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Determination of Flow Patterns in Vertical Upward Two-Phase Flow Channel via Void Fraction Profile

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ABSTRACT

Two-phase flow happens widely in the industrial plants and certain equipment. This paper attempts to study the characteristics of two-phase flow in a vertical piping system. This was achieved by comparing the void fraction, in the working fluid, by employing Constant Electric Current Method (CECM) with the actual observation using high-speed camera. The experiment requires a complete set of two-phase flow system information and was conducted based on various flow conditions. In order to carry out this experiment, the two-phase flow loop was constructed using a specific experimental apparatus and components. The flow channels were constructed using three pipes with three different inner diameters of 21.0 mm, 47.0 mm and 95.0 mm. The flow direction was vertical upward co-current flow with liquid superficial velocity range of 0.025 m/s to 3.0 m/s and gas superficial velocity range of 0.025 m/s to 3.0 m/s, depending on the size of the pipe. The flow pattern investigation focuses on experimental work, which was based on systematic observation and measurements using a high-speed camera and some measuring apparatus. The void fraction measurement using the CECM sensor was integrated into two-phase flow system with constant electric current running in the pipe and data acquisition system controlled virtually via LabVIEW software. Both result of the flow pattern and void fraction graph were then compared to determine the type of flow pattern from the void fraction graph. Information from the previous studies and experiments were collected and the assumption of any theoretical simplifications were used as a reference. According to the result, the flow pattern in pipe can be easily determined using CECM.

Keywords: Two-phase flow; Flow pattern; Void fraction; Superficial velocity.

NOMENCLATURE

A	cross-sectional area
A_L	cross-sectional area occupied by liquid phase
A_G	cross-sectional area occupied by gas phase
D	diameter
j	superficial velocity
j_L	water superficial velocity
j_G	air superficial velocity
I_0	constant current supplied
L	length
Q	flow rate
Q_L	liquid flow rate
Q_G	gas flow rate
R_{TP}	electric resistance of two-phase flow
R_G	electric resistance of gas phase
R_L	electric resistance of liquid phase
s	deviation
V_L	liquid phase voltage
V_{LG}	gas-liquid phase voltage
V_{TP}	gas-liquid phase voltage drop
W_L	mass flow of liquid
W_G	mass flow of gas
ρ_L	liquid density
ρ_G	gas density
μ_L	liquid mean velocity
μ_G	gas mean velocity
α	void fraction
η	hold-up
α_{means}	actual void fraction
α_{pred}	predicted void fraction
ε	error

1. INTRODUCTION

Knowledge of the two-phase flow is very important for engineers in technical applications such as power plants, chemical industries, oil wells and pipelines. Most engineering equipment such as boiler, condenser and cooling system consist of pipelines for circulation systems, which carry two-phase gas-liquid flow. This equipment relies on the efficiency of water and gas flow during operating time. The performance of the system depends on the accuracy of the two-phase flow system. A two-phase flow study is essentially needs in the design and safety aspects of various components in the industries. Thus, this can be applied to improve component quality, improve process safety, increase production efficiency and reduce production and maintenance costs.

There are several techniques and methods have been developed in order to measure the void fraction in the two-phase flow condition. A common and simple method to get the information of flow pattern is by using the visual observation techniques. Taylor and Hewitt (1970) used visual observation techniques to observe the flow pattern inside the tube using high-speed photography techniques. X-radiography techniques has been developed to overcome the refractions issue in visual observation. Heindel *et al.* (2007) developed an X-ray imaging method. Their experimental work characterized and measured various flow features in large vertical systems that had internal diameter of up to 32 cm and as high as 4 m. The X-ray radiography and stereography imaging have been provided by the facility to visualize and time-resolve 3D flow structure in multiphase and opaque fluid flows at up to 60 frames per second. Neutron radiography (NR) technique is another method for measuring and visualizing two-phase flow and void fraction. Mishima (1996) has measured the void fraction using neutron radiography (NR) and image processing techniques. Mishima's tests ran at high frame-rate neutron radiography with a steady thermal neutron beam and used the latest technology for neutron source, scintillator, high-speed video and image intensifier. The Electrical Resistance Tomography (ERT) is one of the advanced methods nowadays in monitoring the flow pattern. The ERT not only produce the conductivity images, but also able to measure some flow parameters. Yixin *et al.* (1997) have done a research by applying the ERT system to monitor the gas-liquid two-phase flow in horizontal pipes. Void fraction measurement using the special equipment like X-ray and tomography methods are relatively expensive and are not cost effective to be measured in real times applications. The new method such as the Constant Electric Current Method (CECM) gives an advantage to the industry to measure the real time void fraction value with a low operating cost.

2. METHODOLOGY

Two parts of experiment were conducted; investigation of flow pattern and void fraction measurement. Both of these experiments require a complete set of two-phase flow system and were carried out based on various flow conditions.

2.1 Experiment Rig

An adiabatic co-current two-phase water-air flow was explored in this experiment. One test rig was used for both flow pattern investigation and void fraction measurement experiments.

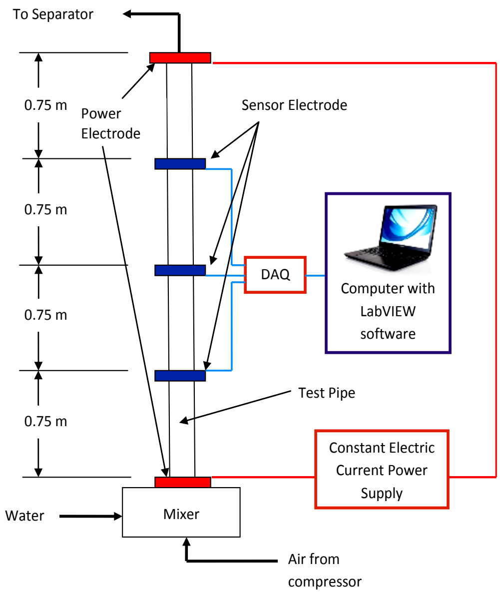


Fig. 1. Schematic view of CECM experiment.

Water was circulated in the flow loop by the water pump and air was supplied in the mixer by the air compressor refer to Fig. 1. The water and air flow rates were measured using flow meters and regulated using the valves and regulators. The two-phase water-air flow will then flow through the transparent acrylic test pipes with different inner diameters of 21, 47 and 95 mm, and 3 m long. Experiments were performed at room temperature (27 °C) and atmospheric pressure (101.3 kPa).

The direction of the flow was vertical upward co-current flow, with a liquid superficial velocity ranging from 0.025 m/s to 3.0 m/s and gas superficial velocity ranging from 0.025 m/s to 3.0 m/s, depending on the size of the pipe.

2.2 Flow Pattern Observation

There are several techniques that have been developed to observe the flow pattern of two-phase flow in pipes, and this experiment uses the most common high-speed photography technique. Digital Single Lens Reflex (DSLR) camera, (Olympus DSLR E-420) with shutter speeds of 1/4000s - 2s was used. High-speed video camera, Casio EX-F1 with capability of 1200 frames per second was used to capture the motion of the bubbles in the experiment. Lighting equipment such as LED lights, halogen lamps and camera flash were used to get a better pictures during the flow pattern recording. The 3 m long pipe was divided into four

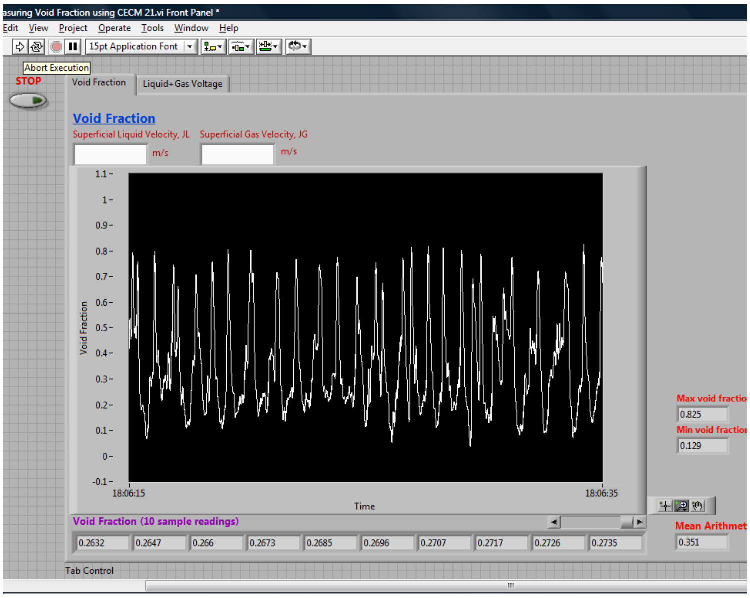


Fig. 2. Void Fraction measurement using LabVIEW software.

sections, and the end of each section was identified as the observation point of the flow pattern.

2.3 Void Fraction Measurement

For void fraction measurement, the Constant Electric Current Method (CECM) was used. All three test pipes were customized in order to install the three pairs of sensor electrodes. Each 3 m long pipes was then cut into four sections with each section having a length of 0.75 m. The sensor electrodes positions are at point 1, point 2 and point 3 with two power electrodes on each pipe. Copper wires connects all the electrodes to the data acquisition (DAQ) module that was connected to a computer installed with DAQ software (LabVIEW). The DAQ software was employed to observe, analyze and store the experimental data as shown in Fig. 2.

The CECM used to measure the void fraction was then integrated into the two-phase flow system with constant electric current running in the pipe and the data acquisition controlled virtually via the LabVIEW software. The constant current power source was used to supply the constant electric current through power electrode, and the sensor electrodes capture any voltage fluctuations due to presence of gas in the channel. At the same time, the DAQ system records the voltage output, and this was analyzed using the LabVIEW software. The fundamental overview of void area measurement is shown in Fig. 3.

$$\alpha = \frac{A_G}{A} = \frac{1}{\left\{1 + \frac{W_L}{W_G}\frac{\rho_G}{\rho_L}\frac{u_G}{u_L}\right\}} \tag{1}$$

or simply,

$$\alpha = \frac{A_G}{A} = \left(\frac{D_G}{D}\right)^2 \tag{2}$$

The reading of the gas-liquid phase voltage was taken. The calibration of voltage reading and void fraction value was carried out to get an accurate reading. The void fraction values at all points of observation were then converted by using the formula below:

$$\alpha = 1 - \frac{V_L}{V_{TP}} \tag{3}$$

$$\alpha = \frac{V_L - V_{LG}}{V_L} \tag{4}$$

where α = void fraction

V_L = liquid phase voltage, V

V_{TP} = gas-liquid phase voltage, V

According to the assessment by Coddington and Macian (2002), two of the correlations yielded good predictions over the whole range of void fractions. These correlations are Bestion correlation (1985) and Toshiba correlation (1992). The following Eqs. (5) and (6) describe the Bestion drift-flux correlation.

$$\alpha = \frac{j_G}{C_o j + v_{gj}} \tag{5}$$

where

$$v_{gj} = 0.188\sqrt{\frac{g d_h \Delta p}{p_g}} \quad C_o = 1 \text{ and} \tag{6}$$

Toshiba correlation (1989) was used as a general correlation for prediction of void fraction based on the experimental data and close to constant value. The following formula is a Toshiba correlation of void fraction prediction:

$$\alpha = \frac{j_G}{C_o j + v_{g\,j}} \quad (7)$$

Where

$$C_o = 1.8 \quad \text{and} \quad v_{gj} = 0.45 \quad (8)$$

The measured void fractions were compared with predictions by the Bestion drift-flux model and the Toshiba correlation. The absolute error, average error and deviation were calculated respectively using the following formulas:

$$\varepsilon = \alpha - \alpha \quad (9)$$

$$\bar{\varepsilon} = \frac{1}{n}\sum \varepsilon \quad (10)$$

$$s = \sqrt{\frac{\sum_{i=1}^{n}(\varepsilon_i - \bar{\varepsilon})^2}{n-1}} \quad (11)$$

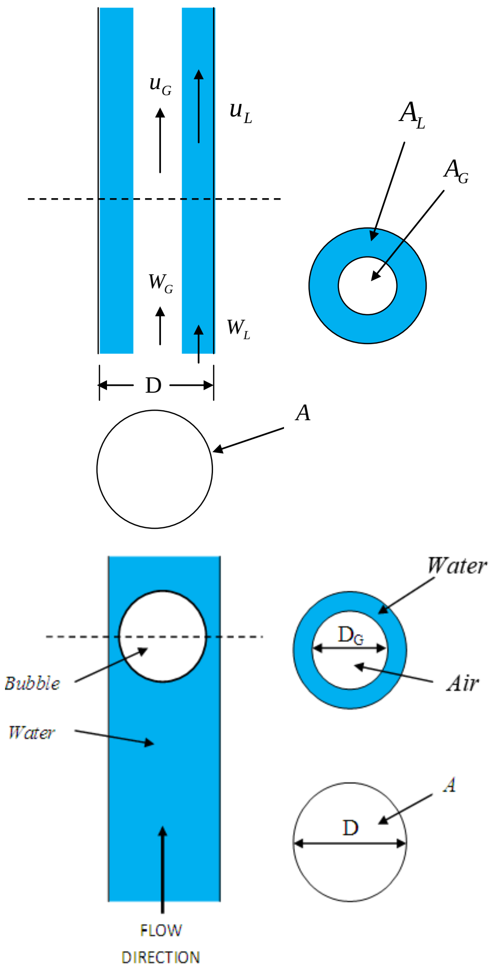


Fig. 3. Fundamental of void fraction measurement.

3. Result And Discussion

The two-phase flow patterns were observed at various water and air superficial velocities. Flow patterns were recorded using the DSLR camera and high-speed video camera. The flow patterns were identified as bubbly flow, bubbly-slug flow, slug flow and churn flow for vertical upward flow. The results were then compared with the flow pattern result by Collier and Thome (1996).

Void fractions were measured by using CECM through the voltage drop technique. The outcome graphs and results from the DAQ system illustrated the value of void fraction and determined the flow patterns of the two-phase flow by comparing the graph with observation result. Each flow pattern has a different shape of void fraction graph, which identified the types and characteristics of the flow.

The void fraction's graph patterns from CECM were compared to the flow patterns recorded by DSLR camera. Figure 4 shows the comparison for both CECM results and flow patterns made on the same water and air superficial velocity for 47.0 mm inner diameter pipe. The outcome graphs and results of the DAQ system illustrates the reading of void fraction and determines the flow pattern of two-phase flow by comparing the graph with the observation result. Each flow pattern has a different pattern that directly indicates the type and characteristic of the flow.

Following this, further comparison of void fraction experiment results with Bestion and Toshiba drift-flux correlations were made, and this is shown in Figs. 5 to 7.

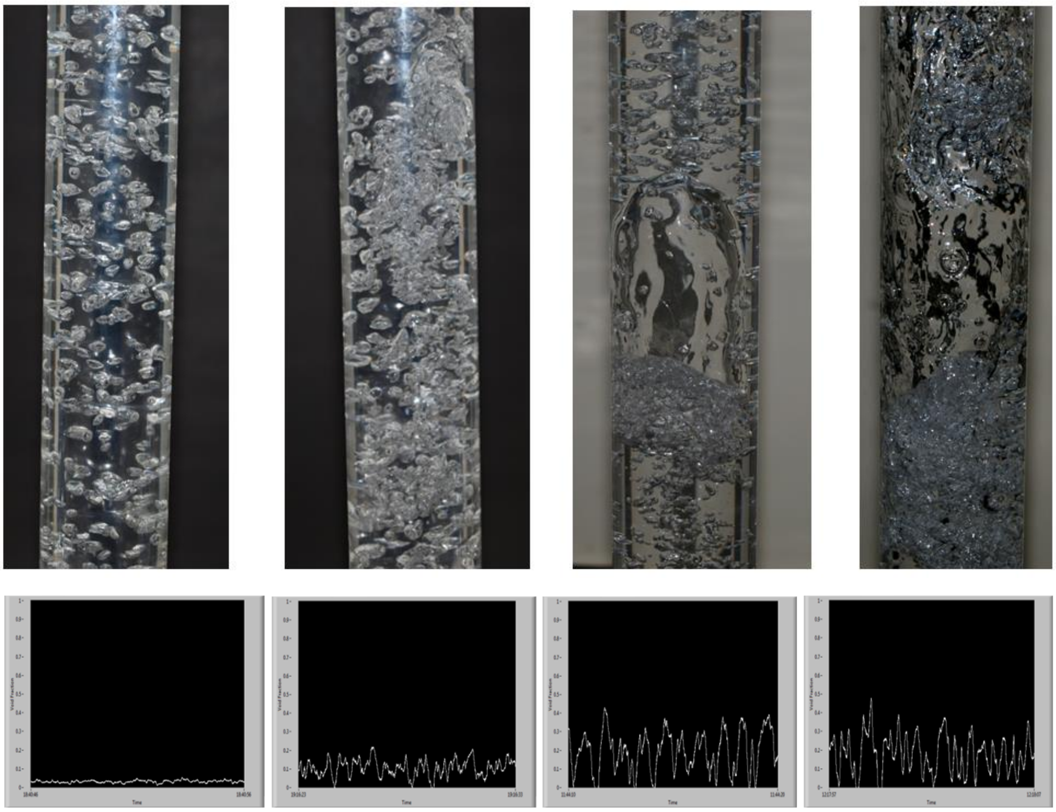
Table 1 show the summary of comparison for average error and average deviation between the experimental result with Bestion and Toshiba correlation in vertical upward flow pipe.

4. Conclusions

In this paper, we examine the characteristics of two-phase air-water flow in vertical pipes and compared to the void fraction value measured using the Constant Electric Current Method. As a result, four flow patterns were successfully observed during the upward vertical flow experiment using the DSLR camera and high-speed video camera. The flow patterns that were captured include bubbly, bubbly-slug, slug and churn for vertical upward flow direction.

Both gas superficial velocity, j_G and liquid superficial velocity, j_L gave an impact to the flow pattern. The liquid superficial velocity j_L had a great impact on the flow pattern transition in small pipe. The results agreed well with the theory by Butterworth *et al.* (1977). However, the liquid superficial velocity, j_L only contributed small effects on flow pattern transition in the large pipe, especially for 47.0 mm and 95.0 mm inner diameter pipes.

Void fraction was successfully measured using the CECM through a voltage drop technique by Fukano (1998). The connections of sensors inside the 21.0 mm, 47.0 mm and 95.0 mm inner diameter pipes were used to measure the difference voltage in two-phase flow. The outcome graphs and results from DAQ system illustrated the reading of void fraction and determined the flow pattern of two-phase flow



i) Bubbly Flow $\alpha = 0.03$ ii) Bubbly-Slug Flow $\alpha = 0.162$ iii) Slug Flow $\alpha = 0.251$ iv) Churn Flow $\alpha = 0.359$

Fig. 4. The example of flow pattern and void fraction graph and measurement for 47.0 mm inner diameter pipe.

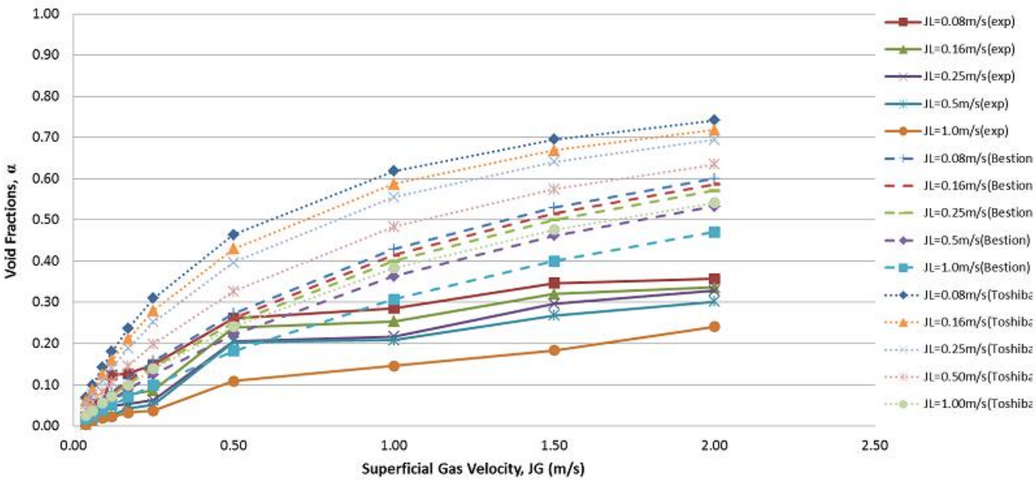


Fig. 5. Comparison between CECM void fraction measurement with Bestion and Toshiba drift-flux correlation for 21.0 mm inner diameter vertical pipe.

Table 1 Summary of comparison for average error and average deviation between the experimental result with Bestion and Toshiba Correlation in vertical upward flow

Correlation	Bestion Correlation			Toshiba Correlation		
Pipe Size	21.0 mm	47.0 mm	95.0 mm	21.0 mm	47.0 mm	95.0 mm
Average Error	-0.0768	-0.0428	0.0185	-0.1640	-0.1633	-0.1198
Average deviation	0.0888	0.0742	0.0249	0.1225	0.1160	0.1214

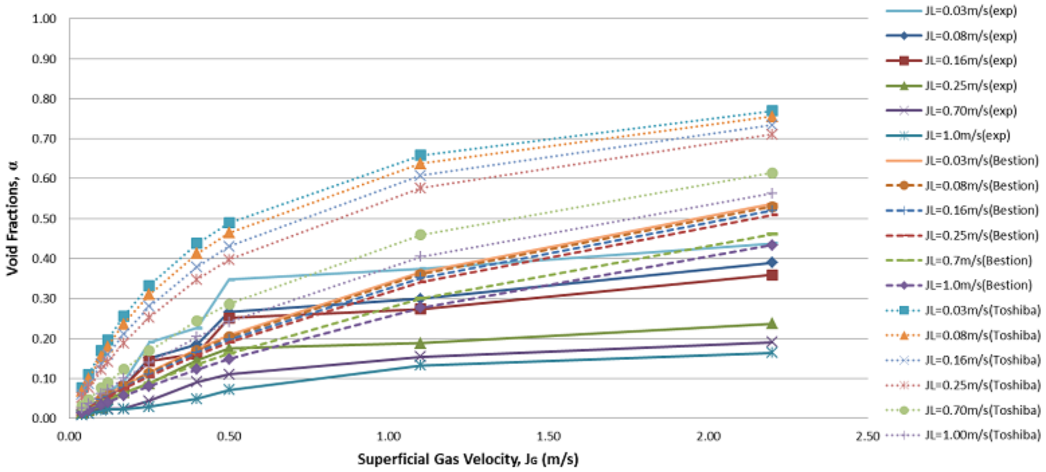


Fig. 6. Comparison between CECM void fraction measurement with Bestion and Toshiba drift-flux correlation for 47.0 mm inner diameter vertical pipe.

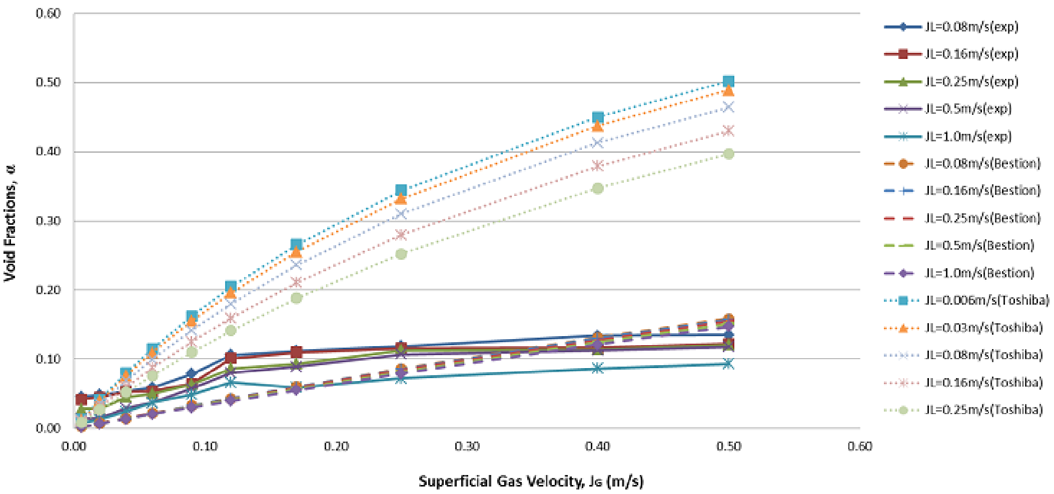


Fig. 7. Comparison between CECM void fraction measurement with Bestion and Toshiba drift-flux correlation for 95.0 mm inner diameter vertical pipe.

by comparing the graph with the observation result. Each flow pattern was found to be different, and this was used to identify the type and characteristic of the flow. The void values recorded in this experiment were found to be directly proportional to the percentage of gas and liquid inside the pipe. However, slight error of the reading during the experimentation can be neglected. The overall reading and result can be accepted to measure the void fraction of two-phase flow by using CECM.

The comparisons of experimental results with Bestion and Toshiba drift-flux correlations were made regarding the measurement of void fraction values. The average error and average deviation were calculated from the void fraction values for all pipes. Overall, it can be said that the void fraction graph directly shows the type flow pattern of a two-phase flow in a vertical pipe. Each flow pattern corresponds to a unique graph pattern in the void fraction value. Thus, the type of flow pattern can be easily determined from the graph without the need of visual observation. This gives an advantage during the determination of flow pattern inside an opaque pipe.

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