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Investigation of Slug Flow Characteristics for Energy Harvesting Applications

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Abstract

The purpose of this research work is to study the characteristics of air-water slug flow for energy harvesting applications. It involves an investigation and analysis of the liquid hold-up, slug frequency and the translational velocity from conductivity rings. The experimental test was carried out with a different flow rate of the air-water slug flow in 2-inch rig horizontal pipe using a ring type conductance probe. The conductivity rings were used to obtain the slug flow characteristics. Forces were generated as a result of the fluctuating pressure of the slug flow on the entire cross-sectional area of the pipe. The acquired signal of the pressure fluctuation was used to simulate the expected outcome. The result shows that a maximum forward slug force of 30N per cross-sectional area of the pipe was obtained and 26N force of the fluctuating pressure through the cross-section was generated at the flange-end. The obtained forces can be applied to using electromagnetic or piezoelectric harvester to generate the electrical output in order to energize electro-mechanical devices.

Keywords: pressure fluctuation, liquid hold-up, slug flow, slug frequency superficial liquid and gas velocity

1. Introduction

Slug flow is described by alternating bubbles of gas and liquid slugs, flowing across liquid films. This combines to form slug unit. The existence of slug flow in pipes covers the entire length of pipe with upward inclination in wide ranges of liquid and gas flow rates. It is possible for the slug to grow continuously all way along the pipe. This occurs in the first instance when the flow is initiated in a stratified system. The slug initiation repeats and subsequently moves with the liquid shed by the previous cycle of wave growth [1]. Two-phase slug flow is commonly found in horizontal pipeline field operations. The repetitive structure of the flow creates fluctuations in the properties of the flow such as pressure and void fraction. It has to be accurately predicted in designing a pipe and other components used in two-phase flow operation. Slug flow is characterized by an intermittent structure that consists of the slug body of liquid which moves down the pipeline at approximately the local gas velocity. The most important properties in the slug flow are the slug frequency and the liquid hold up. Al-Lababidi [2] studied on the slug flow properties. The liquid hold up and slug frequency are the most important slug flow characteristics considered in designing the multiphase pipelines and associated components. The most common techniques used in determining the liquid hold up is by averaging the probe signals in the cross section in contact with the liquid. Other important characteristics of the slug flow are the

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slug velocity, slug length, and film velocity [2]. A simple approach was used to characterize the configuration of gas-aqueous liquid two-phase flow inside a micro-fluidic channel which was first suggested and demonstrated by McConnell and Park [3]. A net electrical charge is spontaneously generated on the micro-fluidic channel substrate when the gas slug passes through the channels measuring spontaneously the generated electric potential caused by the electric charge on the substrate. The generated electric potential was measured by placing the micro-fluidic chip on an additional electrode surface that is connected to an electrometer. The average flow velocity inside the micro-fluidic device was demonstrated to be measured precisely in the proposed approach. Novel gas and liquid flow rate measurement for use in vertically upward and downward gas-liquid pipe flow was proposed by Shaban and Tavoularis [4]. The used method was based on the analysis of time history of area-averaged void fraction using a conductivity wire-mesh sensor. The measurement was collected for air-water with an internal pipe diameter of 32mm at about atmospheric pressure. The relative frequencies and power spectral density of the area-averaged void fraction were calculated and used as representative properties, which were applied to using Principal Component Analysis and Independent Component Analysis. These were used as input to the artificial neural network.

The potential for extracting energy from the fluid in motion can be achieved by the application of technologies that recover energy from discharge rate, vibrations, and pressure fluctuations. Energy can also be harnessed from pressure drops that occur as a result of induced vortex formation in a fluid flow. It can be derived from pressure pulsation that is caused by the fluctuations in the basic pressure head developed by pumps or certain device discharging fluid at a certain rate [5]. The research based on pressure pulsation is scarce. The application of vortex methods was used to study the generation of flow-induced pulsation in piping systems. However, in most of the flow-induced noise, more complicated flow patterns were exhibited. The intensity of pressure pulsation depends on its magnitude and the effects it has on components and systems [6]. The frequency and energy of fluid oscillation can be obtained when a fluid flows across a fluidic device for example cylinder. In this case, the interest lies in the relationship between the components of the frequency of the fluid force and the corresponding responses. The cylinder experiences its generated wake during previous cycle [7]. The vortex shedding frequency (VSF) is affected by the oscillatory motion of the cylinder and vice versa. In some cases, there will be a resonance frequency "lock-in" between the VSF and the frequency of the oscillating cylinder which occurs in submultiples of that frequency.

Fluidic oscillators are the devices that consist of no moving parts which generate fluid jets at some levels of frequency from a flowing fluid. The oscillation of the fluid is being produced by the instability of the fluid dynamics in the device and is characterized by the formation of zones having different pressure either side of the jet thereby controlling the flow direction [8]. A recirculation type of fluid oscillators involves three main separate functions i.e. the vortex formation chamber, the jet formation nozzle and the oscillation chamber. The characteristics of the unsteady flow in the fluidic device, wide range of operating frequency and addition of momentum distribution make the fluidic device attractive for flow control applications. The oscillation of the fluid can produce a frequency of over 20 kHz for a small device which is dictated by the internal geometry of the device and the flow rate. The fluidic device was first developed with a concept of the fluidic amplifier [9]. The frequency of operation in the oscillator is proportional to the flow rate. Fluidic oscillators have been extensively used as a flow rate metering device. Recently, the fluidic oscillator was applied as a flow control device to a host of aerodynamic flow. Such applications include enhancement of jet mixing cavity resonance tone separation and jet thrust vectoring [10]. Some principles of fluidic oscillators which involve negative slope characteristics, mutual blockage of two valves, external feedback, resonator and edge noise and vortical internal feedback were presented by Zimmerman, Tesař and Bandulasena [11]. Moreover, the characteristics of the device should bear in mind to be dependent on the pressure drop within the oscillator and the flow rate that is passing through the device. The fluidic device can either be analog or digital. It consists of an amplifier, diode, modulator sensor, and switch. Each of these elements uses one or more of the following fluid phenomena as its basic principle of operation. Analog fluidic device involves the use of momentum exchange as its principle of operation. This divides the flow into two or more parts in the absence of a control flow. Other analogue fluidic device includes turbulence amplifier to which its principle of operation is based on the jet turbulence that changes the laminar jet into turbulence by applying a radial control flow much lower than the supply flow [12]. The digital fluidic device uses the "Coanda effect" as its principle of operation. Example of such devices is the wall attachable bi-stable amplifier and the vortex amplifier. Energy can be extracted based on the principle of operation of the above fluid phenomena.

Harvesting energy from fluid flow in a pipe could either involved a principle based on the mechanical energy of the moving fluid, harnessing the energy from vibration caused by the moving fluid or due to the variation of the pressure of the moving fluid in the pipe. A cantilever piezoelectric beam was excited in Heating Ventilation and Air-conditioning (HVAC) flow [13]. Several research works were carried out to study the vortex shedding through the vibration of a cylinder in a steady state flow. A comprehensive summary has been made by Bearman [14], Sarpkaya and Schoaff [15], Sumer, Christiansen, and Fredsøe [16] that the frequency of the vortex shedding approaches the natural frequency of lightly damped cylinder. The vibration of the cylinder becomes larger thereby creating resonance "lock in" to occur between the Strouhal frequency and the frequency of the vibrating cylinder [17]. An algorithm to estimate the frequency of vortex shedding by using vortex flow meter has been designed by Chung [18]. The algorithm is divided into two parts: the auto correlation techniques that are to be applied when the VSF is less than 200Hz and Fast Fourier transform to be used for a VSF above 200Hz. The test result shows characteristics of ability by a time lag of 0.512s on VSF under dynamic flow rate at average and higher shedding frequencies. The estimated error of the VSF is less than 0.3% under static flow rate. Vortex shedding downstream from a bluff body placed in the air flow was used ahead of the cantilever assembly. The positioning of a small weight along the cantilever enabled the energy harvester to operate using flow velocities of 2-5 m/s characterized in the HVAC duct. For a speed of 2m/s, the power generation is 0.2mW and power of 3mW is achieved for 5m/s speed. Wang, Pham, Chao, and Chen [19] used the oscillation of piezoelectric films to convert the flow energy into electrical energy by a new energy harvester that transformed the energy from Karman Vortex Street behind a bluff body in a flow of water. Based on the experimental results, an output voltage of 0.12V_{pp} and 0.7nW instantaneous power was generated through pressure oscillation with the amplitude of 0.3kPa at the frequency of about 52Hz. The output power potential can be improved through the use of a piezoelectric material with a high piezoelectric coefficient. Wang and Chang [20] demonstrated energy harvesting from vibration caused by the pressure fluctuations applied to a permanent magnet giving an output voltage of 10mV_{pp} with an amplitude of 254Pa at a frequency of about 30Hz. Under this condition of operation, an instantaneous power output of 0.4μW was determined. Sarciada [21] designed a prototype of an electromagnetic energy harvester from pressure variation induced in a pipe. An output power of 3.78 μW, output voltage rate of 40mV was achieved with 3kPa step pressure change. In this work, conductivity rings were used to characterize the slug flow properties which are similar to the work of Choi, Lee, and Kim [3]. These properties were used to show the possibility for its application in energy harvesting. The slug flow properties were used to obtain the pressure amplitude required to displace energy harvester as in the work of Sarciada [21], Wang and Chang [20], Wang, Pham, Chao, and Chen [19] to generate the electrical output.

2. Experimental Set-up and Procedure

The experimental test was carried out using 2-inch air-water rig located in the laboratory of the Process Systems Engineering Group at Cranfield University. Pipe of the 2-inch rig was designed and developed for the test. The 2" pipe was made up of Perspex material to which the behavior of the fluid can be observed. It has connections between supplying air at a controlled flow rate and at a certain level of temperature and pressure. This allows the mixing of both air and water at the defined flow rate based on the requirement of the experiment. Fig. 1 shows the schematic flow diagram for the experiment. The piping system consists of flowmeters, temperature and pressure sensors. The temperature and pressure transducers were mounted to the rig to measure the properties of the slug flow through the test section which flows out and return back to the storage tank. The water is supplied to the test section by a centrifugal pump of 7.5kW capacity with a maximum flow rate of 75.6m^3/hr using a storage tank made of steel with a capacity of 2m^3. The centrifugal pump delivers the water through the piping and was made in such a way that the water returns back to the tank functioning as a closed loop system. A gas flow meter GFM 34 and a flow rate capacity of 400m^3/hr. were used to meter the air. The air mix with water flow delivered by centrifugal pump upstream is measured by an electromagnetic flow meter ABB K280/0 AS model. It measures the flow rate up to 40m^3/h. and flows downstream of the centrifugal pump. The mixed flow combines to form the slug flow. The signal power of the liquid hold up was provided by pressure transducer PMP 1400 6 bar-g with an output voltage of 0-5V and a temperature transducer, which is capable of sensing the temperature of the fluid at an operating rate of -200 to 400 °C. These transducers and some other electrical devices are connected to computer systems to exchange information. LabVIEW software was used to obtain the signal from the flow. The slug body flows from the section of the conductivity rings and is guided at the flange-end to flow through venturi meter which measures the slug flow before it returns back to the water tank. Fig. 2 shows the section of the conductivity rings and a mesh for the venturi meter connections. Test of different slug flow was investigated. Instrumentation systems were set to measure the data for each test. The LabVIEW software installed in the computer system was used to acquire the signal in the test.

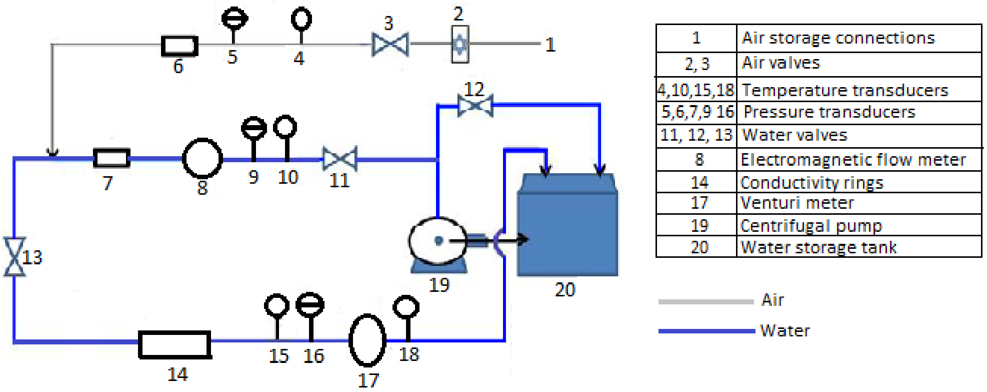
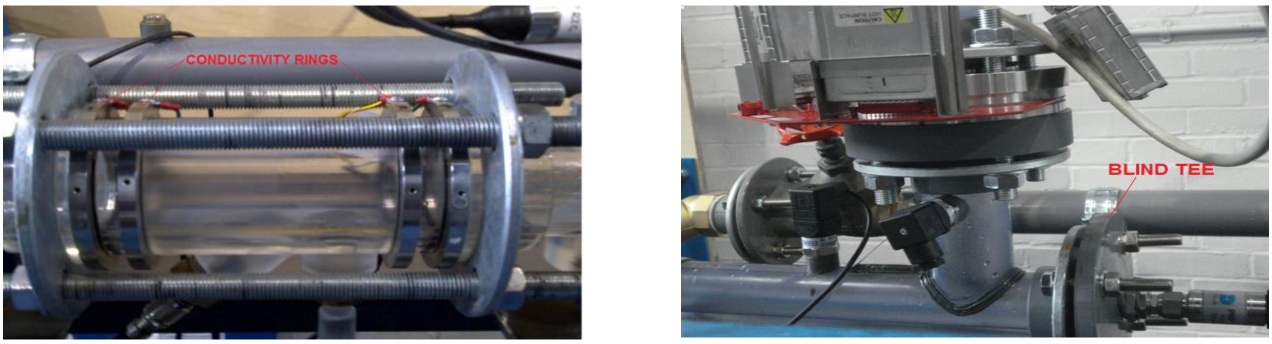


Fig. 1 Schematic diagram for the experimental set-up of the two-phase slug flow



(a) Section of the conductivity rings (b) Venturi meter connection at blind-tee

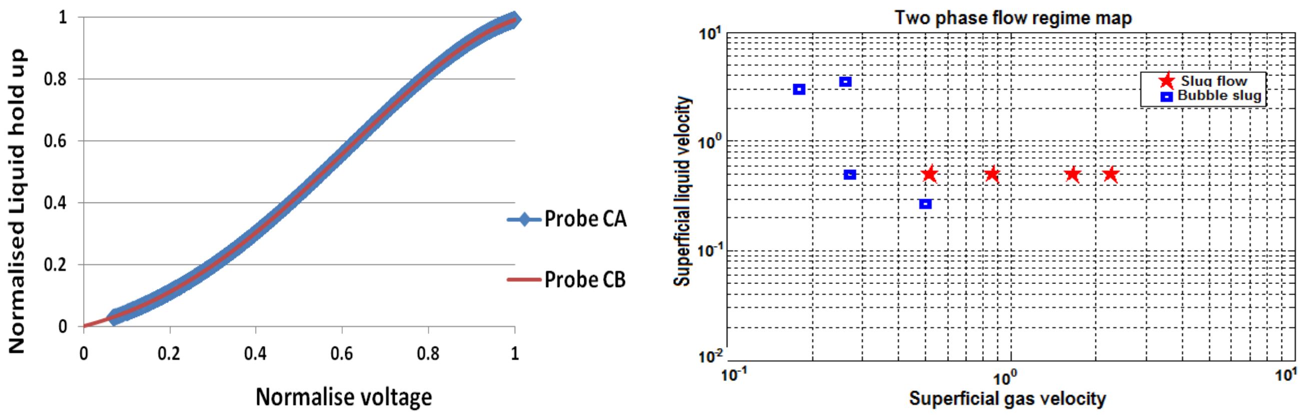
Fig. 2 Conductivity rings and a venturi meter connection in the two-phase flow line

3. Slug Flow Characteristics

The common method usually applied to obtain the slug flow properties is by using the liquid hold up. The techniques used in the determination of the liquid hold up are by averaging the probe signal through the entire cross-section of the liquid in contact. The slug flow in contact with the probe record the signal of the liquid, in which other properties such as the slug frequency, slug transitional velocity which comprised of the superficial liquid and gas velocity, slug length etc. may be determined.

3.1. Liquid hold-up

The conductivity probes used in this experiment consists of two rings of 1cm apart separated by a distance of 18cm was mounted on the pipeline for the test. The rings were used to measure the liquid hold up in the pipe under various flow conditions. These are connected to the data acquisition systems and the signal of the input was recorded in voltage output. The measurement of the liquid hold-up is achieved by measuring the electrical impedance between the electrodes made of various configurations and placed in contact with the fluid. The ring-type electrode covers the entire cross-sectional area of the pipe and is well convenient for measurement in pipes and components that are of a circular cross-section. To characterize the set of the ring probes labeled as C_A and C_B for the measurement of the liquid hold up during the intermittent flow, the liquid hold up was correlated as the function of the normalized voltage output. In this case, the pipe is denoted as 1 when it is full and 0 when it is empty. The correlation of the conductivity probes obtained as stated in the Eqs. (1) and (2) is similar to the work of Ozughalu [22]. The conductivity rings were calibrated in the Laboratory and various results were obtained. The flow regime map was determined by considering the properties of the slug flow which comprise of the superficial liquid and gas velocities while predicting the pattern and the type flow in the experiment as shown in Fig. 3(b).



(a) Calibration of conductivity ring probes C_A and C_B (b) Two phase slug flow regime map

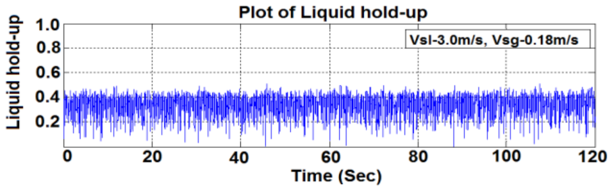
Fig. 3 Calibration of conductivity rings using two-phase slug flow

Eqs. (1) and (2) were used to validate the calibration of the conductivity rings theoretically. The calibration curve obtained as shown in Fig. 3(a) also looks similar to that of Al-Lababidi [2]. E_A and E_B represent output voltage generated at conductivity probes C_A and C_B to which the liquid hold up was correlated and V is the normalized voltage output.

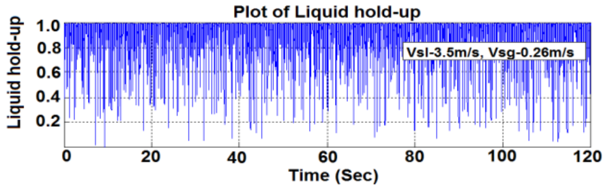
$$E_A = -1.1127(V)^4 + 0.9394(V)^3 + 0.3368(V)^2 + 0.816(V) \quad (1)$$

$$E_B = -1.0591(V)^4 + 0.4111(V)^3 + 1.3447(V)^2 + 0.3286(V) \quad (2)$$

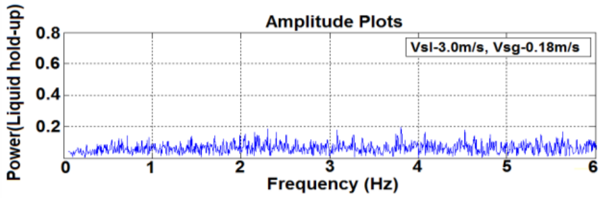
It can be deduced from the calibration of the probe that the relationship between the normalized liquid hold-up and the normalized output voltage, E_A and E_B were characterized as expected. The liquid and the gas phase fraction are directly and inversely proportional to the conductivity. Fast Fourier Transform (FFT) of the signal power was acquired using Matlab. The Fast Fourier Transform of the amplitude power was used to obtain the slug frequency in the flow. The signal power and the frequency of the liquid hold-up are shown in Figs. 4, 5 and 6. These figures were obtained from the flow signal based on the variation of the superficial liquid and superficial gas velocities. Several tests were carried out in order to achieve a useful result in the experiment. It can be observed from Figs. 4, 5 and 6 that the higher the superficial liquid velocity the lower the amplitude power of the liquid hold-up and vice versa. This is typical of the relationship between the slug frequency and the superficial liquid and gas velocity.



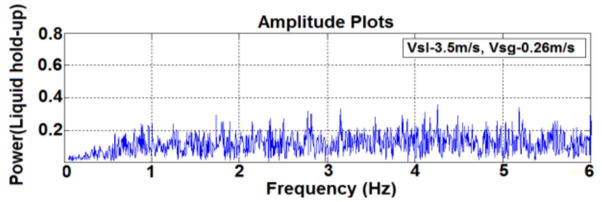
(a) Plot of liquid hold-up for Vsl-3.0m/s, Vsg-0.18m/s



(b) Plot of liquid hold-up for Vsl-3.5m/s, Vsg-0.26m/s

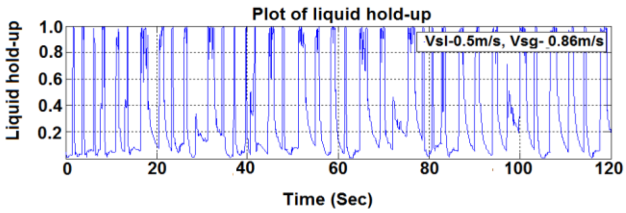


(c) Amplitude plots for Vsl-3.0m/s, Vsg-0.18m/s

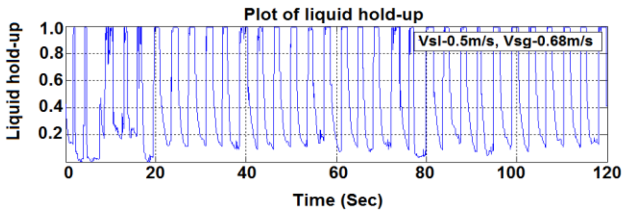


(d) Amplitude plots for Vsl-3.5m/s, Vsg-0.26m/s

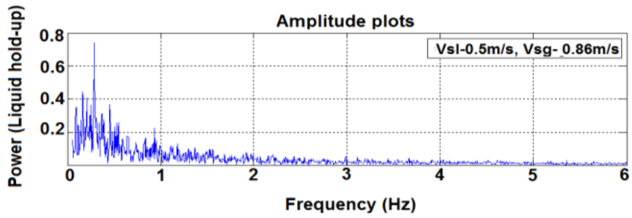
Fig. 4 Plots of liquid hold up FFT of the instantaneous liquid



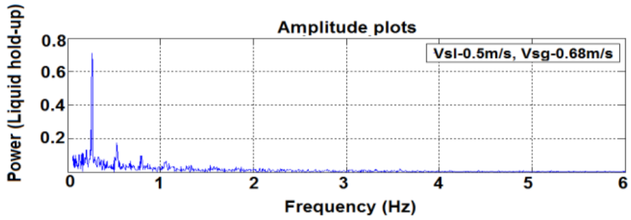
(a) Plot of liquid hold-up for Vsl-0.5 m/s, Vsg-0.86m/s



(b) Plot of liquid hold-up for Vsl-0.5m/s, Vsg-0.68m/s

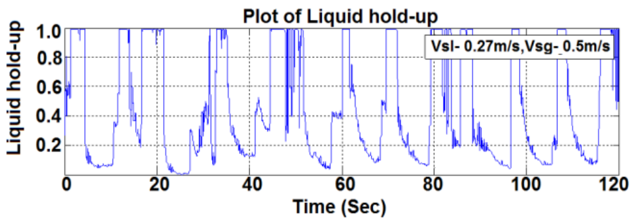


(c) Amplitude plots for Vsl-0.5 m/s, Vsg-0.86m/s

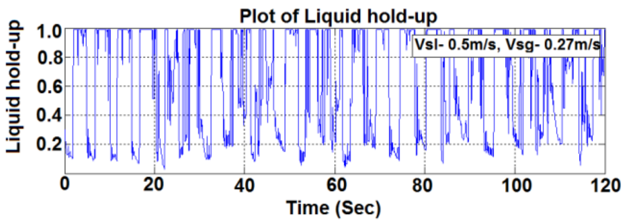


(d) Amplitude plots for Vsl-0.5m/s, Vsg-0.68m/s

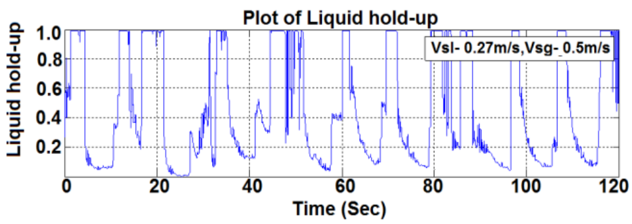
Fig. 5 Plots of liquid hold up FFT of the instantaneous liquid



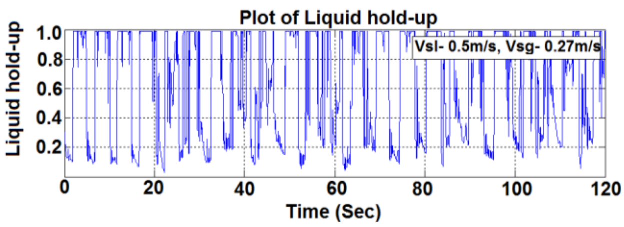
(a) Plot of liquid hold-up for Vsl-0.27m/s, Vsg-0.5m/s



(b) Plot of liquid hold-up for Vsl-0.5m/s, Vsg-0.27m/s



(c) Amplitude plots for Vsl-0.27m/s, Vsg-0.5m/s



(d) Amplitude plots for Vsl-0.5m/s, Vsg-0.27m/s

Fig. 6 Plots of liquid hold up FFT of the instantaneous liquid

3.2. Slug frequency

Slug frequency is an essential parameter used in two-phase flow model to predict the other characteristics of slug flow such as liquid hold-up and pressure drop in pipes. Slug frequency refers to the number of slugs that passes a specific point located along the pipeline over a specific period of time [23]. It is so important in that it is related to severe problems in operation such as pipeline corrosion, pipeline structural instability, well head pressure fluctuations and flooding of the downstream facilities.

During the slugging condition, the pressure drop may be higher in magnitude than in homogenous or stratified flow. Slug frequency should be accurately predicted as it is directly proportional to the pressure drop. The slug frequency of the flow obtained was compared with the correlated slug frequency using correlation developed by Fossa, Guglielmini, and Marchitto [24]. The slug frequency is related as a function of Strouhal number as indicated by Eq. (3).

$$S_t = \frac{S_f \times D}{V_{SG}} = \frac{A \times X_L}{1 + B(X_L) + C(X_L^2)} \tag{3}$$

where A, B, and C are constant and X_L is the liquid volumetric fraction which is expressed as the ratio of the superficial liquid velocity to the velocity of the mixture; water and air and S_f is the slug frequency. The slug frequency obtained from the experiment was validated to the correlation by Fossa, Guglielmini, and Marchitto [24] and had provided a good match.

3.3. Slug Transitional Velocity

The slug translational velocity was acquired in the present work by cross correlation techniques applied to the signal obtained from the conductivity probes C_A and C_B. The slug translational velocity is defined by Eq. (4) and is required to identify the type and the regime of the flow. It consists of components of the superficial liquid and superficial gas velocity [2]. The separation between the two probes was measured at a time frame to obtain the slug translational velocity given in Eq. (4)).

$$V_S = X_{(A-B)} / t_{(A-B)} \tag{4}$$

where V_S is the slug translational velocity determined from the conductivity probes C_A and C_B and $X_{(A-B)}$ is the distance measured between the two probes and $t_{(A-B)}$ is the time delayed between the two conductivity probes C_A and C_B.

4. Result and Discussions

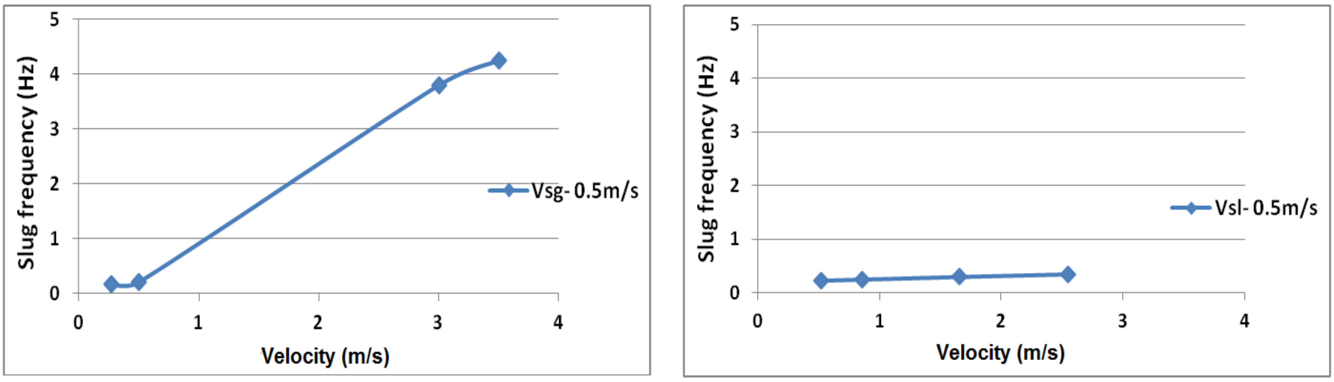
The result of the experimental test carried out for the two-phase slug flow is presented and discussed. It involved an investigation with a different test of air-water flow combination to determine slug flow characteristics. These characteristics comprised of the liquid hold-up, slug frequency and the slug translation velocity which were determined from the signal of the conductivity probes. The forward force of the slug flow was compared to the force generated when the slugs are arrested at the flange-end. The slug frequency and the frequency obtained from the fluctuating pressure at the flange-end are similar. The small variation in the frequencies occurs at higher superficial liquid velocity. The signal of the pressure fluctuation relates the output of the generated force. The force generated can be applied to depress energy harvester in order to extract an electrical outp ut that will energize electro-mechanical devices. The used method in this work is also similar to the work of Wang and Chang [20], Wang, Pham, Chao, and Chen [19]. However, the findings of the present work are based on the force generated due to the slug flow and fluctuating pressure at the flange-end.

Table 1 The comparative analysis of the forward force of the slug flow and the force generated at the blind tee end

Test	V_{SG} (m/s)	V_{SL} (m/s)	F_S (Hz)	F_B (Hz)	F_S (N)	F_B (N)
1	0.52	0.50	0.23	0.23	2.20	21.20
2	0.50	0.27	0.16	0.18	0.70	20.58
3	0.27	0.50	0.20	0.20	1.20	25.48
4	0.18	3.00	3.80	3.40	20.40	15.68
5	0.86	0.50	0.25	0.25	3.50	22.50
6	0.26	3.50	4.25	3.60	29.60	19.60

The forward force of the slug flow was simulated from the signals of the flow properties and was found to be different in magnitude compared to the fluctuating force at the flange. Table 1 shows the simulated result of superficial liquid and gas velocities. This illustrated an analysis to compare the slug frequency and force generated at the flange-end due to the pressure fluctuation and forward slug force. The slug frequency was related as a function of the superficial liquid and superficial gas velocity of the mixed flow. The relationship between the slug frequency and the superficial liquid and gas velocity is shown in Fig. 7. It can be deduced that the slug translational velocity is also a function of the superficial liquid and superficial gas velocity and has a greater impact in the determination of the flow regime or the type of slug flow. It predicts the nature and intensity of the slug flow. It can also be seen from Fig. 7 at constant V_{SL} of 0.5m/s a maximum slug frequency 0.38Hz was achieved while varying V_{SG} and maximum slug frequency of 4.25Hz was obtained at different values of V_{SL} for V_{SG}~0.5m/s. The frequency obtained can be used to predict the amount of energy that can be generated.

It can be observed from Fig. 7(a) that the slug frequency increases with the increase in the superficial liquid velocity. An increase in the superficial gas velocity does not have much effect on the slug frequency as shown in Fig. 7(b). When the slug body flows down to the blind tee end, the pressure fluctuates instantaneously. The fluctuations in pressure were used as the source of energy to which power can be generated. The acquired signal of the pressure fluctuation was used to simulate the expected outcome. The result shows that a maximum forward slug force of 30N per cross sectional area of the pipe was obtained and 26N force of the fluctuating pressure through the cross section was generated at the flange-end. This paper is applicable to the work of Sarciada [21], Wang and Chang [20] used the similar result to achieve a micro unit of power output. The generated force due to the fluctuating pressure at the flange-end was compared with the forward slug force to analyze its potentials for energy harvesting applications.



(a) Superficial liquid velocity (b) Superficial gas velocity

Fig. 7 Slug frequency as a function

5. Conclusions

In this paper, two-phase air-water flow was used to investigate slug flow characteristics which involved the liquid hold-up slug frequency, and the slug translational velocity using conductivity probes. The conductivity rings were used to determine the liquid hold-up, the slug frequency, and the slug translational velocity. These parameters were used to obtain the amount of force produced from the forward slug force and the force generated due to the instantaneous fluctuating pressure when the slug body is continuously arrested at the flange-end. The acquired signal of the pressure fluctuation was used to simulate the expected outcome. The result shows that a maximum forward slug force of 30N per cross-sectional area of the pipe was obtained and 26N force of the fluctuating pressure through the cross-section was generated at the flange-end. The force obtained at the flange-end can be applied to using a piezoelectric or electromagnetic energy harvester to generate an electrical output that will energize electro-mechanical devices induced in the flow.

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