Visualization of droplet entrainment in turbulent stratified pipe flow

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Abstract

We report here on efforts to visualize the detailed flow behaviour whereby droplets are entrained from a liquid layer by a highly turbulent gas flow in horizontal stratifying-annular flow. The experimental facility used involves a 30m long, 0.079m diameter pipeline; typical gas and liquid flow rates are of the order of 11.5 and 0.035 m/s, respectively. State-of-the-art high-speed cine cameras an axial viewing are used, allowing one to investigate the flow behaviour in great detail. Different types of droplet entrainment are identified, including ligament and bag-type breakup, as well as intermediate events, all under the same flow conditions. Results will also be presented on the subsequent motion of entrained droplets (obtained with the axial viewing technique), including droplet deposition on the top of the pipe cross section after a ballistic trajectory directly after entrainment.

Introduction

Multiphase flow in pipelines is frequently observed in the petroleum industry. In particular, this study focuses on the phenomena encountered in gas-condensate line, investigating gas-liquid stratifying-annular flow. In this regime that occurs at high gas flow-rates and low liquid loading, the liquid flows partly as a film around the wall of the pipe and partly as droplets within the gas core. Due to the influence of gravity, this liquid film is very thick at the bottom of the pipe and it decreases on the upper part of the wall. In some cases, this liquid film may fail to wet the top of the pipe and lead to corrosion. The aim of this study is to gain a better understanding of liquid transport mechanisms in stratifying-annular flow.

We visualize here the interface behaviour in the stratifying-annular flow regime and more particularly the diverse mechanisms leading to droplet entrainment using axial viewing techniques firstly designed by Hewitt (1969) and then modified by Badie (2000) in the in-line axial viewing technique. We are investigating the possible mechanisms which constitute a sub-classification of bag break-up and ligament break-up by which the droplets are torn from the waves in horizontal stratifying-annular flow, giving more details from the cine films obtained with the axial viewing technique.

Section 2 presents a review on droplet entrainment in annular flow and stratifying-annular flow. It presents also the principle of axial viewing technique and in particular of the in-line axial viewing technique. Images from visualisation experiment obtained using this technique are presented and discussed in Section 3.

Experimental Facility

In stratifying-annular flow in horizontal pipes, some mechanism must exist to transport the liquid phase towards the top of the pipe, this mechanism counteracting the gravitational force which tends to move the liquid towards the bottom of the pipe.

Three mechanisms have been suggested for maintaining a liquid film around the pipe, namely droplet entrainment, wave spreading (dominant in small diameter pipes) and secondary flow. Droplet entrainment has been suggested to be the main mechanism responsible for maintaining a liquid film in horizontal annular flow in relatively large diameter pipes (0.079m). In this mechanism, droplets are entrained from the film and are deposited at the top to form a liquid film. This liquid film drains then towards the bottom. The liquid film is continuously renewed by this process. Two modes of droplet transport for maintaining a liquid film have been proposed. Large droplets emitted from the bottom passing ballistically to the upper surfaces (dominant in pipes of medium diameter eg. 79mm, WASP) and the turbulent diffusion of small diameter droplets to upper part of pipe (dominant mechanism in large diameter pipes).

Large disturbance waves in co-current annular flow are usually regarded as being the sources of droplet entrainment. (Cooper et al., 1969, Jacowitz and Brodkey, 1964 and Arnold and Hewitt, 1967). The formation of droplets from a liquid layer is a highly complex process and may occur by a variety of mechanisms. Azzopardi (1983) suggested that the principle mechanisms are “bag break-up” (reported earlier for horizontal flow by Woodmansee and Hanratty, 1969) and “ligament break-up”, as illustrated in Figure 1. Bag break-up occurs at lower gas-liquid flow-rate and ligament break-up, at higher gas-liquid flow-rate. The bag break-up mechanism is considered to be the most important in frequency, however it has to be noticed that the bag break-up occurring at lower gas velocities is easier to observe and that the ligament break-up is relevant at higher flow-rates.

In bag break-up (cf. Figure 1), part of the disturbance wave is undercut and an open ended bubble with a thick filament rim is created. Gas pressure builds up within the bubble causing it to expand and finally burst. Part of it forms very small drops whereas a majority is gathered back into the rim by surface tension forces, which rim then breaks up shortly afterwards into a smaller number of larger drops. Ligament break-up is illustrated in Figure 1. The crests of roll waves are elongated and thin ligaments, torn from the film, immediately break down into drops.

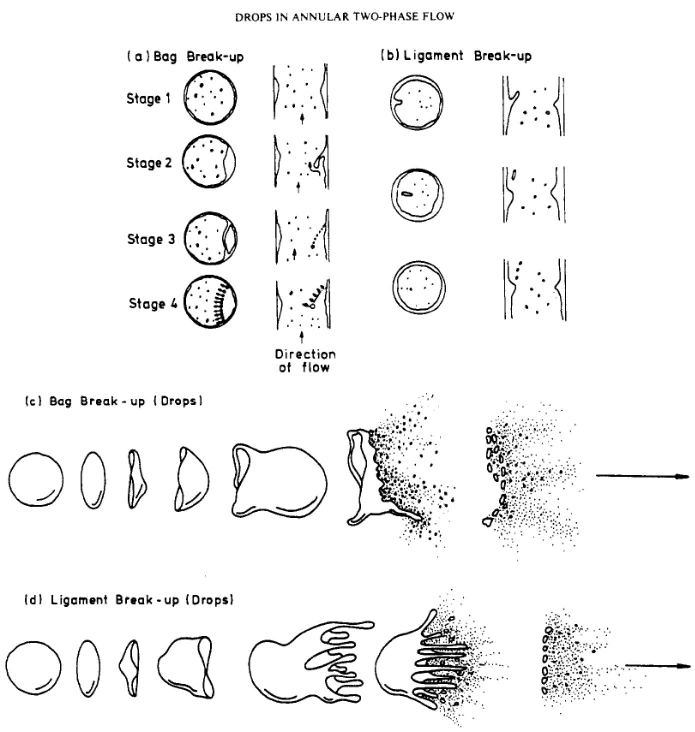

Figure 1: Mechanisms of atomization and drop breakup (Azzopardi, 1997)

The method used here to study this phenomenon was the axial viewing technique. It was originally developed for vertical pipe by Arnold and Hewitt (1967) and Hewitt and Roberts (1969), and applied to horizontal pipe by Fisher and Yu (1975) and then by Badie (2000). A schematic of the original device with small depth of field (Arnold and Hewitt 1967) is shown in Figure 2.

In this method, the flow is viewed along the axis of the pipe so that the optical system is looking directly into the flow. This has the advantage that it allows one to study the circumferential distribution of liquid films in annular flows, the entrainment of droplets from a liquid film, and the radial motion of droplets in the gas.

This device is composed of a viewer, a vertical tube and a camera unit. The viewer is fitted on top of a vertical Perspex tube with an internal diameter of 1 ¼ inch (32 mm). The air is introduced at the bottom of the tube and a porous wall section is used to inject water around the periphery so as to establish air-water flow in the tube.

A short section of the pipe is illuminated. The illuminated zone is recorded through a window, which is kept free of liquid by passing an air purge system over it and down the viewing tube. The fluids flowing through the pipe are diverted into an exit chamber and return to the separation tank via return pipes.

Through the above-mentioned window, the illuminated region of the pipe is recorded using a high speed cine-camera which is focussed on the plane of illumination. This camera is used to capture the axial view of the flow down the inside of the tube that is photographed as well as filmed with a high speed filming at frame rates of 2000-4000 per second.

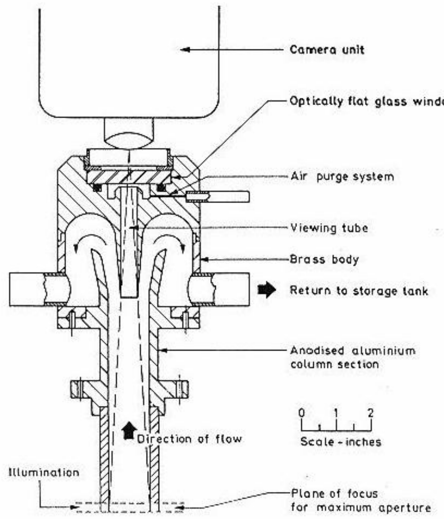

Figure 2: Principle of the axial view technique applied to vertical flow. Axial viewer used by Arnold & Hewitt (1967)

The In-line Axial Viewing System designed by Badie (2000) for horizontal gas-liquid flow with low liquid loading was based on the axial viewer for horizontal flows investigations developed by Fisher and Yu (1975) and Fisher et al.(1978) based on the general idea reported by Hewitt and Roberts (1969).

This viewer, schematised in Figure 3, is less complex to machine and more flexible. Moreover, a part of the main design is a drastically improved air purge system that is used to keep the flat viewing window clear of all impinging droplets.

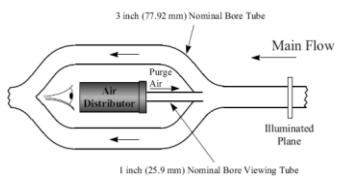

Figure 3: The basic design of the In-Line Axial Viewing System (Badie, 2000).

A protrusion of the viewer provides a platform so that any liquid on the upper wall of the main section drained around the viewing tube, rather than into it. Flow is diverted into two tubes to let space for the viewing and air purge systems. The air purge system (cf. Figure 4) is blowing against the direction of the flow to maintain the window of the viewing tube free of liquid. A camera system is focussed on an illumination plane much further upstream of the diverted flow than in previous studies.

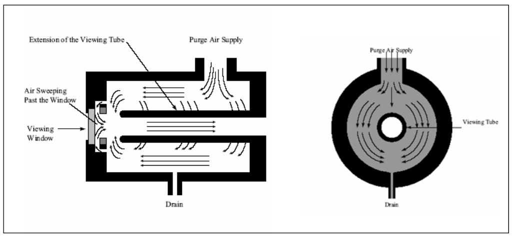

Figure 4: Side view and front view of the air distributor (Badie, 2000).

The WASP (Water, Air, Sand and Petroleum) high pressure facility used for the experimental investigation of two-phase air-water stratifying-annular flow has a 78mm test section. A schematic diagram of the facility is shown in Figure 5.

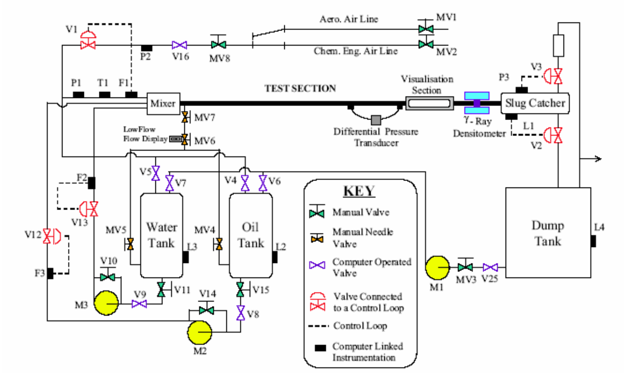

Figure 5: Schematic diagram of the WASP facility (Badie et al, 2001).

Badie (2001) enhances different aspects of the process of entrainment and points out effect of parameters such as the superficial liquid velocity, the superficial gas velocity or the liquid holdup.

Some axial view photography sequences from videos of the flow in 79 mm diameter pipe obtained by Badie (2001) are shown here. An example is a so-called "ballooning" event, shown in Figure 6. At low gas velocities, drop formation is rare but, as the gas velocity is increased, drops may be formed by "bag breakup" (Figure 6), breakup of larger drops (Figure 7) or breakup of ligaments torn from the film.

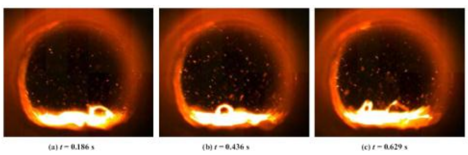

Figure 6: Images of air-oil flows (superficial gas velocity of 15 m.s^{-1} and superficial liquid velocity of 0.01 m.s^{-1} (Badie et al, 2001)).

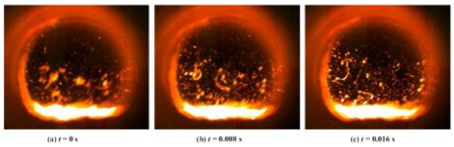

Figure 7: Successive frames of air-oil flows (superficial gas velocity of 15 m.s^{-1} and superficial liquid velocity of 0.01 m.s^{-1} (Badie et al, 2001)).

Increasing the liquid superficial velocity at constant gas velocity increases the amount entrained. This is most probably due to the increased liquid layer thickness at the bottom of the channel giving rise to increased interfacial wave activity and, hence, an increase in entrainment rate.

An increase in superficial gas velocity at constant liquid superficial velocity leads to an increase in the flow rate of entrained droplets. The more the superficial gas velocity is increased, the more the activity in the form of waves is increased since the waves are the source of entrainment events, thus it leads to more droplets entrainment. The onset of entrainment is around 19 m.s^{-1} for the liquid velocity for air-water and 17 m.s^{-1} for air-oil flow for a constant air velocity of 0.02 m.s^{-1} (Badie, 2000).

Results and Discussion

Key results of the visualisation of the phenomenon occurring at the air-water interface are presented here.

This series of snapshot (cf. Figure 8) show a large bag break up. On the interface appear several deformations that will become the node of the system. The bag increases in size and elevates.

Five compartments in the bag are visible that extends again. The filaments delimitating each compartment ruptures. The last remaining remnants of the bag are the straps that delimitate the outside of the bag. These straps rupture into quite large droplets. One node on the right of the bag will evolve as a ring, which one extends break up into droplets and extends again until one of the droplets from the ring reaches the right top of the pipe wall. Air enters in the big wave and the evolution in a bag break up is due to the interaction with the high axial velocity of the air in the gas core and the air in the bag that makes the bag grows. The elevation of the bulk of water is due to the interaction with the air.

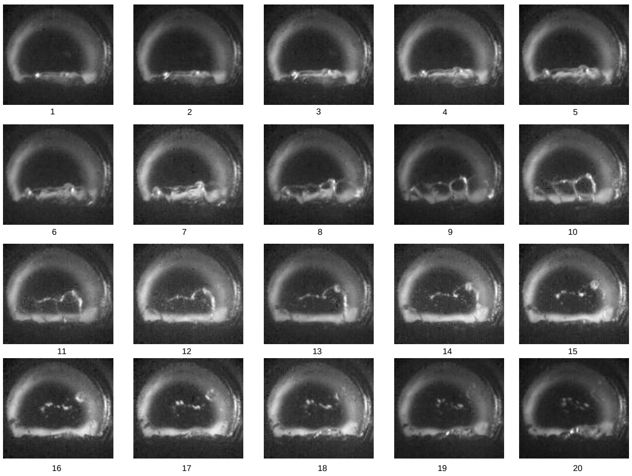

Figure 8: Images of air-water flows with Superficial gas velocity = 11.6 m.s^{-1} and Superficial liquid velocity = 0.036 m.s^{-1}, 500fps – Bag break-up.

In the previous series of snapshot, the small perturbation at the surface of the water flow will evolve in nodes of a system and not in ligament as seen further. These small perturbations evolve above a big perturbation, so it doesn't lead the process, the process being leaded by the big perturbation. The small perturbation will structure the bag to make it more cohesive.

The successive frames in Figure 9 shows a filament which is formed from a bag break up and then split into droplets.

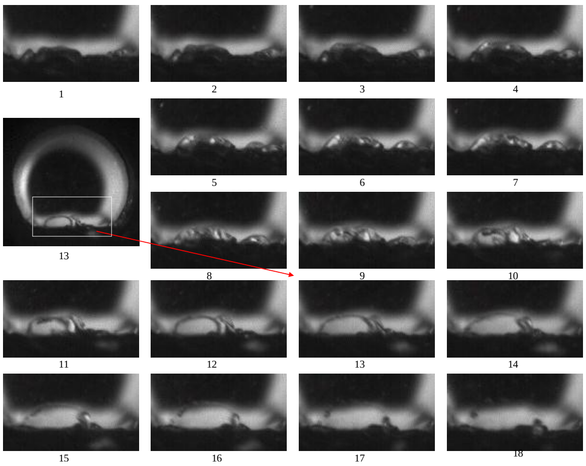

Figure 9: Images of air-water flows with Superficial gas velocity = 11.6 m.s^{-1} and Superficial liquid velocity = 0.036 m.s^{-1}, 500fps – Filament.

On these series of axial views (cf. Figure 10), we can see a ligament on the left hand side of the pipe and from this ligament is created a ballistic droplet. The wall plays a role here because the liquid mass is blocked against the wall and this liquid mass gain an important energy sufficient enough to move towards the top and counteract the gravity effect and the gas velocity.

Moreover, normally it exists an interaction between the water mass with the wall to create the liquid film so that to form an annular flow regime (interaction). Here, we have the opposite mechanism: the repulsion or reflexion. The droplet keeps the same size from the beginning to the end, the surface tension minimising the energy, the droplets then touches the top. The ligament is sucked in towards the top due to the interaction with the gas core.

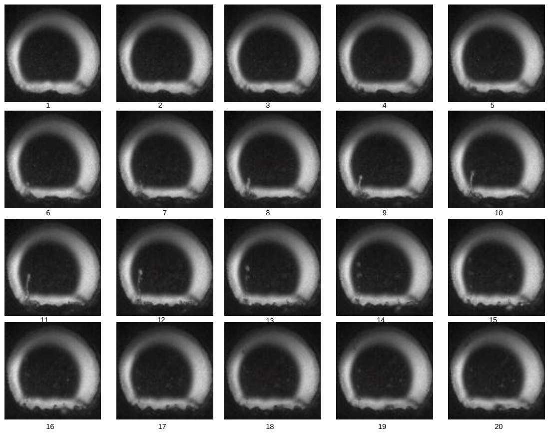

Figure 10: Images of air-water flows with Superficial gas velocity = 13 m.s^{-1} and Superficial liquid velocity = 0.036 m.s^{-1}, 500fps – Ligament.

In each case, the surface undergoes an important deformation with numerous small deformations susceptible to be at the origin of ligaments as seen in Figure 11.

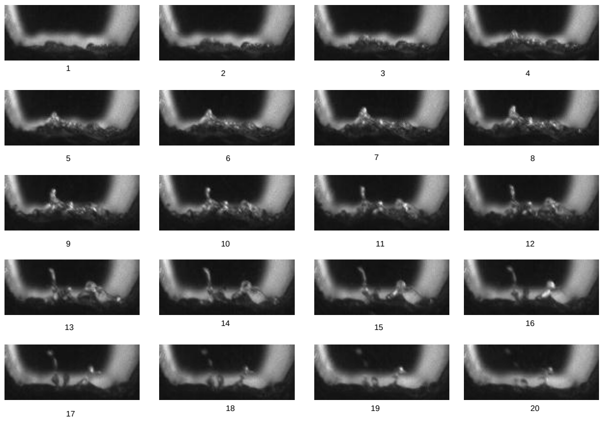

Figure 11: Images of air-water flows with Superficial gas velocity = 11.6m.s^{-1} and Superficial liquid velocity = 0.036 m.s^{-1}, 500fps – Ligament.

Figure 12 shows a ballooning event, a formation of ligaments from the balloon and entrainment of at least three droplets from one of the ligament that has been elongated. One of the droplets reaches the top of the pipe.

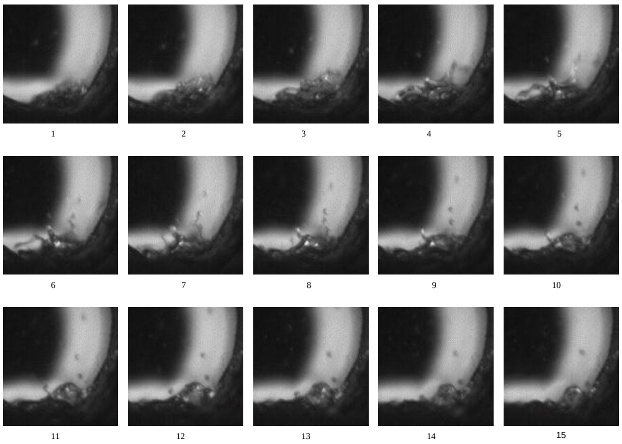

Figure 12: Images of air-water flows with Superficial gas velocity = 11.6 m.s^{-1} and Superficial liquid velocity = 0.036 m.s^{-1}, 500fps – Droplets entrainment at the top of the pipe.

Figure 13 presents the successive frames of a mechanism of droplets entrainment at the top of the pipe. Two "lumps"of liquid with small ligaments or small perturbations on them collide. A ligament extends from the first lump. Two ligaments extend from the second lump after having formed a ring. One of the pair of ligaments from the second bulk has sufficient kinetic energy to remain intact and extend again. The ligament then splits into droplets, the largest droplet is localised at the end of the ligament (on its top part). This droplet finally reaches the top of the pipe. An estimated velocity of this ballistic droplet is 1m/s.
Here, the energy acquired by the droplet from the ligament is due to the collision of the two bulks of water making the ligament sliding on each other towards the top and also due the separation of the filament in two ligaments giving the energy to the main part leading to the ballistic droplet.

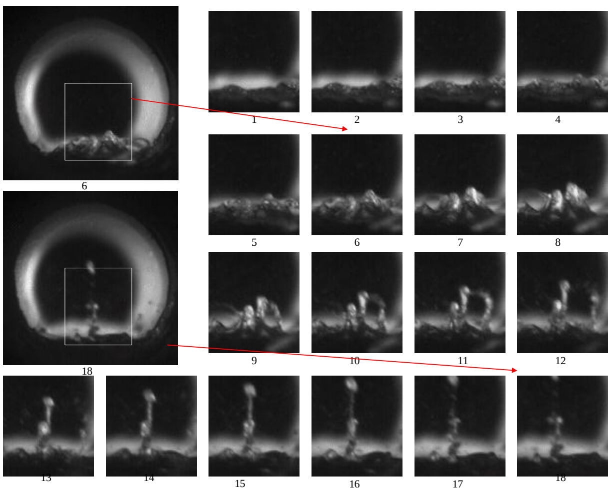

Figure 13: Images of air-water flows with Superficial gas velocity = 11.6 m.s^{-1} and Superficial liquid velocity = 0.036 m.s^{-1}, 500fps - Droplets entrainment at the top of the pipe.

Conclusions

The axial viewing technique allowed us to visualise how evolve the deformations of the gas-liquid interface.
Ligament were seen to appear from small perturbation on the liquid surface, these small deformations were growing individually, stretched towards the top to form a ligament. In the case of a bag breakup, it was issuing from a big deformation at the interface, this lump of liquid elevating solidarily, and then breaking up by steps, each part of the remnant of the bag breakup evolving individually and sometimes one filament rupturing giving to one of the both part energy enough to transform as a ligament. Future work is including axial views as well as side visualisations allowing one to gain information in 3D of the events.

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