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Measurements of translational slug velocity and slug length using an image processing technique

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ABSTRACT

Slug flow is a common flow regime that occurs in various industries, such as oil, gas, and power generation industries. In this study, the mean slug translational velocity and slug liquid length were measured using Phantom 9.2 software and an image processing analysis technique. The adopted image processing technique involved the analysis of video frames recorded from a high-speed camera (Phantom 9.2) in a horizontal transparent pipe using a combination of the approximate median method and blob analysis, along with an additional morphological process for detecting and segregating individual slugs. The experimental data were obtained from a designed two-phase flow test section, in which sets of superficial water and air velocities were selected to generate numerous slug flows. A good agreement with a maximum deviation of 6.7% between the estimated slug parameters from the adopted technique and the Phantom cine view controller software was achieved. Additionally, the developed technique provided precise results with a high processing speed of 10 frames per second.

1. Introduction

Slug flow occurs from stratified gas–liquid flow when interface waves develop via the classical Kelvin–Helmholtz instability until they fill the entire pipe cross section [1]. In slug flow, liquid slugs move at high mixture velocity as elongated bubbles flow with smaller velocity in the long domain. Slug flow occurrence may cause problems in piping systems. In addition, slug flow occurrence may cause large bubbles for the constant mixture velocity in the individual gas and liquid delivery flow systems. These bubbles may result in liquid carryover, gas carry-under, or considerable excursion levels that consequently lead to a sudden shutdown in processing plants. The slug phenomenon induces significant forces because of the high momentum when the slug passes through pipes, elbows, tees, and other process equipment. Furthermore, severe damage may occur in pipe connections and support when low frequencies of slug flow reach the resonance natural frequency of piping structures [2].

Two-phase slug flows are encountered in numerous industrial applications. Therefore, the analysis of this type of flow during the design stages should be considered to protect piping systems and equipment. In line with this requirement, various measuring techniques and technologies have been adopted in the analysis of multiphase slug flow in oil and gas pipelines, fuel channels in power generation plants, separation in oil production plants, and nuclear reactors. Examples include the experimental techniques that were used in previous research, which include conductive and capacitive probes [3], X-ray [4], gamma-ray tomography [5], ultrasound transducers [6], wire-mesh sensors [7], optical tomography [8], and high-speed cameras [9].

Slug length, slug frequency, volume fraction distribution, slug translational velocity, momentum, and momentum transfer at the interface are the most important parameters for characterizing slug flow [10]. Given the intermittent and irregular nature of slug flow, slug parameters usually vary with time. Therefore, the mean value is usually used to describe slug flow characteristics.

Considering that slug characteristics vary transiently along piping systems, the determination of slug characteristics, such as slug velocity, slug length, slug frequency, and volume fraction, is usually challenging and tedious [11]. Therefore, developing a measuring technique that can compute slug characteristics accurately with minimum computational time is important. Several techniques have been used to compute slug characteristics experimentally. Specifically, high-speed videometry (non-intrusive method) is used to measure slug velocity and slug length from recorded video. This method averages the slug lengths for several slugs to determine the mean slug length and computes slug velocity by determining the required time needed for the slug to

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Nomenclature

D	Pipe diameter (m)
D_i	Pipe inner diameter (m)
fps	Frame frequency (frame s^{-1})
G	Gas mass flow rate (kg m/ s^2)
L	Liquid mass flow rate (kg m/ s^2)
L_S	Liquid slug length (m)
P	Pressure (Pa)
j_G	Superficial gas velocity (m/s)
j_L	Superficial liquid velocity (m/s)
j_m	Mixture velocity (m/s)
j_S	Slug velocity (m/s)
NoF	Number of frames (frame)
T	Temperature (C°)
x	Slug initiation position

move between two points. Slug moving time is obtained from the frequency of recorded video frames. Thus, camera shutter speed and sensor capability are the crucial features that should be considered in high-speed camera selection to obtain reliable and precise results. Previously, slug characteristics were analyzed by segmenting the images via several morphological techniques, such as wavelets [12] and filtering [13].

Davies [14] and Hale [15] conducted flow visualization experiments of slug initiation in a horizontal transparent pipe measuring 10 m in length and with an internal diameter of 0.074 m. In the work of Davies [14], a high-speed video camera with a frame frequency of 1000 frames was placed at the pipe entrance to examine the slug initiation; tiny waves were able to develop at the top of the rebuilding liquid layer and continue to grow as long as they were placed over the sloping surface. Sato et al. [16] used an image processing technique to measure the void fraction distribution and thereby identify the air–water flow regime. Video frames were processed using FORTRAN FDM98 language, and the water phase was dyed black to further enhance phase visualization and differentiation. They observed that water phase was concentrated at two gray levels. Ahmed [2] used capacitance probes, hot-film anemometer, and image processing techniques to determine slug length and velocity; the results were in good agreement with existing models and correlations of slug flow. Amaral et al. [17] used an image processing technique to measure bubble velocity and detect bubble contours. They then compared their results with theoretical predictions and achieved a good agreement; however, they suggested that future work should focus on reducing processing time. Therefore, the present study uses an image processing technique to compute slug translational velocity and length while considering image processing time and measurement accuracy.

Several studies have developed image processing techniques to investigate slug flow characteristics; however, image processing time is lengthy and needs improvement [17]. In addition, analyzing aerated slug with high velocities is difficult because the pixel density difference for the slug liquid and slug pocket in an image may become similar. Therefore, most previous investigations on slug flow characteristics were limited to non-aerated flow regimes. Such a scenario motivates the current research to introduce a new technique that can precisely measure slug velocity and slug length at different aeration levels but with a short computation time.

This study aims to investigate air–water slug flow along a horizontal transparent pipe with a diameter of 0.074 m by using a non-intrusive image processing method that automatically extracts slug velocity and slug length from high-speed cameras; the method requires minimal computation time for image processing. This method uses foreground estimation and region of interest (ROI) detection, along with blob enhancement operations for detecting and tracking slug motion. The developed technique is used to determine slug velocity and length for a specially designed and fabricated two-phase flow loop. The gas and liquid phases used in this investigation are air and water. Twelve tested cases are selected and analyzed using the newly developed technique. In addition, the obtained results from the developed technique are compared with the existing correlations in the literature. Although slug detection at high superficial velocities is extremely challenging and complicated, the developed technique is able to compute slug length and slug velocity with high accuracy and short computational time. Moreover, this technique does not require an advanced illumination system, such as Particle Image Velocimetry (PIV).

2. Experimental set-up

The test rig used to conduct the air–water slug flow is schematically presented in Fig. 1. A Plexiglas pipe with an inner diameter of 0.074 m and a length of 8 m was mounted on fixed rigid steel frames. The water was stored in a tank with 0.4 m^3 capacity; the tank was used to feed the closed loop through a PVC pipe. Another tank with a capacity of 0.3 m^3 was used to collect the return fluid from the test section. The water was fed to the test section through a centrifugal pump with a maximum flow rate of 1 m^3/min and 19 m pressure head. A calibrated ultrasonic flow meter with $\pm 0.5\%$ accuracy was used to measure the water flow rate. A solenoid valve was used to open/close the water supply loop. The water was pumped to the mixer section, in which water mixes with injected air and the resultant mixture flows to the test section. The inlet mixer section was designed with an elongated plate in the middle to separate the air and water, avoid any perturbation that might occur at the inlet, and enhance the stratification level at the pipe inlet, as shown in Fig. 2. The elongated plate in the mixer section was placed in the middle to ensure that the volume fraction of the air and water phases at the inlet was always equal to 0.5. Air was supplied to the test section from the central compressor, which can deliver 42.5 m^3/min of air at pressures of up to 0.85 MPa. The airflow rate was measured and controlled via a calibrated mass flow controller (Omega FMA-2600A), which measured the airflow within the range of 0–2 Sm^3/min with an accuracy of $\pm 0.05\%$.

Flow visualization and recording was obtained using a Phantom 9.2 high-speed video camera with a recording rate of up to 153,846 frames per second (fps) at the minimum resolution. The camera used a mesh resolution technique (Phantom 9.2 cine view controller), which can track slug movement between any two points and determine the time from the recorded frames.

Air and water velocities were selected from a Baker chart [18] (as shown in Fig. 10) to ensure that the flow regime was always slug flow. In this study, the water superficial velocity ranged from 0.7 m/s to 1.0 m/s, and the air superficial velocity ranged from 0.7 m/s to 2.8 m/s. In addition, entire experimental tests were conducted under the atmospheric pressure of P=1.013 bar and room temperature of T=24 °C.

Prior to starting each experimental run, the water level in the tank was checked along with the air supply system; the electrical connections between the acquisition system and the instruments as well as the connection between the display system and the