hewitt, 1998), diffraction technique

(Simmons and Azzopardi, 2001), fibre optic probes (Riesco & Trusler, 2005; Hammad et al, 1997, 2000; Ramos et al, 2001) etc. Although the conductivity technique is attractive due to its instantaneous response and simple design, the majority of the researchers have reported limited success in liquid-liquid flows. This is mainly due to the intrusive nature of detection, which disturbs the flow phenomena. It is particularly disadvantageous for liquid-liquid cases where the oil/organic phase often wets the probe and alters its response. Moreover, the conductivities of the two liquids are also close to one another. The other probes being used in recent times are also intrusive and their use is further limited by the high cost. Therefore, it was felt that the starting point for an investigation of patterns in liquid-liquid flows is to develop a unique non-intrusive measurement system, which can provide an instantaneous identification of the flow patterns.

A novel optical probe based on the difference in optical properties of the two liquids has been devised for this purpose. It estimates the different patterns on the basis of the proportion of light attenuated and scattered by the two-phase mixture. The detailed description and working principle of the optical probe are given in chapter 3. The statistical analyses of the raw signals namely the probability density function (PDF) analysis and the wavelet multiresolution technique have been adopted to develop an objective flow pattern indicator. The indicator could identify the different patterns both in the water continuous and oil continuous pattern as well as the transition from water continuous to oil continuous pattern. The information thus obtained has been represented in the form of a flow pattern map. The map has been compared with the experimental data and the theoretical models reported in literature. Further attempts have been made to study the effect of entry geometry on the existence of the different flow patterns.

4.2 Method of analysis of the random signals obtained from the optical probe

Apart from visual observation of the optical probe signals, analysis of the random signals has also been performed for a better understanding of the flow phenomenon. The Probability Density Function (PDF) analysis and the wavelet transform (WT) have been adopted for this purpose.

4.2.1 Probability Density Function analysis

The probability density function (PDF) for any parameter relates the possible values of the parameters to probabilities that they will be observed in the real system. The probability of a particular characteristic of a system, within a specified time interval, is defined as the degree of belief held by the person providing the information that the quantitative system characteristic will have a value in a particular interval under the specified condition of measurement. In such assessments, the probability associated with a value of a parameter corresponds to the relative frequency with which randomly sampled values would lie in different intervals of the allowed range of values in the limit as the number of samples go to infinity. A probability density function can be seen as a "smoothed out" version of a histogram. The shape of a PDF serves as a useful diagnostic tool (Drahos and Cermak, 1989). Several authors (Jones and Zuber, 1975; Jones and Delhaye, 1976; Matsui, 1984; Song et al., 1995; Cheng et al., 1998; Jana et al., 2006a) have used them with considerable success for identification of two phase flow patterns. The details of the PDF analysis have been provided in Jones and Delhaye (1976). If a random variable X has a cumulative distribution function F(x) which is differentiable, the probability density function is defined as f(x) = dF / dx. The probability of observing X in the interval $x \le X < x + dx$ is then f(x)dx. For several variables X_1, X_2, \dots, X_n the probability density function is

$$f(x_1, x_2, \dots, x_n) = \frac{\partial^n F(x_1, x_2, \dots, x_n)}{(\partial x_1 \partial x_2, \dots, \partial x_n)}$$
(4.1)

A better method of quantification of the PDF curves can be accomplished by means of the statistical mcments namely median, variance, skewness and kurtosis. While the mean gives us the average value of the distribution, the variance is a measure of the distribution about the mean. The skewness (third moment) characterizes the asymmetry of the PDF and the kurtosis (fourth moment) characterizes the flatness of the distribution compared with the Gaussian one.

4.2.2 The wavelet multiresolution technique

The wavelet transform (WT) is a relatively recent technique for time-frequency analysis, which has good time resolution at high frequencies and good frequency resolution at low frequencies. It has been used with considerable success for identification of phase distributions during different two phase flow situations by several researchers (Ren et al., 2001; Ellis et al, 2003, 2004, Briens et al., 2005, Drahos et al., 2004. Jana et al., 2006b) in the recent past. WT can be viewed as a sort of mathematical microscope as different parts of the time series may be examined by automatically adjusting the focus. Wavelets are generated by stretching, compressing and shifting of a function called 'the mother wavelet'. A wavelet expansion is similar in form to the well-known Fourier series expansion but is defined by a two-parameter family of functions

$$f(t) = \sum_{k} \sum_{j} a_{jk} \psi_{jk}(t)$$
(4.2)

Where j and k are integers and the functions $\psi_{jk}(t)$ are the wavelet expansion functions, which usually form an orthogonal basis. The two-parameter expansion coefficients a_{jk} are called the discrete wavelet transform (DWT) coefficients of f(t) and the coefficients are given by

$$a_{jk} = \int f(t)\psi_{jk}(t)dt \tag{4.3}$$

The wavelet basis functions are a two-parameter family of functions that are related to a function $\psi(t)$ called the generating or mother wavelet by

$$\psi_{ik}(t) = 2^{j/2} \psi_{ik}(2^j t - k) \tag{4.4}$$

where k is the translation and j the dilation or compression parameter. Therefore, the wavelet basis functions are obtained from a single wavelet by translation and scaling. In fact, a signal can be decomposed to obtain a time history of the different frequency bands, which is termed as multiresolution analysis. In the present study, Daubachies 4 wavelet with level 5 is chosen as the analyzing wavelet due to its sufficient number of vanishing moments and smoothness. For all wavelet analysis, Matlab 6 with its wavelet toolbox has been utilized. One full-decomposed signal from the optical probe with five

details and one approximation is depicted in figure 4.1. In the figure d_1 reflects the smallest scale and the highest frequency band; d_2 , d_3 , etc. represent progressively lower frequency bands and the approximation, a_5 reflects the large-scale low frequency resolution.



Figure 4.1: A full scale decomposed signal using Daubachies4 wavelet with level 5 at U_{SK} 0.06 m/s and U_{SW} 0.7 m/s

4.3 Estimation of flow patterns from visual and photography

Initially it was felt necessary to compare the probe signals and the results of statistical analyses with visual and photographic observations wherever possible. It was noted that the patterns could be discerned by visualization at low phase flow rates in the water continuous pattern. At higher flow rates the patterns cannot be distinguished, as the appearance becomes hazy. A pictorial representation of the different flow regimes as observed from photographs has been presented in figure 4.2 and a comparative study is depicted in figures 4.3 and 4.4. The information thus obtained is exploited to understand the flow phenomenon at high phase velocities and in the oil continuous regime.

Figure 4.2 shows that at low flow rates of the two phases the flow is **smooth stratified** with complete separation of the two liquids. On increasing the phase flow rates, the faster phase tends to sweep past the slower one. This causes waviness at the interface and marks the onset of the **stratified wavy** pattern.

On the other hand, an increase in water velocity from the wavy stratified regime shifts the flow to a unique stratified appearance. In this pattern, the region between the two liquids is occupied by a third mixed layer containing drops of both the liquids. It has been termed as the **three-layer** flow. A further increase in water velocity destroys the continuity of the kerosene layer and causes a dispersion of oil droplets in water. Initially the oil droplets are concentrated at the upper portion of the pipe and tend to form a homogeneous mixture with a further increase in water velocity. This is termed as **dispersed** flow.

At lower kerosene velocities, the wavy interface occasionally tends to touch the upper wall thus presenting a flow regime similar in appearance to the **plug** flow regime of gasliquid flows. Although such a distribution has been named as "plug flow" by Beretta et al. (1997), the kerosene chunks do not form elongated Taylor bubbles, which characterize gas-liquid slug flows. They are irregular, deformed and often appear as larger drops or agglomerates of drops. This flow pattern does not exist at higher kerosene velocities where the wavy stratified pattern gives way to the three layer flow.



Horizontal displacement denotes higher kerosene velocities Vertical displacement denotes higher water velocities

Size of each flow regime is a rough estimate of its region of existence within the experimental range

Figure 4.2. Schematic description of the flow regimes

4.4 Characterization of the flow patterns from probe signals and their PDF analysis

As mentioned in Chapter 3 the probe signals for two phase flow are normalized with respect to that obtained for only water (V/V_{max}) in order to facilitate a comparative study. The fluctuating signals thus obtained are the time series in voltage and give qualitative information regarding the chordal average phase distribution across a pipe cross-section.

The photographs and schematic diagram of the flow patterns along with the probe signals and the corresponding PDF curves have been presented in figures 4.3, 4.4, 4.5 and 4.6. Each of the figures denotes the sequential change in the flow patterns with increasing water velocity at a constant kerosene flow rate. They are numbered as 4.3.1, 4.3.2 etc. The flow patterns have been depicted under fully developed conditions as observed visually and during transition to understand the changes of the discrete structures leading to the different transitions. The depiction for each distribution is represented in three parts (a), (b) and (c) denoting the schematic and photograph of the phase distribution, the probe signals and the corresponding PDF curves respectively. The moments of the PDFs are also indicated for their quantification. The mean value, standard deviation, skewness and kurtosis are denoted by m, σ , s and k respectively in figures 4.3-4.6. In all the figures U_{SW} denotes the superficial velocity of water and U_{SK} is the superficial velocity of kerosene.

4.4.1 At low kerosene velocities

Figure 4.3 shows that when the flow is **smooth stratified** at low phase velocities $(U_{SW}=0.07 \text{ m/s}; U_{SK}=0.06 \text{ m/s})$ the complete separation of the two liquids with a smooth interface between them is shown by a smooth probe response at a high voltage value and a unimodal PDF with minimum spread.

As the water velocity is increased at constant kerosene flow rate, the flow exhibits a stratified-wavy pattern. The waviness at the interface results in an oscillating response.

The increased water velocity results in a higher mean value of the signal as expected. The corresponding PDF (figure 4.3.2c) exhibits a reduced height and higher variance. It is platykurtic and skewed to the left.

The continuity of the kerosene layer has been broken down in the **plug flow pattern** with intermittent kerosene chunks being intercepted by water bridges. They remain as irregular chunks or an agglomeration of droplets as shown in figure 4.3.3a. The change in the flow distribution is evident from the irregular and random probe response and the PDF curve under these conditions brings out certain interesting features. In figures 4.3.1 and 4.3.2, the PDF has shifted to higher values of voltage with increase of water velocity as expected but with the onset of plug flow, the increased water velocity has resulted in the shift of the PDF towards lower voltage values. This arises because scattering of light by the large plugs of oil with high residence time becomes important along with its attenuation. Moreover, the PDF curve appears to be multi-peaked unlike its smooth nature at lower water velocities. It exhibits a relatively larger spread and shifts its skewness from a positive to a negative value thus highlighting the breakdown of kerosene continuity and the onset of dispersion.

A further increase in water velocity results in a dense dispersion of small sized droplets, which are mostly concentrated towards the upper portion of the pipe. The probe signals and the PDF curve (figure 4.3.4) denotes a shift of the response towards still lower values of voltage due to an increased scattering of light. The low spread of the PDF arises due to the hindrance of the light path by the dense array of droplets. Further, the smooth nature of the PDF highlights the time invariant distribution of the **dispersed flow pattern** at a particular cross-section.



Figure 4.3: Schematic & photograph, probe signal and PDF of different flow patterns at U_{SK} 0.06 m/s

4.4.2 At moderate kerosene velocities

At a kerosene velocity of 0.3 m/s (figure 4.4), the flow is **stratified wavy** at low water flow rates. The unimodal PDF at higher voltage value and its low spread in figure 4.4.1c is consistent with the PDF observed for stratified wavy pattern at low kerosene velocities (figure 4.3.2c). At increased water velocity, the interfacial waves cannot reach the upper wall to form the plug flow pattern due to the high phase velocity of kerosene. On the contrary, they break down to form drops at the interface as it is evident from figure 4.4.2. This results in a **three layer flow pattern** where the kerosene layer at the top is separated from the water layer at the bottom by an intermediate layer of droplets in the central region (figure 4.4.3). The probe signal is of oscillating nature with dense spikes to represent the appearance of interfacial droplets. The PDF shifts to lower voltage values due to the increased influence of scattering from the interfacial droplets apart from attenuation by the individual liquids. It is also characterized by a spread out nature with multiple indentations, which also denotes an increase of kerosene dispersion in water.

It may be noted that figure 4.4.2 presents the transition from the stratified-wavy to the three layer pattern. The mean value of the PDFs is not significantly affected by the increased water velocity. On the contrary, it is characterized by a smaller peak, increased variance and the appearance of indentations. Thus the situation appears to possess the combined characteristics of a stratified distribution with a tendency for interfacial dispersion. It may be noted that this feature could not be discerned from visual observations.

As the water velocity is increased further, the drops tend to be distributed uniformly forming the **dispersed flow pattern** (figure 4.4.4). This is characterized by a low spread of the histogram (low oscillation) in agreement to the observation of figure 4.3. The PDF also regains its smooth nature with the onset of dispersed flow. The above observations denote a uniform distribution of a dense array of droplets, which propagate through the conduit at high velocities. Their small residence time and high population results in insufficient light passage.

In order to obtain a better understanding of the three layer pattern, its inception and termination of the three-layer pattern is presented at a still higher velocity of kerosene in figure 4.5. The photographs have not been shown because they present a hazy appearance at the high velocities encountered. The figure shows that once interfacial droplets begin to form, an increase in water velocity shifts the mean to higher voltage values (figures 4.5.1-4.5.3). This is accompanied by the appearance of multiple peaks while the spread is relatively unaffected. The total breakdown of kerosene continuity and the onset of dispersed flow (figure 4.5.4) is characterized by a shift of the PDF to lower voltage values, a decrease in its spread and resuming its smooth appearance (in agreement to figures 4.3 and 4.4).



Figure 4.4: Schematic & photograph, probe signal and PDF of different flow patterns at U_{SK} 0.3 m/s



Figure 4.5: Schematic & photograph, probe signal and PDF of different flow patterns at U_{SK} 0.5 m/s

4.4.3 At high kerosene velocities

The visual observations fail at higher velocities of kerosene ($U_{SK} > 1 \text{ m/s}$). The entire tube appears to be bluish in colour. This merely shows that kerosene is the dominating phase but provides no further information about the distribution of the two liquids. Attempts have, therefore been made to identify the phase distribution from the probe signals and the PDF curves. The information obtained from the comparison of the random signals and the PDFs with the visual observations at low velocities have been exploited for this purpose. The results have been represented in a tabular form for U_{SK} =1.78 m/s in figure 4.6.

From the figure, it is evident that at low water velocities the flow passage appears to be hazy with kerosene flowing as a continuous medium and water droplets clinging to the lower portion of the pipe. The probe signals show random oscillations and the PDF is smooth and unimodal.

An increase in water velocity brings about a drastic change in the probe response and the PDF curve. This probably hints at a change in the continuous phase from water to kerosene under these conditions. There is an increase in the oscillation of the response and the oscillations point towards the higher voltage values. The PDF curve shifts to $V/V_{max} < 0.5$ with an increase in the spread and an abrupt change in the sign of the skewness from negative to positive. It may be noted that an identical situation (breakdown in the smoothness of the PDF curve and the change in skewness-sign) was noted during plug flow in figure 4.3.3. A comparison of figures 4.5 and 4.6 clearly brings out the differences in the nature of the curves obtained for the water continuous and the oil continuous regions.

A subsequent increase of water velocity shifts the peak to still lower values of V/V_{max} accompanied by a decrease in the spread and the renewal of a smooth PDF curve (figure 4.6.4) with a positive value of skewness. A similar observation is noted during dispersed

flow in figure 4.3.4 and probably suggests the presence of a continuous kerosene phase with a water-in-oil type of distribution.



 $_{\rm K} = 1.78 \, {\rm m/s}$

Figure 4.6: Schematic diagram, probe signal, PDF and PDF-moments of the different flow patterns at $U_{SK} = 1.78 \text{ m/s}$

4.5 The wavelet analysis to identify the transition boundaries

The wavelet analysis of the random signals has next been performed to supplement the information obtained from the PDFs. As mentioned earlier, the Daubechies 4 wavelet analysis has been used to decompose the normalized probe signals into five levels. It is expected that the high frequency fluctuations is caused by the passage of droplets while the large-scale low frequency fluctuations arise from a waviness of the continuous interface. For a concise presentation of the results, the present study has reported the d₁ and a₅ signals in order to understand the fluctuations due to passing droplets and wavy interfaces respectively. Accordingly, the d₁ and a₅ resolutions of the decomposed signals reported in figures 4.3-4.6 have been presented in a tabular form in figures. 4.7-4.10 respectively. Further, the variance and skewness of the different levels of frequency (d₁ to d₅), the approximation (a₅) and the main signal (s) has been depicted graphically as a function of phase superficial velocities in figure 4.11 a-d to facilitate a comparative study.

It is evident that pure stratified flow at low phase flow rates is characterized by almost straight-line signals of d_1 and a_5 (figures 4.7.1, 4.7.2, 4.8.1), which justifies the low PDF spread in figures 4.3.1, 4.3.2 and 4.4.1. Moreover the onset of waviness at the interface is marked by an increase in the spread at all levels of decomposition and the approximation (figure 4.11a) of the random signal. This shows that the stratified wavy pattern occurs due to a continuous increase in the interfacial waviness.

On the other hand, a further increase in the water velocity presents a different picture. The onset of plug (at low kerosene flow rates) or the three layer pattern (at high oil velocities) is characterized by an increase in the d_1 fluctuations. The a_5 signal is relatively unaffected in this case. This shows that the transition occurs not due to an increased waviness of the phase boundary but due to the break down of the interface to form droplets. A comparison of the wavelets of figures 4.8.1 and 4.8.2 (corresponding to figures 4.4.1 and 4.4.2) as represented in figure 4.11b ascertains that the flow represented by figure 4.4.2 lies in the transition boundary between stratified wavy and the three layer pattern since the increased water velocity results in an increase in the d_1 fluctuations.

while the a_5 fluctuations are relatively unaffected. With a further increase in water velocity the fluctuations in the d_1 level continues to increase in the fully developed three layer pattern while the a_5 fluctuations remain more or less constant thus emphasizing the formation of droplets. The wavelet analysis further shows that the reduced variance in the fully dispersed pattern occurs due to a reduction in the d_1 fluctuations.



Figure 4.7: d_1 and a_5 of the probe signal at U_{SK} 0.06 m/s

The aforementioned observations have been summarized in figures 4.11 a-c which show that the change in variance with decomposed level becomes more drastic as one moves from the stratified to the three layer pattern and subsequently becomes more gradual with the onset of dispersed flow. Moreover the variation decreases with increase in kerosene velocity thus showing a greater homogeneity in phase distribution at higher phase velocities. This is probably manifested by the reappearance of the smooth nature of the PDF curve. An identical situation is noted during the inception of dispersed flow from the plug flow pattern at low kerosene velocities and three-layer flow at higher oil flow rates. Interestingly figure 4.11d shows that the large spread in figure 4.6.2c marking the shift of phase continuity is denoted by a continuous increase in fluctuations from d_1 to d_3 levels of the decomposed signal. The increase in the spread from d_1 to d_3 confirms the coalescence of kerosene to form the continuous phase.



Figure 4.8: d_1 and a_5 of the probe signal at U_{SK} 0.3 m/s



Figure 4.9: d_1 and a_5 of the probe signal at U_{SK} 0.5 m/s

•



Figure 4.10: d_1 and a_5 of the probe signal at U_{SK} 1.78 m/s



Figure 4.11: Change of variance with different levels of the decomposed signal at U_{SK} a) 0.06 m/s; b) 0.3 m/s; c) 0.5 m/s; d) 1.78 m/s.

4.6 The Sampling Technique to understand the distribution of water in oil at high kerosene velocities

An additional check was felt necessary to ascertain the distribution of water in the oil dominating region at high oil flow rates. For this, a sampling technique has been devised to estimate the distribution of water in the oil phase. Three sampling syringes, each with 20 ml capacity, are installed in the test rig beside the optical probe. Syringe A and B are connected to the top and bottom wall of the pipe while syringe C is installed to draw the two phase mixture from the pipe center as shown in figure 4.12. Syringes A and B are located at diametrically opposite points and syringe C is located at a distance of 10 cm from A. It is ensured that syringes A and B are flush mounted with the tube wall. The two-phase mixture is drawn simultaneously through the three syringes for all the flow conditions depicted in figure 4.12 and allowed to settle. The proportion of the two liquids is noted after gravity separation. The results are presented in Table 4.1. The table

indicates that at low water velocities (figures 4.6.1 and 4.6.2) water exists at the bottom of the pipe while a uniform emulsion of the two results at high phase velocities. Accordingly, the situation in figure 4.6.1 is designated as **oil and water in oil** flow. Since figure 4.6.2 denotes a situation similar to the plug flow pattern with kerosene as the continuous phase and intermittent water as chunks at the bottom wall. This distribution is designated as **inverted plug flow** with kerosene as the continuous phase and intermittent water as chunks at the bottom wall. Such a pattern has not been reported for gas liquid systems. In order to distinguish water dispersion in oil from oil dispersed in water flow, the former is designated as the **inverted dispersed** flow pattern.



Figure 4.12: Sampling technique in the pipe

U _{SW} (m/s)	Fraction of water at U _{SK} = 1.78 m/s from syringe		
	(A) Top	(C) Center	(B)Bottom
0.18	0.00	0.00	0.10
0.3	0.00	0.00	0.45
0.7	0.02	0.09	0.69
1.3	0.32	0.35	0.43

Table 4.1: Composition of two phase mixture as obtained from the sampling probe.

4.7 The flow pattern map from the objective indicator

It is evident from the aforementioned discussion that the PDF curve and the wavelet analysis has provided an objective flow pattern indicator which identifies the existence and termination of the different patterns and the underlying transitions from the following quantitative measures: (a) the mean value of response, (b) the variance (c) the skewness of the PDF curves and (d) the fluctuations at the different levels of decomposition (d_1-d_5) and a_5 of the signals.

The objective identifier has shown that pure stratification is observed when the mean response is greater than 0.87 and the PDF curve is smooth with a variance less than 0.01. The stratified dispersed pattern (plug flow at lower velocities and three layer pattern at higher oil flow rates) occurs for a mean response less than 0.87 with the variance ranging from 0.02 to 0.025. This is also characterized by the appearance of multiple peaks in the PDF and a sudden rise in the d_1 fluctuations as compared to the spread at the other levels in figure 4.11. The fully dispersed pattern is distinguished from the stratified-dispersed pattern (three layer flow at high kerosene velocities and plug flow at lower oil flow rates) by the reappearance of a smooth PDF with a spread less than 0.02 and a more gradual variation of the spread at the different levels. It may be noted that the maximum spread

during change in phase continuity denotes coalescence of the dispersed phase and a constantly changing interface from oil to water and vice versa.

The information thus obtained from the statistical content of the probe signals has been used to construct a flow pattern map. In the map presented in figure 4.13 the different flow patterns are denoted by notations where SS, SW, 3L, P, D, O & W/O, IP and ID depict stratified smooth, stratified wavy, three layer, plug, dispersed, oil and water in oil, inverted plug and inverted dispersed flow patterns respectively. The fully dispersed pattern is characterized by a total dispersion of kerosene as droplets in the continuous water phase whereas the stratified dispersed pattern has kerosene both as continuous layer and as droplets.



Figure 4.13: Flow pattern map with transitions

4.7.1 Comparison with data from literature

A survey of the past literature shows that flow pattern maps obtained from experimental data have been presented by Angeli & Hewitt (2000), Lovick and Angeli (2004) and Trallero (1995) while the theoretical analysis to predict the pattern transitions have been proposed by Brauner & Moalem Maron (1993).

The present map has been superimposed in the experimental flow pattern maps reported in literature in figures 4.14 a, b and c respectively. In the first two figures, the present data has been represented as regions of existence of the different flow patterns where the data from literature are superimposed as points. The points for the different patterns are denoted by different symbols as mentioned in the figures. The notations to identify the different patterns have been adopted from the original works. Both the figures show that the region of transition is close to the transition reported in the present system. However, the boundary of the dual continuous flow covers a larger area in the map proposed by Lovick and Angeli (2004) as compared to the present system. This probably arises because they used an oil with different physical properties (ρ =828 kg/m.³ and μ =6 mPa.s) in a larger diameter (0.038m) pipe.

Similar comparisons have also been made with the experimental data of Trallero (1995) in figure 4.14c. Interestingly, the transition boundaries appear to be very close for all the cases although the present work has used oil with different physical properties as compared to the oil ($\rho = 0.85$ gm/cm.3 and $\mu = 28.6$ cP) of Trallero (1995) in a different diameter (5.01 cm) tube.

The present map has next been compared with the theoretical analysis by Brauner & Moalem Maron (1993) in figure 4.15. They have proposed equations to predict the transitions from (a) smooth to wavy stratified flow, (b) the onset of dispersion from wavy stratified flow and (c) the transition from dispersed "oil in water and water" flow to

dispersed "oil in water" pattern as well as that from "oil and water in oil" to dispersed "water in oil" pattern.

The transition criterion to predict the stratified to stratified wavy boundary has evolved from a linear stability analysis performed on the transient formulation of the two fluid model and corresponds to the long wave neutral stability boundary (Brauner and Moalem Maron, 1993). The curve obtained from this criteria (Curve A) has been superimposed in the present flow pattern map in figure 4.15. The figure shows that curve A lies close to the transition predicted in the present work and the nature of the curves are similar.

The transition from the stratified to the dispersed "oil in water and water" flow pattern has been predicted as the boundary where the two-fluid formulation (for stratified configuration) becomes ill-posed (Brauner and Moalem Maron, 1991,1992), the condition for ill-posedness being given as:

$$\tilde{\rho}_{2}U^{2}{}_{2}\gamma_{2}(\gamma_{2}-1) + \tilde{\rho}_{1}U^{2}{}_{1}\gamma_{1}(\gamma_{1}-1) - (\gamma_{2}U_{2}-\gamma_{1}U_{1})^{2} + \frac{D}{\rho_{12}}[(\rho_{2}-\rho_{1})g\cos\beta - C_{h}\rho(U_{1}-U_{2})^{2}S_{i}(A_{1}^{-1}+A_{2}^{-1})] \leq 0$$
(4.5)
where
$$\tilde{\rho}_{2} = 1 + \frac{\rho_{2}}{\rho_{1}}\frac{A_{1}}{A_{2}}, \tilde{\rho}_{1} = 1 + \frac{\rho_{1}}{\rho_{2}}\frac{A_{2}}{A_{1}}, \rho_{12} = \frac{D(dA_{2}/dh)\rho_{1}\rho_{2}}{A_{2}}\left[\rho_{1}+\rho_{2}\frac{A_{1}}{A_{2}}\right]$$

In equation 4.5 subscript 1 is the lighter phase, while 2 denotes the heavier phase. ρ , A, D, S, γ and β denote density, area, diameter, perimeter, shape factor and angle of inclination with the horizontal respectively.

Equation (4.5) has been represented as curve B in figure 4.15. It is observed to lie at the onset of the plug flow pattern at low velocities and the three layer pattern at higher oil flow rates.

The transition to Dispersed oil in water and Dispersed water in oil patterns from the mixed stratified pattern is based on the postulation that a homogeneous dispersion can be maintained when the turbulence level in the continuous phase is sufficiently high. The

continuous phase disperses the second phase into small and stable droplets of a maximum diameter, d_{max} which is less than the critical diameter, d_{crit} where d_{crit} is obtained from:

$$\frac{d_{crit}}{D} = Min\left(\frac{d_{c\sigma}}{D}, \frac{d_{cb}}{D}\right)$$
(4.6)

In equation. (4.6) $d_{c\sigma}$ represents the maximal drop diameter above which drops are deformed and d_{cb} represents the maximal drop diameter above which drops would go to the wall due to buoyancy.

The transitions have been represented as curves C and D in figure 4.15 for oil and water dispersions respectively and are calculated from the extended Hinze model. They are observed to lie close to the predictions of the present work for both the cases.



Figure 4.14a: Comparison of the present flow pattern map with the map proposed by Angeli-Hewitt (2000)



Figure 4.14b: Comparison of the present flow pattern map with the map proposed by Lovick-Angeli (2004)



Figure 4.14c: Comparison of the present flow pattern map with the experimental data of Trallero (1995)



Figure 4.15: Comparison of the present transitions with the theoretical curves proposed by Brauner and Moalem Maron (1991,1992,1993)

4.8 Identification of phase inversion

Phase inversion is a unique phenomenon reported for liquid-liquid systems both in stirred vessels and under flow conditions. During this phenomena the dispersed phase inverts to form the continuous phase and vice versa with slight changes in the operating conditions. The detection of phase inversion is very important from the industrial point of view since it leads to a system with different physical behaviour. In flow systems it leads to a maximum in pressure gradient (Angeli and Hewitt, 1998) thus influencing the phase flow rates. However, the majority of the studies are confined to batch processes and in flow systems, the studies have been influenced by the information obtained from stirred vessels (Selker and Sleicher, 1965; Norato et al., 1998; Zaldivar et al., 1995). The experimental identification of inversion has primarily been carried out through visual observations (Angeli and Hewitt, 2000; Lovick and Angeli, 2004), measurement of

effective conductivity (Ioannou et al., 2005) of the mixture and estimation of pressure gradient (Ioannou et al., 2005).

In the present work the optical probe has been used to understand the phase inversion phenomenon properly. To understand phase inversion the analysis of the probe signals along with an additional sampling technique at $U_{SK}=1.78$ m/s has been carried out and it is described in the previous section. To obtain a better picture of phase inversion, efforts have next been made to analyze optical probe signals at increasing kerosene velocities for constant water flow rates. The water flow rates are selected such that the pattern exhibits dispersed flow characteristics under all flow conditions. It may be noted that the distribution could be observed only at low kerosene velocities and nothing could be visualized with increase in oil flow rate (approximately for $U_{SK} \ge 0.5$ m/s).

The results have been represented for one particular water velocity ($U_{SW}=1.3$ m/s) in figure 4.16 to avoid repetition. The figure is represented in a tabular form where the different rows of the table are marked as 4.16.1, 4.16.2 etc. The depiction for each distribution is represented in three parts (a), (b) and (c) denoting the schematic and photograph of the phase distribution, the probe signals and the corresponding PDF curves respectively. The moments of the PDFs are also indicated for their quantification in the last column.

The figure shows that at low oil velocities, the PDF is unimodal with a large spread and negative skewness. As the kerosene velocity is increased, the PDF shifts to the left as expected. This is also accompanied by a decrease in the spread (till figure 4.16.3). However, all the PDFs are skewed to the left denoting a tendency of kerosene dispersion. As the kerosene velocity is increased further (figure 4.16.4), the response exhibits a remarkable change which can be better understood from the changes in the nature of the PDF curve. The curve is characterized by a sudden increase in spread, an abrupt shift of the mean value to V/Vmax < 0.5 and a shift of the skewness to positive values. This signifies a predominance of kerosene in the flow passage.

A further increase in kerosene velocity is accompanied by a reduction in the oscillation of the probe signal with the oscillations pointing towards higher voltage values. The PDF shifts to still lower voltages and is marked by a further reduction in the spread. Such a change in figure 4.3.4 indicated a dense distribution of droplets whose intense scattering resulted in the reduced spread.





The wavelet analysis has next been performed for a better appraisal of the flow phenomena. For a comparative study, the oscillations at different levels of frequency (d1 to d₅), the approximation (a₅) and the main signal (s) are compared at different flow conditions. This has been shown graphically in figure 4.17 where the variance from d_1 - d_5 , as and the main signal (s) are represented as functions of phase superficial velocities. The graph shows that the d₁ fluctuations are highest at the lowest kerosene flow rate. As the kerosene flow rate is increased, there is a slight decrease in d₁ fluctuations while the fluctuations at the other levels remain comparatively unchanged. This explains the marginal reduction in the PDF spread with increased kerosene velocity and has been attributed to the increased influence of light scattering by the dense dispersion of droplets. However, the d₁ fluctuations continue to be higher as compared to the spread at the other levels. This continues till the phase inversion point corresponding to figure 4.16.4. The wavelet analysis marking the onset of oil continuity presents certain interesting features. It is denoted by a remarkable increase of the spread from d_1 - d_3 level and a negligible difference in the oscillations of the d_5 and a_5 signal. This shows that the increased PDF spread under these conditions is due to an increase in the variance at all levels of decomposition as well as the as signal thus hinting at kerosene coalescence to form a continuous phase. It can therefore be deduced that the onset of inversion occurs due to the coalescence of the dispersed phase and is marked by a random distribution of the two liquids with a continually changing interface.

At still higher kerosene velocities the fluctuations at all levels reduce but the magnitude of spread increases from d_1 - d_3 . Thus figure 4.17 distinguishes between the water continuous and the oil continuous flow patterns from the degree of variance at the different levels of the decomposed signal shows that the coalescence of oil droplets brings about phase inversion.



Figure 4.17: The spread at the different levels of the decomposed signal for U_{SW} = 1.3 m/s

4.8.1 The Flow pattern map to denote phase inversion

The results of the aforementioned experiments have been represented in the form of a flow pattern map in figure 4.18 where the input proportion of oil (β) is plotted as a function of the mixture velocity U_M (U_{SW}+U_{SK}). The figure shows that the flow exists as oil droplets dispersed in water at low oil input fractions (denoted as curve A in figure 4.18) and water dispersed in oil (curve B) at high oil input for a constant mixture velocity. In the region between the two curves there is a random mixture of the two liquids in which the dispersed phase gradually coalesce to form the continuous phase with change of fluid velocities. This has been termed as the ambivalent range in literature and is marked by coalescence of the dispersed phase, a random mixture of the two liquids and a continually changing interface.

It can be observed that the curves A and B (when produced) appear to meet at a point. This shows that the range of the ambivalent region reduces with increasing mixture velocities and at very high phase flow rates, the change from dispersed to inverted dispersed flow is expected to occur spontaneously. An identical observation has been reported by Tidhar et al.(1986) for different pairs of liquids flowing in a motionless mixer where they plotted the oil fraction as a function of Weber number.


Figure 4.18: Flow pattern map for the transition from the water continuous to the oil continuous regime

4.8.2 Comparison of the predicted phase inversion with results from literature

The flow pattern map thus obtained is compared with the empirical equations and analytical models reported in literature to predict phase inversion. The empirical equations to predict inversion have been proposed by Arirachakaran et al.(1989) and Yeh et al.(1964).

The empirical model suggested by Arirachakaran et al.(1989) states that

$$\varepsilon_{w}^{\ \prime} = \left(\frac{U_{SW}}{U_{m}}\right) = 0.5 - 0.1108 \log_{10}\left(\frac{\mu_{o}}{\mu_{w}}\right)$$
(4.7)

where ε_w^{I} is the critical water cut for phase inversion, μ_w and μ_o are the water and oil viscosity. U_{sw} and U_m represents the water and mixture superficial velocities respectively. The model proposed by Yeh et al. (1964), states

$$\varepsilon_{W}^{\prime} = 1/\left[1 + (\mu_{o} / \mu_{W})^{0.5}\right]$$
(4.8)

Both the equations have been superimposed in the flow pattern map as curves C and D in figure 4.19. The figure shows that the equations predict straight lines, which lie in the ambivalent region. They indicate that phase inversion is independent of oil input fraction, which is true at high mixture velocities. Curve D due to Yeh et al. (1964) appears to be closer to the point of intersection of the extrapolated of curves A and B (when produced). The analysis of phase inversion as proposed in the literature by Tidhar et al., 1986; Brauner and Ullmann 2002 has been postulated to occur when the surface energies of the two possible dispersions, oil dispersed in water and water dispersed in oil, are equal. Based on this, the critical oil holdup for phase inversion has been given by the following correlation by Brauner and Ullmann, 2002

$$\varepsilon_{0}^{1} = \frac{\left[\sigma / d_{32}\right]_{w/o} + \frac{S}{6}\sigma\cos\alpha}{\left[\sigma / d_{32}\right]_{w/o} + \left[\sigma / d_{32}\right]_{o/w}}$$
(4.9)

In equation 4.9 α is the liquid-solid surface contact angle with $0^{0} \le \alpha < 90^{0}$ denoting a surface preferentially wetted by water (hydrophilic surface) and $90^{0} < \alpha \le 180^{0}$ denoting a surface wetted by oil (hydrophobic surface); s=4/D is the solid surface area per unit volume and D is the pipe diameter, σ is the interfacial tension and d₃₂ is the Sauter mean drop diameter. The subscripts w/o and o/w denote a water-in-oil and an oil-in-water dispersion respectively. Under conditions where the oil-water surface tension in the pre inversion and post inversion is the same (no surfactants or surface contaminants are involved) and solid-liquid wettability effects can be neglected, the above equation yields

$$\varepsilon_0^1 = \frac{\overline{\rho}\overline{\upsilon}^{0.4}}{1 + \overline{\rho}\overline{\upsilon}^{0.4}}$$
(4.10)

where $\overline{v} = v_o / v_w$ is the rates of the kinematic viscosities of oil to water and $\overline{\rho} = \rho_o / \rho_w$ is the density ratio of oil to water.

The model also predicts a single curve close to curve D. This has been represented as curve E in figure 4.19. Attempts have next been made to superimpose the onset of dispersed flows (equation 4.6) as predicted by Brauner (2001).

The transitions have been represented as curves F and G in figure 4.19 for oil and water dispersions respectively. They are observed to lie close to the predictions of the present work.



Figure 4.19: A comparison of the present map with results of literature

4.9 Effect of mixer geometry

Experiments are next performed to understand the influence of mixer design on phase distribution. The mixers are described schematically in Chapter 3, figure 3.2. For the experiments, mixer 1 in the 0.025 m pipe is replaced by mixers 2 and 3 respectively and the entire set of experiments are repeated for each of them. The regions of existence of the different flow patterns as observed visually for the three mixers are represented by lines in the flow pattern map of figure 4.20. In the figure SS, SW, P, TL and D denote smooth stratified, wavy stratified, plug, three-layer and dispersed flow patterns are close to one another for mixers 1 and 2. This shows that the initial lateral mixing of the fluids due to the perforations in mixer 2 does not influence the downstream distribution. Interestingly, a different result is obtained with mixer 3, which ensures stratified flow at the entry due

to the segregation in the form of a baffle. The flow is smooth stratified at low phase velocities and becomes stratified wavy with increase in liquid flow rates as has also been observed with the previous mixer. However the stratified appearance exists over a large range of flow velocities in this case. The plug flow pattern appears only for water superficial velocities greater than 1 m/s at low kerosene velocities and exists for a narrow range beyond which the pattern becomes dispersed flow. The three-layer pattern, which exists over a large range with mixers 1 and 2 is not observed with mixer 3. The results thus exhibit a marked influence of mixer design on flow pattern. It shows that any pattern can be made to exist over a large range or disappear completely by merely changing the design of the mixer section. This occurs because the mixer decides the initial configuration of the two phases and any pattern once formed does not tend to change far downstream due to the inertia of motion of the fluids.



Figure 4.20: Flow pattern of 0.025 m diameter pipe with mixer 1, 2, and 3

4.10 Conclusion

A novel optical probe has been designed and fabricated in the present study to estimate the flow patterns during liquid-liquid horizontal flow. Apart from visual observation of the probe signals, the statistical analysis namely the probability density function analysis and wavelet multiresolution technique has been adopted for a better aprisal of the flow phenomena. The PDF moments and the variance at different levels of the decomposed signals by the wavelet multiresolution technique have enabled the development of an objective flow pattern indicator.

Initially the results of the indicator have been compared with visual observations at low flow rates. The information thus obtained is next exploited to understand the distribution at high velocities of the two liquids and in the oil continuous regime. A flow pattern map has been constructed from the information thus obtained. It represents the regions of existence of pure stratification, dispersed stratification and fully dispersed flows in the water continuous region. The study reveals the presence of inverted plug flow and inverted dispersed flow in the oil continuous regime, which have been further verified by a sampling technique. The close agreement of the present flow pattern map with the maps available in literature reveals the effectiveness of the objective flow pattern indicator for liquid-liquid horizontal flows. The indicator also identifies phase inversion by the shift of V/V_{max} below 0.5 and the change in the sign of the skewness from negative to positive. The PDF spread is also maximum in the ambivalent region thus denoting a chaotic distribution of the two phases with a continually changing interface. The ambivalent range as predicted in the present study is in close agreement to the results reported in literature.

Studies have also been directed to understand the influence of the mixer design on the downstream distribution of the two liquids. For this experiments have been performede

with three different designs of the mixer. The study has revealed that slight changes in the mixer design does not influence the downstream patterns. However, a completely different design may ensure the disappearance or a prolonged existence of a particular flow distribution.

.

Chapter 5

Estimation of pressure drop and holdup

5.1 Introduction

such that

In the study of the hydrodynamics of single phase flow, the most important flow parameter is the mass flow rate or the volumetric flow rate of the fluid. For two phase flow, the variables important from the engineering point of view include not only the flow rate but also the in-situ proportion of the two phases in the flowing mixture. This is because the pressure drop as well as heat and mass transfer characteristics are functions of its in-situ composition. The composition is usually not equal to the inlet proportion (β) of the two fluids where the inlet proportion (β) is expressed in terms of the phase volumetric flow rates as:

$$\beta = \frac{Q_2}{Q_2 + Q_1}$$
(5.1)

while for gas liquid flows the in-situ proportion of two phases are frequently expressed as void fraction (ϵ) or liquid holdup (H_L) where each of them is defined as

$$\varepsilon = \frac{V_G}{V_L + V_G} \tag{5.2}$$

$$H_L = \frac{V_L}{V_L + V_G} \tag{5.3}$$

$$\varepsilon + H_L = 1 \tag{5.4}$$

In equation 5.1, 5.2 and 5.3 V_L and V_G refer to the volumes occupied by the liquid and the gas phase at any instant of time. Q_1 and Q_2 refer to the volumetric flow rates of phases

1 and 2 respectively. This arises because the lighter phase often tends to slip past the heavier one. The slip depends on the relative velocities of the two phases but also on their interfacial distribution. As a result the liquid holdup can not be obtained directly from the known inputs of a system and several studies both experimental (Hamersma and Hart, 1987; Hart et al, 1989; Chen et al, 1997) and theoretical (Hart et al, 1989; Chen et al, 1997, Barnea and Brauner, 1985; Taitel and Dukler, 1976) have been carried out to estimate the liquid holdup during gas-liquid flows.

Moreover, the pressure drop during flow of a two phase mixture is also of obvious interest since it governs the pumping power required in the system. A survey of the past literature shows that the majority of the studies on pressure drop (Chen et al, 1997; Hart et al, 1989; Barnea et al, 1983; Taitel and Dukler, 1976) in two phase flows have also been confined to gas-liquid systems. Most of the investigations in liquid-liquid flows have attempted to carry out a systematic study in the light of the information already available for gas-liquid flows. The literature on pressure drop and holdup in liquid-liquid systems have been described in chapter 3. The survey shows that a few researchers (Charles and Lilleleht, 1966; Stapelberg & Mewes, 1994) have tried to use the Lockhart and Martinelli (1949) parameter to predict the pressure drop or holdup in liquid-liquid flows but reported a poor prediction. This difference has later been attributed (Thesing, 1980) to the density difference existing between gas-liquid and a liquid-liquid system apart from the effect of pipe diameter. However, due to the relatively low density difference between the two-fluids, the role of gravity in liquid-liquid systems reduces. Therefore, wall-wetting properties of the liquids and surface tension forces become important. Moreover in stratified flow the interface between the liquid phase is not necessarily planar. This has been considered by Brauner and Moalem Maron (1989) who have modified the Taitel and Dukler (1976) model for gas-liquid flows to incorporate the concept of "hydraulic diameter" of the phases for analyzing the flow of liquid-liquid systems. Studies by Gorelik and Brauner (1999) and Ng. et al. (2001) have expressed the shape of the liquid-liquid interface by using the variational principle of minimizing the system free energy. Ng. et al. (2001) have extended their studies to predict the possible interface shapes as a family of curves described by a single parameter b as a function of



135**4**4 ₁₀₀

Eötvös number and the radius of curvature. Brauner et al. (1996) have performed a detailed analysis using the two fluid model considering curved interface. They attempted to predict the insitu interfacial configuration as a function of holdup, Eötvös number and wettability angle by the minimization of the total system energy. In case of dispersion where one of the liquids forms a continuous phase and the other is dispersed in it, the in situ holdup and the corresponding pressure drop are often predicted by the homogeneous or the no slip model (Hassan and Kabir, 1990, Flores et al., 1997). However it has been observed by Hapanowicz and Troniewski (2002) that the model often fails during inverted dispersed flows. They have attributed this to the change in the system viscosity of the emulsion.

Based on above discussion the present work has been divided into three parts.

i) Extensive experiments have been carried out to understand the hydrodynamics of liquid-liquid flows through horizontal pipes. In order to measure the pressure drop and holdup in the different flow patterns, experiments have been carried out over a wide range of superficial velocities. The deviation of the insitu composition from the input fraction is noted to understand the effect of slip between the phases. For this the insitu composition is expressed as the proportion of the heavier liquid (water) in the flowing mixture viz

$$H_{W} = \frac{V_{W}}{V_{W} + V_{K}}$$
(5.5)

where V_W and V_K denote the volumes of the flow passage occupied by water and kerosene respectively. This is designated as water holdup (H_w) in the present work to maintain parity with the nomenclature adopted for gas liquid flows.

ii) Next, attempts have been made to identify the dependence of pressure gradient on superficial velocities in the different flow patterns. Further efforts have been directed to identify the flow patterns from the time dependent pressure signals and the statistical analysis of the random signals.

iii) Thirdly, an analysis of the holdup and pressure drop characteristics have been performed in the different flow patterns. It may be noted that the flow velocity have been selected such that the holdup and pressure drop can be studied both in water continuous

and oil continuous regimes. For the purpose of analysis the different distributions in water continuous regime has been classified as stratified, stratified mixed and dispersed flow. The detailed description of the flow patterns is provided in Chapter-4. On the other hand, a large number of data could not be collected in the different distributions of the oil continuous regime. Therefore different distributions in the oil continuous regime namely oil and water in oil, inverted plug flow and inverted dispersed flow are grouped together and designated as the oil continuous pattern. The separated flow models have been considered for stratified flow while the homogeneous flow model has been adopted for dispersed and oil continuous flow. Both the separated and homogeneous models are used to analyse the stratified mixed pattern as it combines the characteristics of stratification with dispersion. The models have been validated with the present experimental data as well as the data reported in literature.

5.2 Experimental measurement

The estimation of the in-situ volume fraction occupied by either of the phases in the conduit has been carried out by the quick closing valve technique as discussed in chapter 3. A pressure transducer connected to the tappings at a distance of 2.1 m is used to measure the pressure drop. The method of estimation of pressure drop has been described in chapter 3. In order to note the differential pressure signals additional tappings at distances of 0.025 m from the two tappings has been used to understand the interfacial phenomena. The distance has been selected according to the observation of Matsui (1984) who has stated that a spherical cap bubble or a cluster of small bubbles in the size of the pipe radius can be recognized if the distance between the tappings connecting a pressure transducer is selected to be equal to the inside radius of the pipe. Thus, the test section has recorded differential pressure signals across two different distances namely 2.1 m 0.025 m.

The statistical properties of the differential pressure signals at the short scale do not add any new feature for a particular flow pattern in comparison to the results obtained from the 2.1 m scale. Therefore, only the results obtained from the pressure sensor, located between tappings at a distance of 2.1 m, have been described in the following sections. The superficial velocities of the test liquids are varied from 0.03–2.5 m/s to cover the stratified, stratified mixed, dispersed and oil continuous flow patterns. The experiments are carried out by increasing the water velocity at a constant value of kerosene velocity. The velocity of kerosene is then changed and the readings are repeated over the entire range of water velocity.

5.3 Holdup results

The measured data have been represented as holdup (H_W) versus superficial water velocity (U_{SW}) with kerosene velocity (U_{SK}) as parameter in figure 5.1 for the entire range of flow velocity. All the curves indicate a similar trend of variation of H_W with phase velocities. H_W increases with the increase in water velocity and decrease in kerosene velocity as expected. It is evident from figure 5.1 that at lower kerosene velocities, the increase in holdup with water flow rate is very rapid for lower water velocities while at higher water flow rates the change becomes more gradual. In this situation, the oil is dispersed as droplets in the continuous water phase and is probably carried away rapidly by water. At higher oil velocities the holdup increases slowly with increasing water flow rate over the entire range of water velocity. The flow situation at higher kerosene velocities marks the inception of inverted dispersion/ oil continuous pattern. The rapid transportation of water droplets by the continuous oil phase may be responsible for the steady but gradual increase in holdup.



Figure 5.1: Holdup as a function of superficial water velocity at constant oil flow rate

A further attempt has been made to note the difference between the insitu and input volume fractions of the two phases in order to note whether the input volume fraction can be used to analyze liquid-liquid flows in the absence of data on insitu volume fractions. Figure 5.2 shows that H_w lies close to β at higher values of input volume fraction for stratified flow. This probably arises due to negligible slip between the phases under these conditions. However, significant deviation occurs at lower β . For other flow patterns β and H_w are not very close to each other and there is significant difference between the two both for the dispersed and the oil continuous pattern. The higher value of H_w for β more than 0.5 in the dispersed pattern signifies the slip of the oil droplets in the water phase, whereas lower values of H_w for β less than 0.5 in the oil continuous pattern depicts the presence of a faster flowing dispersed water phase.



Figure 5.2: Holdup as a function of input phase fraction for different flow patterns

5.4 Pressure gradient results

Extensive measurements of the pressure gradient have been carried out over a wide range of flow velocities. Measurements of pressure gradient for different flow patterns are plotted against the superficial water velocity with kerosene flow rate as parameter in figure 5.3. An increase in the phase flow rate leads to a substantial increase in the pressure drop. The reason behind the increasing trend of pressure gradient with phase velocity can be attributed to the scaling of pressure drop with the square of the velocity. Next the slope of the pressure gradient curves as a function of fluid superficial velocities has been noted. In order to identify the influence of phase flow rates on pressure gradient the results have been expressed in two different ways. The pressure gradient has been represented as a function of water superficial velocity (U_{SW}) with the kerosene superficial velocity at a constant water flow rate in figures 5.4a – c and as a function of kerosene velocity at a superimposed in the figures to note the flow patterns under different flow conditions. The

figures show that pressure gradient increases with superficial velocity of either of the phases as expected. A comparison of the two figures show that the increase is more pronounced with increase in kerosene velocity (figures 5.5a and b) as compared to that with water velocity (figures 5.4a - c). Moreover the slope of the curves appears to change under certain flow conditions.





At low kerosene flow rates (figure 5.4a) the increase is initially gradual when the flow exhibits smooth stratified characteristics with complete segregation of the two liquids. The pressure gradient appears to be almost independent of water velocity under these conditions and it increase slightly with the onset of waviness at the interface. As the amplitude of the waves increases further at higher water velocities, distinct plugs of kerosene intercepted by water bridges are observed. This results in a steeper slope of the curve probably due to the fluctuating nature of flow. At still higher velocities, the plugs break down to form droplets dispersed in the continuous water phase. This is marked by a reduction in the slope of the curve probably due to the more mixed character of flow and a reduction in interfacial disturbances.

The change in slope becomes less pronounced at higher kerosene velocities (figures 5.4b and c) when the stratified wavy flow pattern gives rise to the three layer flow pattern which subsequently forms dispersed flow at higher water velocity.

In figures 5.5a and b an increase in the steepness of the curves marks the transition from smooth to wavy stratified flow pattern in agreement to the observations reported in figure 5.4a. However, a further increase in kerosene velocity increases the steepness of the curve and a higher magnitude of the average pressure gradients when one enters the regime of oil continuity. This is contrary to the reduction in slope, which occurred with the onset of dispersion from plug flow in figure 5.4a and probably arises due to an increase in the proportion of the pipe being wetted by the oil phase. Thus the above observations indicate that the slope of the pressure gradient curve exhibits a weak dependence on flow pattern but no distinct trend could be deduced from it.









5.4.1 Identification of flow patterns from time dependent pressure signals

The pressure signals are recorded for two minutes to ensure that the recording time is greater than the period of individual fluctuations and two different statistical analysis namely the probability density function (PDF) analysis and the wavelet multiresolution technique of the pressure signals has been performed. The result of the analysis has been presented in a tabular form in Tables 5.1-5.4.

Tables 5.1-5.3 represents the flow patterns at different constant values of kerosene velocity while Table 5.4 shows the patterns at a constant water velocity. The rows of the tables are numbered as 5.1.1, 5.1.2 etc. They depict the flow situations for different water velocities at the constant value of kerosene superficial velocity for the first three tables and vice versa for Table 5.5. The three columns of the table are designated as (a), (b) and (c) denoting the probe signals, the corresponding PDF curves and the wavelet resolution respectively. The PDF curves in column 2 have been quantified by the height and position of the peak as well as its standard deviation denoted by h, p and σ respectively. In the tables SS, SW, P, TL, D, O & W/O and ID represents the smooth stratified, stratified wavy, plug, three layer, dispersed, oil and water in oil and inverted dispersed flow patterns respectively. The table show that the pressure signals are not very effective especially at high phase velocities but the PDFs and wavelet decompositions give us some insight into the interfacial distributions.

5.4.1.1 The PDF analysis

Table 5.1.1 representing smooth stratified flow is denoted by steady output at low pressure (0.027 kPa). The corresponding PDF is straight with a high peak approaching 100% of total count and negligible spread (Table 5.1.1b). This is a clear indication of undisturbed interface where the repetition of the mean value is very frequent and the oscillations about the mean is low. An increase in water velocity results in the stratified wavy flow pattern which is marked by a shift of the mean towards the right due to the higher velocity contribution. A reduction in the peak to about 60% of the total count along with an increased standard deviation represents more frequent fluctuations around the mean as compared to the previous case. At still higher water velocities, when the plug

flow pattern sets in, the peak is depressed further to about 20% of the total count and the spread around the mean is higher. This is also indicative of the fluctuating character of the flow. The PDF is more spread out about a higher pressure gradient in the "dispersed oil in water and water" flow pattern. The peak height reduces to about 10% of the total count with a corresponding increase in standard deviation.

In Table 5.2 and 5.3 at increased kerosene velocities, the stratified wavy pattern is denoted by an increase in the standard deviation as compared to Table 5.1. As the water velocity is increased further, the "three layer" flow pattern is denoted by a unimodal PDF at higher pressure gradient and an increase in its spread. While the peak was positioned around 0.75 kPa in the "stratified wavy" pattern, it has shifted to values between 1.5 to 2 kPa in the "three layer" pattern in both the tables. Subsequently the nature of the PDF does not appear to be significantly influenced by the flow pattern. The dispersed flow pattern is denoted by a pressure gradient greater than 2.0 kPa and a slight increase in the value of standard deviation. An observation of the PDFs representing the different patterns in Tables 5.2 and 5.3 show that the phase velocities do not influence the quantitative measure of the PDF to the right.

Table 5.4 shows that the stratified wavy flow pattern is characterized by an increased spread, lower peak and higher mean as compared to the stratified smooth distribution and the "oil and water in oil" flow pattern at low water velocity is less chaotic as compared to the dispersed flow at low kerosene flow rates (Table 5.1).

It is noted that although the PDFs could differentiate the flow patterns on the basis of the peak position, mean and standard deviation, they could not provide any further information regarding the interfacial distribution. They proved to be less effective at higher phase velocities. The wavelet technique has next been tried for a better appraisal of the flow phenomena.

5.4.1.2 The Wavelet analysis

The Daubachies 4 wavelet analysis has been used to decompose the random probe signals into 5 levels, each with a different frequency band. As the signals are decomposed, the frequency range decreases while the scale captured by the signal increases. In our study, we have primarily concentrated our attention on d_1 and a_5 in order to understand the fluctuations due to passing droplets and wavy interfaces respectively. It is expected that the high frequency fluctuations will be caused by the passage of droplets while the large scale low frequency fluctuations will arise from waviness of the continuous interface. Accordingly the d1 and a_5 components of the pressure signals reported in column 1 are presented in column 3 of the tables.

Table 5.1.1c denoting smooth stratified flow shows an almost straight line d_1 and a_5 further justifying the negligible spread in the PDF curve and denoting the smooth nature of the interface separating the two liquids. An increase in waviness with increase of water velocity (Table 5.1.2c) is manifested by slight increase in fluctuations of both d_1 and a_5 . The plug pattern is denoted by higher fluctuation in d_1 and the a_5 signal is also marked by intermittent peaks. This signifies the periodic nature of the plug flow pattern with kerosene drops being intercepted by occasional water bridges. As the kerosene velocity is increased, the d1 fluctuations continue to increase further in the dispersed flow pattern while the a_5 signal becomes relatively smooth. Moreover, the d1 fluctuations appear to occur as intermittent packets of spikes probably due to the non uniform distribution of the droplets across the cross section while the relatively smooth a_5 as compared to the plug flow pattern denotes the absence of low frequency waves at the interface.

The wavelet technique (in Tables 5.2.1c and 5.3.1c) denotes that the stratified wavy pattern at higher kerosene velocities is marked by the increase in the waviness of a_3 rather than the fluctuations of d_1 . This suggests that an increase in the amplitude of the low frequency waves results in their breakdown to form drops as one enters the "three layer" pattern. The high frequency ripples do not play a major role in this transition. The "three layer" flow pattern is denoted by uniform fluctuations in both d1 and a_5 with the fluctuations in d1 being more uniform and higher at increased kerosene velocity.

Interestingly, the intermittent pulses in a_5 and d_1 characterizing plug flow are no longer evident in the three layer pattern. The onset of dispersion from the three layer distribution is marked by an increase in the d_1 oscillations while the a_5 signal remains relatively unchanged as expected and denotes an increase in the frequency and reduction in the size of the droplets as one enters the dispersed pattern from three layer flow.

Table 5.4 at a constant water velocity brings out certain interesting results. A transition from "stratified smooth" to "stratified wavy" flow pattern has been marked by an increase in the standard deviation of the PDFs both for increasing water and kerosene velocities. However, at a constant kerosene velocity (Table 5.1), the increase in standard deviation has been observed to occur primarily due to an increase in the fluctuations of a_5 rather than d_1 . On the other hand, in Table 5.4 the increase in the standard deviation of the PDF occurs due to an increase in the d_1 fluctuations. Moreover, a comparison of the wavelet analysis in the "oil and water in oil" flow pattern with that obtained in dispersed (oil in water) flow pattern shows that the former presents lesser turmoil and more orderliness (lesser fluctuations of both d_1 and a_5) as compared to the latter case.

The above observations show that the random pressure signals can serve as an effective identifier of flow patterns. While the PDF curves can distinguish between the different patterns on the basis of the mean position, peak height and standard deviation, the wavelets have enabled us to understand the mechanisms underlying the transitions from the d_1 and a_5 curves.



Table 5.1: Pressure signal, PDF and a5-d1 of wavelet with varying U_{SW} at U_{SK} =0.06 m/s



Table 5.2: Pressure signal, PDF and a5-d1 of wavelet with varying U_{SW} at U_{SK} =0.5 m/s



Table 5.3: Pressure signal, PDF and a5-d1 of wavelet with varying U_{SW} at $U_{SK}=0.7$ m/s



Table 5.4: Pressure signal, PDF and a5-d1 of wavelet with varying U_{SK} at $U_{SW}=0.07$ m/s

5.5 Analysis of pressure drop and holdup

Further attempts have been made to analyze the holdup and pressure drop in the different flow patterns. For this the flow patterns considered are stratified, stratified mixed, dispersed and the oil continuous pattern. The separated flow model has been considered for stratified pattern, while the homogeneous flow model has been adopted for dispersed and the oil continuous flow patterns. Both the homogeneous and separated flow models have been adopted for the stratified mixed pattern as it combines the characteristics of stratification with interfacial dispersion.

5.5.1 The stratified flow pattern

The stratified flow pattern has been analysed using the two fluid model which considers the two liquids to flow in separate layers without any interaction at the interface. Such a system is stable at a particular water holdup/height of the water layer under specified flow rates of the two phases only when a) the total system energy (TE) is minimum where the total energy comprises of kinetic energy (KE), potential energy (PE) and surface energy (SE) of the two phases. Mathematically:

$$TE = KE + PE + SE \tag{5.6}$$

and b) the pressure drop is equal in both the phases or,

$$\frac{\partial p_{\kappa}}{\partial Z} = \frac{\partial p_{W}}{\partial Z}$$
(5.7)

The details of the analysis is provided in Chakrabarti et al. (2005).

In order to obtain holdup, the interface is assumed to be flat and the holdup H_w is expressed in terms of θ the angle, which the interface makes with the pipe center in figure 5.6. The value of θ satisfying the aforementioned conditions will yield the value of H_w under the specified flow variables.

Mathematically, the stable interface should simultaneously satisfy a Minimum of $TE(\theta)$ and minimum of $DP(\theta)$

Where
$$DP(\theta) = \frac{\partial p_K}{\partial Z} - \frac{\partial p_W}{\partial Z}$$
 (5.9)

The problem is formulated with the objective function to be minimized is $F(\theta) = TE(\theta) + K_{*} \{DP(\theta)\}^{2}$ (5.10)

117

(5.8)

In equation 5.6

KE = Kinetic energy / unit length =
$$\frac{1}{2} A_W \cdot \rho_W \left(\frac{Q_W}{A_W}\right)^2 + \frac{1}{2} A_K \cdot \rho_K \left(\frac{Q_K}{A_K}\right)^2$$
 (5.11)

 $PE = Potential energy / unit length = A_{W}.\rho_{W}.g. h_{W} + A_{K}.\rho_{K}.g. h_{K}$ (5.12)

SE = Surface energy / unit length = $R. \theta. \sigma_{WP} + R. (2\pi - \theta). \sigma_{KP} + 2R.Sin(\theta/2). \sigma_{KW}$ (5.13)

Where A_W and A_K are the areas occupied by water and kerosene phase. ρ_{W} , ρ_K and Q_W , Q_K are the density of water and kerosene and the volumetric flow rate of water and kerosene respectively. Subscripts W, K and KW represent the water, kerosene and oil-water interface respectively. h_K and h_W are the respective heights of the centroid of the oil phase and the water phase σ_{WP} , σ_{KP} and σ_{KW} are the surface tension at water-perspex, oil-perspex and oil-water interface respectively. R is the inner radius of the conduit, In order to estimate the total system energy from equations 5.11-5.13 the cross sectional area occupied by the water (A_W) and kerosene (A_K) and the heights of the centroid of the different phases from the bottom of the pipe are required.



Figure 5.6: Cross sectional view of the two phases under stratified flow for prediction of the geometric parameters in the present analysis.

These have been evaluated from geometrical consideration of the stratified configuration shown in figure 5.6,

$$A_{W} = \frac{R^{2}}{2} \left(\theta - 2Sin\frac{\theta}{2}Cos\frac{\theta}{2} \right) = \frac{R^{2}}{2} \left(\theta - Sin\theta \right)$$
(5.14)

$$A_{\mathcal{K}} = \pi R^2 - A_{\mathcal{W}} = \frac{R^2}{2} (2\pi - \theta + Sin\theta)$$
(5.15)

$$h_{W} = R - \frac{4R}{3} \frac{\sin^{3} \frac{\theta}{2}}{(\theta - \sin\theta)}$$
(5.16)

$$h_{\kappa} = R + \frac{4R}{3} \frac{Sin^{3}(\frac{\theta}{2})}{\{2\pi - \theta - Sin(\theta)\}}$$
(5.17)

Substituting the values of A_K , A_W , h_K and h_W in equation 5.11 and 5.12 we get

$$PE = \frac{R^2}{2} (\theta - Sin\theta) \left\{ R - \frac{4R}{3} \frac{Sin^3 \frac{\theta}{2}}{(\theta - Sin\theta)} \right\} g. \rho_W + \frac{R^2}{2} (2\pi - \theta + Sin\theta) \left\{ R + \frac{4R}{3} \frac{Sin^3 (\frac{\theta}{2})}{(2\pi - \theta - Sin(\theta))} \right\} g. \rho_K$$
(5.18)

$$KE = \frac{\rho_W Q_W^2}{R^2(\theta - Sin\theta)} + \frac{\rho_K Q_K^2}{R^2(2\pi - \theta + Sin\theta)}$$
(5.19)

The pressure gradient in each of the two liquid layers can be expressed as the force exerted by a particular phase per unit length per unit area occupied by it.

For $U_W > U_K$

Force exerted by the water phase per unit length

•

=(Shear stress (τ) of water X perimeter of wall occupied by water) + (Shear stress at the interface X perimeter of the interface)

 $= \tau_{W.}R.\theta + \tau_{KW.}2R.Sin(\theta/2)$ So.

$$\frac{\partial p_{W}}{\partial Z} = \frac{1}{A_{W}} \left[\tau_{W} R \theta + \tau_{KW} 2RSin \frac{\theta}{2} \right]$$
(5.20a)

Similarly for the oil layer this has been obtained as:

$$\frac{\partial p_{\kappa}}{\partial Z} = \frac{1}{A_{\kappa}} \left[\tau_{\kappa} R(2\pi - \theta) - \tau_{\kappa w} 2RSin \frac{\theta}{2} \right]$$
(5.20b)

from the consideration that the force exerted by the oil phase per unit length

=(Shear stress (τ) of oil X perimeter of wall occupied by kerosene) + (Shear stress at the interface X perimeter of the interface)

For
$$U_K > U_W$$

$$\frac{\partial p_W}{\partial Z} = \frac{1}{A_W} \left[\tau_W R \theta - \tau_{KW} 2RSin \frac{\theta}{2} \right]$$
(5.20c)

$$\frac{\partial p_K}{\partial Z} = \frac{1}{A_K} \left[\tau_K R(2\pi - \theta) + \tau_{KW} 2RSin \frac{\theta}{2} \right]$$
(5.20d)

In the above equations the relationship of velocity with shear stress has been expressed (Brauner and Moalem Maron, 1989) as

$$\tau_{W} = f_{W} \rho_{W} \frac{U_{W}^{2}}{2}$$
(5.21)

$$\tau_{\kappa} = f_{\kappa} \rho_{\kappa} \frac{U_{\kappa}^{2}}{2}$$
(5.22)

$$\tau_{KW} = f_{KW} \rho_{KW} \frac{(U_K - U_W)}{2} |U_K - U_W|$$
(5.23)

where

$$f_{\mathcal{W}} = C \left(\frac{U_{\mathcal{W}} D_{\mathcal{W}} \rho_{\mathcal{W}}}{\mu_{\mathcal{W}}} \right)^{-n}; f_{\mathcal{K}} = C \left(\frac{U_{\mathcal{K}} D_{\mathcal{K}} \rho_{\mathcal{K}}}{\mu_{\mathcal{K}}} \right)^{-n}$$

 $f_{KW} = f_K$ at $U_K > U_W$; $f_{KW} = f_W$ at $U_W > U_K$ and $\rho_{KW} = \rho_K$ at $U_K > U_W$; $\rho_{KW} = \rho_W$ at $U_W > U_K$

where τ , U, f, ρ , μ , D and S denote shear stress, velocity, friction factor, density, dynamic viscosity, hydraulic diameter and perimeter of the corresponding phase with the tube wall. The constants C and n depend on the Reynolds number of the corresponding phase, viz. C = 16 and n = 1 for $N_{Re} < 2100$ and C = 0.046; and n = 0.2 for $N_{Re} > 2100$ (Taitel and Dukler, 1976).

 D_W and D_K are calculated from the fractional areas and wetted circumference occupied by either of the phases, viz.,

$$D_{W} = \frac{4A_{W}}{(S_{w} + S_{KW})} \qquad D_{K} = \frac{4A_{K}}{(S_{K})} \quad \text{at } U_{W} > U_{K}$$
$$D_{K} = \frac{4A_{K}}{(S_{K} + S_{KW})} \qquad D_{W} = \frac{4A_{W}}{(S_{W})} \quad \text{at } U_{K} > U_{W}$$

From the above expressions $TE(\theta)$ and $DP(\theta)$ have been evaluated. Equation 5.10 when expressed in terms of the geometric variables yield a non linear expression in terms of θ . The equation is solved with the bound $0 \le \theta \le 2\pi$ using '*fmin*' algorithm available in 'MATLAB' and the holdup H_W is obtained from the superficial velocities of the two phases and the conduit diameter for a horizontal pipe.

5.5.2 The analysis by Brauner et al. (1996)

Apart from the two fluid model of the present analysis, further attempts have been made to validate the present experiments with the model proposed by Brauner et al. (1996). On the basis of this model several researchers (Brauner and Moalem Maron, 1998; Raj et al, 2005 etc) attempted to predict the stable curvature for known liquid holdup from the principle of minimization of total system energy and used the stable curvature to predict the pressure drop as well as holdup.

According to this analysis H_W has been predicted from the combined momentum equation of the two phases under smooth stratified flow in horizontal pipes viz:

$$\frac{\tau_{\kappa}S_{\kappa}}{1-H_{w}} - \frac{\tau_{w}S_{w}}{H_{w}} \pm \tau_{\kappa w}S_{\kappa w}\left(\frac{1}{1-H_{w}} + \frac{1}{H_{w}}\right) = 0$$
(5.24)

The lower sign corresponds to $U_W > U_K$. Although such a situation does not arise for gasliquid systems, the velocity of the lower phase can be comparable and even higher than the lighter fluid in liquid-liquid flows. In equation. 5.24 the wall and interfacial shear stresses and the corresponding friction factors can be derived from equations 5.21-5.23. The detailed estimation of the geometrical parameters (figure 5.7) has been described by Brauner et al. (1996). In this description the fractional areas and wetted circumference have been expressed in terms of the interfacial angle ϕ^* , formed due to the curved interface (figure 5.7) and view angle of the interface from the pipe center ϕ_0 by utilizing a bipolar coordinate system. Thus the prediction of H_w merely reduces to an estimation of the interface curvature under the specified flow conditions. The curvature has been predicted from the postulation that the stable interface should correspond to the minimum of the total system energy change responsible for the curving process. The curving of the interface to either concave or convex shape results in a change in the system center of gravity, thereby increasing its potential energy. It also changes the phase contact area with the tube wall and among themselves, thereby resulting in a change of the system surface energy. Therefore, the change in the total system energy due to the curving of interface can be expressed as a summation of the change in potential and surface energies.

Brauner et. al. (1996) has obtained an expression for the total energy of such a system with respect to a stratified system with plane interface as:

$$\frac{\Delta E}{L} = R^{3} \rho_{W} g(1 - \overline{\rho}) \begin{cases} \left[\frac{\sin^{3} \phi_{o}}{\sin^{2} \phi^{*}} (\cot \phi^{*} - \cot \phi_{0}) \left(\pi - \phi^{*} + \frac{\sin(2\phi^{*})}{2} \right) + \frac{2}{3} \sin^{3} \phi_{o}^{P} \right] + \\ \varepsilon_{V} \left[\sin \phi_{o} \frac{\pi - \phi^{*}}{\sin \phi^{*}} - \sin \phi_{o}^{P} + \cos \alpha (\phi_{o}^{P} - \phi_{o}) \right] \end{cases}$$
(5.25)

Where α is fluid/wall contact angle, ε_{ν} is Eötvös number, $\rho = \rho_{K}/\rho_{W}$ and ϕ_{0}^{P} denotes the corresponding ϕ_{0} at plane interface.

The value of ϕ^* corresponding to a minimum of equation. 5.25 provides the stable interfacial configuration. The minimum has been obtained by plotting $\Delta E/L$ as a function of ϕ^* for a fixed value of holdup. The model yields the minimum value of $\Delta E/L$ at $\phi^* = 180^{\circ}$ for gravity dominated systems. The contribution of surface energy shifts the minimum value away from $\phi^* = 180^{\circ}$. The extent of the influence of surface energy is determined by the deviation of ϕ^* from 180° for a given value of H_W .

It is to be noted that the holdup predicted here according to this model corresponds to ideal wettability of the polymethyl-methacrylate surface (acrylic tube) by water ($\alpha=60^{\circ}$).

It is expected that other pipe materials with different wettability angle, will affect the interfacial structure and change the potential for water lubrication.



Figure 5.7. Cross sectional view of the two phases as represented by Brauner et al. (1996)

5.5.3 The dispersed and oil continuous flow pattern

The dispersed and oil continuous flow patterns have been analysed using the homogeneous flow theory which assumes the two fluid to be uniformly mixed and flowing under no slip conditions. The model assumes the mixture to behave as a pseudo fluid with suitable average properties such that it obeys the usual equations of single component flow. These properties of the pseudo fluid are weighted averages and are not necessarily the same as the properties of either phase.

In the present work the density (ρ) and viscosity (μ) of the two phase mixture are evaluated from the following relationships

$$\rho = H_{w}\rho_{w} + (1 - H_{w})\rho_{\kappa} \tag{5.26}$$

$$\mu = H_{w}\mu_{w} + (1 - H_{w})\mu_{\kappa} \tag{5.27}$$

where ρ and μ are the mean density and mean viscosity of the mixed phase.

Various authors have suggested different modifications of the equation to predict the homogeneous mixture viscosity. These modifications are based on the assumption that the viscosity of two-phase mixture in flow depends on the type of phases, their fractions,

temperature, the magnitude of dispersed phase particles and the degree of turbulence. Accordingly Palugniok, and Troniewski (1972) have given two different equations:

$$\mu = \frac{\mu_c}{1 - H_d} \left(1 + 1.5 H_r \frac{\mu_d}{\mu_d + \mu_c} \right)$$
(5.28)

for dispersion-type liquid mixtures

$$\mu = \mu_c \left(1 + 2.5H_d + 7.17H_d^2 + 16.2H_d^3 \right)$$
(5.29)

for emulsion-type liquid mixtures

In the work of Gilewicz (1957), Hatschek's equation is also recommended for the determination of the viscosity of liquid mixture and it is expressed as

$$\mu = \mu_c \sqrt[3]{\left(\frac{1}{1 - H_d}\right)}$$
(5.30)

The viscosity of two-phase liquid mixture containing clusters of droplets of one phase can be calculated from equation 5.30 and 5.31.

$$\mu = \mu_c^{H_c} \cdot \mu_d^{H_d} \tag{5.31}$$

During droplet flow of water in oil, liquid-liquid mixture can also be treated as the colloidal system. For the determination of the viscosity of colloidal system the experimentally confirmed Einstein equation is recommended, where the mixture viscosity is defined as

$$\mu = \mu_c (1 + 2.5H_d) \tag{5.32}$$

Subscripts c and d in equation 5.28-5.32 indicate the continuous and the dispersed phase respectively.

Hapanowicz and Troniewski (2002) proposed the following empirical equation to estimete the mixture viscosity for water in oil pattern:

$$\frac{\mu}{\mu_{k}} = 8.45 N_{\text{Re}\,k} N_{\text{Re}\,k}^{-0.715} H_{W}^{1.73} F r_{W}^{-0.282}$$
(5.33)

where N_{ReK} , N_{ReW} and Fr_W are the superficial Reynolds number based on superficial velocities of kerosene, water and the Froude number based on the superficial water velocity respectively.

5.5.4 The Stratified mixed flow pattern

Considering the phase distribution in the stratified mixed pattern, both the homogeneous and the separated flow models have been adopted to predict the holdup and pressure drop in this pattern.

5.6 Comparison of the theoretical analyses with experimental data

The hydrodynamic parameters namely holdup and pressure drop have been estimated from the aforementioned theoretical analyses and compared with the experimental data. For stratified flow the data have been compared with the present model obtained by the simultaneous consideration of a) the principle of minimization of total system energy and b) the criteria of equal pressure drop of the system in both the phases have been used. The data have further been validated with Brauner et al (1996) model. Figure 5.8a shows that both the present analysis and Brauner et al (1996) model predict the holdup data within ±15% for the stratified pattern. For lower holdups the present analysis predicts well whereas for higher holdups Brauner et al (1996) model shows better results. For pressure drop prediction, the present model leaves a better note (figure 5.8b) for low phase flow rates.

For the prediction of holdup of stratified mixed pattern the homogeneous flow model obtains comparable results with the separated flow models (figure 5.9a) and even the present analysis is in close agreement with the experimental pressure drop data (figure 5.9b). This is probably due to the continuity of both the phases in the three layer pattern. The above results show that neither the homogeneous model nor the separated flow model is suitable for the three layer pattern and a new model combining the continuity of the two phases with the interfacial dispersion will be suitable to analyse this flow pattern. In case of dispersion and oil continuous flow pattern the homogeneous flow model is used.

Figure 5.10a shows that holdup is predominantly under predicted by the homogeneous ^{model} in the dispersed flow pattern. This can be attributed to the slip of the oil droplets

over the water phase. The same underprediction is also evident in the pressure drop predictions of figure 5.10b. On the other hand, figure 5.10a shows that the water holdup is underpredicted at low and high values of H_W while the reverse occurs for the intermediate range. A comparison with the flow pattern map of Chapter 4 indicates that the distribution is oil and water in oil at the low values of H_W plug for the intermediate values of inverted dispersed for the higher values. It is thought that the slip of the water droplets over the continuous oil oil phase results in the lower values of predicted H_W in the oil and water in oil pattern while at higher values of H_W , the change in the system viscosity caused the deviation (Hapanowicz and Troniewski, 2002). The deviation between the predicted and experimental values of pressure drop is also evident from figure 5.11b.



Figure 5.8:a) Experimental holdup vs. predicted holdup for stratified flowb) Experimental pressure drop vs. predicted pressure drop for stratified flow



Figure 5.9: a) Experimental holdup vs. predicted holdup for stratified mixed flowb) Experimental pressure drop vs. predicted pressure drop for stratified mixed flow



Figure 5.10: a) Experimental holdup vs. predicted holdup for dispersed flow b) Experimental pressure drop vs. predicted pressure drop for dispersed flow



Figure 5.11: a) Experimental holdup vs. predicted holdup for the oil continuous flow patternb) Experimental pressure drop vs. predicted pressure drop for the oil continuous flow pattern

Therefore, additional efforts have been made to predict the pressure drop for the oil continuous flow pattern by using the different equations of viscosity as presented in equation 5.28-5.33. The results of this exercise is represented in figures 5.12 a-f. the figs show that the prediction from equation 5.31 (figure 5.12d) is observed to be in good agreement with the experiments.


Figure 5.12: Pressure drop prediction with different viscosity equations for the oil continuous flow pattern

5.7 Experimental data reported in literature

The models have also been validated with data reported in literature by Lovick & Angeli (2004). They have performed experiments with water and petroleum oil ($\rho = 828 \text{ kg/m.}^3$, $\mu = 6 \text{ mPa.s}$) as the test fluids in a pipe of diameter 0.038 m and at mixture velocities ranging from 0.8 m/s to 3 m/s. They have reported that the stratified wavy, dispersion of oil in water, dispersion of water in oil and dual continuous type of flow pattern have prevailed under these flow conditions. The comparison between the theoretical data on holdup, pressure drop and the corresponding experimental values has been shown in figure 5.13a,b. The slip between the phases at higher phase velocities probably responsible for poor prediction from all the theoretical analyses.



Figure 13: Prediction of Lovick and Angeli' 2004 experimental data

a) Holdup

b) Pressure drop

5.8 Conclusion

2

In the present study extensive experiments have been carried out to understand the pressure drop and holdup of liquid-liquid flow through horizontal pipes. Attempts have next been made to analyze the holdup and pressure drop in the different flow patterns. The two fluid models have been considered for the stratified pattern while the homogeneous flow model has been adopted for the dispersed and the oil continuous pattern. Both the homogeneous and the two fluid model have been considered for the stratified mixed pattern as it combines the characteristics of both the distribution. Further attempts have been made to identify the flow patterns from the statistical analysis of the time dependent pressure signals.

Chapter 6

Liquid-liquid two phase flow through an orifice

6.1 Introduction

In any two phase system flow metering is an open challenge (Oddie and Pearson, 2004). Unlike single phase flow the techniques for flow measurement in two phase flow are yet to be standardized. In principle, coriolis and gyroscopic flow meters and meters based on crosscorrelation technique are suitable for two phase flow. However, they are expensive and are not free from the problem of installation and maintenance. There is a need of critically examining the suitability of simple conventional flow meters for two phase flow applications. Such studies will suggest the required modification in the conventional meters to suit the purpose.

For single phase flow orifice is one of the most commonly used devices for flow rate measurement. Although single orifice or arrays of orifices constituting perforated plates are often used to reduce flow non-uniformities for gas-liquid flow, the effect of the presence of an orifice on the flow phenomenon of a two phase liquid-liquid flow is relatively unknown. As the slip affects the in situ distribution of the phases for liquid-liquid flow, the presence of an orifice may additionally affect the flow pattern.

Most of the work on two phase flow through orifices, have been carried out on air-water, steam-water or refrigerant (liquid-vapour) system. Several studies (Lin, 1982; Kofaezen, 1976; Janssen, 1966; Chen et al., 1986) confirm that the quality or flow rate can be predicted with good accuracy by the pressure drop measurements across the orifices for a wide range of density ratio of the phases for gas-liquid system. Accumulation of significant amount of liquid in the upstream of an orifice at low gas flow rates of a gas containing moisture has been reported (Aguta et al., 1995) to affect the flow and the

height of the accumulated layer has been found to decrease until the formation of a stratified liquid layer. Several researchers (Wenran, and Yunxian 1995; Kojasoy et al., 1997) have studied to develop a theoretical model for the measurement of two parameters namely mass flow rate and phase fraction. Studies have also been reported on pressure changes through sudden expansion and sudden contraction of thick and thin-orifice plates (Kojasoy et al., 1997; Ferreira, 1997; Fossa and Guglielmini 2002) and the differential pressure across the orifice plate were used by them to correlate the liquid flow rate with the total gas liquid two-phase flow. The slotted orifice flow meter has been designed by several researchers (Morrison et al., 2001; Geng et al., 2006) to overcome the irregularities of upstream flow. It has been reported to be useful in poorly designed metering runs, compact metering runs, and compact header configurations with rough pipe whose response to the presence of two phase flow is predictable. No accumulation of liquid in the upstream and the downstream of the orifice plate for the air/water mixture has been reported by them.

On the other hand only a few studies (Buhidma and Pal 1996; Pal, 1993) has been made on liquid-liquid two phase flow and the studies are confined to oil-water emulsion flow only. Pal (1993) inferred that orifice and venturi meters are feasible flow metering devices for oil/water emulsions. Empirical expressions are given to predict the discharge coefficients for the emulsions (stable and unstable) of geometrically similar meters. The correlations are inferred to be accurate within $\pm 5\%$. Buhidma and Pal (1996) used wedge meters and segmental orifice meters for feasible flow estimation of oil-water emulsions. The differential pressure produced across these meters are proposed to follow the squared relationship of flow over a wide range of Reynolds number. They demonstrated that the discharge coefficients of the segmental orifice decrease with an increased opening.

The aforementioned study enables us to think of an online metering device to estimate the total mass flow of the two liquids inside the conduit over a wide range of phase flow rates. For this orifice has been used to check whether it can be used to obtain data on mass flow rate of liquid-liquid flow. Prior to testing the effectiveness of an orifice as an online flow metering device, studies have been directed to observe the influence of the orifice on the phase distribution of the two liquids in the pipe. The flow patterns have

been identified using the optical probe along with photographic technique. The probability density function (PDF) analysis of the random signals obtained from the optical probe has been adopted to quantify the observations and the crosscorrelation function between the probe signals upstream and downstream of the orifice has been estimated to check the repeatability of the phenomena. Extensive measurements of pressure drop across the orifice have been carried out over a wide range of flow velocities in order to cover the different flow patterns. Attempts have next been made to correlate the pressure drop with an orifice discharge coefficient for the different patterns and to explore its possibility as an online metering device.

6.2 Measurement technique

The optical probe along with photographic technique has been adopted to study the flow pattern along the length. The location of the probes as well as the measurement technique involved in the present study has been described in detail in Chapter 3.

The pressure drop along the length is measured by U tube manometers. Six pressure taps are located along the length in the upstream section and seven pressure taps in the downstream region. The pressure drop is measured with respect to the first pressure tap 30D (D = diameter of the pipe) upstream from the orifice. The location of the pressure taps has been described in detail in Chapter 3.

6.3 Method of analysis

Apart from visual observation of the probe signals, PDF analysis of the random signals has also been performed for a better understanding of the flow phenomenon and a detailed description of the analysis (PDF) is provided in Chapter 4.

6.3.1Cross correlation function

The cross correlation function between the probe signals upstream and downstream of the orifice are determined to check the repeatability of results. This is a standard method of estimating the degree to which two series are correlated (Song et al., 2006; Angelsky and Maksimyak, 1998; Yan and Ma 2000; Deng et al., 2001; Hribernik et al., 2003; Vial et al., 2001). It requires simultaneous measurement of the probe signal at two different

sections and the evaluation of the cross-correlation function (CCF) between these signals. The CCF of the two time series x(t) and y(t) is defined as follows:

$$C_{y}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} x(t) y(t-\tau) dt$$
(6.1)

The CCF is able to detect if the two signals are correlated. When x(t) and y(t) are coherent, the CCF exhibits a peak at $\tau \neq 0$, which corresponds to the mean time delay between the signals. The sharp peak at $\tau=0$ corresponds to the phenomena occurring, simultaneously, near both the sensors. So this technique is used to understand the relation between the signals obtained from the probes upstream and downstream of the orifice. This enables one to understand the repetitive nature of the flow pattern before and after the orifice.

6.4 Experimental measurement

The experiments have been carried out by increasing the water velocity at a constant low value of kerosene velocity. The kerosene velocity is then increased and the readings are repeated over the entire range of water velocity for the constant oil flow rate. The velocity of each phase is varied between 0.03 - 1.5 m/s. For each kerosene velocity, the signals are recorded from the four probes and the flow patterns are viewed and photographed. The pressure drop is measured with respect to the first pressure tap 30D upstream from the orifice along the length

6.5 Flow patterns at the upstream

The flow patterns observed visually as well as by photographic technique at low phase flow rates in the upstream section of the orifice are found to be similar to the patterns reported in Chapter 4. The different flow patterns observed over a wide range of phase flow rates are presented in figure 4.2 of Chapter 4. The figure shows the pattern to be smooth stratified with a complete separation of the liquids under low phase velocities and the interface becomes wavy with increase in the velocity of either of the liquids. At low oil velocities increase in water velocity breaks the continuity of the kerosene layer and gives rise to the plug flow pattern characterized by intermittent plugs of kerosene intercepted by water bridges. The plugs break down to form the dispersed flow pattern at still higher velocities. At higher oil velocities, the flow is stratified wavy at low water flow rates. The waves cannot reach the upper wall to form the plug flow pattern at the increased kerosene velocity. On the contrary, they break down to form droplets at the interface, thus resulting in a three layer flow pattern with a kerosene layer at the top separated from the water layer at the bottom by an intermediate layer of droplets. This eventually gives rise to the dispersed pattern.

6.6 Flow patterns downstream of the orifice

An interest was next felt to observe the change in the downstream flow pattern. Initially the patterns have been identified by photographic technique but in most of the cases the photographs cannot be evidenced for any conclusion. Therefore, the signals recorded simultaneously from probes O2 to O5 (figure 3.1) characterize the change in the patterns from the upstream to the downstream sections. They are depicted in figures 6.1-6.3 in a tabular form. Each of the figures denotes the sequential change in the flow patterns with increasing water velocity at a constant kerosene flow rate. They are numbered as 6.1.1, 6.1.2 etc. The photographs of the flow patterns along with the probe signals for different probe locations are presented in columns (a) to (d) of these figures. The corresponding PDF curves of (a) to (d) have been presented in a single graph along with their corresponding moments in column (e). In this column m, σ and s denotes the mean value, standard deviation and skewnwss of the curves respectively.

6.6.1 At low oil velocities

At low flow rates of kerosene and water ($U_{SK}=0.06 \text{ m/s}$; $U_{SW}=0.07 \text{ m/s}$), the smooth stratified flow in the upstream sections is indicated by both probes O2 and O3 (fig 3.1a.b) with a straight line output and almost negligible oscillation. This fact is reinforced by a sharp unimodal PDF (figure 6.1.1d) with minimum spread and indicates that the upstream flow pattern is not affected by the orifice obstruction even at a distance of 1D from it. On the other hand the signals from O4 (figure 6.1.1c) exhibit increased oscillations and a low average response. The oscillating nature results in a higher standard deviation of the PDF and hints upon the onset of dispersion at the vena contracta. The presence of interfacial droplets at very low concentration is also evident from the signals of O5 about 70D from

the orifice. This is indicated by its sharp peak with low variance, where the cumulative effect of scattering and attenuation has resulted in a lower average value of the response.

A similar trend is also observed in the stratified wavy pattern at higher water velocities. The signal from O5 in this case is predominated by the scattering effect and a higher standard deviation thus indicating that the interface is a mixture of haphazardly distributed bigger and smaller oil droplets.

With the onset of the plug flow at the upstream section, the signals of O2 and O3 represent a multi-peaked PDF due to the plug formation, whereas the downstream flow pattern presents a hazy appearance. The response of O4 justifies more turbulence in the conduit (figure 6.1.3c) after the orifice by the appearance of an indented PDF with a high variance and low peak height. The intense scattering lowers its average response. The signal from probe O5 represents a sharp peak with low standard deviation thus indicating the uniform nature of the hazy pattern which can be considered to be a uniform distribution of fluid droplets throughout the pipe. It may be noted that the nature of the dispersion in the downstream is different from the conventional dispersion in pipe flow, where one fluid (the oil phase) can be observed to be dispersed in the second continuous phase (water). In this case tiny droplets of both phases appear to cover the whole of the tube and the transparent whitish appearance enables better light passage to result in a higher average response of probe O5 in comparison to O4.

A further increase in water velocity results in a dense dispersion of small sized droplets, which are mostly concentrated towards the upper portion of the pipe at the upstream section whereas the flow becomes totally dispersed at the downstream with the possibility of the formation of tiny droplets (figure 6.1.4d). This results in a sharper PDF peak from O5 response while the average value of the O4 response indicates a greater non-uniformity in distribution just after the orifice.

6.6.2 At moderate oil velocities

At higher kerosene velocities, the flow in the upstream section (as denoted by the signals from probe O2) is stratified wavy at low water flow rates (figure 6.2.1). However at O3, the response behaves in a different manner and shows increased fluctuations. This increases the standard deviation and reduces the peak height of the PDF. In addition, the scattered light also results in a lower response. The developed flow as represented by O5 shows a higher peak at a higher voltage and low spread, which denotes a uniform dispersion of droplets as described above.

When the water flow rate is increased further, the three layer pattern at the upstream breaks down to form a dispersed flow after the orifice. This causes a very low value of the probe response (figure 6.2.2) due to excess scattering of light. At a water velocity of 1.2 m/s, the onset of dispersion in the upstream is characterized by the dispersed phase confined to the upper portion of the pipe. This changes to a uniform dispersion in the downstream as is reflected by a high peak and low spread of the O5 signal. The average response in this case is also low due to a turbid emulsion, which hinders the light passage. Thus it is evident from the above discussion that the pattern of dispersion changes and visually becomes more whitish with increase in water velocity. The response from O4 becomes erratic with the onset of dispersion and this is characterized by a double peaked PDF.

An identical situation has also been noted at higher kerosene velocities and one representative case is presented in figure 6.3. Here the sharp unimodal PDF of O2 changes from figures 6.3.1-6.3.4 to show uneven peaks. The formation of the droplets at the interface changes the response of O3, located just before the orifice. The time series is frequently associated with downward spikes intermittently, to give a wide spread of the bimodal PDF. This probably arises due to the irregular motion of the drops before the orifice till $U_{SW}=0.7$ m/s. For a developed three layer pattern at the upstream ($U_{SW} = 1$ m/s), the response of O3 becomes steady, may be due to the ordered movement of the non uniform interfacial drops. The developed flow in the downstream for all these cases is emulsified or dispersed and their PDF response is similar. It portrays a sharp peak with low spread. The average value is also low probably due to the hindrance posed by the white opaque emulsion.









6.4 Analysis of cross correlation function

The differences in the flow distribution before and after the orifice have further been confirmed by cross correlating the signals obtained from the upstream and downstream probes. figures 6.4-6.6 describes the cross correlation function (CCF) between the signals obtained from O2 and O3; O3 and O4; O4 and O5 and O2 and O5 for some of the flow situations. The coefficients obtained from the cross correlation analysis between two signals hint at the degree of similarity of the phenomena occurring between the two probes. When the two signals are coherent, the CCF exhibits a peak. For the stratified smooth pattern in the upstream, the O2 and O3 (figure 6.4a) signals are observed to be correlated with a peak. At higher flow rates of the phases for other flow patterns (figure 6.5a, 6.6a) O2 and O3 are correlated but the width or sharpness of the peaks are different, probably due to a sudden change in the interfacial phenomena in the vicinity of the orifice. The O4 and O5 signals are also correlated with a dominant peak for a dispersed downstream pattern. However, the O3 and O4 as well as the O2 and O5 signals are not at all correlated for any particular pattern or flow rate. This shows that the vortex at the vena contracta totally changes the flow pattern after the orifice.



Figure 6.4: Cross correlation of the optical probe signals. Upstream flow pattern: stratified smooth (U_{SK}=0.06 m/s; U_{SW}=0.07 m/s)







Figure 6.6: Cross correlation of the optical probe signals. Upstream flow pattern: three layer ($U_{SK}=0.5 \text{ m/s}$; $U_{SW}=1.0 \text{ m/s}$)

6.5 Flow pattern map at the downstream of the orifice

The above discussion clearly brings out the differences in phase distribution prior to and after the orifice. The range of existence of the different patterns in the downstream have been identified from the PDF curves. The quantitative values of the mean and the variance have provided an objective indicator for pattern estimation. The information thus obtained is presented in the form of a flow pattern map in figure 6.7a. It represents the regions of existence of stratification and dispersed flows after the orifice.

At low flow rates of oil and water when the flow pattern is stratified smooth in the upstream, the interface becomes slightly wavy with droplets in the downstream. This is denoted by a reduced height and an increased variance of the PDF as compared to the stratified smooth pattern. With increasing velocity of water, dense interfacial droplets appear in the photograph. The PDF is marked by a sudden decrease in height and a wider spread. At the onset of dispersion in the downstream, the PDF regains its height and its variance becomes low.

At higher oil flow rates, when the pattern becomes stratified wavy in the upstream, interfacial droplets in the downstream poses in such a manner that their size and distribution causes a poor transmission of light. Their interfacial distribution causes lesser fluctuation in the response. This is not found in the conventional three layer flow pattern, where the interface is marked by indentations in the response. The PDF of this pattern is represented by a sharp peak with low standard deviation. With increasing water flow rate the pattern becomes dispersed as its PDF is represented by a low average response, low spread and high peak. When the kerosene flow rate is further increased at higher water velocities, the flow becomes dispersed with an appearance of white emulsion. The PDF is represented by a sharp long peak with low standard deviation (\sim 0.02).

From the above discussion, the downstream flow pattern map has been divided into three regions namely the stratified wavy with droplets (SWd), the three layer pattern (TL) and the dispersed flow (D).

6.6 Comparison with the upstream flow pattern map

Further attempts have been made to superimpose the downstream map in the flow pattern map of the upstream section (figure 6.7b). In this figure, the dotted line represents the lines of transition of the different flow patterns in the downstream section, whereas the solid lines represent the upstream transitions. The figure shows that the regions of transition are different for both the cases. At low flow rates of both the phases the upstream shows a stratified smooth appearance, whereas stratified wavy flow with droplets (very low concentration) and the three layer pattern have been identified in the downstream region. However, after the boundary of the three layer pattern, dispersion occurs in the downstream map. Thus it is evident from figure 6.7b that the flow pattern changes drastically after the orifice and the map is primarily occupied by dispersed flow or emulsion in the latter case. This indicates a possibility of using an orifice as a homogenizer/emulsifier in liquid-liquid flow systems.



Figure 6.7a: Flow pattern map at the downstream section of the orifice



Figure 6.7b: A comparison of the maps at the upstream and downstream section of the orifice

6.7 Pressure drop

The pressure drop as estimated along the length of the pipe from the upstream to the downstream section and the pressure profiles are depicted in figure 6.8a-d. Each figure denotes the pressure drop along the test conduit as a function of water velocity for a constant flow rate of kerosene. The figure shows that the pressure drop obtained from the six tappings in the upstream maintains a consistent nature with an almost constant value but after the orifice the pressure drop between the nearest upstream and downstream tap (1D upstream, 0.8D downstream) exhibits a maxima. After the length crosses 5D in the downstream region, the pressure drop gradually attains a constant value.



Figure 6.8: Pressure profile before and after the orifice for different velocities of the two liquids

Next the equation to estimate volumetric discharge rate for single phase, steady flow through an orifice viz

$$Q_m = \frac{A_o C_d}{\sqrt{1 - \beta_o^4}} \left(\frac{2\Delta p}{\rho_m}\right)^{1/2}$$
(6.2)

has been applied to the present two phase flow situation by incorporating averaged fluid properties for the mixture. In equation $6.2 A_0$ is the area opening of the orifice meter,

 Δp is the pressure difference between the nearest upstream and downstream pressure taps from the orifice, β_0 is the orifice to pipe diameter ratio, ρ_m is the mixture density and C_d is the discharge coefficient. In the present situation Δp is noted between the taps located at 1D before orifice and 0.8D after orifice.. As the flow rate has been considered as total phase flow rate (Q_m), the density is evaluated with the consideration of an average phase density. This is calculated from the homogeneous flow model for the dispersed and three layer pattern while the two fluid model adopted in the present study, has been used for the calculation of the insitu holdup for the stratified pattern before the orifice. Density and viscosity are estimated from the following relationships

$$\rho_{m} = H_{w}\rho_{w} + (1 - H_{w})\rho_{K} \tag{6.3}$$

$$\mu_m = H_w \mu_w + (1 - H_w) \mu_K \tag{6.4}$$

where μ_m is the mean viscosity of the mixed phase and H_w represents the in situ fraction of water. Subscripts w and k represents water and kerosene respectively. Figures 6.10a and **b** describes the relationship of discharge coefficient of each upstream flow pattern with total phase velocity and Reynolds number ($\rho_m DU_m / \mu_m$) respectively. In the expression of Reynolds number, D is the pipe diameter and U_m is the mixture velocity. Prior to this, the change of discharge coefficient with Reynolds number has been evaluated for pure water in figure 6.9. The discharge coefficient is found to be constant over a wide range of Reynolds number both for pure water and oil-water mixture and is close to 0.78. This indicates the suitability of an orifice meter as a flow measuring device for liquid-liquid two phase flows. Figure 6.11 shows that the average value of C_d can predict the flow rate within ±5% accuracy, except for some data points at lower phase flow rates. This probably arises due to the close density of the two liquids and the mixed character of flow.



Figure 6.9: Variation of C_d with N_{Re} for pure water





- a) variation with mixture velocity
- b) variation with N_{Re}



Figure 6.11: Comparison of predicted flow rate with the actual one ($C_d = 0.78$)

6.8 Conclusion

Extensive experiments are carried out to understand liquid-liquid two phase flow through an orifice plate with a two fold purpose. Firstly it has enabled us to understand the influence of an obstruction on the phase distributions during liquid-liquid flows. Secondly the effectiveness of an orifice as a two phase flow metering device has been tested over a wide range of flow velocities. The study has revealed that an orifice can be recommended as a homogenizer/emulsifier for liquid-liquid flow systems and orifice meters can be used as feasible flow metering devices for such flows.

Chapter 7

Conclusions and Recommendations

In the present work, an attempt has been made to investigate the hydrodynamics of liquid-liquid two-phase flow through a horizontal pipe. The study is primarily experimental in nature to understand the physics of flow. An indigenously developed optical probe has been used for the identification of the different flow patterns. The Statistical analysis namely the probability density function (PDF) analysis and the wavelet transform of the optical probe signals have been adopted for development of an objective flow pattern indicator. A flow pattern map has been constructed from the information obtained from the pattern indicator. It represents the regions of existence of stratification and dispersion both for the water continuous and the oil continuous pattern. The present flow pattern map has been observed to be in close agreement with the experimental maps and theoretical models available in literature.

The experiments have next been performed to measure the pressure drop and water holdup over a wide range of phase flow rates in the different flow patterns. The flow velocities have been selected such that the holdup and pressure drop can be studied both in the water continuous and the oil continuous regimes. Efforts have been directed to identify the flow patterns from the time dependent pressure signals and the statistical analysis of the random signals. An analysis of the holdup and pressure drop characteristics have been performed in the different flow patterns. The separated and homogeneous models are used to analyse the hydrodynamic parameters in the stratified and dispersed flow patterns respectively. The models have been validated with the present experimental data as well as the data reported in literature.

An interest was next felt to test whether an orificemeter can be used as an online metering device to estimate the total mass flow of the two liquids inside the conduit. Prior to testing the effectiveness of an orifice as an online mass flow metering device,

studies have been directed to observe the influence of the orifice plate on the phase distribution of the two liquids in the pipe. The optical probe along with photographic technique is used for this purpose.

7.1 Conclusions

The salient features of the present investigations are:

- i) During liquid-liquid horizontal flow the visual and photographic techniques can identify flow patterns only at low phase flow rates in the water continuous regime. At higher flow rates the patterns cannot be distinguished as the appearance becomes hazy.
- ii) The novel optical probe designed and fabricated in the present study can identify the flow patterns both in the water continuous and the oil continuous regimes. The statistical analysis namely the probability density function analysis and the wavelet multiresolution technique of the probe signals has enabled the development of an objective flow pattern indicator.
- iii) A flow pattern map has been constructed from the information obtained from the statistical analysis of the probe signals. It shows the existence of pure stratified, mixed stratified and dispersed flows in the water continuous regime and the presence of oil and water in oil, inverted plug and inverted dispersed flows in the oil continuous regime.
- iv) The presence of inverted plug flow and inverted dispersed flow in the oil continuous regime have been further verified by a sampling technique.
- v) The ambivalent range during phase inversion as predicted in the present study is in close agreement to the results reported in literature.
- vi) The influence of the mixer design on flow pattern has revealed that slight changes in the mixer design does not influence the downstream patterns whereas a completely different design may ensure the disappearance or a prolonged existence of a particular flow distribution.
- vii) The water holdup increases with the increase in water velocity and decrease in kerosene velocity as expected. An increase in the phase flow rate leads to a substantial increase in the pressure drop.

- viii) The input fraction cannot always be used to estimate the in situ phase fraction of the two liquids. The deviation has been attributed to a significant amount of slip between the phases.
- ix) The separated flow model has been noted to be applicable for the stratified flow pattern while the homogeneous flow model is suitable for dispersed flow patterns. Both the homogeneous and separated flow models have been observed to deviate significantly in the stratified mixed pattern.
- Extensive experiments on liquid-liquid horizontal flow through an orifice
 plate have revealed the following observations:
 - a) An orifice can be recommended as a homogenizer/emulsifier for liquid-liquid flow systems.
 - b) Orifice meters can be used as feasible flow metering devices for such flows.

7.2 Recommendations for future work

The above discussion reveals some important facts regarding the hydrodynamics of liquid-liquid two phase flow through a horizontal conduit. However, it has been felt that further investigations, both experimental and theoretical, is needed to supplement the findings of the present study. Some of the important areas, which need a greater attention, are as follows.

- The effect of fluid properties on different hydrodynamic parameters needs to be investigated by performing experiments with different oils.
- ii) An exhaustive study over a wide range of conduit diameter is needed to bring out the effect of diameter on flow behaviour.
- Acrylic pipes are used in the present study. Other pipes with different material of construction should be used to understand the effect of pipe material on the hydrodynamics.
- iv) A rigorous model incorporating the characteristics of stratified flow with interfacial dispersion needs to be developed to predict the pressure drop and holdup in the stratified mixed flow regime.
- v) The mechanisms of drop formation and their characteristic size are important for analyzing the hydrodynamic and transport phenomena in the flow of liquid-liquid dispersions. Therefore a substantial effort needs to be made to model the phenomenon of droplet formation and their coalescence in dense dispersions.
- vi) A rigorous analysis is required to predict the hydrodynamics in the oil continuous regime.
- vii) Additional studies are also required to understand the influence (if any) of orifice to conduit diameter ratio and orifice characteristics on the flow phenomena.

References

Aaron, A. A., Domanski P.A. Experimentation, analysis, and correlation of refrigerant-22 flow through short tube restrictors. ASHRAE Transactions. 1990, 96, 729-742.

Abduvayt, P., Manabe R., Watanabe T., Arihara N. Analysis of oil-water flow tests in horizontal, hilly-terrain and vertical pipes. In: Proc. Annual SPE Tech. Conf., Houston, Texas (SPE 90096). 2004, in CD ROM.

Aguta, R. M., Olsen K. E., Boe A., Saasen A., Aas B. Experimental investigation of liquid accumulation effects during orifice gas metering of two-phase flow, The Chemical Engineering Journal. 1995, 59, 281-285.

Alkaya, B. Oil-water flow patterns and pressure gradients in slightly inclined pipes. M.S. Thesis, The University of Tulsa, USA. 2000.

Al-Sheikh, J. N, Saunders, D. E., Brodkey, R. S. Prediction of flow patterns in horizontal two phase flow in pipes. Canadian Journal of Chemical Engineering, 1970, 48, 21-29.

Andritsos, N. and Hanratty, T. J., Internacial instabilities for horizontal gasliquid flows in pipelines. International Journal of Multiphase Flow. 1987, 13, 583-603.

Angeli, P., Hewitt, G. F. Drop size distributions in horizontal oil-water dispersed flows. Chemical Engineering Science. 2000a, 55, 3133-3143.

Angeli, P., Hewitt, G. F. Flow structure in horizontal oil-water flow. International Journal of Multiphase Flow. 2000b, 26, 1117-1140.

Angeli, P., Hewitt, G. F. Pressure gradient in horizontal liquid-liquid flows. International Journal of Multiphase Flow. 1998, 24, 1183-1203.

Angelsky, O. V., Maksimyak, P. P. Optical correlation measurements of the structure parameters of random and fractal objects. Measurement Science and Technology. 1998, 9, 1682–1693.

Arirachakaran, S., Oglesby, K.D. Malinowsky, M.S., Shoham, O., Brill J.P. An analysis of oil/water flow phenomena in horizontal pipes. In: SPE Paper 18836, SPE Prod. Operating Symp., Oklahoma. 1989, March 13-14, 155.

Arney, M., Bai R., Guevara, E., Joseph D.D. and Liu, K. Friction factor and holdup studies for lubricated pipelining: I. Experiments and correlations. International Journal of Multiphase Flow. 1993, 19,1061-1076.

Badie, S., Hale, C. P., Lawrence, C. J., Hewitt, G. F. Pressure gradient and holdup in horizontal two-phase gas-liquid flows with low liquid loading. International Journal of Multiphase Flow. 2000, 26, 1525-1543.

Baker, O. Simultaneous flow of oil and gas. Oil Gas Journal 1954, 53, 185-195.

Bannwart, A. C, Oscar, Rodriguez, M. H., Carlos, H. M. de Carvalho, Isabela S. Wang, Rosa M. O. Vara. Flow Patterns in Heavy Crude Oil-Water Flow. Journal of Energy Resources Technology. 2004, 126, 184-189.

Bannwart A. C. Modeling aspects of oil-water core-annular flows. Journal of Petroleum Science and Engineering. 2001, 32, 127-143.

Bannwart, A. C., Rodriguez, O. M. H, de Carvalho, C H. M, Wang, IS, Vara RMO. Flow Patterns in Heavy Crude Oil-Water Flow. Journal of Energy Resources Technology. 2004, 126, 184-189.

Barnea, D., Luninsky, Y. and Taitel Y. Flow Pattern in Horizontal and Vertical Two Phase Flow in Small Diameter Pipes. Canadian Journal of Chemical Engineering. 1983, 61, 617-620.

Barnea, D., Shoham, O., Taitel, Y. Flow pattern characterization in two phase flow by electrical conductance probe. International Journal of Multiphase Flow. 1980, 6, 387-397.

Barnea, D., Brauner, N. Holdup of the liquid slug in two phase intermittent flow. International Journal of Multiphase Flow. 1985, 11, 43-49.

Baron, T., Sterling, C. S, Schueler A.P. Viscosity of suspensions-review and application of two phase flow. Proc. Midwestern conf. on fluid mechanics. Univ of Minnesota Institute of Technology, Minneapolis. 1953, 103.

Beretta, A., Ferrari, P., Galbiati, L., Andreini, P.A. Horizontal oil-water flow In small diameter tubes. Flow patterns. International Communication of Heat and Mass Transfer. 1997, 24, 223-229.

Beretta, A., Ferrari, P., Galbiati, L., Andreini, P.A. Horizontal oil-water flow in small diameter tubes. Pressure drop. International Communication of Heat and Mass Transfer. 1997, 24, 231-239.

Bergles, A. E., Suo, M. Investigation of boiling-water flow regime at high pressure. Dynatech Report no. NYO-3304-8, HTFS 1909. 1966.

Brauner, N. Two-Phase Liquid-Liquid annular Flow. International Journal of Multiphase Flow. 1988, 17, 389-400.

Brauner, N., Moalem Marom, D. Two-phase liquid-liquid stratied flow. PCH Physical Chemical Hydrodynamics. 1989, 11, 487-506.

Brauner, N., Moalem Maron, D. Analysis of stratified/nonstratified transitional boundaries in inclined gas-liquid flows. International Journal of Multiphase Flow. 1992, 18, 541-557.

Brauner, N. and Moalem Maron, D. Stability analysis of stratified liquid-liquid horizontal flow. International Journal of Multiphase Flow. 1992, 18, 103-121.

Brauner, N., On the relations between two-phase flow under reduced gravity and earth experiments. International Communication of Heat and Mass Transfer. 1990, 17, 271-282.

Brauner, N., The Prediction of Dispersed Flows Boundaries in Liquid-Liquid and Gas-Liquid Systems. International Journal Multiphase Flow. 2001, 27, 911-928.

Brauner, N., Moalem Marom D. Two-phase liquid-liquid stratified flow. PCH Physical Chemical Hydrodynamics. 1989, 11, 487-506.

Brauner, N., Moalem Maron, D. Analysis of stratified/nonstratified transitional boundaries in horizontal Gas-liquid flows. Chemical Engrneering Science. 1991, 46, 1849-1859.

Brauner, N., Moalem Maron, D. The role of interfacial shear modeling in predicting the stability of stratified two-phase Flow. Chemical Engineering Science. 1993, 48, 2867-2879.

Brauner, N., Moalem Maron, D., Rovinsky J. A two-fluid model for stratified flows with curved interfaces. International Journal of Multiphase Flow. 1998, 24, 975-1004.

Brauner, N., Rovinsky, J., Moalem Maron, D. Determination of the interface curvature in Stratified two-phase systems by energy Considerations. International Journal of Multiphase Flow. 1996, 22, 1167-1185.

Brauner N., Ullmann A., Modelling of phase inversion phenomenon in twophase pipe flow. International Journal of Multiphase Flow. 2002, 28, 1177-1204.

Briens, L.A., Ellis, N. Hydrodynamics of three-phase fluidized bed systems examined by statistical, fractal, chaos and wavelet analysis methods. Chemical Engineering Science. 2005, 60, 6094-6106.

Buhidma, A., Pal, R. Flow measurement of two phase oil in water emulsions using wage meters and segmental orifice meters. Chemical Engineering Journal. 1996, 63, 59-64.

Cengel, J. A., Faruqui, A. A., Finnigan J. W., Wright C. H., Kundsen, J. G. Laminar and turbulent flow of unstable liquid-liquid emulsions. AIChE Journal. 1962, 8, 335 – 339.

Chakrabarti, D.P., Das, G., Ray, S., Pressure drop in Liquid-liquid Two Phase Horizontal Flow: Experiment and Prediction. Chemical Engineering Technology. 2005, 28, 1003-1009.

Chang-Kyung Sung. Two instability criteria for the stratified flow-in-horizontal pipe-at-cocurrent flow conditions. International Communication of Heat-and Mass Transfer. 1999, 26, 55-64.

Charles, M.E., Lilleleht, L.U. Correlation of pressure gradients for the stratified laminar-turbulent pipeline flow of two immiscible liquids. Canadian Journal of Chemical Engineering. 1966, 44, 47-49.

Charles, M.E., Redberger, R.J. The reduction of pressure gradients in oil pipelines by the addition of water: numerical analysis of stratified flow. Canadian Journal of Chemical Engineering. 1961,40, 70-75.

Charles, M.E., Govier, G.W., and Hodgson, G.W. The horizontal flow of equal density oil-water mixtures, Canadian Journal of Chemical Engineering. 1961, 39, 287-36.

Chaudry, A. B., Emerton, A. C., Jackson, R. Flow regimes in the cocurrent upward flow of water and air. Presented at symposium of two phase flow, Exeter, England. 1965.

Chen, D. K., Chen, Z. H., Zhao, Z. S., Zhuo, N. The local resistance of gasliquid two phase flow through an orifice. International Journal of Heat and Fluid Flow, 1986, 17, 231-238.

Chen J.P., Liu, Z.J. Chen, Y.M. Niu, Trans-critical R744 and two-phase flow through short tube orifices. International Journal of Thermal Sciences. 2004, 43, 623–630.

Chen, X.T., Cai, X. D., Brill, J.P. Gas-liquid stratified-wavy flow in horizontal pipelines. Journal of Energy Resources Technology. 1997, 119, 209-216.

Chesters, A. K, Issa, R. A. Framework for the modelling of phase inversion in liquid-liquid systems. 5th International Conference on Multiphase Flow, ICMF'04. Yokohama, Japan, May 30–June 4, 2004, Paper No. 271.

Choi, J., Chung, J. T, Kim, Y. A generalized correlation for two-phase flow of alternative refrigerants through short tube orifices, International Journal of Refrigeration. 2004, 27, 393–400.

Clark, A. F., Shapiro, A. 1949. U.S. Patent No. 2,533,878

Cox, A. L. 1985. A study of horizontal and downhill two-phase oil-water flow. M.S. thesis, The University of Texas.

Deng, X., Dong, F., Xu, L. J., Liu, X. P., Xu, L. A. The design of a dual-plane ERT system for cross correlation measurement of bubbly gas/liquid pipe flow. Measurement Science and Technology. 2001, 12, 1024–1031.

Drahos, J., Ruzicka Marek C. Problems of Time Series Analysis in Characterization of Multiphase Flows. 5th International Conference on Multiphase Flow, ICMF'04, Yokohama, Japan. 2004, May 30–June 4, Paper No. K04.

El-Hamouz, A. M., Stewart, A. C. On-line drop size distribution measurement using a Par-Tec M300 laser back scatter instrument. SPE int. 1996, 366672, 1-14.

El-Hamouz, A. M., Stewart, A.C, Davies G.A. A study of kerosene water dispersions in shear flow through pipes and fittings. In: Proceedings of the first international symposium on two phase flow modeling and experimentation. 1995, 987-997.

Ellis, N., Bi, H.T., Lim, C. J., Grace, J. R. Influence of probe scale and analysis method on measured hydrodynamic properties of gas-fluidized beds. Chemical Engineering Science. 2004, 59, 1841-1851.

Ellis, N., Briens, L. A., Grace, J. R., Bi, H.T., Lim, C. J. Characterization of dynamic behaviour in gas-solid turbulent fluidized bed using chaos and wavelet analyses. Chemical Engineering Journal. 2003, 96, 105-116.

Fairuzov, Y. V., Arenas-Medina P., Verdejo-Fierro J., Gonzalez-Islas R. Flow pattern transitions in horizontal pipelines carrying oil-water mixtures: Full-scale experiments. Journal of Energy Resources Technology. 2000, 122, 169-176.

Farrar, B., Bruun, H. H. A computer based hot-film technique used for flow measurements in a vertical kerosene-water pipe flow. International Journal of Multiphase Flow. 1996, 22, 733-751.

Faruqui, A. A., Knudsen, J. G. Velocity and temperature profile of unstable liquid-liquid dispersions in vertical turbulent flow. Chemical Engineering Science. 1962, 17, 897-907.

Ferreira, V. C. S. Differential pressure spectral analysis for two-phase flow through an orifice plate, International Journal of Pressure Vessel and Piping. 1997, 73, 19-23.

Fleming, J. Carbon dioxide as the working fluid in heating and/or cooling systems. Bulletin of the International Institute of Refrigeration. 2003, 83 7–15.

Flores, J. G., Chen, X.T., Sarica, C., Brill, J.P. Characterization of oil-water flow patterns in vertical and deviated wells. Paper SPE 38810 presented at 1997 SPE Annual Technical Conference and Exhibition, San Antonio, TX, USA, October 5-8, 601-610.

Flores, J. G., Sarica, C., Chen, X.T., Brill, J. P. Investigation of holdup and pressure drop behavior for oil-water flow in vertical and deviated wells. Trans. ASME Journal of Energy Resour. Tech. 1998, 120, 8-14.

Fossa, M., Guglielmini, G. Pressure Drop And Void Fraction Profiles During Horizontal Flow, Experimental Thermal and Fluid Science. 2002, 26, 513–523.

Garci'a-Valladares, O., Numerical simulation of trans-critical carbon dioxide (R744) flow through short tube orifices. Applied Thermal Engineering. 2006, 26, 144–151.

Garcy'a-Valladares, O., C.D. Pe'rez-Segarra, A. Oliva. Numerical simulation of capillary-tube expansion devices behaviour with pure and mixed refrigerants considering metastable region. Part 1: mathematical formulation and numerical model. Applied Thermal Engineering. 2002, 22, 173–182.

Garcý 'a-Valladares, O., Review of numerical simulation of capillary-tube using refrigerant mixtures. Applied Thermal Engineering. 2003, 24, 949–966.

Gemmell, A. R. and Epstein, N. Numerical analysis of stratified laminar flow of two immiscible Newtonian liquids in a circular pipe. Canadian Journal of Chemical Engineering. 1962, 40, 215-224.

Geng, Y, Zheng, J., Shi, T. Study on the metering characteristics of a slotted orifice for wet gas flow. Flow Measurement and Instrumentation. 2006, 17, 123–128.

Gorelic, D., Brauner, N. The interface configuration in two-phase stratified flow. International Journal Multiphase Flow. 1999, 25, 877-1007.

Govier, G. W., Omer, M. M. The horizontal pipeline flow of air-water mixtures. Canadian Journal of Chemical Engineering. 1962, 40, 93-104.

Govier, G. W., Radford, B. A., Dunn, J. C. The upward vertical flow of airwater mixtures: I. Effect of air and water rates on flow pattern, holdup and pressure drop. Canadian Journal of Chemical Engineering. 1957, 35, 58-70.

Guzhov, A. I., Grishan, A. L., Medredev, V. F., Medredeva, O. P. Emulsion formation during the flow of two immiscible liquids in a pipe. Neft Khoz. 1973, 8, 58–61 (in Russian).

Hamad, F. A., Imberton, F., Brunn, H. H. An Optical Probe for measurement in liquid-liquid two-phase flow. Measurement Science and Technology. 1997, 8, 1122-1131.

Hamad, F. A., Pierscionek, B. K., Brunn, H. H. A dual optical probe for volume fraction, drop velocity and drop size measurements in liquid-liquid two-phase flow. Measurement Science and Technology. 2000, 11, 1307-1318.

Hamersma, P. J., Hart, J. A pressure drop correlation for gas/liquid pipe flow with a small liquid holdup. Chemical Engineering Science. 1987, 42, 1187-1196.

Hapanowicz, J., Troniewski, L. Two-phase flow of liquid-liquid mixture in the range of the water droplet pattern. Chemical Engineering and Processing. 2002, 41, 165–172.

Hart, J., Hamersma, P. J., Fortuin, J. M. H. Correlations predicting frictional pressure drop and liquid holdup during horizontal gas-liquid pipe flow with a small liquid holdup. International Journal of Multiphase Flow. 1989, 15, 947–974.

Hasan, A.R. and Kabir, C.S. A simplified model for oil/water flow in vertical and deviated wellbores, SPE In Proceedings and Facilities. 1999, 141, 56-62.

Hasson, D., Nir, A. Annular Flow of Two Immiscible Liquids: II, Canadian Journal of Chemical Engineering. 1970, 48, 521-526.

Hasson, D., Mann, U., and Nir A. Annular Flow of Two Immiscible Liquids: I, Mechanisms, Canadian Journal of Chemical Engineering. 1970, 48, 514-520.

A Gilewicz, J., Emulsie, 1957, PWN, Warszawa.

Hawkes, N. J., Lawrence, C.J., Hewitt, G.F. Studies of wispy-annular flow using transient pressure gradient and optical measurements. International Journal of Multiphase Flow. 2000, 26, 1565-1582.

Hewitt, G. F., Roberts, D. N. Studies of two phase flow patterns by simultaneous X-rays and photography. Atomic energy research establishment Report M2159, Harwell, England, 1969.

Hewitt, G. F. Measurement of two phase flow parameters. Acadenic Press, New York, 1978.

Hill, A.D., Oolman, T. Production Logging Tool Behavior in Two-Phase Inclined Flow. Journal of Particle Technology. 1982, 2432-2440.

Hinze, J. O. Fundamentals of the hydrodynamic mechanism of splitting in dispersion processes. AICh.E. J. 1955, 1, 289-295.

Holman, J. P. Experimental Methods for Engineers, 5th ed., New York, McGraw-Hill, 1989.

Hong-bo Li, Wu-Chao, Zheng-Yong-gang. Plane-flow model of non-Newtonian turbulent stratified flow in wells-and pipes. Journal of Petroleum Science and Engineering. 2004, 44, 223-229:

Howarth, W. J. Coalescence of drops in a turbulent flow field. Chemical Engineering Science. 1964, 19, 33-38.

Hribernik, A, Bombek, G, Markocic. Velocity measurements in a shotblasting machine. Flow Measurement and Instrumentation. 2003, 14, 225–231.

Hsu, Y. Y., Graham, R. W. A visual study of two phase flow in a vertical tube with heat addition. NASA Technical Note D-1564. 1963.

Huang, A., Joseph, D. D. Stability of eccentric core annular flow. Journal of Fluid Mechanics. 1995, 282, 233-45.

Hubbard, M.G., Dukler, A. E. The characterization of flow regimes for horizontal two-phase flow. Proc. Heat Transfer and Fluid Mech. 1966, Institute. Stanford University Press -M. Saad & J.A. Moller eds.

Ioannou, K., Hu, B., Matar, Omar, K., Hewitt G.F., Angeli P. Phase inversion in dispersed liquid-liquid pipe flows. 5th International Conference on Multiphase Flow, ICMF'04, Yokohama, Japan, May 30–June 4, 2004, Paper No. 108.

Ioannou, K., Nydal, Ole, J., Angeli P. Phase inversion in dispersed liquid-liquid flows. Exp. Ther. Fluid Sci. 2005, 29, 331-339.

Isbin H. S., Moen R. H., Wickey R. O., Mosher D. R., Larson H. C. Two phase steam water pressure drop. Chem. Eng. Symp. 1959, Ser. 55, p 75.

Jana, A. K., Das, G., Das, P. K. Flow regime identification of two-phase liquidliquid upflow through vertical pipe. Chemical Engineering Science. 2006a, 61, 1500 -1515.

Jana, A. K, Das, G., Das, P. K. A novel technique to identify flow patterns during liquid-liquid two-phase upflow through vertical pipe, Industrial and Engineering Chemistry Research. 2006b, 45, 2381-2393.

Janssen, E. Two-phase pressure loss across abrupt contractions and expansions, steam-water at 600 to 1400 psia. Proc. 3rd Int. Heat Transfer Conf., Chicago, 1966.

Jin, N. D., Nie, X.B., Ren, Y.Y., Liu, X.B. Characterization of oil/water twophase flow patterns based on nonlinear time series analysis. Flow Meas. Inst. 2003, 14, 169-175. Jones, O. C., Zuber, N., The interrelation between void fraction fluctuations and flow pattern in two phase flow. International Journal of Multiphase Flow. 1975, 2, 273-306.

Jones, O.C., Delhaye, J. M. Transient and Statistical Measurement Techniques for Two Phase Flows: A Critical Review. International Journal of Multiphase Flow. 1976, 3, 89-116.

Kamei, T., Serizawa, A. Measurement of 2-dimensional local instantaneous liquid film thickness around simulated nuclear fuel rod by ultrasonic transmission technique. Nuclear Engineering and Design. 1998. 184, 349-362.

Kim, Y. Two-phase flow of HCFC-22 and HFC-134a through short-tube orifices, Ph.D. Dissertation, Texas A&M University, College Station, 1993.

Kim, Y., Neal. D.L. O. Two-phase flow of refrigerant-22 flow through short tube orifices, ASHRAE Transactions. 1994, 100, 323-334.

Kofaezen, A. B. Hydraulic resistance for horizontal twophase flow through orifices. Teploenergetika. 1976, 23, 549-558.

Kojasoy, G., Landis F., Kwame-Mensah P., Chang C. T. Two-Phase pressure Drop in Multiple Thick and Thin-Orifice Plates. Experimental Thermal and Fluid Science. 1997, 15,347-358.

Kordyban, E. S., Ranov, T. Mechanism of slug formation in horizontal twophase flow. Journal of Basic Engineering. 1970, 92, 857-864.

Kordyban, E. S. Some characteristics of high waves in closed channels approaching Kelvin-Helmholtz instability. A.S.M.E. J. Fluids Eng. 1977, 99, 339-346.

Kosterin, SI. Izvestia Akademii Nauk., SSSR., OTN. 1949, 12, 1824 (USSR)

Kruse, H., Heidelck, R., Suss, J. The application of CO2 as a refrigerant, Bulletin of the International Institute of Refrigeration 1999,79, 2–21.

Kruyer, J., Redberger, P. J. Ellis, H. S. The pipeline flow of capsules. Journal of Fluid Mechanics. 1967, 30, 513-531.

Kurban, A. P. A. Stratified liquid-liquid flow. Ph.D. Thesis, Imperial College, University of London, UK. 1997.

Lin, P. Y., Hanratty, T. J. Prediction of the initiation of slugs with linear stability theory. International Journal of Multiphase Flow. 1986, 12, 79-98.

Lin, Z. H. Two-Phase Flow Measurements With Sharp-Edged Orifices. International Journal of Multiphase Flow. 1982, 8, 683-693.

Liu, J. P., Niu, Y. M., Chen, J. P., Chen, Z. J., Feng, X. Experimentation and correlation of R744 two-phase flow through short tubes, Experimental Thermal and Fluid Sciences. 2004, 28, 565–573.

Liu, L., Matar, O. K., Hewitt, G. F. Laser-induced fluorescence (LIF) studies of liquid-liquid flows. Part I: Flow structures and phase inversion. Chemical Engineering Science. 2006a, 61, 4007 – 4021.

Liu, L., Matar, O. K., Hewitt, G. F. Laser-induced fluorescence (LIF) studies of liquid-liquid flows. Part II: Flow pattern transitions at lowliquid velocities in downwards flow. Chemical Engineering Science. 2006b, 61, 4022 -4026.

Liu, S., Li, D. Drop coalescence in turbulent dispersions. Chemical Engineering Science. 1999, 54, 5667-5675.

Li, Hong-60., Wa Chao, Zheng Yong-goug. Journal of Pet. Science & Engl., 2004,44, 163 223-229.

Lockhart, R.W., Martinelli, R.C. Proposed correlation of data for isothermal two-phase, two-component flow in pipes. Chemical Engineering Progress. 1949, 45, 39-48.

Lorentzen, G. Revival of carbon dioxide as a refrigerant. International Journal of Refrigeration. 1994, 17, 292–301.

Lovick, J., Angeli, P. Droplet size and velocity profiles in liquid-liquid horizontal flows. Chemical Engineering Science. 2004a, 59, 3105 – 3115.

Lovick, J., Angeli, P. Experimental studies on the dual continuous flow pattern in oil-water flows. International Journal of Multiphase Flow. 2004b, 30, 139–157.

Lum, J.Y.L, Al-Wahaibi, T., Angeli, P. Upward and downward inclination oilwater flows. International Journal of Multiphase Flow. 2006, 32, 413-435

Lum, J.Y.L., Lovick, J., Angeli, P. Low inclination oil-water flows. Canadian Journal of Chemical Engineering. 2004, 82, 303-315.

Lynch, G. P., & Segel S. L. Direct measurement of the void fraction of a two phase fluid by nuclear magnetic resonance. International Journal of Heat and Mass Transfer. 1977, 20, 7-14.

Madhane, J. M., Gregory, G. A., Aziz, K. A flow pattern for gas-liquid flow in horizontal pipes. International Journal of Multiphase Flow. 1974, 1, 537-553.

Malinowsky, M. S. An experimental study oil-water and air-oil-water flowing mixtures in horizontal pipes. M.S. thesis, The University of Tulsa. 1975.

Matsui, G. Identification of flow regimes in Vertical gas-liquid two-phase flow Using differential pressure fluctuations. International Journal of Multiphase Flow. 1984, 10, 711-720.

McAdams, W. H., Woods, W. K., Heroman, L.C. Vapourisation inside horizontal tubes. Part II: benzene±oil mixtures. Transaction of ASME. 1942, 64, 193-200.

Mishima, K., Ishii, M. Theoretical prediction of onset of horizontal slug flow. Trans. A.S.M.E. J. Fluids Eng. 1980, 102, 441-445.

Moalem Maron, D., Brauner, N. Kruka, V. R. 1990, The mechanisms of two phase liquid-liquid viscous core flow. Proc. 6th Miami Int. Symp. Heat and Mass Transfer.

Morrison, G L., Terracina, D., Brewer, C, Hall, K.R. Response of a slotted orifice flow meter to an air/water mixture, Flow Measurement and Instrumentation,. 2001, 12, 175–180.

Mouza, A. A., Vlachos, N. A., Paras, S. V., Karabelas, A. J. Measurement of liquid film thickness using a laser light absorption method. Experiments in Fluids. 2000, 28, 355-359.

Mugele, R. A., Evans, H. D. Droplet size distribution in sprays. Industrial and Engineering Chemistry. 1951, 43, 1317-1324.

Mukherjee, H. K., Brill, J. P. and Beggs H.D. Experimental Study of Oil-Water Flow in Inclined Pipes, Transactions of the ASME. 1981, 103, 56-66.

Nadler, M., Mewes, D. Flow induced emulsification in the flow of two immiscible liquids in horizontal pipes. International Journal Multiphase Flow. 1997, 23, 55-68.

Nädler, M., Mewes, D. The effect of gas injection on the flow of immiscible liquids in horizontal pipes. Chemical Engineering & Technology. 1995, 18, 156-165.
Ng, T. S., Lawrence, C. J, Hewitt G. F. Interface shape for two-phase laminar stratified flow in a circular pipe. International Journal Multiphase Flow. 2001, 27, 1301-1311.

Oddie, G., Shi, H., Durlfosky, L. J., Aziz, K., Pfeffer, B., Holmes J. A. Experimental study of two and three phase flows in large diameter inclined pipes. International Journal of Multiphase Flow. 2003, 29, 527–558.

Oddie, G., Pearson, A. Flow-rate measurement in two-phase flow. Annual Review of Fluid Mechanics. 2004, 36, 149-172.

Oglesby, K. D. An experimental study on the effects of oil viscosity, mixture velocity, and water fraction on horizontal oil-water flow. M.S. thesis, The University of Tulsa. 1979.

Oliemans, R. V. A. The lubricating film model for core annular flow. Ph. D. Dissertation, Delft University Press. 1986.

Oliemans, R.V.A., Ooms G. Core-Annular Flow of Oil and Water Through a Pipeline. Multiphase Science and Technology. 1986, 2, eds. G.F. Hewitt, J.M. Delhaye, and N. Zuber, Hemisphere Publishing Corporation, Washington.

Ooms, G., Segal A., Van der Wees A. J., Meerho R. and Oliemans R.V.A. Theoretical Model for Core-Annular Flow of a Very Viscous Oil Core and a Water Annulus Through a Horizontal Pipe. International Journal Multiphase Flow. 1984, 10, 41-60.

Pal, R. Emulsions: pipeline flow behaviour, viscosity equations and flow measurement. PhD Thesis, Univ of Waterloo, Ontario. 1987.

Pal R. Flow of Oil-in-Water Emulsions through Orifice and Venturi Meters, Ind. Eng. Chem. Res. 1993,32, 1212-1217.

Pal, R. Pipeline flow of unstable and surfactant-stabilized emulsions. AIChE Journal. 1993. 39. 1754-1764.

Pal, R. Metering of two-phase liquid-liquid emulsions. A state of the art review. Industrial and Engineering Chemistry Research. 1994, 33, 1413-1435.

Payne V., O-Neal, D.L. Mass flow characteristics of R407C through short-tube orifices, ASHRAE Transactions. 1998, 104,197–209.

Raissan, C. Flow regime studies up to critical heat flux conditions at 80 Kg/m². CEA Grenoble, Report no. TT22. 1965.

Raj, T. S., Chakrabarti, D. P, Das, G. Liquid–Liquid Stratified Flow through Horizontal Conduit. Chemical Engineering and Technology. 2005, 28, 899-907.

Redberger, P. J., Charles, M. E. Axial laminar flow in a circular pipe containing a fixed eccentric core. The Canadian Journal of Chemical Engineering. 1962, 40,148-151.

Ren, J., Mao, Q., Li, J., Lin, W. Wavelet analysis of dynamic behaviour in fluidized beds. Chemical Engineering Science. 2001, 56, 981-988.

Rodriguez, O. M. H., Oliemans, R. V. A. Experimental study on oil-water flow in horizontal and slightly inclined pipes. International Journal of Multiphase Flow. 2006, 32, 323-343.

Russell, T. W. F., Charles, M. E. The Effect of the Less Viscous Liquid in the Laminar Flow of Two Immiscible Liquids. Canadian Journal Chemical of Engineering. 1959, 37,18-34.

Russell, T. W. F., Hodgson, G. W. Govier, G.W. Horizontal pipeline flow of oil and water. Canadian Journal of Chemical Engineering. 1959, 37, 9-17.

Scot, P.M., Knudsen, J.G. Two-Phase Liquid-Liquid Flow in Pipes. AIChE Symposium Series. 1972, 68, 38-44.

Scott, G. M. A study of two-phase liquid-liquid flow at variable inclinations. M.S. thesis, The University of Texas. 1985.

Sembira, A., Merchuk, I. C., Wolf, D. Characteristics of a motionless mixer for dispersion of immiscible fluids-I. A modified electroresistivity probe technique. Chemical Engineering Science. 1986, 41, 445-455.

Shinnar, R. On the behaviour of liquid dispersions in mixing vessels. Journal of Fluid Mechanics. 1961, 10, 259-275.

Simmons, M. J. H., Azzopardi, B. J. Drop size distributions in dispersed liquidliquid pipe flow. International Journal of Multiphase Flow. 2001, 27, 843-859.

Sinclair, A.R. Rheology of Viscous Fracturing Fluids. Journal of Petroleum Technology. 1970, 711-719.

Singh, G.M., Hrnjak, P., Bullard, W. Flow of refrigerant 134a through orifice tubes. International Journal of HVAC&R Research. 2001, 3, 245–262.

Solomon, J. V. Construction of a two phase flow regime transition detector. M. Sc. Thesis, Mechanical Engineering Department, MIT. 1962.

Song, C. H., No, H. C., Chung, M. K. Investigation of bubble flow developments and its transition based on the instability of void fraction waves. International Journal of Multiphase Flow. 1995, 21, 381-404.

Stapelberg, H., Mewes, D. The pressure loss and slug frequency of liquidliquid-gas slug flow in horizontal pipes. International Journal of Multiphase Flow. 1994, 20, 285-303.

Taitel, Y., Dukler, A. E. A Model for Predicting Flow Regime Transitions in Horizontal and near Horizontal Gas-Liquid Flow. AIChE Journal. 1976, 22, 47-55.

Theissing, P. A generally valid method for calculating frictional pressure drop in multiphase flow. Chemical Ing. Technik. 1980, 52, 344-345 (in German).

Tidhar, M., Merchuk, J. C., Sembira, A. N, Wolf, D. Characteristics of a motionless mixer for Dispersion of immiscible fluids-II. Phase Inversion of liquid-liquid systems. Chemical Engineering Science. 1986, 41, 457-462.

Trallero, J. L. Oil water flow patterns in horizontal pipes. Ph.D thesis, The University of Tulsa. 1995.

Ullmann, A., Brauner, N. Closure relations for two-fluid models for two-phase stratified smooth and stratified wavy flows. International Journal of Multiphase Flow. 2006, 32, 82–105.

Ullmann, A., Goldstein, A., Zamir, M., Brauner, N. Closure relations for the shear stresses in two-fluid models for laminar stratified flow. International Journal of Multiphase Flow. 2004, 30, 877–900.

United Nations Framework Convention on Climate Change UNFCCC, Kyoto Protocol, 1997.

Valle, A., and Kvandal, H. K. Pressure drop and dispersion characteristics of separated oil-water flow. In Celata, G.P., and Shah, R.K. Edizioni ETS, eds., In Proceedings of the International Symposium on Two-Phase Flow Modelling and Experimentation. 1995, Oct. 9-11, Rome, Italy, 583-591.

\$ Sung, C. K., Int. Comm. Heat & Man Tranfer, 1999, 26, 55-64 166

Valle, A., Utvik, O. H. Pressure drop, flow pattern and slip for two phase crude oil/water flow: experiments and model predictions. International Symposium on Liquid-Liquid Two-Phase Flow and Transport Phenomena, Antalya, Turkey, 1997, 3-7 Nov.

Vedapuri, D., Bessette, D., Jepson W.P. A segregated flow model to predict water layer thickness in oil-water flows in horizontal and slightly inclined pipelines, in In Proceedings Multiphase'97, Cannes, France. 1997, June 18-20, 75-105.

Vial, C., Camarasa, E., Poncin, S., Wild, G., Midoux, N., Bouillard, J. Study of hydrodynamic behaviour in bubble columns and external loop airlift reactors through analysis of pressure fluctuations. Chemical Engineering Science. 2000, 55, 2957-2973.

Vigneaux, P., Chenais, P., Hulin, J. P. Liquid-liquid flows in an inclined pipe. AIChE Journal., 1988, 34, 781-789.

Vlachos, N. A., Paras, S.A., Karabelas, A. J. Prediction of holdup, axial pressure gradient and wall shear stress in wavy stratified and stratified/atomization gas/liquid flow. International Journal of Multiphase Flow. 1999, 25, 365-376.

Wallis, G. B. Dobson, J. E. The onset of slugging in horizontal stratified airwater flow. International Journal of Multiphase Flow. 1973, 1, 173-193.

Wallis, G., B. One dimensional two phase flow, New York, McGraw-Hill, 1969.

Ward, J. P., Knudsen, J. G. Turbulent flow of unstable liquid-liquid dispersions: drop sizes and velocity distributions. AIChE Journal. 1967, 13, 356-365.

Wenran, W., Yunxian, T. A new method of two-phase flow measurement by orifice plate differential pressure noise, Flow Meas. Instrum. 1995, 6., 265-270,

White, P. D., Huntington, R. L. Horizontal co-current two phase flow of fluids in pipe lines. Petrol Eng. 1955, 27, 40-48.

Xu, S., Lian, W., Wang, S. Experimental studies on orifice behavior and twophase flow in flash chamber, Desalination. 2002, 150, 93-98.

Yan, Y., Thrope, B. Flow Regime Transitions Due To Cavitation In The Flow Through An Orifice. International Journal of Multiphase Flow. 1990, 16, 1023-1045.

Yan, Y., Ma, J. Measurement of particulate velocity under stack-flow conditions. Measurement Science and Technology. 2000, 11, 59-65.

Yeh, G., Haynie, Jr. F.H., Moses, R.E. Phase-volume relationship at the point of phase inversion in liquid dispersions. AIChE Journal. 1964, 102, 260-265.

Yu, H. S., Sparrow, E. M. Experiments on two-components stratified flow in a horizontal duct. Journal of Heat Transfer Trans., A.S.M.E. 1969, 91, 51-58.

Zakin, J. L., Pinaire, L. R., Borgmeyer, M. E. Transportation of oils in oil-inwater emulsions. Journal of Fluid Engineering. 1979, 101, 100-110.

Zhou, G., Kresta, S. M. Correlation of mean dropsize and minimum dropsize with the turbulence energy dissipation and the flow in an agitated tank. Chemical Engineering Science., 1998, 53, 2063–2079.

Appendix -I

Uncertainty and repeatability of the experimental results

The repeatability of the experimental results and uncertainty involved in them are discussed in this section. First the uncertainty of a few important parameters are estimated.

For uncertainty analysis the procedure described by Holman (1989) has been followed. If P is the parameter function of the independent variables $p1, p2, p3 \dots pn$, then $P=P(p1, p2, p3 \dots pn)$ (A.1) Let the error associated with these independent variables be $e1, e2, e3 \dots en$ and the resulting uncertainty in P be e, then

$$e = \left[\left(\frac{\partial P}{\partial p \mathbf{l}} e \mathbf{l} \right)^2 + \left(\frac{\partial P}{\partial p 2} e \mathbf{2} \right)^2 + \dots + \left(\frac{\partial P}{\partial p n} e n \right)^2 \right]^{\frac{1}{2}}$$
(A.2)

The water holdup has been estimated by collecting the entrapped holdup in a measuring cylinder, which is having a least count of 10 ml.

Holdup (H_W)=Volume of the water (V_W)/ Total entrapped volume (V=V_W+V_K)

Or
$$H_W = \frac{V_W}{V_W + V_K}$$
 (A.3)

The error associated in carrying out this measurement can be evaluated as

$$e = \left[\left(\frac{\partial H_{W}}{\partial V_{W}} e^{1} \right)^{2} + \left(\frac{\partial H_{W}}{\partial V_{K}} e^{2} \right)^{2} \right]^{\frac{1}{2}}$$

$$= \left[\left(\frac{V_{K}}{V^{2}} e^{1} \right)^{2} + \left(-\frac{V_{W}}{V^{2}} e^{2} \right)^{2} \right]^{\frac{1}{2}}$$
(A.4)
(A.5)

The inaccuracies in the measurements induce an uncertainty of around $\pm 1\%$.

A sample calculation is given below

 $e = [(260/1110^2 \times 10)^2 + (-850/1110^2 \times 10)^2]^{0.5}$

which yields an uncertainty of 0.072%.

The liquid flow rates have been measured with rotameters of different ranges. The rotameters for both the liquids range from 0 to 0.001 m^3 /s with a least count of $1.66 \times 10^{-5} \text{ m}^3$ /s for R1 and 0 to $1.66 \times 10^{-4} \text{ m}^3$ /s where the least count is $3.33 \times 10^{-6} \text{ m}^3$ /s for R2 and these rotameters have an uncertainty of ± 2 % (supplied by the manufacturer).

To measure the pressure drop, two pressure tappings have been provided at distances of 2.1 m and 0.025 m in the test section. Honeywell 24PCB differential pressure transducer has been used to measure the pressure drop. The transducer has a least count of 1.0×10^{-2} Pa and ± 2 % uncertainty (supplied by the manufacturer).

In order to obtain reliable output from the optical probe, the signals have been recorded for a sufficiently long time. The initial test results have revealed that a period of 2 minutes is sufficient for this purpose. The reproducibility of the results was checked by recording the signals for longer time periods under different combinations of phase velocities in the different flow patterns. Different windows of time span 2 minutes have been selected from the same continuous signal and the PDFs have been constructed from them. The moments exhibit high repeatability and agree within $\pm 5\%$ for all the cases with a time span of 2 minutes or more. So a time period of 2 minutes is selected for recording the probe signals.

Reproducibility of holdup data has been checked during experimentation. The measurements of holdup have been carried out for several times for a particular inlet velocity of both the fluids to obtain consistent results and the accuracy of measurements. The results agree within $\pm 1.5\%$.

Outcome of the dissertation

<u>Patent:</u>

Optical Probe for Multiphase Flow Patent # : 915 / KOL / 2005 D. P. Chakrabarti, G. Das, P. K. Das

List of publications:

International Journals:

Liquid-Liquid Stratified Flow through Horizontal Conduit T. Sunder Raj, D. P. Chakrabarti, G. Das Chemical Engineering & Technology; 2005.Vol 28, pp 899-907

Pressure drop in Liquid-liquid Two Phase Horizontal Flow: Experiment and Prediction D. P. Chakrabarti, S. Ray, G. Das Chemical Engineering & Technology; 2005.Vol 28, pp1003-1009

Liquid-liquid two phase flow through a horizontal T junction S.Pandey, A. Gupta, D.P. Chakrabarti, G. Das and S. Ray Chemical Engineering Research and Design, accepted.

Behaviour of pressure gradient and transient pressure signals during liquid-liquid two phase flow D.P. Chakrabarti, P. Ghoshal, G. Das Chemical Engineering & Technology, accepted.

The transition from water continuous to oil continuous flow pattern D. P. Chakrabarti, G. Das, P. K. Das AIChE Journal (under review- rebuttal to reviewer sent)

Stratification of liquid-liquid flow through horizontal pipes D. P. Chakrabarti, G. Das, P. K. Das Chemical Engineering Science (under review)

Oil water flow through different diameter pipes- similarities and differences T. K. Mandal, D. P. Chakrabarti, G. Das Chemical Engineering Research and Design (under review)

Liquid-liquid two phase flow through an orifice D. P. Chakrabarti, G. Das, P. K. Das Industrial and Engineering Chemistry Research (under review)

Conferences:

Flow regime identification by laser imaging technique in two-phase flow through horizontal pipes.

D. P. Chakrabarti, A. K. Jana and G. Das

Published in the proceedings of 1st National Conference of Research Scholars and Young Scientists in Chemical Engineering (**CRSYS**, 2004: held in IIT,Kharagpur, India from 25th -27th 'Sept'2004) edited by S. Dey., S. Ray., K. Mohanty and D. P. Chakrabarti.

Identification of the flow regime in small diameter pipe and comparison with large diameter pipe

T. K. Mandal, D. P. Chakrabarti, Gargi Das

Published in the proceedings of 1st National Conference of Research Scholars and Young Scientists in Chemical Engineering (CRSYS, 2004: held in IIT,Kharagpur, India from 25th -27th 'Sept'2004) edited by S. Dey., S. Ray., K. Mohanty and D. P. Chakrabarti.

The stratified configuration during liquid-liquid flows through horizontal Conduits Dhurjati Prasad Chakrabarti, Gargi Das

57th annual session of the Indian Institute of The Chemical Engineers (CHEMCON 2004)

Mumbai, India, 27 - 30 December' 2004

Flow regime identification from pressure signal in liquid-liquid two phase horizontal flow.

Parama Ghoshal, D. P. Chakrabarti, G. Das

31st National Conference on Fluid Mechanics and Fluid Power (NCFMFP 2004) Kolkata, India, 16-18 December, 2004,

Liquid-liquid stratified flow

D. P. Chakrobarti, T. Sunder raj, G. Das

Third International Conference on Theoretical Applied, Computational and Experimental Mechanics (ICTACEM 2004) :27-12-2004 to 31-12-2004, IIT Kharagpur.

