Analysis of interfacial behavior in two-phase flow using image processing

Digpriya¹, S Saini¹, J Banerjee¹
¹Department of Mechanical Engineering, S V National Institute of Technology, Surat, Gujrat-395007, India.

E-mail: digpriya22@gmail.com; jaish0220@gmail.com; jbaner@med.svnit.ac.in;

Abstract. Two-phase flow has a wide range of application from petroleum to space industry. Gas-liquid two-phase flow in horizontal pipe commonly occurs in petro-chemical, nuclear and geothermal industry, where simultaneously gas and liquid are transported through pipelines. During the transportation of gas-liquid flow simultaneously, due to the interaction of two phases, slug forms from the stratified-wavy flow. Slug flow consists of strong aeration at the slug front which is responsible for pipe failure and hazards in industries. Thus, it is required to understand the phenomena of slug formation in industrial pipeline to avoid the catastrophic pipe failure. In the present research, image processing technique is used to accurately analyze the interfacial behavior of two-phase flow. The interfacial behavior plays crucial role, as it is the plane where the two phases interact and interaction of the phases leads to the transition of different two-phase pattern. Experimentally captured images are processed using image processing algorithm, to study the variation of liquid film thickness. With the help of liquid film thickness transition of the interface is analyzed for different superficial Reynolds number of liquid and gas. Further, a PDF analysis is reported to understand the mechanism of the growth of the wavy interface.

Keywords: Stratified-wavy; Slug. Image processing; Liquid film thickness.

1. Introduction

Two-phase flow is widely seen in oil (petroleum and chemical industry) and gas (nuclear power plant and nuclear industry) industry during transportation of oil and natural gas through pipelines. In transportation of two-phase flow from offshore to onshore and further process facility the flow regime changes due to change in fluid flow parameters (inlet flow rate of gas and liquid, density of both the phases and local phase velocity of gas and liquid ([1]-[7])) in the pipeline. Two-phase flow is the simultaneous flow of two distinct phases in a channel or pipe having common interfaces [25], which may show large number of flow patterns (separated flow, intermittent flow and dispersed flow ([1]-[4])) depending on the variation in fluid flow properties of the phases. Some of the flow regime of two-phase flow like slug (type of intermittent flow in which liquid slug flows alternatively between the elongated gas bubbles associated with strong aeration at the slug front ([6]-[7])) leads to safety issues and severe damage in terms of corrosion ([8]-[10]) and leakage of transportation pipeline ([11]-[12]).

Considering this, a lot of research has been reported in this field ([1]-[4], [7], [13]-[19]) and studies in gas-liquid horizontal two-phase flow remains an active area of research due to buoyancy, asymmetric distribution of gas phase and interfacial instability such as K-H instability [15]. Earlier studies reported by ([6], [14]-[19]) analyzed in detail the transition of stratified-wavy flow to slug flow regime in horizontal pipe flow. Kordyban and Ranov [15], are first who identified the transition of
stratified-wavy flow to slug flow pattern in horizontal channel. They reported that high velocity air flows over the wave crest which leads to suction pressure higher than the downward gravity force. This phenomenon leads to Bernoulli Effect on the wavy flow and flow transits into slug flow pattern. Saini and Banerjee [18], analyzed the roll waves using subjective methodology of flow visualization technique. They suggested that beyond the critical wave height, waves undergo the plunging kind of wave breaking which leads to slug formation in pipe flow. In addition, Saini et al. [19], reported the critical liquid height for transition of wavy flow to slug flow using Laser Doppler Velocimetry (LDV).

In spite of the extensive research, the influence of fluid flow properties on gas-liquid interface is not yet explicitly understood. In this direction several researchers proposed analysis of the gas-liquid interface using image processing technique. Dinh et al. [20] presented a new application of image processing technique to two-phase bubbly/slug flow in vertical pipe for identification and measurement of bubble parameters. Do Amaral et al. [21] have also developed a method to extract quantitative parameters through image processing algorithms and measured bubble dimensions, velocity and frequency etc. Image processing technique is used for interfacial analysis of wavy flow sub-patterns ([22]-[23]). Liu et al. [24] used image processing technique to swirling flow regime in vertical channel. They have obtained liquid film thickness for different swirling flow regime, as the liquid film in swirling flow plays an important role in mass, momentum and heat transfer.

In addition, researchers have used multiple techniques to analyze the interfacial characteristics of two-phase flow regime such as capacitance probe, conductance probe, particle image velocimetry and image processing etc. Among all these techniques, image processing technique shows more potential because it is a non-intrusive technique and interface of two-phase flow can be easily analyzed by developing a suitable image processing algorithm. There is a wide scope for development of suitable algorithm for image processing so as to accurately analyze the interfacial behavior of two-phase flow. In the present work, visualization and characterization of two-phase flow is reported using image processing technique. Further analysis of wavy flow is done by introducing probability distribution of wave profile. Transition of stratified to wavy flow and wavy flow to slug flow is also analyzed by increasing liquid superficial Reynolds number. In this work, image processing technique is used for accurate analysis interfacial properties of two-phase flow.

2. Experimental setup
The experiments for gas (air)-liquid (water) are carried out on existing two-phase flow test rig [10]. The test facility mainly includes, two-phase flow test rig system and high-speed photography system (HSPS). The two-phase flow test rig facility includes some major components like air-flow loop, water flow loop, SCADA (Supervisory control and data acquisition), test section for two-phase flow measurement etc. The test facility contains three different pipe diameters of 12 mm, 25 mm and 50 mm made of Perspex glass and each of 14 m length as shown in figure 1. The two-phase flow experiments reported here are performed on pipe of 50 ±0.20 mm inner diameter. The liquid (water) is pumped from the 200 L tank using centrifugal pump which passes through the water filter, heat bath exchanger (for maintaining the liquid temperature constant), Coriolis mass flow meter and Pneumatic valve before entering in the test section. Simultaneously, air is introduced in the test section which supplied from a screw compressor at 4 bar pressure and ambient temperature. Before entering the test section, air passes through a filter (which remove the condensed air and produces the dry air), Coriolis mass flow meter and pneumatic valve. At the outlet of the test section a separation tank is placed in which air vent to outside the chamber and water collects in the supply tank. Hence, water is recirculated in the test section as shown in figure 1.
Figure 1. Two-phase flow test rig system.

Figure 2. High-speed Photography System.

Table 1. Summary of the experimental condition

| Parameter                          | Value                                    |
|------------------------------------|------------------------------------------|
| Pipe diameter                      | 50±0.20 mm                               |
| Two-phases                         | Air and water                            |
| Liquid density                     | 1000 kg/m³                               |
| Gas density                        | 1.2 kg/m³                                |
| Dynamic viscosity of liquid        | 7.7733*10⁻⁴ kg/ms                        |
| Dynamic viscosity of gas           | 1.868*10⁻⁵ kg/ms                         |
| Range of liquid superficial Reynolds number (Re_SL) | 5000 to 12700                           |
| Range of gas superficial Reynolds number (Re_SG) | 2270                                    |

A high-speed photography is conducted for the flow visualization of the two-phase flow patterns. For high-speed camera made of Photron FASTCAM is used for capturing the images of obtained flow patterns in pipe flow. The images are captured at the 2000 fps (frame rate per sec) and 1280x616 resolution. The high-speed photography system (shown in figure 2) consists of a Photron made FASTCAM camera with specification, speed: 30 to 100000 FPS, resolution: 1280x1280. The other components with high-speed camera are tripod, workstation, portable white board, alight and a scale etc.

3. Methodology
The technique adopted here for the study of interfacial behavior of two-phase flow is image processing technique. In this technique, digital images (captured using high-speed photography system) are processed using an algorithm to eliminate noise. Digital image is made of an element called pixel, which gives information of color intensity at a point of an image. We use this property of digital image for image processing. In this work using high-speed camera in order to capture the maximum number of frames per second, so that the interfacial phenomenon of two-phase flow can be captured with higher order of accuracy with each frame.

Different flow patterns of two-phase flow are recorded using of FASTCAM Photron camera. The raw images are taken from PFV (PHOTRON FASTCAM VIEWER APPLICATION). These raw images are further processed in the MATLAB software. In MATLAB software there are sequential processes for processing an image, the software contains an image processing tool box, which have inbuilt function to read and process the image further. In image processing technique, we process the raw image to get the most contrast and less noise image.
The raw (RGB) image is first read in MATLAB software by ‘imread’ inbuilt function. The function reads the RGB image in form of three-layer matrices with respect to Red, Green and Blue planes. For analysis of particular area of interest of raw image, ‘imcrop’ function is used to crop the image. The cropped RGB image is then converted into binary image to visualize the interface clearly.

In order to get the detectable interface, ‘imfill’ function is used, which is used to fill the holes of dispersed air-water area. The final processed binary image has clearly visible and detectable air-water interface. Now the data for the interface can be extracted. Further, some mathematical MATLAB functions like ‘polyfit’ and ‘polyval’ are used for smoothening of the irregular interface. With the help of attached scale on the pipe and measurement of pipe diameter, pixel values can be converted into true coordinate values. The true coordinate values can be used to calculate interfacial properties like liquid film thickness of two-phase flow. The flow chart of image processing algorithm to get the interface of two-phase flow is shown figure 3.

![Flowchart for image processing algorithm](image)

**Figure 3.** Flowchart for image processing algorithm.
4. Results

4.1. Characterization of two-phase flow

The two-phase flow has different flow patterns, as it is an interactive flow of two distinct phases. So whenever fluid properties of any phase or both the phases varies, then it is reflected as different flow patterns [25]. Interface of these flow patterns can be precisely visualized and analyzed by using the image processing technique. In the present work, characterization of two-phase flow is done by analyzing the liquid film thickness of different flow patterns with axial distance and time, with the help of image processing algorithm.

4.1.1. Stratified smooth flow. The Stratified smooth flow regime is captured at Re\textsubscript{SG}, 2270 and Re\textsubscript{SL}, 5000 shown in figure 4. The interface between the two phases of fluid, is smooth and no fluctuation observed at the gas-liquid interface as shown in figure 5. The obtained results of liquid film thickness varying with time is obtained from analysing 400 sequenced images as shown in figure 6.

![Figure 4](image.png)

**Figure 4.** Raw image of stratified smooth flow pattern.

![Figure 5](image.png)

**Figure 5.** Stratified smooth interface along axial length for sequenced image frames.

![Figure 6](image.png)

**Figure 6.** Time-trace of mean liquid film thickness of stratified smooth flow pattern.

It is observed that the mean height of liquid film thickness is nearly constant along with time. Thus, this flow pattern falls under stratified smooth flow pattern. Also, very little fluctuation in liquid film thickness is observed from the processed images. The plot for the mean liquid film thickness shows that the liquid film thickness for stratified smooth flow remains undisturbed with time.

4.1.2. Wavy flow. As the Re\textsubscript{SL} is increased from 5000 to10900, keeping the Re\textsubscript{SG} constant (2270), the flow pattern alters from stratified smooth to stratified wavy flow as captured in image shown in figure 7. Increase in Re\textsubscript{SL} disturbs the smooth interface and it leads to wave formation due to pressure fluctuation over the interface (as shown in figures 8). By the visualization only, we can infer that the interface is wavy.

Alteration in liquid film thickness of wavy interface with axial distance and time-trace of mean liquid film thickness is shown in figure 8 and figure 9 respectively. The fluctuations of the liquid film thickness with axial distance is of the order of 5 mm, and it is calculated by using image processing algorithm.
4.1.3. Slug flow. With further increase in Re_{SL} to 12700, by keeping Re_{SG} constant as 2270, the wavy flow pattern altered into slug flow pattern. When the Re_{SL} is increased, the waves with large amplitude grows and it touches to the upper wall of the pipe and blocks the path of air flow, this phenomenon leads to slug formation. The pipe fills with liquid momentarily in a small time interval and we can visualize the periodic flow of liquid slug and elongated gas bubble. In raw image (figure 10), the nose of the formed slug can be seen and further in figure 11 and 12, we can depict that the interface height reaches up to 50 mm, which is equal to the diameter of the pipe.

The interface of the slug flow pattern is highly unstable which is shown in raw image (figure 10). Thus, processing the interface with the image processing algorithm doesn’t give a smooth interface, shown in figure 11. The disturbed red line shows the processed interface of slug nose without smoothening of the curve. Further a smooth blue curve is obtained by developed algorithm, which helps in examine the flow pattern.
4.2. Interfacial analysis of wavy flow

In literature, different types of wavy flow patterns have been found in two-phase flow in a horizontal pipe ([22]-[23]-[27]) i.e. 2D small amplitude waves, 2D large amplitude waves, 3D small amplitude waves, 3D large amplitude waves and roll waves etc. In present work (at superficial Reynolds number of water 10900 and that of air 2270), we observed that 2D large amplitude waves are not uniform non-sinusoidal. The wave properties such as amplitude and wavelength of the wavy interface are changing at the same ReSL. In figure 13, at same ReSL, we can see the two different interfacial wave at time $t_1$ and time $t_2$.

To analyze the asymmetric behavior of wavy interface in more detail, the probability distribution analysis is carried out for 110 sequenced image frames for 55 milli seconds. A complete wave cycle of wavy interface is taken and divided into four quadrants [26] as shown in figure 14.
crest and trough of the wave are divided by zero crossing line (undisturbed position of interface). The length and height of the four quadrants for each different image frame is calculated with the help of image processing algorithm. Further, the non-uniformity of the interfacial wave is shown with the probability distribution of wave quarters, which is calculated from the image processing algorithm.

In order to calculate probability distribution of quarter wave length and height, the x-axis is divided into number of uniform bins and probability of quarter length and height is calculated for each bin. The length and height of the wave quarters Q1, Q2, Q3 and Q4 lies in different range of bins, shown in figures 15 and 16 respectively. Similarly, the upstream and downstream side of quarters also fall under different range of length. From the probability distribution, it is depicted that the length and height of crest and trough is not uniform. Thus, by PDF analysis, it is reported that the 2D large amplitude wave is non-uniform (and asymmetric) with space and time.

![Figure 15. Probability distribution of quarter wave length.](image)

![Figure 16. Probability distribution of quarter wave height.](image)

By probability distribution analysis, it is observed that length of the wave quarters Q1, Q2, Q3 and Q4 are not equal. The crest length which is the sum of length of Q3 and Q4 is different. The difference in crest wave quarters Q3 and Q4 is due to the presence of different magnitude of pressure on windward side and leeward side as was demonstrated in terms of sheltering mechanism by Harold Jeffrey [28]. It states that the pressure on the wave slope facing the air will be greater than those away from it. Similarly, the trough quarters Q1 and Q2 also differ in length due to the sheltering effect.

The variation in wave height in the wave quarters depicts the wave growth due to given perturbation. In literature, the wave growth phenomenon is referred as Kelvin Helmholtz instability [15], which states that due to perturbations, stratified smooth interface changes into wavy interface and the waves grows and one of the peak rises and approaches to the pipe wall. The growth (response) of the interface observed based on image processing here shows that it is not sinusoidal, as the wave length of quarters of the crest (Q3 and Q4) and that of trough (Q1 and Q4) have different values. This can be attributed to the sheltering effect.

4.3. Transition of stratified smooth to slug flow pattern

With an increase in Re_{SL}, at constant Re_{SG}, the stratified smooth flow regime transits into wavy flow. As Re_{SL} is further increased, the waves start growing and it touches the upper wall of the pipe and undergoes the plunging kind of wave breaking [18]. This phenomenon leads to slug formation in pipe flow with vigorous aeration in liquid body. As shown in figure 17, transition of stratified smooth to slug flow has been reported with image processing technique by showing the increment in the liquid film thickness from stratified smooth to slug flow pattern. The interface of stratified smooth, wavy and slug flow regime shown in figure 17, is obtained by using the algorithm. As the Re_{SL} is increased from 5000 to 12700 with constant Re_{SG} 2270, the liquid film thickness increased from 24 mm (for stratified flow) to 50 mm (for slug flow in which liquid slug occupies the complete cross-section area of the pipe) while flow regime changed from stratified smooth to slug.
With the above results, it can be seen that the liquid film thickness is linked with the flow pattern. As the flow pattern changes from stratified smooth to wavy flow pattern, the liquid film thickness increases and passage for air-flow reduces, resulting in decrease in pressure over the interface which leads to the wave growth. Further, when the liquid film increases (due to increase in ReSL), one of the peaks of wavy interface grows significantly and touches the upper wall of the pipe, leading to the blockage of air-flow. It increases the pressure at the windward side of wave-slope, thus the air-flow pushes the water in the flow direction and forms liquid slug.

5. Closure
In the present work, a method is developed to extract the interface of different two-phase flow pattern, through image processing algorithm. The interfacial analysis of two-phase flow is reported by using experimental flow visualization as well as image processing technique. In the present work, the two-phase flow pattern is analyzed in terms of interface fluctuation and the alteration in liquid film thickness is done by varying the ReSL at fixed ReSG. The probability distribution of wavy interface depicted that the wavy interface is not uniform and non-sinusoidal. By the PDF analysis, it could be concluded that for the growth of the wavy interface, sheltering and K-H instability mechanism both are responsible. The transition of the interface from stratified smooth to slug flow pattern is analyzed with increase in ReSL and it is observed that the liquid film thickness increases with increase of mass flow rate of any of the phase, air or water.

6. References
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