APPLICATION OF IMAGE PROCESSING TECHNIQUES TO CHARACTERIZE INTERMITTENT FLOW INITIATION IN HORIZONTAL GAS-LIQUID FLOWS

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Abstract. We present an experimental work on the development and implementation of a technique to process digital images obtained by high-speed recording of the onset of intermittent flows (slug and plug) in a 26.4-mm ID circular pipe. The processing algorithm was based on the Canny edge detection method to determine the position of the interface. Indirect back illumination of the flow was provided by two 130-W (60 kLux) LED sources to enhance the contrast between the phases in the images. The image acquisition frequency was set at 200 Hz. Quantitative results on the formation of ‘slug precursors’ and their growth into liquid slugs are presented as sequences of still images of the inlet region. Frequency data obtained from the evaluation of the power spectral density of the image sequences were in good agreement with a similar analysis carried out for capacitance sensor data.

Keywords: Intermittent flows, high-speed image processing, flow development, void fraction, slug frequency.

1. INTRODUCTION

The physical mechanisms associated with the onset of intermittent flow patterns in horizontal pipes are well established in the literature; starting from a stratified flow pattern at the inlet of the test section, interfacial waves grow in amplitude and wave length until breaking waves or ‘slug precursor’ filling the pipe cross-section start to appear (Fan et al., 1993; Fossa, 2001; Ujang et al., 2006; Kadri et al., 2009). As a slug precursor accelerates due to a pressure buildup upstream of it, it picks up the liquid ahead of it and grows in size, forming a liquid slug. Models based on the Kelvin-Helmholtz instability theory have been proposed to predict disturbance growth and the associated transition to slug flow. A review of such methods has been presented recently by Lu (2015).

Compared to the amount of data for steady-state, fully-developed intermittent flows (slug and plug flow) in horizontal and slightly inclined pipes, there is a considerable dearth of quantitative data on the phase distribution and developing flow structure in the entrance region. Vallée and co-workers (Vallee et al., 2007, 2008) evaluated experimentally the formation of waves and slug precursors in a 2-m long 250 (height) x 50 (width) mm² transparent test section using high-speed video analysis. The data were compared with a numerical simulation of the two-phase flow in the developing region using a commercial software package. Czapp et al. (2012) combined high-speed stereo Particle Image Velocimetry (PIV) and Laser Induced Fluorescence (LIF) to obtain the instantaneous 3D liquid velocity field during slug formation in a 9.46-m long, 54-mm ID circular pipe.

More recently, several studies have been presented in which techniques for processing digital images of two-phase flows have been used to determine phase fractions and/or intermittent flow parameters, such as slug velocity, frequency and size, in both the developing and fully developed flow regimes (Ahmed, 2011; Mohmmed et al., 2016; Kuntoro et al., 2016; Dinaryanto et al., 2017). The purpose of the present work is to develop an experimental method based on the processing of sequences of digital images of the initiation of intermittent flows (slug and plug flow) in an 26.4-mm ID horizontal tube. A high-speed camera has been combined with a LED source to illuminate the flow and provide the desired contrast between the phases. The experiments have been carried out using air and water and the results were compared against data obtained using capacitance sensors. In the future, the results will be used to evaluate the performance of mathematical models for developing slug flow in a horizontal pipe.
2. EXPERIMENTAL WORK

2.1 Experimental facility

The experimental apparatus utilized in this study (Fig. 1) has been described in detail in previous papers (de Oliveira and Barbosa, 2014; de Oliveira et al., 2014), so only the main features and specific modifications to the setup will be presented here. The apparatus was originally conceived to investigate gas-liquid flows in a vertical return bend positioned at the end of two horizontal legs. The test section is made from 26.4-mm ID borosilicate glass tube segments, with a length of approximately 5 m between the inlet flow mixer and the return bend (curvature radius of approximately 161 mm). In the present study, however, only the upper leg has been used. A flow mixer/injector (1) has been designed and constructed (Fig. 2) using a dividing plate and wire meshes to guarantee a smooth stratified flow regime at the test section inlet. Inlet flow conditions, such as the geometry of the inlet flow mixer are extremely important to establish the flow developing length. Eventually, as the flow becomes approximately developed, the two-phase flow parameters become independent of the inlet configuration. However, inlet geometries which favor a higher liquid level at the inlet lead to higher slug frequencies in the developing region, since it is easier for interfacial disturbances to bridge the pipe cross-section (Vallee et al., 2007; Lu, 2015).

In the present experiments, the most important part of the test section is a flow visualization box (10) built around the borosilicate glass tube to minimize image distortion due to the curvature of the tube wall. The box is made from acrylic resin and filled with an aqueous solution to match the refractive index of the borosilicate glass. The flow visualization box is positioned at a distance of approximately 8.9 ID from the tube inlet and it has a length of 975 mm.

Gas holdup was evaluated by two non-intrusive capacitance sensors positioned approximately one meter downstream of the flow visualization box. A full description of the capacitance sensors has been given elsewhere (de Oliveira and Barbosa, 2014; de Oliveira et al., 2014). Two absolute pressure sensors were installed at the inlet and outlet of the test section. Their measurements were used to calculate the air density. The ambient and inlet air flow temperatures were maintained at 24°C.

Figure 1. Schematic diagram of experimental facility. Key to components: (2) thermostatic bath, (3) centrifugal pump, (4) Coriolis mass flow meter, (5) particulate filter, (6) a coalescent filter, (7) pressure regulator, (8) micrometric valve, (9) hot-wire mass flow meter, (10) flow visualization box, (P) pressure measurement, (T) temperature measurement, (α) possible locations of holdup (capacitance) sensors.

2.2 Time-resolved Plug and Slug Flow measurements

To carry out time-resolved measurements of the phase distribution in slug and plug flows, a high speed camera (Phantom V310) equipped with a 35-mm Carl Zeiss lens was positioned perpendicular to the test section, at approximately...
two meters from the tube, as shown in Fig. 3. The length of the interrogation area (in the flow visualization box) was approximately 900 m and the resolution of the image was 1.21 pixels/mm. The images were acquired at a rate of 200 Hz. Illumination was provided by two 130-W (60 kLux) LED sources.

An algorithm was developed to capture the position of the two-phase interface by processing the sequences of digital images using the Canny edge detection method (Canny, 1986), as described in detail in Barbosa et al. (2016). Figure 4 illustrates the steps in the image processing implemented in Matlab. An iterative procedure, whose final result is illustrated in Fig. 4(e), consists of dilation and filling processes to identify the region where the light intensity changes from 0 (black) to 1 (white) and construct an array with liquid height as a function of axial position. After applying the Canny method, two edge lines are obtained as a result of the curvature of the interface. To avoid using an interpolation scheme to determine the mean position of the interface, the bottom line was taken as the reference.

In the present analysis, the two virtual probes were positioned near the end of the flow visualization box, as shown schematically in Fig. 5. The distance between the virtual sensors was 70 mm, which is the same distance between the capacitance probes positioned downstream of the flow visualization box. The capacitance sensors were used as a reference to the measurements undertaken in this work.

The velocity of the two-phase flow structures (e.g., liquid slugs) can be determined using the signals from two different probes as $L/\tau_o$, where $L$ is the longitudinal distance between the probes and $\tau_o$ is the time delay associated with the peak of the cross-correlation function of the two signals (Bendat and Piersol, 2010). The dominant frequencies of the flow structures were calculated from the power spectral density (PSD) which, for each probe (virtual or capacitance), is computed from the Fourier transform of the autocorrelation function of the signal after subtraction of the mean value (DC component removal).

2.3 Experimental conditions

Figure 6 shows the experimental conditions evaluated in this work in the flow pattern map of Mandhane et al. (1974). Two distinct flow regimes have been studied in this work, namely slug flow and plug flow. A very good agreement between
the Mandhane et al. (1974) flow pattern map and the flow patterns actually observed in the present two-phase flow loop has been reported by de Oliveira (2013). Table 1 shows the superficial velocities associated with each flow condition.

<table>
<thead>
<tr>
<th>Case number</th>
<th>$j_l$ [m/s]</th>
<th>$j_g$ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slug #1</td>
<td>0.274</td>
<td>1.698</td>
</tr>
<tr>
<td>Slug #2</td>
<td>0.269</td>
<td>1.894</td>
</tr>
<tr>
<td>Plug #1</td>
<td>0.178</td>
<td>0.526</td>
</tr>
<tr>
<td>Plug #2</td>
<td>0.190</td>
<td>0.610</td>
</tr>
</tbody>
</table>
3. RESULTS

Figure 7 shows a comparison between the void fraction signals obtained from the image processing and the capacitance sensors. A generally good agreement is observed in terms of the average void fraction in the elongated bubble region. The image processing results in longer liquid slugs (shorter elongated bubbles) because of the difficulty in detecting interfaces in the turbulent bubble wake region, where the interface is broken into small bubbles. The higher void fraction predicted by the image analysis in the bubble nose region may be related to the curvature of the interface, which cannot be captured in the plane (projected) images.

Figure 7. Comparison of void fraction sensor and image analyses signals for Plug#1 case.

Figure 8 shows sequences of reconstructed images of the liquid height and phase distribution obtained from the image processing analysis for cases Slug#1 and Slug#2. The abscissas show the distance from the inlet of the flow visualization box and the time intervals between successive images (earliest at the top) are 25 and 35 ms for cases Slug#1 and Slug#2, respectively. In both cases, a slug precursor is formed at around 220 mm, having originated from film disturbances growing near the entrance of the flow visualization box. The increase in pressure upstream of the precursor accelerates the newly formed liquid slug, which grows in size as it engulfs the slower moving liquid ahead of it. The increase in pressure is also responsible for the decrease in liquid height upstream of the precursor.

Figure 8. Reconstructed images of the flow distribution in the inlet region for cases (a) Slug #1, (b) Slug #2.

Figure 9 shows the phase distribution for cases Plug #1 and Plug #2, respectively. Due to the lower displacement velocities of the flow structures (lower gas superficial velocities), the time interval between consecutive pairs of images is
0.12 and 0.11 s for cases Plug #1 and Plug #2, respectively. The presence of a relatively higher liquid content near the tube inlet leads to a larger number of small amplitude interfacial waves compared with cases Slug #1 and Slug#2, so an unstable wave growth (blocking the tube cross section) already occurs upstream of the flow interrogation area (visualization box).

![Reconstructed images of the flow distribution in the inlet region for cases (a) Plug #1, (b) Plug #2.](image)

Figures 10 and 11 show the power spectral density (PSD) results for the slug flow and plug flow cases, respectively. A very good agreement is observed in both flow regimes with respect to the dominant frequency associated with the structures of each flow regime. As expected, the frequency was higher for the slug flow cases due to larger average relative velocity between the phases and associated Kelvin-Helmholtz instability.

![Power spectral density (PSD) results for the slug flow cases (a) Slug #1, (b) Slug #2.](image)

In both flow regimes depicted in Figs. 10 and 11, the capacitance sensor captured a wider range of frequencies, with the image processing technique smoothing out some of the higher frequency structures.
Figure 11. Power spectral density (PSD) results for the plug flow cases (a) Plug #1, (b) Plug #2.

Figure 12 shows spatio-temporal flow displacement maps for cases Slug #1 and Slug #2 generated with the image processing results. The gray scale corresponds to the liquid height, in mm, so the liquid slugs are seen as the darker regions in both maps. In these maps, it becomes easier to evaluate the liquid slug growth rate and its displacement velocity. A region of thinner liquid film is observed in the elongated bubble immediately behind the liquid slug. Further upstream (i.e., nearer to the flow inlet), interfacial waves are seen in the displacement maps. Their smaller inclination with respect to the horizontal axis indicate that the waves travel at a lower velocity than the liquid slug ahead of them.

Figure 12. Flow displacement maps of the slug flow regime (a) Slug #1, (b) Slug #2.

Table 2 shows the time delay associated with the peak of the cross-correlation function of the two signals and the frequency obtained from the power spectral density calculation. As can be seen, a very good agreement is observed between the two techniques (image processing and capacitance sensors).

Table 2. Experimental conditions.

<table>
<thead>
<tr>
<th></th>
<th>Slug#1</th>
<th>Slug#2</th>
<th>Plug#1</th>
<th>Plug#2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time delay Image [s]</td>
<td>0.035</td>
<td>0.034</td>
<td>0.065</td>
<td>0.065</td>
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<tr>
<td>Time delay Sensor [s]</td>
<td>0.038</td>
<td>0.036</td>
<td>0.061</td>
<td>0.06</td>
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<tr>
<td>Frequency Image [Hz]</td>
<td>0.34</td>
<td>0.36</td>
<td>0.093</td>
<td>0.094</td>
</tr>
<tr>
<td>Frequency Sensor [Hz]</td>
<td>0.34</td>
<td>0.36</td>
<td>0.094</td>
<td>0.093</td>
</tr>
</tbody>
</table>
4. CONCLUSIONS

The main conclusions arising from this work are as follows:

1. The image processing technique developed in this study was successful at providing quantitative data of the initiation of intermittent flows (slug and plug) near the inlet region of a 26.4-mm horizontal pipe;

2. The image sequences confirmed the evolution of waves into slug precursors and then into liquid slugs, which grew in size as they accelerated along the tube, picking up the liquid from the tail of the elongated bubble ahead of it. The decrease in liquid height due to pressure buildup upstream of the liquid slug was also clear from the images. In plug flow, due to the relatively higher liquid content, the disturbances become unstable and bridged the pipe cross section earlier than in slug flow (i.e., upstream of the flow visualization box), so the transition from stratified to intermittent flow could not be entirely captured in the image sequences;

3. The power spectral density and the time delay from the cross-correlation of the signals generated from virtual probes in the image sequences agreed well with data generated from capacitance sensor measurements performed simultaneously for all the conditions evaluated.

Future work will be focused on using the experimental data to evaluate the performance of numerical models of intermittent flow initiation in horizontal pipes.

5. ACKNOWLEDGEMENTS

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6. REFERENCES


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