

TOWARDS A UNIVERSAL DIMENSIONLESS MAP OF FLOW REGIME TRANSITIONS IN HORIZONTAL LIQUID-LIQUID FLOWS

Ibarra R.*, Zadrazil I., Markides C.N. and Matar O.K.

*Author for correspondence

Department of Chemical Engineering,
Imperial College London,
London, SW7 2AZ,
United Kingdom,

E-mail: r.ibarra-hernandez13@imperial.ac.uk

ABSTRACT

The characterisation of co-current horizontal liquid-liquid pipe flow is commonly carried out through experimental investigations in laboratory conditions, which are used to reveal the geometrical features (i.e., spatial distributions) of the two immiscible liquid phases flowing in the pipe. This information is then used to classify the resulting flows into distinct regimes, such as stratified, intermittent and dispersed flow, with very different characteristics. The vast majority of flow regime maps have been compiled based on the (dimensional) mixture or superficial flow velocities of the two phases. This limits the applicability and transferability of these flow regime maps since the maps obtained are a unique representation of the specific flow under investigation. In this paper, newly acquired experimental data together with data available from the literature are used to analyse the conditions that are associated with flow transitions in horizontal liquid-liquid flows. The present experimental study was performed in an 8.5 m long horizontal acrylic pipe of 32-mm internal diameter, using an aliphatic oil (Exxsol D140) and water as the test fluids. A dimensional analysis is carried out to describe the flow regime transitions in a dimensionless flow regime map that represent the governing forces in the flow: inertial, viscous, gravitational (buoyancy) and capillary forces (interfacial tension). The constructed dimensionless flow regime transitions map, based on experimental data, enables the identification of flow regimes in horizontal pipes for different flow velocities, fluid properties and pipe sizes.

INTRODUCTION

The co-current flow of two immiscible liquids in a pipe is relevant to many diverse applications across a range of scales, from microfluidic mixers and reactors to transportation pipelines in the oil-and-gas industry. In particular, a number of studies have been carried out to characterise oil-water flows in horizontal pipes, such as, Russell *et al.* [1], Charles *et al.* [2], Oglesby [3], and Trallero [4]. These studies have developed flow regime maps as functions of dimensional variables (i.e. mixture or superficial velocities). As a result, flow regime transitions are unique to each study and cannot be transferred and applied reliably to characterise flows of different fluids, or

at different geometrical scales and flow conditions (i.e. pipe sizes, fluid properties, flow rates).

Dimensional analysis can be employed to assist with the improved characterisation of these flows by providing dimensionless descriptions of the important/controlling independent variables. Based on these dimensionless variables, improved flow regime maps can be proposed that collapse information across scales, fluids and conditions.

Scale-up or scale-down can only be performed if similarity exists between a model flow and the actual flow of interest. This similarity comprises three main aspects: geometric similarity, kinematic similarity and dynamic similarity. Geometric similarity concerns the reproduction of all flow/phase length-scale ratios; kinematic similarity concerns ratios of velocities; and dynamic similarity relates ratios between the forces acting on the flow.

NOMENCLATURE

A	[m ²]	Cross-sectional pipe area
D	[m]	Inside pipe diameter
Eo	[-]	Eotvös number
Fr	[-]	Froude number
g	[m/s ²]	Gravitational acceleration
L	[m]	Length
Q	[m ³ /s]	Volumetric flow rate
Re	[-]	Reynolds number
U	[m/s]	Velocity
We	[-]	Weber number
WC	[-]	Water cut

Special characters

α	[-]	Wettability
ε	[m]	Pipe roughness
λ	[-]	Non-slip liquid holdup
μ	[Pa.s]	Viscosity
ρ	[kg/m ³]	Density
γ	[N/m]	Interfacial tension

Subscripts

L	Liquid
m	Mixture
o	Oil phase
so	Superficial oil
sw	Superficial water
T	Total
w	Water phase

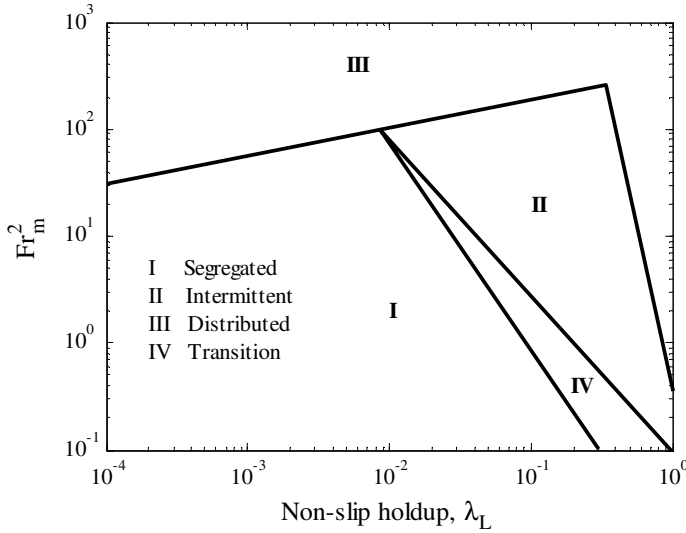


Figure 1 Gas-liquid dimensionless flow regime map for horizontal pipes (adapted from Beggs and Brill [6])

Dimensionless parameters have been used previously in the literature to generalise the regime map of gas-liquid flows in pipes (see, for example, Baker [5], Beggs and Brill [6] or Weisman and Kang [7]). These dimensionless flow regime maps, in which transitions are constructed from experimental data, have proven to be relatively reliable for a given set of conditions. The extension of these maps to different conditions required further analysis because the flow instabilities that result in regime transitions are governed by specific combinations of fluid properties, pipe sizes and flow velocities [8]. Transitions to dispersed flows can be characterised by the Reynolds number while instabilities at the interface by the Weber number. Beggs and Brill [6] developed a dimensionless flow regime map as a function of the non-slip liquid holdup λ_L and the mixture Froude number $Fr_m = U_m / \sqrt{gD}$, as shown in Figure 1. Beggs and Brill [6] performed experiments using air and water in pipes with diameters between 1 and 1.5 in. As a result, the effect of fluid properties was not included in their dimensionless flow regime map. Nevertheless, acceptable results were obtained over a wide range of oil properties mainly attributed to the consistent behaviour of gas-liquid flows in pipes where flow regime transitions are well defined.

This is expected to differ from liquid-liquid flows, where the complex hydrodynamic behaviour makes the regime characterisation a more challenging task due to the additional parameters (and effects) in the system, such as, interfacial phenomena, pipe wettability, and phase inversion.

The purpose of this present study is to develop a dimensionless flow regime map with which to characterise the transitions of liquid-liquid flows in horizontal pipes. Experimentally acquired data are compared with information from previous studies as reported in the literature. The data are used to compile a universal flow regime map for the transitions between stratified flow, dual continuous, dispersion of oil in water with a water layer and dispersed flows.

DIMENSIONAL ANALYSIS OF LIQUID-LIQUID FLOWS

Dimensional analysis is based on the determination of the dimensionless variable groups that describe a flow system. Dimensionless groups can be identified either by empirical or by fundamental considerations. Empirically, dimensionless groups can be identified from the analysis of experimental data acquired for a specific set of conditions. Dimensional groups based on fundamental considerations take into account the governing equations of the flow system (mass, momentum, energy), therefore providing information on the relative magnitude of the normalised terms in these equations [9].

Dimensionless groups can be obtained from the implementation of the Buckingham Π theorem, based on the knowledge of the independent system variables and the fundamental dimensions. In liquid-liquid flow systems, a significant number of independent variables are encountered due to the presence of two phases flowing in the same pipe. Specifically, for fully develop, steady-state and isothermal flow in horizontal pipes, eleven relevant independent variables are obtained, which are the: oil superficial velocity (U_{so}), water superficial velocity (U_{sw}), oil density (ρ_o), water density (ρ_w), oil viscosity (μ_o), water viscosity (μ_w), interfacial tension (γ), inside pipe diameter (D), pipe roughness (ϵ), wettability (α), and gravitational acceleration (g). In addition, assuming isothermal flow, three fundamental dimensions are selected, namely: mass, length and time.

Dimensional analysis utilises the independent system variables and fundamental dimensions to obtain the dimensionless groups that fully define the flow problem and which can be used to relate full-scale to model flows. Based on the Buckingham Π theorem, the number of dimensionless groups is equal to the number of system variables minus the fundamental dimensions. As a result, eight dimensionless groups are expected that can describe the physical phenomena in liquid-liquid flows. In this study, the dimensionless groups that are listed in Table 1 below have been selected.

Table 1 Dimensionless groups in horizontal liquid-liquid flow

No.	Dimensionless groups	
1	Wettability	α
2	Relative roughness	ϵ/D
3	Density ratio	$\tilde{\rho} = \rho_o / \rho_w$
4	Viscosity ratio	$\tilde{\mu} = \mu_o / \mu_w$
5	Water cut	$WC = \frac{U_{sw}}{U_{so} + U_{sw}}$
6	Mixture Reynolds number	$Re_m = \frac{\rho_m U_m D}{\mu_m}$
7	Eotvös number	$Eo = \frac{(\rho_w - \rho_o) g D^2}{\gamma}$
8	Mixture Froude number	$Fr_m = \frac{U_m}{\sqrt{gD}}$

In Table 1, the mixture velocity U_m is defined as the total volumetric flow rate divided by the cross-section area of the pipe, $U_m = Q_T/A$. In addition, the mixture density and viscosity are averaged based on the volumetric phase fractions assuming no-slip conditions (Dukler *et al.* [10]):

$$\rho_m = \rho_w WC + \rho_o (1 - WC) \quad (1)$$

$$\mu_m = \mu_w WC + \mu_o (1 - WC) \quad (2)$$

EXPERIMENTAL METHODS

The experimental data were acquired in the Two-Phase Oil-Water Experimental Rig (TOWER), shown in Figure 2. The flow facility consists of a 32-mm internal diameter horizontal test section made of acrylic with a total length of 8.5 m. The test fluids were water and an aliphatic oil (Exxsol D140). Table 2 shows the physical properties of the test fluids.

The two phases were circulated by using pumps with a maximum capacity of 160 L/min each. The volumetric flow rates of each phase were measured by two NB liquid turbine flowmeters installed in each line, with capacities of 2-20 L/min and 14-140 L/min, and an accuracy of $\pm 0.5\%$ of full scale. The fluids were introduced into the test section by a T-junction with a horizontal plate to separate the fluids, as shown in Figure 3. The oil phase was introduced from the top of the channel while the water phase from the bottom of the channel. A set of two meshes and one flow straightener were installed in the inlet section to reduce secondary flows and turbulent eddies, and to make the velocity profile more uniform. Table 3 shows the inlet configurations used in the experimental investigations.

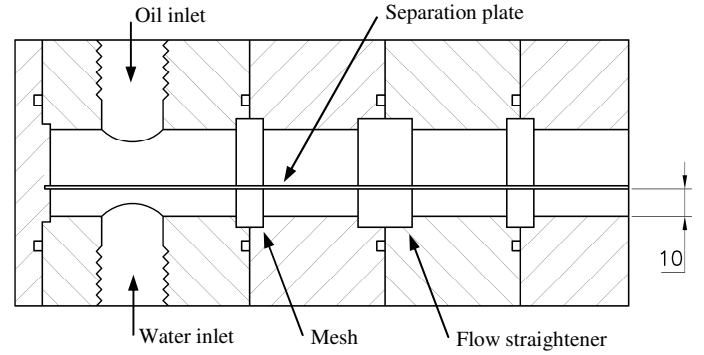


Figure 3 Inlet section schematic for $WC \leq 0.5$

Table 3 Inlet configuration for the current experimental investigations

Water cut	Inlet plate location
$WC \leq 0.5$	10 mm from the bottom of the pipe
$WC > 0.5$	10 mm from the top of the pipe

Experimental investigations have been carried out for various water cuts and mixture velocities. Water cuts were varied from 0.1 to 0.9 and mixture velocities from 0.25 to 1.25 m/s. Flow regime identification was conducted at the visualisation section which was located at 6.7 m from the inlet such that $L/D = 209$. An Olympus iSpeed 2 high-speed camera with a maximum resolution of 800×600 pixels at 1000 fps was utilised to identify the flow regimes. Images were recorder at either 800 or 1000 fps.

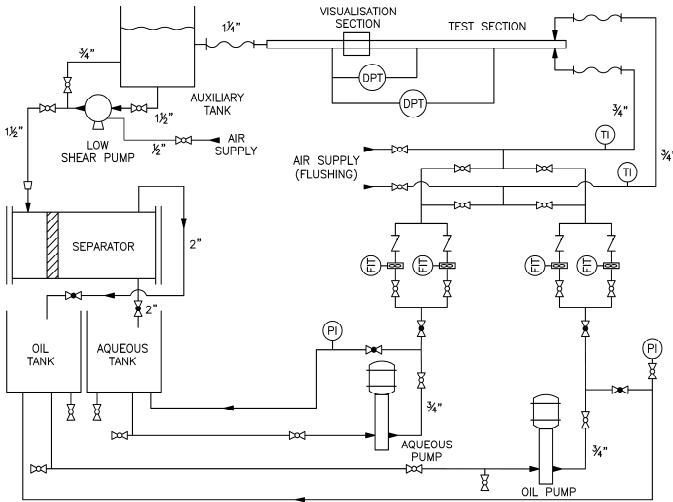


Figure 2 Test flow loop schematic

Table 2 Fluids physical properties

	Oil (Exxsol D140)	Water
Density (kg/m^3)	825	998
Viscosity at 25°C (mPa.s)	5.4	0.9
Interfacial tension (mN/m)	40	

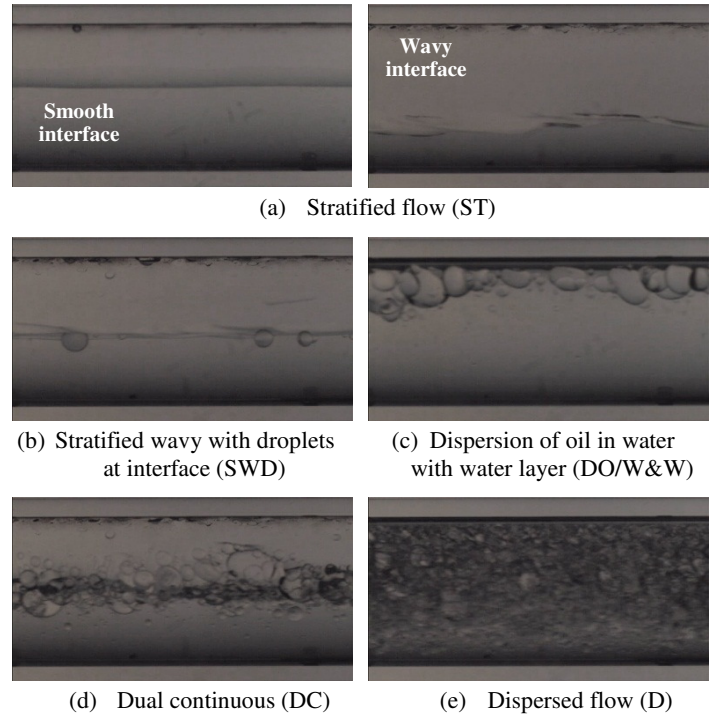


Figure 4 Instantaneous images of the flow regimes observed in a 32-mm internal diameter horizontal acrylic pipe

RESULTS

Five different flow regimes, as shown Figure 4, were observed in the experimental campaign: (1) stratified flow (smooth or wavy interface), (2) stratified with droplets only at the interface, (3) dispersion of oil in water with a water layer (single continuous), (4) dual continuous (layers of dispersions of oil in water and water in oil), and (5) dispersed flow. From the acquired experimental data, a flow regime map, presented in classical dimensional form in Figure 5, was constructed as a function of the mixture velocity and water cut.

Referring to Figure 5, stratified flows are predominant at low mixture velocities ($U_m = 0.25$ m/s). As the mixture velocity is increased, instabilities are sufficient enough to break the interface and promote the formation of droplets. These droplets are observed only at the interface for $U_m = 0.50$ - 0.75 m/s. At $U_m = 0.85$ m/s, a transition to dual continuous occurs where droplets of both phases are encountered in the continuous layers of the other phase. Fully dispersed flows are only observed for $WC = 0.9$ and $U_m > 1.0$ m/s and for $WC = 0.5$ and $U_m = 1.25$ m/s. Stratified flows are also observed at $WC = 0.2$. This behaviour is attributed to the inlet plate configuration in which the *in situ* water layer height closely matched the height of the inlet plate reducing interface instabilities along the test section.

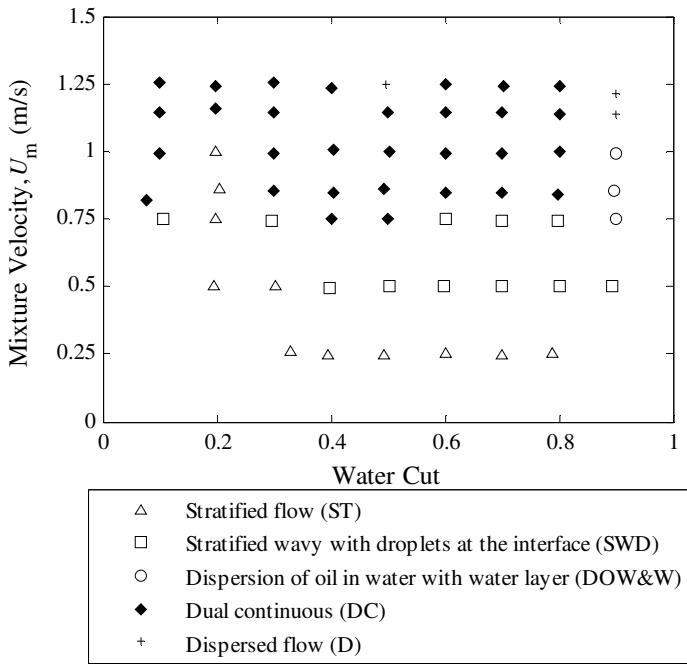


Figure 5 Dimensional flow regime map in a 32-mm internal diameter horizontal acrylic pipe using oil and water

DIMENSIONLESS FLOW REGIME MAPS

Flow regime maps can be drawn by using a dimensional variable basis, such as mixture or superficial velocities, as done in the previous section. The implementation of *dimensionless* flow regime maps can enable a comparison across different studies and the development of a more generalised flow regime transition map applicable to a wide range of flows. The dimensionless groups shown in Table 1 are used here as

descriptions of the liquid-liquid flows of interest. From these dimensionless groups, the Reynolds number and the Eotvös number include the governing forces in the flow system: inertial, viscous, gravitational (buoyancy) and capillary forces (interfacial tension). Hence, the effect of fluid properties (i.e. density, viscosity and interfacial tension), flow velocity and pipe diameter are included in these dimensionless parameters.

It was found that a dimensionless flow regime map constructed using the ratio between mixture Reynolds number and Eotvös number as a function of water cut can be employed to characterise the co-current flow of two immiscible liquids. Figures 6 to 8 show the dimensionless flow regime map for the current experimental campaign, as well as data from Lovick and Angeli [11] and Soleimani [12], respectively. In addition, Table 4 summarises of experimental flow conditions that apply to these studies.

Table 4 Summary of experimental condition on horizontal liquid-liquid studies

Authors	D (mm) L/D Test pipe	Inlet type	ρ_w	μ_w	γ
			ρ_o (kg/m ³)	μ_o (mPa.s)	(mN/m)
Lovick and Angeli (2004)	38	T-Junction (oil inline - water from bottom)	997	0.9	39.6
	210 SS		828	6.0	
Soleimani (1999)	24.3	T-Junction	997	0.9	17
	246 SS		801	1.6	

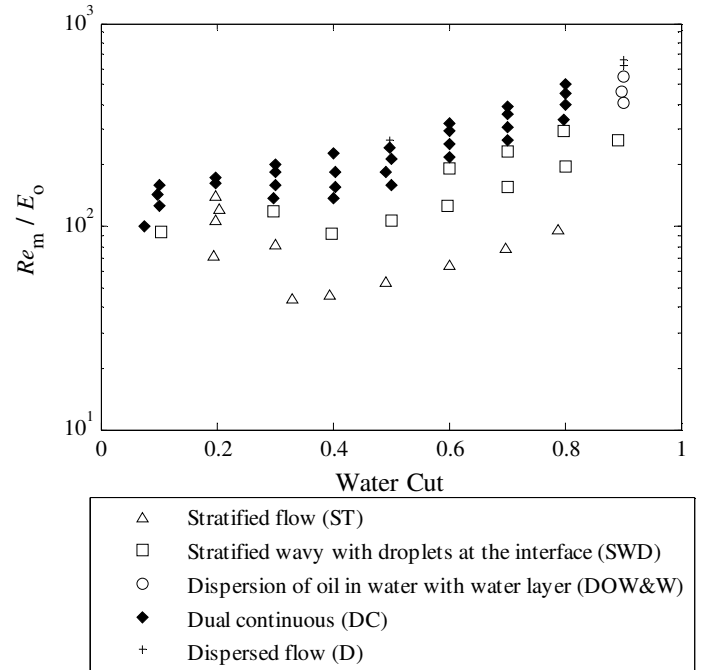


Figure 6 Dimensionless flow regime map in a 32-mm internal diameter horizontal acrylic pipe using oil and water

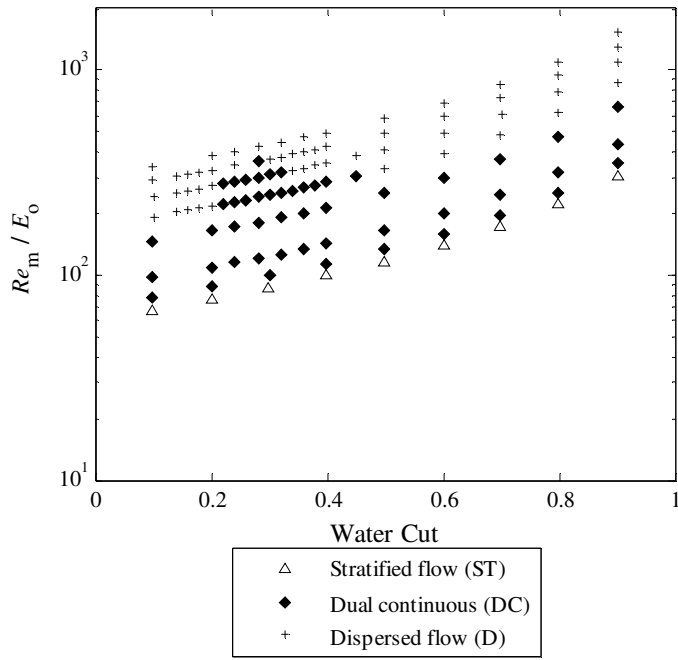


Figure 7 Dimensionless flow regime map in a 38-mm internal diameter horizontal SS pipe (adapted from Lovick and Angeli [11])

The Reynolds number, which is defined as the ratio of inertial forces to viscous forces, offers some insight into the expected velocity field in the flow. Viscous forces are dominant in laminar flows, which can be related to the appearance of stratified liquid-liquid flows. When the inertial forces become dominant, the flow becomes turbulent promoting mixing due to instabilities at the interface. At this point, a transition to non-stratified flows may be expected to occur. The Eotvös number represents the ratio of gravitational (buoyancy) to capillary forces (interfacial tension). Brauner *et al.* [13] found that the interface shape in stratified liquid-liquid flows is a function of the Eotvös number, wettability and the *in situ* phase fractions.

The characterisation of the flow regime transitions in a universal dimensionless flow map must take into account the criteria used to define the flow regimes for each study. Different authors have used different definitions for the liquid-liquid flow regime classification resulting in an overlap when comparing different flow regime maps. For example, Soleimani [12] divided dispersion of oil in water with a water layer (DOW&W) into two sub-categories: single continuous dispersions and dual continuous dispersions (i.e. layers of dispersion of oil in water and dispersion of water on oil). However, dispersions of oil in water with a water layer having one continuous phase are only encountered at high water cuts while the flow regime characterised by layers of dispersion of oil in water and dispersion of water on oil is commonly defined as dual continuous. Lovick and Angeli [11] included the flow regime stratified wavy with droplets at the interface into the dual continuous flow category.

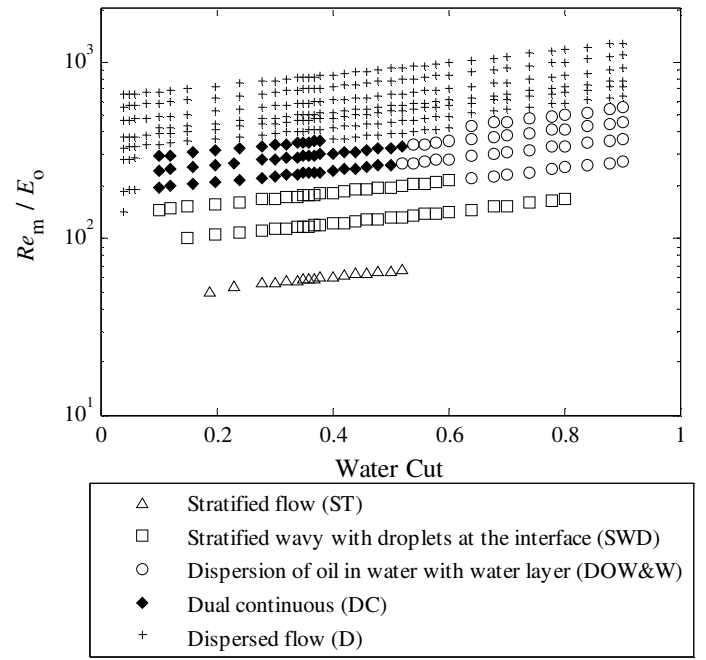


Figure 8 Dimensionless flow regime map in a 24.3-mm internal diameter horizontal SS pipe (adapted from Soleimani [12])

The dimensionless flow regime maps, presented in Figures 6 to 8, show that the transition from stratified flow to non-stratified flow has an upward trend as increasing the water cut. This trend is also observed in Figure 7 and Figure 8 for the transition between dual continuous and dispersed flows. However, only Figure 7 shows a peak in the dual continuous regime at about $WC = 0.3$. This can represent the inversion point in the flow at which the continuous phase becomes the dispersed phase and vice versa.

Figure 9 shows the final result from the present investigation, which is a dimensionless map of combined flow regime transitions from the analysis of the current experimental data along with the studies from Lovick and Angeli [11] and Soleimani [12]. The flow regime classification was unified to characterise the flow using the classification observed in this study (Figure 4). As increasing the ratio Re_m/E_o for a fixed water cut, transitions from separated flows to dispersed flows are observed. Dispersions of oil in water with a water layer are only encountered for high water cuts and Re_m/E_o between 210 and 800. Stratified flows with droplets at the interface are not observed for low water cuts $WC < 0.1$. At these conditions, a regime transition from stratified flow to dual continuous is observed as increasing Re_m/E_o . This can be attributed to the small water layer height where droplets migrate away from the interface. This phenomenon can also explain the steeper downward trend as decreasing water cut in the transition boundary to dispersed flows for $WC < 0.25$.

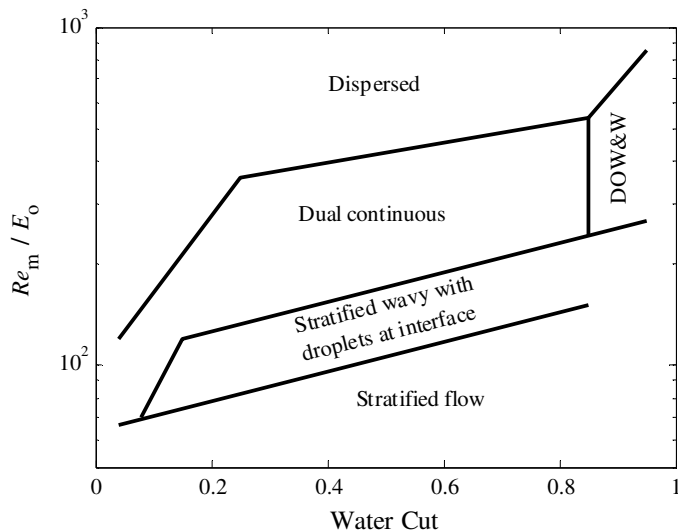


Figure 9 Dimensionless flow regime transitions map

The effect of the *in situ* phase fraction on the flow behaviour has not been included in the above approach as this value is similar to the corresponding water cut (i.e. no-slip condition) for horizontal flows. For inclined flows, the *in situ* phase fraction needs to be included in the flow analysis as the slippage between both phases increases. The Reynolds number expression can be redefined to incorporate the *in situ* fluid velocities.

CONCLUSION

Experimental data have been acquired in a 32-mm internal diameter horizontal acrylic pipe using initially stratified flow of water and Exxsol D140 as the oil phase. Flow regimes were identified using instantaneous images of the flow from a high-speed camera. A dimensional flow regime map was constructed for different flow velocities and phase fractions, which showed five different flow regimes: (1) stratified flow (smooth or wavy interface), (2) stratified with droplets at the interface, (3) dispersion of oil in water with a water layer, (4) dual continuous, and (5) dispersed flow.

A dimensional analysis was carried out to characterise the liquid-liquid flow system under investigation using dimensionless groups from the knowledge of the relevant independent flow-system variables. Based on these dimensionless groups, the flow regime transitions for the analysed experimental data were described by the ratio of the mixture Reynolds number to the Eotvös number, plotted as a function of the water cut. These dimensionless numbers represent the key governing forces in the flow system (i.e. inertial, viscous, gravitational and capillary forces) and include the relevant variables in horizontal liquid-liquid flows (i.e. fluid properties, flow velocities and pipe sizes).

The developed dimensionless flow regime transition map enables the identification of flow regimes for different conditions, namely, flow velocities, fluid properties and pipe sizes. While it is true that the flow map was constructed from the implementation of dimensionless parameters, the flow regime transitions were based on experimental data. Therefore,

the applicability of the dimensionless transition map is limited to the data available. Beyond the data generated in the present study, additional data from two references were also used [11,12]. It is noted that the criteria used to classify flow regimes differ for different studies complicating the comparison of liquid-liquid flow regimes maps. Extension to different conditions requires further analysis, while application of the proposed regime map to new (or existing) sets of data can help refine and verify the effectiveness of the map.

ACKNOWLEDGEMENTS

This work has been undertaken within the Consortium on Transient and Complex Multiphase Flows and Flow Assurance (TMF). The authors gratefully acknowledge the contributions made to this project by the UK Engineering and Physical Sciences Research Council (EPSRC) and the following: ASCOMP, BP Exploration; Cameron Technology & Development; CD adapco; Chevron; KBC (FEESA); FMC Technologies; INTECSEA; Granherne; Institutt for Energiteknikk (IFE); Kongsberg Oil & Gas Technologies; MSi Kenny; Petrobras; Schlumberger Information Solutions; Shell; SINTEF; Statoil and TOTAL. Thanks are extended to Hannah Moran and Samuel Cockman for their support during the experimental investigation stage.

REFERENCES

- [1] Russell, T. W. F., Hodgson, G. W. and Govier, G. W., Horizontal pipeline flow of mixtures of oil and water. *Can. J. Chem. Eng.*, Vol. 37, No. 1, 1959, pp. 9-17
- [2] Charles, M. E., Govier, G. W. and Hodgson, G. W., The horizontal pipeline flow of equal density oil-water mixtures. *Can. J. Chem. Eng.*, Vol. 39, No. 1, 1961, pp. 27-36
- [3] 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
- [4] Trallero, J.L., Oil-Water Flow Pattern in Horizontal Pipes. *Ph.D. thesis*, The University of Tulsa, 1995
- [5] Baker, O., Design of pipelines for the simultaneous flow of oil and gas. *Oil and Gas Journal*, Vol. 53, 1954, pp.185-195
- [6] Beggs, H.D. and Brill, J.P., A study of two-phase flow in inclined pipes. *J. Pet. Tech.*, 1973, 607-617
- [7] Weisman, J. and Kang, S.Y., Flow pattern transitions in vertical and upwardly inclined lines. *Int. J. Multiphase Flow*, Vol. 7, 1981, pp. 271-291
- [8] Brennen, C.E., Fundamentals of multiphase flows. Cambridge University Press, 2009
- [9] Awad, M.M., Two-phase flow. In: Kazi, S.N. *An overview of heat transfer phenomena*. Intech, 2012, pp. 251-340
- [10] Dukler, A.E., Wicks, M., Cleveland, R.G., Pressure drop and hold-up in two-phase flow. *AIChE J.* Vol. 10, 1964, pp. 38-51
- [11] Lovick, J. and Angeli, P., Experimental studies on the dual continuous flow pattern in oil-water flows. *Int. J. Multiphase Flow*, Vol. 30, 2004, pp. 139-157
- [12] Soleimani, A., Phase Distribution and Associated Phenomena in Oil-Water Flows in Horizontal Tubes, *Ph.D. thesis*, Imperial College London, 1999
- [13] Brauner, N., Moalem Maron, D., and Rovinsky, J., A two-fluid model for stratified flows with curved interfaces. *Int. J. Multiphase Flow*, Vol. 24, 1998, pp. 975-1004