International Journal of Multiphase Flow 90 (2017) 1–12

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Flow pattern transition in liquid-liquid flows with a transverse cylinder

Maxime Chinaud, Kyeong Hyeon Park, Panagiota Angeli*

Department of Chemical Engineering, University College London, London WC1E 7JE, UK

ARTICLE INFO

Article history:
Received 24 June 2016
Revised 21 October 2016
Accepted 26 November 2016
Available online 30 November 2016

Keywords:
Oil-water flow
Bluff body
Stratified flow
Dispersed flow
PIV measurements
Flow pattern map actuation

ABSTRACT

The effect of a cylindrical bluff body on the interface characteristics of stratified two-phase, oil-water, pipe flows is experimentally investigated with high speed Particle Image Velocimetry (PIV). The motivation was to study the feasibility of flow pattern map actuation by using a transverse cylinder immersed in water in the stratified pattern, and particularly the transition from separated to dispersed flows. The cylinder has a diameter of 5 mm and is located at 6.75 mm from the bottom of the pipe in a 37 mm ID acrylic test section. Velocity profiles were obtained in the middle plane of the pipe. For reference, single phase flows were also investigated for Reynolds numbers from 1550 to 3488. It was found that the flow behind the cylinder was similar to the two dimensional cases, while the presence of the lower pipe wall diverted the vorticity layers towards the top. In two-phase flows, the Froude number (from 1.4 to 1.8) and the depth of the cylinder submergence below the interface affected the generation of waves. For high Froude numbers and low depths of submergence the counter rotating von Karman vortices generated by the cylinder interacted with the interface. In this case, the vorticity clusters from the top of the cylinder were seen to attach at the wave crests. At high depths of submergence, a jet like flow appeared between the top of the cylinder and the interface. High speed imaging revealed that the presence of the cylinder reduced to lower mixture velocities the transition from separated to dual continuous flows where drops of one phase appear into the other.

1. Introduction

Two phase flows in pipes (gas-liquid and liquid-liquid) have been studied extensively both experimentally and theoretically, because of the wide range of applications including oil and gas transportation, evaporation and condensation systems, two phase reactions and separations. The studies in their majority deal with gas-liquid systems and free surface flows. The large density and viscosity ratios, as well as the limited range of surface tension values encountered in gas-liquid flows allow certain simplifications that enable the development of models for predicting their hydrodynamic behaviour (Taitel and Dukler, 1976; Barnea and Taitel, 1994; Taitel and Barnea, 1990). These models, however, may not be suitable for liquid-liquid systems. Initial studies on liquid-liquid flows produced flow pattern maps and empirical correlations for the prediction of pressure drop. Many current efforts focus on the detailed measurements of local flow parameters, such as interfacial wave characteristics, drop sizes and phase distribution (Barral and Angeli, 2013a; Morgan et al., 2013; Hu and Angeli, 2006; Simmons and Azzopardi, 2001; Hu et al., 2006). The flow pattern transitions depend on the flowrates and properties of the phases, the pipe size and inclination and have been attributed to many different physical mechanisms (e.g. Brauner and Moalem-Maron, 1993; 1991).

An important transition is from stratified flows, where a well-defined interface separates the two continuous liquid layers, to dispersed flows, where drops of one or both phases form into the other. Two different theoretical approaches have been used to predict the boundary between stratified and dispersed flows. In one approach the stability analysis of the momentum balance equations with appropriate closure relations is studied (Lin and Hanratty, 1987; Brauner and Moalem-Maron, 1992). The transition is then considered to happen when a disturbance on the interface in stratified flows, induced by Kelvin-Helmholtz instabilities, is amplified. In the other approach, the balance of forces such as gravity, surface tension, drag force and pressure difference, is considered. From the interfacial waves drops will eventually detach, which signify the transition to dispersed patterns (Al-Wahaibi and Angeli, 2007; Ishii and Grolmes, 1975).

Experimentally it is challenging to study flow pattern changes because of the transient nature of the flow and uncertainty in their occurrence. The study of the transition from separated to dispersed

* Corresponding author.
E-mail address: p.angeli@ucl.ac.uk (P. Angeli).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.11.011

flows would entail capture of the first drops that detach from the interface at some unknown location in the pipe. At the beginning of the transition the drop detachment occurrences are very few which makes their study even more difficult. A novel approach to study flow pattern transitions is to actuate the changes. This would facilitate their study as the transition can be controlled and localised and can find industrial applications in the cases where certain patterns are desirable.

One way to force a transition in the flow pattern map is to generate shear flow by using a bluff body. This approach is common in the naval industry where hydrofoils are used to disperse bubbles in water and reduce drag (up to 15% for Lin and Rockwell, 1995; Duncan and Dimas, 1996). When a hydrofoil is submerged in water, the flow disturbances generated in the wake of the bluff body interact with the free surface and generate bubbles. Despite their extensive use by industry, hydrofoils have complicated geometry, which does not allow theoretical analysis of the flow. For this reason, most of the investigations dealing with a submerged body beneath a free surface have used cylinders instead. In liquid-liquid flows the first study, which demonstrated that a cylinder inside a pipe actuates the flow pattern map, was published by Park et al. (2016). The results showed that the presence of the bluff body generated waves at the oil-water interface in stratified flows and shifted the transition from stratified to dispersed patterns to lower mixture velocities. In the work by Park et al. (2016), however, only high speed imaging was used to study the interfacial waves. It was not possible therefore to directly link any flow structures generated by the bluff body to changes in interfacial configuration.

The studies on the interaction of a bluff body with fluids which are relevant here, can mainly be categorised into two fields. The first field considers the interaction of a free surface flow past a bluff body, while the second considers flow past a bluff body in the presence of a solid wall. In the studies with free surface flows behind a cylinder solid boundaries are not considered (assumption of deep water) and Reynolds numbers of the order of magnitude of 1000 have been used. Large scale structures, von Karman vortices, are emitted in the wake of the cylinder with a well-defined frequency. The interface motion and the droplet detachment mainly depend on the depth of submergence of the cylinder from the free surface and the Froude number. Theoretical analysis and numerical simulations for the 2D problem show that for large depths of submergence and low Froude numbers, the interface propagates as a classical gravity wave with small amplitude. However, even for large depths of submergence induced, interfacial waves are still observed with increasing Froude number, which may lead to droplet detachment (Triantafyllou and Dimas, 1989; Dimas, 1998).

Velocity fields downstream a submerged cylinder have been obtained both experimentally and numerically which revealed different hydrodynamic patterns and corresponding interface motion that depended on the Froude number and depth of submergence (Sheridan et al., 1997; Reichl et al., 2005). The presence of a free surface close to the submerged cylinder modified the von Karman vortex structure; a jet like-flow developed above the cylinder which, for some conditions, attached to the interface and generated disturbances (wave motion). Sheridan et al. (1997) have pointed out the crucial role of the jet like-flow attachment/detachment on the interface and on the breaking waves and droplet detachment.

For the actuation of flow regime transition in pipe flows the solid wall boundaries need to be considered as well. The effect of walls on the flow behind a transverse cylinder has been studied both experimentally and numerically (Wang and Tan, 2008a; Zovatto and Pedrizzetti, 2001; Ding et al., 2004). To the best of our knowledge, all studies available have been conducted in rectangular tanks where the third dimension is neglected. For a cylinder placed between two solid boundaries the *blockage ratio*, defined as the ratio between the cylinder diameter and the distance between the two walls, can affect the flow (Chen et al., 1995). It has been found, however, that no significant changes in the hydrodynamic patterns behind the cylinder can be observed for blockage ratios below 0.5. Another important parameter in confined flows is the *gap ratio*, defined as the distance from the wall to the bottom of the cylinder over the cylinder diameter. Below a critical gap ratio the flow is blocked beneath the cylinder. In such cases the cylinder acts like a surface-mounted obstacle where the coupling of the wall and the cylinder vorticity layers suppresses the vortex periodic shedding (Lei et al., 1999). Zovatto and Pedrizetti (2001) estimated the critical gap ratio from numerical simulations in 2D single phase flows to be around 0.3. They also found that the presence of a wall close to the cylinder disturbed the large scale vortical structures and induced asymmetry to the vorticity contours. In general, the presence of the wall did not affect significantly the vortex shedding frequency and the Strouhal number was about 0.2, similar to unbounded flows (Bearman and Zdravkovich, 1978; Choi and Lee, 2000). However, at gap ratios lower than 0.25 the Strouhal number was found to be higher and equal to 0.4 (Grass et al., 1984). These values seem to represent a transitional regime between non-disturbed vortex shedding and blockage characterized by the absence of any vortex shedding.

The numerical or theoretical studies available on the effect of a rigid wall on the vortex shedding behind a cylinder are generally considering 2D configurations (Wang and Tan, 2008a; Ding et al., 2004; Lin et al., 2009). In pipe flow, 3D effects can become predominant. A further assumption generally used in the literature is that the incoming interface approaching the cylinder is flat.

The aim of the current work is to study experimentally the effect of a transverse cylinder on stratified liquid-liquid pipe flows. In a previous paper by Park et al. (2016), it was shown that interfacial waves were generated when a cylinder was present in stratified oil-water flows. These waves had frequencies which gave Strouhal number equal to 0.2, as expected for von Karman vortices behind a bluff body and were different from the frequencies measured when the bluff body was not present (frequencies were constant and close to 20 Hz). To be able to directly link however, the interfacial waves with the presence of the bluff body it is important to study the velocity fields downstream the cylinder and obtain the structure of the vortices generated by the bluff body. Velocity fields will be investigated with Particle Image Velocimetry (PIV).

PIV techniques have been extensively used in the two last decades to obtain velocity fields in a variety of flow configurations (Adrian and Westerweel, 2011; Raffel et al., 2013). In large scale flows, tracer particles are introduced in the fluid studied and illuminated by a laser light sheet which defines the plane of measurement. From consecutive images of the tracers, velocity fields are obtained via cross correlation. The accuracy of the PIV measurements is of the order of 0.05 pixel (Stanislas et al., 2008) and is limited by the variation of particle image intensity (Nobach and Bodenschatz, 2009). Errors in PIV can arise for example from particle image size, gradients inside the correlation box, and their quantification is still an active research field (Wieneke, 2015; Charonko and Vlachos, 2013; Sciacchitano et al., 2013). The PIV studies on liquid-liquid stratified flows in pipes are limited (Morgan et al., 2013; Kumara et al., 2010). In stratified two phase flows in general, light is reflected from the interface especially when it is very wavy, which can decrease the accuracy of the PIV measurements in its vicinity. Techniques that have been developed to overcome this generally involve complicated PIV codes or measurement set ups (Theunissen et al., 2008; Birvalski et al., 2014, Zhou et al., 2015; Cheng et al., 2015).

In what follows, the experimental facilities, the location of the cylinder in the pipe and the PIV measurements are described first. Single phase flow results are then presented and the effects of wall