INVESTIGATION OF THE VOID FRACTION OF GAS-LIQUID TWO PHASE FLOW IN VERTICALLY-UPWARD CHANNEL

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RESEARCH REPORT SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF MECHANICAL ENGINEERING

FACULTY OF ENGINEERING
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Name of Degree: Master of Mechanical Engineering

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Field of Study: Power Plant Engineering

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ABSTRACT

Void fraction is an important process variable for the volume and mass computation required for transportation of gas-liquid mixture in pipelines, storage in tanks, metering etc. Inaccurate measurement would introduce errors in product measurement with potentials for loss of revenue. Accurate measurement is often constrained by invasive and expensive online measurement techniques. This work focuses on the use of Constant Electric Current Method (CECM) using specially developed sensor to measure void fraction in a vertically arranged gas-liquid two-phase flow channel. The effects of velocities of both phases were examined with variety of combinations using an industrial scale two-phase flow loop. The results show that at a constant rate of liquid superficial velocities, the void fraction increases with the increasing gas superficial velocities and at a higher velocity of liquid phase, the value of void fraction becoming lower. Besides, at lower liquid superficial velocity, the void fraction at the upper side of flow channel is higher than the lower position. However, when the liquid phase dominates the flow channel at higher liquid superficial velocity, and when the gas superficial velocity is further increased, the flow become chaotic and a rough turbulent condition has developed, and therefore void fraction can be seen fluctuating up and down at the higher position.

Keywords: Two-phase flow, Void fraction, Measurement method, Flow measurements, Constant electric current method

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ABSTRAK

Pecahan lompang merupakan proses pemboleh ubah proses yang penting bagi pengiraan volum dan jisim yang diperlukan untuk pengangkutan campuran gas-cecair dalam saluran paip, penyimpanan dalam tangki, pemeteran dan sebagainya. Pengukuran yang tidak tepat akan menyebabkan kesilapan dalam pengukuran produk seterusnya berpotensi kehilangan hasil. Pengukuran yang tepat sering dikekang oleh teknik pengukuran dalam talian yang invasif dan mahal. Kerja-kerja ini memberi tumpuan kepada penggunaan Kaedah Arus Elektrik Berterusan (CECM) menggunakan sensor yang dibangunkan khas untuk mengukur pecahan lompang dalam saluran aliran dua fasa gas-cecair. Kesan halaju kedua-dua fasa diperiksa dengan pelbagai kombinasi dengan menggunakan gelung aliran dua fasa skala industri. Keputusan menunjukkan bahawa pada kadar tetap halaju cecair, pecahan lompang bertambah dengan halaju gas yang semakin meningkat dan pada halaju fasa cecair yang lebih tinggi, nilai pecahan lompang menjadi lebih rendah. Selain itu, pada halaju rendah cecair, pecahan lompang di bahagian atas saluran aliran lebih tinggi daripada kedudukan yang lebih rendah. Walau bagaimanapun, apabila fasa cair menguasai saluran aliran pada halaju cecair yang lebih tinggi, dan apabila halaju gas semakin bertambah, aliran menjadi huru-hara dan keadaan bergelora terbentuk, pecahan lompang dapat dilihat turun dan naik di kedudukan yang lebih tinggi.

Keywords: Aliran dua fasa, Pecahan lompang, Kaedah pengukuran, Pengukuran aliran, Kaedah arus elektrik yang berterusan

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In the Name of Allah, the most Beneficent, the most Merciful.

First and foremost, I praise to Allah, the almighty, on whom ultimately, we depend for sustenance and guidance. I praise Allah for providing me this opportunity and granting me the capability to proceed successfully.

“And whoever is conscious of Allah, He will make for him a way out, and will provide for him from where he does not expect. And whoever relies upon Allah – then He is sufficient for him. Indeed, Allah will accomplish His purpose. Allah has already set for everything a [decreed] extent.” (Quran Translation, Chapter 65, Verse 2-3)

I am using this opportunity to express my sincere gratitude and special appreciation to the following people who made this project thesis possible.

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My family especially Mom and Dad

Friends

For any error and adequacies that may remain in this work, of course the responsibility is my own.

Thank you. May Allah the Almighty bless all of us.

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TABLE OF CONTENTS

University of Malaya

University of Malaya

University of Malaya

LIST OF FIGURES

University of Malaya

University of Malaya

LIST OF TABLES

University of Malaya

LIST OF SYMBOLS AND ABBREVIATIONS

Roman Letters

a	:	Ground acceleration [m/s^2]
A	:	Area [m^2]
A_C	:	Cross sectional area of calibration rod [m^2]
A_E	:	Cross sectional area of experimental flow channel [m^2]
A_G	:	Cross sectional area of bubble [m^2]
d	:	Diameter of a bubble [mm]
D_C	:	Diameter of calibration rod [mm]
D_E	:	Diameter of flow or experimental channel (=D or ID) [mm]
F	:	Force [N]
g	:	Gravitational acceleration [m/s^2]
I_0	:	Electric current [mA]
ID	:	Internal diameter [mm]
j	:	Volumetric flux (=j_G+j_L) [m/s]
j_G	:	Superficial velocity of gas phase [m/s]
j_L	:	Superficial velocity of liquid phase [m/s]
L_B	:	Length of a bubble [mm]
L/D	:	Axial position (for sensor) [-]
m	:	Mass [kg]
$\dot{m}$	:	Mass flow rate [kg/s]
P	:	Pressure [MPa]
Q_b	:	Volumetric gas flow rate [m^3/min]
r_0	:	Radius of flow channel [mm]
R_G	:	Electric resistance in the gas phase [Ω]

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R_L	:	Electric resistance in the liquid phase [Ω]
R_{TP}	:	Electric resistance in the gas-liquid two-phase flow [Ω]
s	:	Thickness of bubble layer[mm]
S	:	Slip ratio [-]
t	:	Time [s]
T	:	Temperature [^{o}C]
T_0	:	Period of circle [s]
v	:	Velocity [m/s]
v_b	:	Velocity of a rising bubble [m/s]
v_G	:	Gas mean velocity [m/s]
v_L	:	Liquid mean velocity [m/s]
v_{GJ}	:	Drift velocity of gas phase [m/s]
v_∞	:	Terminal velocity of rising bubble [m/s]
V_L	:	Voltage fluctuation for single phase flow [V]
V_{TP}	:	Voltage fluctuation for two-phase flow [V]

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Greek Letters

α	:	Void fraction [-]
α_{avg}	:	Average of void faction between two axial position [-]
$\alpha_{avg(l)}$	:	Average of void faction at local position [-]
$\alpha_{avg(L)}$	:	Lowest value of average void fraction [-]
$\alpha_{avg(H)}$	:	Highest value of average void fraction [-]
α_{limit}	:	Limit of void fraction [-]
$\alpha_{\max(l)}$	:	Maximum value of local void fraction [-]
δ	:	Thickness of liquid film [mm]
η	:	Holdup [-]
ρ	:	Density [kg/m^3]
μ	:	Viscosity [Pa·s], [kg/m·s]
υ	:	Kinematic viscosity [m^2/s]
σ	:	Electrical conductivity [S/m]

Abbreviation

CECM	:	Constant Electric Current Method
LOCA	:	Loss of Coolant Accident

Properties (at room temperature and atmospheric pressure)

Density of Water	:	$\rho_{water} = 998\ kg/m^3$
Density of Air	:	$\rho_{air} = 1.2\ kg/m^3$
Viscosity of Water	:	$\mu_{water} = 8.9 \times 10^{-4} Pa \cdot s$
Viscosity of Air	:	$\mu_{air} = 18.6 \times 10^{-5} Pa \cdot s$

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LIST OF APPENDICES

University of Malaya

CHAPTER 1: INTRODUCTION

The title of this report provides the reader with a general notion of the concepts which are likely to be explored in this report. This work is primarily concerned with the measurement of volumetric rate or termed as void fraction, in a vertically arranged gas-liquid two-phase flow channel that has been considered as important in many engineering systems as it is closely related with the system safety and performance. Ultimately the purpose of the work is to investigate the effects of velocities of both phases using an industrial scale two-phase flow loop on void fraction by Constant Electric Current Method (CECM). At the outset of this project, it is necessary to define the problem statement, objectives, scope, aims and stage overview of the project as was as the layout of the report.

1.1 Problem Statement

Two-phase gas-liquid flow occurs when both the gas and liquid phases exist in the flow as different components (e.g., air-water, helium-water, etc.), or in the event when the flow of a fluid is experiencing a phase change as a result of evaporation or condensation. Such a flow can commonly be found in the nuclear, petroleum, and process industries. The complex nature of two-phase gas-liquid flow is the consequence of the flow being influenced by several flow parameters. Void fraction is one of the major flow parameters that affect the behaviour of two-phase flow. Thus, in the effort to gain a better understanding of the complexities involved in two-phase flow, it is necessary to study and understand the characteristics of the void fraction.

1.2 Objectives

With the above discussions, it is therefore very important to conduct some physical experimentations to study the changes on flow structures that resulted by difference in

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gas-liquid velocities on the two-phase flow in pipe as replication to the real plants. Fundamentally, the objectives of the present work are;

i. To conduct direct measurement on the void fraction with a full-scale analysis using Constant Electric Current Method (CECM); and
ii. To investigate the effects of velocities of gas-liquid phase using an industrial scale two-phase flow loop on void fraction.

1.3 Scope of Works

The terminology and definition of void fraction are described in detail to provide a clear objective of the current work. The investigations are including the examination on how the velocities of both phases will contribute to the void fraction value.

In order to conduct the above measurements, a systematic sensor has been developed and installed in the flow channel by Zainon (2013). This sensor is therefore becoming one of the important facilities for two-phase flow experimentation at the Thermal-hydraulics and Power Plant Laboratory, Department of Mechanical Engineering, University of Malaya, Malaysia. The performance of this sensor has been validated by the calibration conducted both for the static and dynamics methods with tested reliability on many parameters including the void fraction and liquid film thickness on the wall of flow channel.

It has been mentioned and discussed for so many times as the above that the vast applications of the two-phase flow for processing and power plant involve with heat transfer and high temperature fluid. However, throughout the current work, the heat application was not possible due to many aspects of limitations. Therefore, all the experimentations were carried out based on the two-phase flow at the atmospheric pressure and room temperature conditions as replication for the real condition. This

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condition however, very well met many criteria of the heat application which is very importantly in terms of ratios of void fraction that determine the condition during heat addition into the flow in pipes.

Several assumptions were made for the current investigations as follows:

i. Two-phase flow channel as a control volume at steady state.
ii. Pipe inner surface is seamless
iii. Negligible leakage
iv. Negligible induced vibrations due to very small fluctuations

1.4 Stage Overview

In order to achieve the aims of the project within only two semesters of Master of Engineering, it will be necessary to perform the task by dividing into two major stages. Therefore, the stages are described and summarised in this section.

1.4.1 Stage One (1)

i. As a start, literature reviews are conducted and completed to obtain background information of the project and the fundamental knowledge.
ii. Select the parameter to focus on and subsequently develop the method to conduct the experiment.

1.4.2 Stage Two (2)

i. The second stage of the project is focusing on the experimental work to accomplish the objectives.
ii. Preparation of the apparatus and materials for conducting the experiment.
iii. The collected results are observed and discussed.
iv. Write up experimental results.
v. Recommendations for future study are also proposed.

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1.5 Report Layout

The report of the project can be summarised into chapters as described below:

Chapter 1- *Introduction* - This chapter describes the background information as to the significance of adopting the research topic. Additionally, the aims of the project and its scope are outlined in this section.

Chapter 2 – *Literature Review* - This chapter provides an insight into the previous researches and development that have been conducted directly related to this research topic or indirectly in the sense that the similar or different approaches to study behaviour of two-phase flow. Besides, the literature review also provides in-depth information of the topic focusing on the measurement techniques of void fraction in different arrangement of channel based on previous findings. Furthermore, the focus of the literature review is then narrowed to the relation of void fraction, measurement techniques and other parameters.

Chapter 3 - *Methodology* - In this Chapter, experimental procedures are explained in-depth by highlighting the method, experiment facility, parameters and criteria used in this study. In addition, sufficient amount of details is provided for repetition of the experiments to be conducted by trained individuals in the future.

Chapter 4 – *Results and Discussion* – In this chapter the result of the experiment that has been performed is presented and discussed. Observations of the results was done to identify and meet the project aim and objective. It follows by the discussion that deliberates on assessment on the effects of velocities of both phases with variety of combinations using an industrial scale two-phase flow loop on void fraction.

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Chapter 5 – *Conclusion and Recommendations* - This chapter will address the summary of the experimental findings. Besides, this Chapter also looks into the recommendation for the future works and study.

Having proceeded to outline the scope, aims, and tasks to be completed in the pursuit of the project as well as the lay out of this report, it is now necessary to turn attention to the literature review of the current study.

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CHAPTER 2: LITERATURE REVIEW

This chapter presents a critical review of the literature associated to this project, which includes broad understanding of the fundamentals of gas-liquid two-phase flow in particular those relating to vertical flows as these have direct relevance to this study. It will also discuss void fraction and its measurement techniques.

2.1 Fundamental of Two-Phase Flow

Two-phase flow is the simplest form of multiphase flow and it involves the simultaneous movement of two distinct phases in a pipe; the gas, liquid and/or solid, of any substance or combination of substances. Therefore, it can basically define as the interacting flow between two phases either gas-liquid, gas-solid or liquid-solid flow. Two-phase flow can further be divided into two forms which are boiling and non-boiling two phase flow. Boiling two phase flow is attained when a single-phase fluid evaporates due to heat transfer and the simultaneous flow of liquid and vapor of the same component in the pipe is termed single component two phase flow. Boiling two phase flow is observed in steam-water flow in power generating plants, flow of refrigerants in air conditioning systems. Non-boiling two phase flow involves two distinct components and is observed in oil production activities where there is flow of natural gas and crude oil through pipes. The application of two phase flow is found in major areas like the cooling of fuel rods in a nuclear reactor for power generation, enhancing mass transfer in the chemical processing industry, understanding and predicting wax deposition during crude oil and natural gas transportation in the oil and gas industry, condensate formation in natural gas transportation.

Gas-liquid two phase flow phenomenon has been studied since the 1930’s in four major aspects which are flow patterns, void fraction, pressure drop and heat transfer. Due to the very broad nature of two-phase flow, research in each major aspect is concentrated

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on certain pipe orientation, fluid combination or range of system pressure. For example, some researchers investigate flow patterns, void fraction or heat transfer in specific pipe orientation or develop correlations to predict heat transfer, void fraction or pressure drop for certain fluid combination. The present study is dedicated to void fraction in non-boiling air-water two phase flow in vertical pipes which only covers upward flow.

Furthermore, there are three methods of investigation of the two-phase flow models. The first classical method would be the experimental approach through laboratory scales referring to industrial scales that is equipped with appropriate instrumentation, where it is practiced since 1950s such as, works by Sterman (1956), Hughmark (1965), Gardner (1980), Michiyoshi and Serizawa (1989) and many others. The second method is through theoretical studies based on the calculation and correlation with the support from the previously obtained experimental data. They can be referred in early works by Barcozy (1966), Gregory et al. (1978), Mukherjee and Brill (1983), and a lot more until as recent as, Zhao and Hibiki (2019). The third and most progressively grow of works is via the modeling and analyses using the Computational Fluid Dynamics (CFD) which has been speed up along with the development in computer technologies. Some of the analytical and CFD works in two-phase flow are such as by Kataoka and Ishii (1987), Huq and Loth (1992), Huq et al. (1992), Okawa, Kataoka, and Mori (2002), Okawa et al. (2002) and Sharma et al. (2019).

As the two phases flow together in the same dimensional area it become a very intricate mixture of flow, and therefore the analysis of this flow system also becomes very challenging. Therefore, certain assumptions are needed and it is particularly very important to define the boundary conditions of the two-phase flow for simplification (Lenzinger & Schweizer, 2010). Wallis (1969) stated that the two-phase flow can be treated as one- dimensional flow to study the continuity relationship. This is a convenient

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approach to obtain the single- and two-phase energy and momentum. The distributions of each phase in the two-phase flow are really important in order to identify the characteristics of the flow. The fundamental information in two-phase flow such as heat transfer, flow pattern, void fraction, phase distribution and pressure loss are all related parameters in the two-phase flow study. Past research (Revankar & Ishii, 1992; Taitel & Dukler, 1976; Zuber & Findlay, 1965) give lots of existing information that will guide the analyses using mentioned parameters.

In this report, the two-phase flow system is concentrated on the mixture of gas- liquid, and in particular the discussions are mostly focus for the cases of air-water flow in pipes. As gas-liquid two-phase flows are commonly encountered in many engineering applications such as the cooling systems, household equipment, thermal power plants, oil recovery/refinery plants, chemical processes, etc., hence, a thorough understanding in two-phase flow is the requirement for engineers and designers working in many of engineering and manufacturing sectors. These knowledges enable to enhance the economic designs, optimization of operating conditions and assessment of safety factors for the system. For the economic designs, related information is needed by designers to optimize the system or equipment to be manufactured in the competitive market Boccardi et al. (2008). The second contribution of the quantitative information study is the optimum operating conditions where the operators of the plant need to decide, and other requirements on related knowledge are needed to diagnose faults and to operate at maximum capacity.

The key to this type of challenges may involve an experimental investigation of a particular geometry or two-phase flow regime which has not previously been studied. For instance, the failure of boiler tubes due to flow stratification which might be able to be prevented by the changes of flow condition, and those flow condition must be based on

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the history of works recorded previously Rahmani et al. (2009). Furthermore, it is important to consider the safety aspects of these systems in order to guarantee their reliability and stability over the entire operating range; from start-up to full power and vice versa. Knowing the maximum safe operating limits in plant operation is really important in order to balance the optimum operation condition and safety limit of the system. For instance, in some critical conditions such as nuclear reactors, the maximum heat absorbed from the fuel bundle must be carefully calculated and knowledge of the full range of operating conditions are required in order to ensure that the safety margins can be allowed (Chun & Ryu, 2000; Nayak et al., 2006).

In addition, some major challenges in two-phase flow systems are including the prediction and measurement of the void fraction, pressure distribution along the pipe and thickness of the liquid film on the wall of the pipe. A detail and critical evaluation on the two-phase flow is particularly very important in order to ensure the safety of the plant.

2.2 Two Phase Flow in Two-Dimensional Column

In many engineering applications, liquids are usually stored in a large container of various shapes; cylinders, rectangular and spheres. In this section, discussion on the large cylinder and rectangular containers will be focused with fluid stored inside having interchangeable of phases or containing both the liquid and gas at the same time. For instance, the steam generators produce steam from water and the phase might alternately changes as the condensation occurs.

For the simplicity of analysis many workers start with examining the behavior of rising bubbles in a container such as works done by Krishna and van Baten (1999), Zainon and Serizawa (2002), Talaia (2007) and Wang et al. (2019). They performed experimentation on rising bubbles with different diameters in a two-dimensional column with a static liquid. They found that in a gas-liquid system, detail descriptions of rising characteristics

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of gas bubbles are quite important. In addition, the gas bubble will move upward in a system that has a gas bubble generation from the bottom of the vessel and in any observation, it can be seen the motion is not in a straight line. This phenomenon happens because the gas is traveling below a substance that has a higher density, then the motion is in sinuous depending on their sizes. This phenomenon has also been obtained more than five centuries ago by Leonardo da Vinci as in the original drawing shown in Figure 2.1.

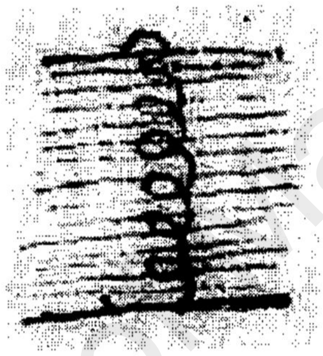

Figure 2.1 Sinuous motion of gas bubble by Leonardo da Vinci. The original text containing his writings are available on CD-ROM, Leonardo da Vinci, Corbis Corporation 1996 (Krishna & van Baten, 1999)

In addition, Krishna and van Baten (1999) performed experimentations in a two-dimensional rectangular column which was filled with water and simulated the trajectories of rising bubbles of 4 to 20 mm in diameter. They applied the volume- of-fluid (VOF) technique as the CFD tool which was also implemented by Hirt and Nichols (1981). From the simulation-experimental comparison, small bubbles at 4 and 5-mm diameter show large side-to-side motions similar to observations by Da Vinci. Medium size bubbles at 7,8 and 9-mm diameter bubbles move like jellyfish, and another bigger size in this work, bubble at 12 mm diameter behave like flutter wings. They concluded that the swing of motion of the bubbles will become lower by the increasing bubble diameter. At larger diameter, around 20 mm and above, the bubble will form a spherical cap where both the experiment and simulation agreed well.

Besides, Talaia (2007), Amaya-Bower and Lee (2010)and Wang et al. (2019) focuses on the effects of drag forces and buoyancy on the bubble velocity while rising in a liquid column where it is naturally depends on the buoyancy force, drag coefficient, property of fluids and the bubble diameter as well. They investigated the terminal velocity of the bubble and concluded that the dynamic viscosity effect played an important role.

Furthermore, many engineering processes also involve with more bubbles generation in a container such as mixing of difference substance in the paint industries, chemical stirrer, etc. These processes require bubbles generation in huge amount or in group of bubbles called swarms. Acuña and Finch (2010) also used the two-dimensional column with slot-type spargers and digital high-speed camera to track the velocity of swarm bubbles of diameters 0.2 to 5-*mm* and void fraction from 2% to 30%.

2.3 Two Phase Flow in Annular Channel

Structures like pipes that convey fluid are widely used in chemical plants, municipal water supply, boiling water reactor, heat exchanger tubes, hydropower system, etc and sometimes are in very complex arrangements. Many kinds of fluid with various types of flow including the two-phase flow are being transported in the piping system and the studies in this field have been conducted from a long time ago (Wallis, 1969).

Besides, power and processing plants also have different orientation (i.e. vertical, horizontal and inclined) and arrangement of the pipe flow due the applications and the design of the plant. These orientations will thus contribute to many other phenomena which differ from one to another. In this study, the analyses of two-phase flow in pipe are only focused on the vertical arrangement. The working fluids in this two-phase flow system are air and water flowing co-currently in an annulus transparent pipe.

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In addition, some major problems in two-phase flow systems are including the prediction and measurement of the void fraction, pressure distribution along the pipe and thickness of the liquid film on the wall of the pipe. These three parameters are the most significant factor in order to ensure the safety of the equipment or plant. Pozos et al. (2010) and Ebrahimi et al. (2019) reported that the presence of air in water pipelines causes many drawbacks if not controlled, such as loss of carrying capacity, change of physical properties of fluid, disruption of hydrodynamics and reduction of system efficiency. Besides, pipes leakage and burst due to impropriate treatments of two-phase flow are very common in many sectors. This will lead to serious disasters to humans and environment and some time with results of casualties. For instance, Gardner (2011) reported that leakages due to unpredictable pressure distribution caused by the drilling shakes and current flow in oil recovery plant are one of the major problems for oil producers as well and even in the inland pipe transport.

Correspondingly, Mishima and Ishii (1984) and Bergant et al. (2006) discovered that the pipe failure in the nuclear reactor occurred due to the two-phase flow induced vibration which also happen during the fluid hammer phenomena in ordinary thermal power plant. In a high temperature condition, Serizawa (1974), Fukano and Ousaka (1989) and Fukano (1998) found that measurement of liquid film thickness is very important in order to avoid the phenomenon such as the Loss of Coolant Accident (LOCA), where dried liquid on the heating wall will cause the melting of heating element or sometime termed as core meltdown. Therefore, in regards with the design of many industrial equipment such as heating element, various types of heat exchangers and in bigger scale like steam generators and nuclear fuel rods, engineers would also face challenges dealing with high temperature fluid. On top of that, it will be more complex if the system involves the two-phase flow as many parameters are needed to be considered

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such temperature, heat flux, mass flow rate etc. in order to optimize the design as discussed above.

With complicated situation in the two-phase flow, the first thing that should be considered is the void fraction. This factor is very important since it govern the whole situation in the flow channel.

2.4 Void Fraction

Before the discussion on available literature of void fraction correlations, it is necessary to understand the concept of void fraction and hence, a brief discussion on general concept and basic definition of void fraction is presented below.

2.4.1 Definition and Models

Void fraction is defined as volumetric gas rate in the liquid flow and can be considered as the most essential parameters in analysing the two-phase flow. In detail, it can be described as ratio of the gas volume (the voids in the flow channel) to the total volume of the flow channel. Let us consider an adiabatic case with a mass flow rate, $\dot{m}_L$ of liquid, with density, ρ_L and a mass flow rate, $\dot{m}_G$ of gas, with density, ρ_G are flowing upwards in a vertical pipe with a diameter, D_C, length z, and cross-sectional area, A_C.

Consequently, by considering that equilibrium has been achieved, the parameters in both phases can be treated as the following assumption referring to Figure 2.2. In this case, the liquid mean velocity can be represented as v_L and the gas mean velocity as v_G, while the cross-sectional area of the core of the flow channel that filled by the gas phase represented as A_G and its diameter as D_G.

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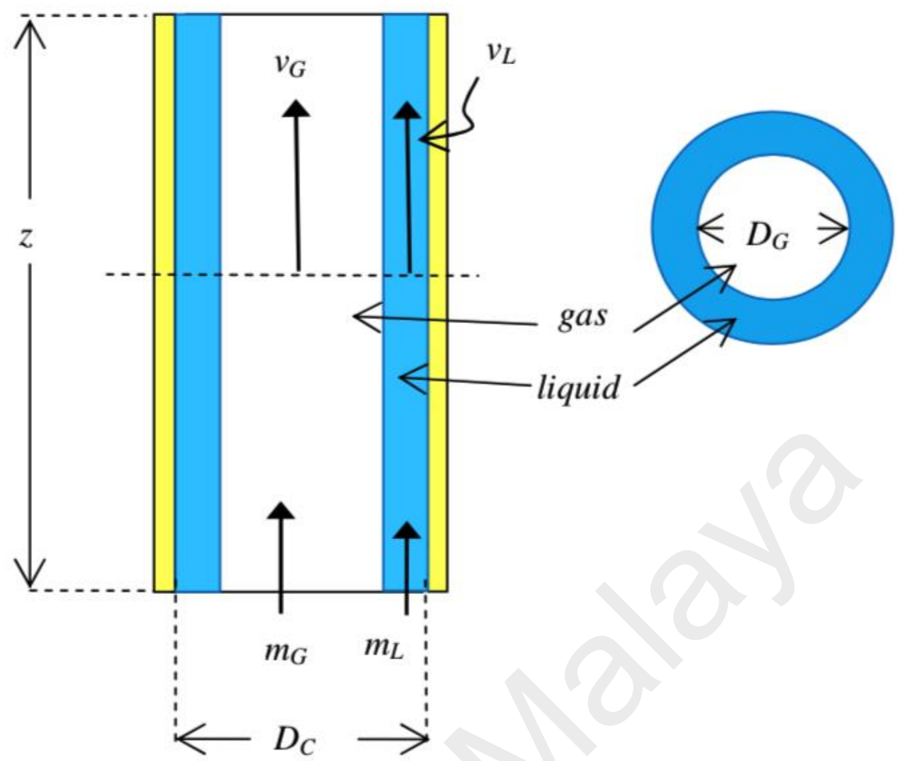

Figure 2.2 Fundamental depiction of void fraction (Zainon, 2013)

Information from Figure 2.2 can be expressed into the mathematical form as follows, where the volume of area ratio representing the void fraction,

$$\alpha = \frac{A_G}{A_C} = \frac{1}{\left(1 + \frac{m_L \rho_G v_G}{m_G \rho_L v_L}\right)} \tag{2-1}$$

Or simply,

$$\alpha = \frac{A_G}{A_C} = \left(\frac{D_G}{D_C}\right)^2 \tag{2-2}$$

2.4.2 Homogenous flow model

In one-dimensional method, a fundamental assumption can be carried out as a steady state has been established in the flow channel. Here the velocity of each phase is assumed to be constant even though some variations exist, but they are negligible. Therefore, average parameters are assumed over the cross-section and this model is termed as the *drift flux model* as suggested by Zuber and Findlay (1965).

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For simplicity of the equation, the force, F can be treated as one of the parameters described above and the governing equation for this assumption can be written as follows,

$$\langle F \rangle = \frac{1}{2} \int_A F \, dA \tag{2-3}$$

The weighted mean value of F can be expressed as,

$$\bar{F} = \frac{\langle \alpha F \rangle}{\alpha} = \frac{\frac{1}{A} \int_A \alpha F \, dA}{\frac{1}{A} \int_A \alpha \, dA} \tag{2-4}$$

Applying the volumetric flux, j and j_G and j_L as the superficial velocities of gas and liquid phase respectively, the average gas velocity can be written as,

$$\langle v_G \rangle = \langle j \rangle + \langle v_{Gj} \rangle \tag{2-5}$$

And the weighted mean velocity for gas flow can be expressed as,

$$\bar{v}_G = \frac{\langle j_G \rangle}{\langle \alpha \rangle} = \frac{\langle \alpha j_G \rangle}{\langle \alpha \rangle} = \frac{\langle \alpha j \rangle}{\langle \alpha \rangle} + \frac{\langle \alpha v_{Gj} \rangle}{\langle \alpha \rangle} \tag{2-6}$$

Where, v_{Gj} is the drift velocity of gas phase relative to j, the total flow velocity

While expression for superficial velocity in one-dimensional model, can be written as,

$$j_{GL} = \alpha v_{Gj} \tag{2-7}$$

And therefore, equation (2-7) can be written as,

$$\bar{v}_G = C_0 \langle j \rangle + \frac{\langle \alpha v_{Gj} \rangle}{\langle \alpha \rangle} \tag{2-8}$$

Where,

$$C_0 = \frac{\langle \alpha j \rangle}{\langle \alpha \rangle \langle \boldsymbol{j} \rangle} = \frac{\frac{1}{A} \int_A \alpha j \, dA}{\frac{1}{A^2} \int_A j \, dA \int_A \alpha \, dA} \tag{2-9}$$

Similarly, the weighted mean liquid velocity is given by,

$$v_L = \frac{\langle j_L \rangle}{\langle 1-\alpha \rangle} = \frac{\langle j - j_G \rangle}{\langle 1-\alpha \rangle} = \frac{\langle \alpha j \rangle}{\langle \alpha \rangle} + \frac{\langle \boldsymbol{j} \rangle - \langle j_G \rangle}{\langle 1-\alpha \rangle} \tag{2-10}$$

And the slip ratio given by,

$$S = \frac{j_G}{j_L} = \frac{\langle 1-\alpha \rangle}{\frac{1}{\left(C_0 + \frac{v_{Gj}\alpha}{\langle \alpha \rangle \langle j \rangle}\right) - \langle \alpha \rangle}} \tag{2-11}$$

In the case of no local velocity difference (slip velocity) between phases, $u_{Gj} = 0$:

$$S = \frac{\langle 1-\alpha \rangle}{\frac{1}{c_0 - \langle \alpha \rangle}} \tag{2-12}$$

For $C_0 \neq 1$, the slip ratio is not unity, even though the phases are travelling at the same velocity at each point in the channel. This arises because of differences between the distribution of velocity and void fraction. If v_{Gj} is constant across the channel, then equation (2-8) can be converted into a void-quality relationship of the form:

$$\langle \alpha \rangle = \frac{j_G}{C_0 \langle j \rangle + v_{Gj}} \tag{2-13}$$

This equation shows that $\langle \alpha \rangle$ can be determined if C_0**,** v_{Gj} and the average gas or vapour volumetric flux $\langle j_G \rangle$ are known for a given flow regime; i.e. bubbly, slug churn-turbulent. Noting that v_{Gj} and C_0 are flow-pattern dependent quantities then any void fraction predictions based on equation (2-13) would reflect the flow-pattern effects on the void fraction. In fully-developed bubble and/or slug flow, C_0 is usually of the order of 1.1~1.2. It is often convenient to correlate data for void fraction in terms of the parameters C_0 and v_{Gj}.

2.5 Measurement Techniques of Void Fraction

In reality, there is no opportunity to observe a real flow of two-phase mixtures inside the pipe despite the two-phase flow is used widely in industrial plant, piping system, and

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in some equipment of close system. In recent decades, several advanced techniques for void fraction measurement have been developed to obtain accurate and reliable experimental data. They have proposed many techniques as will be discussed in the following sections for many purposes such as void fraction measurement, flow patterns identifications, velocity measurement and other parameters. These developments were supported by studies on relationship and many correlations in the two-phase flow in order to determine the flow characteristics of a particular system. Therefore, efforts on laboratory experimentations are always the best way to provide some insights and valuable quantitative information of the phenomena in the two-phase flow system.

2.5.1 Neutron Radiography (NR)

This method has been applied by many researchers such as Mishima and Hibiki (1996), Takenaka et al. (1998), Harvel et al. (1999) and Zboray and Trtik (2018). The advantage of this method is that it can differentiate the concentration of substance and deliver those images through an opaque or mostly black body channel and deliver them into the optical images via scintillator. Recently, Zboray and Trtik (2018) have demonstrated dynamic cold neutron imaging of air-water two-phase flows up to 800 frames per second imaging rates at ambient temperature and atmospheric pressure conditions. The disadvantages include the unnecessary triggering signal system, long recording time and difficult setup.

2.5.2 Conductance Probes

The resistance probe is among the earliest and most common method to measure the void fraction. These measurement method were used by many researchers such as Serizawa (1974), Song et al. (1998) and Yang et al. (2003). Typically, the tube wall is connected to the fully insulated needle probe except its tip through the fluid. The conductance between the needle probe and the wall varies depending on the phase of the flow which is either in gas phase or liquid phase.

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Another conductance method was done by Fossa (1998), which used plate and ring-shaped electrodes to measure the fluctuation of electric voltage due to conductance in gas-liquid flow. A pair of electrodes is placed in the flow channel and electric current is supplied in the water flow to obtain the voltage during the single-phase flow. When the gas is injected to the liquid flow, some voltage fluctuation will occur, and these fluctuations are detected by the ring sensors installed flushed to the inner side of the flow channel. The differences between the two voltages during single and two-phase therefore provide the reading for the void fraction.

Another method is the Constant Electric Current Method (CECM) (Zainon, 2013)). For the current work, the CECM was applied since it is the most reliable method so far in various experimentations (Fukano, 1998; Furukawa & Fukano, 2001). Detail explanation is in section 3.1.2.

2.5.3 Impedance Void Meter

Costigan and Whalley (1997) measured void fraction in a vertical 32-*mm* inner diameter tube with flow pattern ranging from bubbly to annular flow, where they also have conducted good calibrations, the same method used by Ma et al. (1991) which is an impedance probe that connected to a signal processing circuit which gave a linearized output with fast response. Besides, Cheng et al. (2002) conducted void fraction measurement using this technique for 28.9-*mm* diameter with liquid constant velocity of 0.356 *m/s* with four different bubbles to study the patterns transition due to changes of bubble sizes.

2.5.4 Electrical Resistance Tomography and Capacitance Tomography

Electrical Resistance Tomography (ERT) was also used by Tan et al. (2007) for identification of flow pattern, also works as void fraction measurement technique. The measured data does not require the reconstruction of images to characterise the two- phase

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flow. Capacitance tomography is a system consists of stand-alone long electrodes which objects are illuminated from five projections. The luminous intensity of the object is measured and changed into discrete signals, but it is reconstructed based on the matrix algorithm. In addition, void fraction measurement using this system has been performed by Ismail et al. (2005) for horizontal gas-oil and Rzasa (2009) for air-water two-phase flow in horizontal arrangement.

2.5.5 Other methods

An attempt has been made by Cha et al. (2002) to apply the electromagnetic flow meter on the measurement of parameters in two-phase flow using the alternating current. They have done the calibration using non-conducting rod as void simulator to examine the effect of bubble position and signal from the flow meter that they designed and fabricated, and then compared with visual observation of flow patterns. The results turned to be very good and they concluded that this electromagnetic flow meter can be applied in determination of flow regime of two-phase flow.

2.6 Relation of Void Fraction, Measurement Techniques and other Parameters

The effects of axial location are found to be significant for the flows that develop and change the patterns. Researchers have studied this effect by using analytical and simulation as well as experimental works. For the analytical studies, the development of constitutive relation pertaining to this matter must be supported by an appropriate experimental data. For instance, Hibiki et al. (2001) performed a vertical upward flow of air-water and made a systematic investigation of the effects of three location of axial position.

Besides, double sensor probe also used by Hibiki et al. (2003) for measurement of local parameter in vertical upward of air-liquid system in double annulus with pipes of 19.1- *mm* in a 38.1-*mm* inner diameters. Interfacial velocity, area concentration and void

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fraction were measured with liquid velocity, while turbulence intensity were measured by the laser Doppler anemometer where they managed to validate the proposed constitutive equations with the current experimental data for local parameter measurement (Hibiki et al., 2001).

Measurement in two-phase flow is very important in many aspects of applications. For a rectangular channel, for high velocity flow, the turbulent effect is a very important factor to be considered. Panidis et al. (2000) demonstrated experiments to study the two-phase grid turbulence structure and used the Laser Doppler Velocimetry (LDV) to measure the liquid phase velocity. They also applied the hot film anemometry and optical probe to measure the local void fraction and estimated the velocity and size of the bubble using the photographic method. The results show that inhomogeneities in flow property distributions and void fraction are strongly affected by the dispersed phase in the turbulence field.

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CHAPTER 3: METHODOLOGY

Gas-liquid two-phase flow in pipes are commonly encountered in many engineering equipment such as the condensers and evaporators, gas-liquid reactors as well as combustion systems in processing and power plant industries applications. The two-phase flow is in fact a challenging subject principally because of the complexity of the form in which the two-fluid exist inside the flow channel, and they are divided in scientific term as the regime.

In the two-phase flow, the concept of holdup is very significant where it defines the relative fraction of one of the phases in a particular flow channel. This is not necessarily equal to the relative fraction of that phase while the entering fluid mixture. This implies that the measured value of velocity, pressure, temperature and other parameters of each phase might differ before and along the mixing section. As one of the most important parameters that always play an important role in the determination of flow conditions, the velocity of each phase is termed as the superficial velocity.

In order to conduct such investigations, the current scale down two-phase flow experimental rig was developed, and experimentations were carried out for wide range of flow conditions. Furthermore, the experimental facility was equipped with high end measurement technologies and reliable sensors.

3.1 Experimental Setup

3.1.1 Description of Test Facility

All experiments were carried out on an inclinable rig at the Thermal-hydraulics and Power Plant Laboratory, Faculty of Engineering, University of Malaya. The experimental facility used which had been employed earlier for two-phase flow studies by Zainon (2013), Zainon et al. (2014) and Zubir et al. (2019). The current experimental facility comprises of many scales of piping system in the range of 1.2 m ~ 6.0 m of transparent annulus flow channel with inner diameter of 20 mm and an implanted sensor on the inner wall. The configuration of the current facilities and actual experimental facility are shown in Figure 3.1 and Figure 3.2 respectively.

The working fluids for the system are air and water. Water is supplied from tap source into the 500-litre capacity reservoir and filtered before pumped into the flow loop as shown in Figure 3.1.

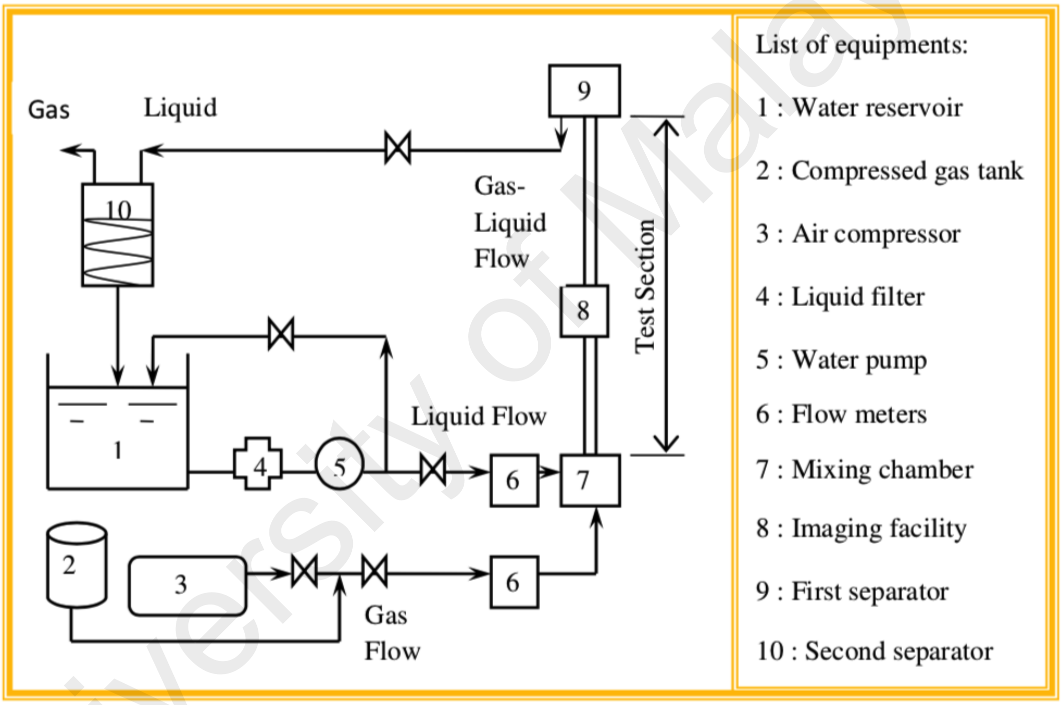

Figure 3.1: Experimental apparatus for vertical upward two-phase flow (Zainon, 2013)

The water flow rate is measured before it enters the mixing chamber with Kofloc flow meter. Then, based on the 20-mm inner diameter flow channel, the velocity of the liquid phase is determined. The water temperatures are also recorded via thermocouple and digital reader placed at the reservoir. Throughout the experimentations, it is maintained at 27-30 °C.

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Figure 3.2 Actual photo of experimental facilities in Thermal-hydraulics and Power Plant Laboratory, University of Malaya

In addition, the air is injected into the system from the compressed gas tank or air compressor to create the two-phase flow. Then, air flows through the gas pipe into the mixing section where the flow rates were measured by two different gas flow meters for low and high mass flow rate. The tip of the gas line is covered with porous cap with very fine holes to introduce fine bubble into the test section. Thus, liquid and gas mix together and the gas bubbles move upward co-currently with the liquid flow in the mixing section.

The upper end part of the test section was installed with small separator to allow the gas bubble separate from the liquid and was connected with another two-phase flow that will deliver both the gas and liquid into a bigger separator at the top of the flow loop. The liquid is then directed back into reservoir and recirculated into the flow loop.

3.1.2 Development of Void Sensor using Constant Electric Current Method (CECM)

As discussed in Section 2.5, there are many systematic approaches in measurement of two-phase flow parameters such as, void fraction, liquid film thickness and velocities conducted by many scholars in the history of two-phase flow. Among all, the electric conductance methods are well-known, easy to understand and easy to be implemented as well. Nevertheless, there are different type of electric conductance methods being practiced such as, void impedance meter applied by Costigan and Whalley (1997) and Cheng et al. (2002), conductance probe by Mishima and Ishii (1984) and Hibiki et al. (2001) also the constant electric current method by Fukano (1998). In this study, the Fukano method is applied since it is proven as the most reliable method so far in many experimentations carried out by Fukano (1998), Furukawa and Fukano (2001) and as recent as Uesawa et al. (2016).

The detail configuration for test section is shown in Figure 3.3 where the sensor electrodes are placed in between the power electrodes. This flow channel was divided

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into three sections where at each section the void sensor was installed. The first void sensor was placed in the Section I which is at 400 *mm* from the bubble injection and the section II starts with the second void sensor at 300*mm* from the first sensor and followed by another section with another 300*mm* gap making the third section. In between sections II and III another sensor was placed in the middle. The void fractions data were taken from all the four locations of void meters, with more concentration were paid on the upper three since the flow patterns will be more stable in these sections. With this arrangement, the power electrodes are able to supply a sufficient density of constant electric current, making a uniform distribution along the flow channel. Thus, at any location, the voltage reading will be in the same value, hence enable a good result for the measurement.

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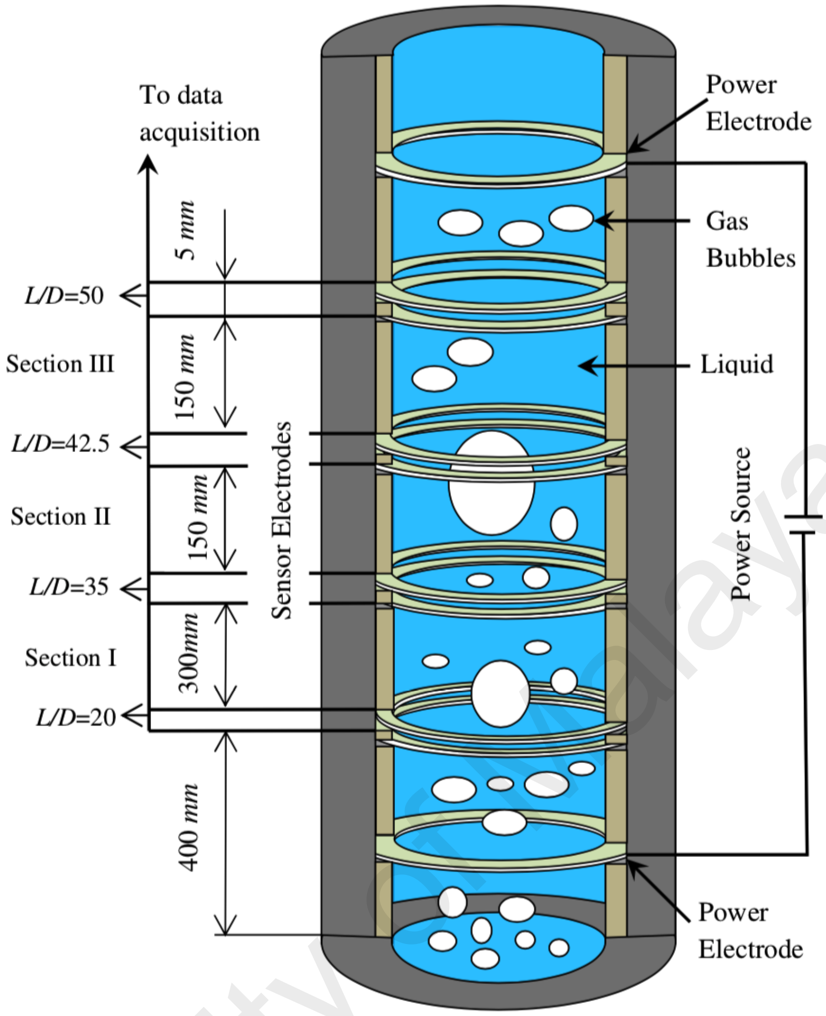

Figure 3.3: Detail configuration of the test section for vertical upward two-phase flow. (Zainon, 2013)

Then, the voltage output captured by the sensor electrodes is transferred to the pre-amplified data acquisition by National Instruments. This voltage fluctuation data is then digitally processed by LabView software to compute the void fraction. In this case, the increase in voltage output with the increase of electrical resistance caused by the existence and increasing of the gas flow rate in the two-phase flow experiments is independent of the locations of the gas phase in the cross section of the flow channel. Therefore, some shortcomings encountered in other conductance method, such as the voltage fluctuation during measurement of various parameters in different flow patterns in the channel can

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be avoided. Details configuration and development of this sensor can be referred to works by Fukano (1998) and Zainon (2013).

3.1.3 Experimental Parameters

Table 3.1 shows the operating conditions and variables used in this experiment to recognize the the effects of velocities of both phases with variety of combinations using an industrial scale two-phase flow loop on void fraction. There are fifty-two (52) sets of operating parameters designed for the experiment.

Table 3.1 List of gas and liquid superficial velocities

Liquid superficial velocities, j_L[m/s]	Gas superficial velocities, j_G[m/s]
0.25	0.025
0.50	0.050
0.75	0.075
1.0	0.100
1.5	0.150
2.0	0.250
2.5	0.500

With the range of liquid and gas superficial velocities as in the above table, the function of slip ratio and its limit to the effects that caused by velocities of both phases can be evaluated. From equation (2-11), the range of slip ratio, $S=j_G/j_L$, will be, 0.01 ~ 3.0, a good approach for the application on industrial scale gas-liquid two-phase flow.

3.2 Basic Equations

Using an electrical resistance concept, considering electrical resistance during two-phase flow, R_{TP} in a unit length of the channel as,

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$$\frac{1}{R_{TP}} = \frac{1-\eta}{R_G} + \frac{\eta}{R_L} \tag{3-1}$$

where the electric resistances; R_G for gas phase and R_L for liquid phase when they are solely occupies the whole cross section of the channel and η is the percentage of liquid volume to the total volume of the channel or the holdup.

Considering V_{TP} as the voltage drop in a unit length when constant current I_0 is supplied, and for air-water two- phase flow, the resistances size should be, $R_G >> R_L$, therefore, the holdup can be expressed as,

$$\eta = \frac{R_L}{R_{TP}} = \frac{I_0 R_L}{I_0 R_{TP}} = \frac{V_L}{V_{TP}} \tag{3-2}$$

where, V_L is the voltage output during the sole existence of liquid that occupied whole cross section of the flow channel.

3.3 Calibrations

In order to validate the reliability of the measurement of this sensor, a good calibration based on proper method must be carried out. Two calibration methods were conducted for this purpose as the following.

3.3.1 Static Calibrations

The easiest way to calibrate this sensor is by using a static method. It can be conducted by applying the electrical resistance concept; where any non-conductive material can be applied to replace the real gas bubble in the test channel in order to capture the voltage fluctuation. For this purpose, cylindrical acrylic rods with four different diameters were inserted one by one into the channel that initially filled up with water.

In order to replicate a single bubble passes through the channel flow, shorter rods of which length is longer than the sensor gap (5-*mm*) were used. On the other hand, for estimation of group of bubbles passing through the whole channel, longer rods with

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various diameters were applied. Therefore, when these rods were placed in the center of the sensor electrodes, the voltage fluctuation were recorded, and they actually differ among positions of the sensors. Hence, very careful and systematic data recording is recording in this case.

The concept of the void fraction based on nonconductive rod is as follows,

$$\alpha = \frac{A_C}{A_E} = \left(\frac{D_C}{D_E}\right)^2 \tag{3-3}$$

where A_C, A_E, and D_C, D_E are the cross-sectional area and diameter of calibration rod of the experimental flow channel respectively.

In this work, a 20-mm diameter flow channel and six different diameters of calibration rods were used. Table 3.2 gives the ratios of the cross-sectional areas based on these rods to the experimental channel.

Table 3.2: Area ratio based on calibration meter

Calibration Rod Diameter, D_C [mm]	Area Ratio, α [-]
4	0.0400
5	0.0625
8	0.1600
10	0.2500
15	0.5625
18	0.8100

According to equation (3-2, when $V_L = V_{TP}$, holdup is $\eta = 1$, which implies that only liquid exist in the channel. Hence, void fraction can be expressed as,

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$$\alpha = 1 - \eta = 1 - \frac{V_L}{V_{TP}} \tag{3-4}$$

when, $0 < \eta < 1$. In both cases for calibration rod tests, the radial effect (location of the rod at the radial of the channel), and the amount of constant current were also investigated. This is to check if there is any effect of the bubble's locations since the positions of bubbles in a flow channel are unexpected.

Based on equations (3-3) and (3-4), calibration tests were carried out and their curves were plotted. Figure 3.4 shows the result of the test model for calibration where four different amounts of electric current supplied into the channel, which initially filled with water. Here, it is found that within these current ranges, the calibration line is fitted well with the accuracy of 2%. Hence, it can be concluded that the amount of electric current supplied into the liquid in the flow channel does not affect the measurement of void fraction.

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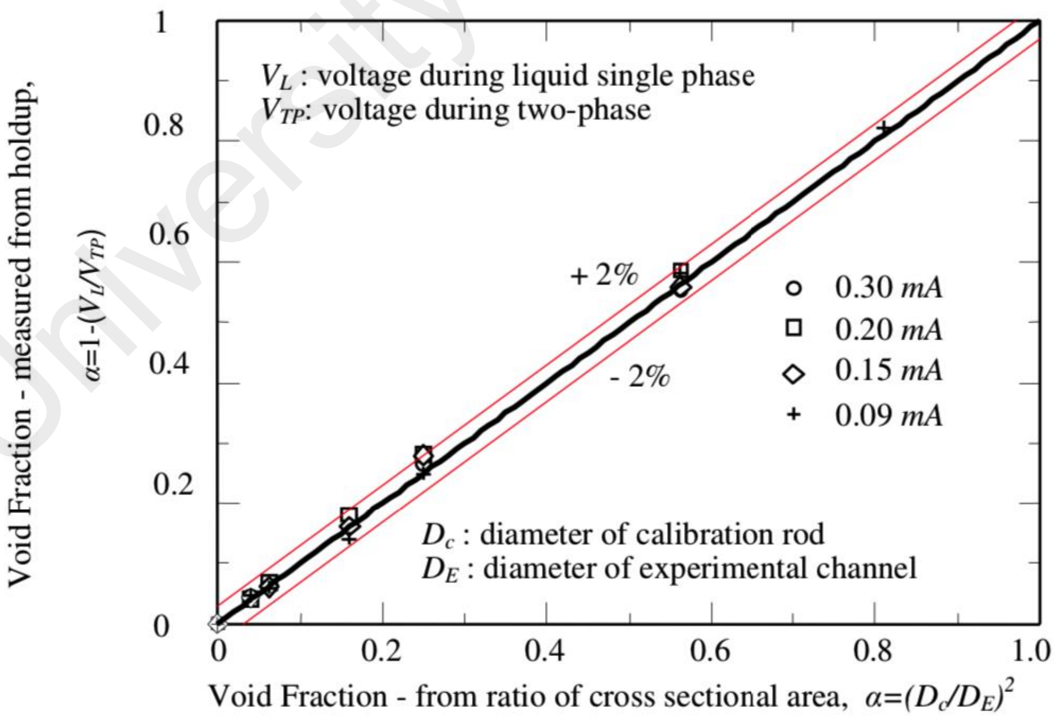

Figure 3.4 Electric current effect on holdup

The effects of radial location of the voltage drop was investigated and the result is shown in Figure 3.5. In this case, the calibration was placed in the centre, left and right positions and a constant electric current was supplied into the liquid in the flow channel. Here, it also revealed that the voltage drop is almost constant regardless of the position rod in the experimental channel and thereof confirmed that there will be no effect of bubble positions for void fraction measurement using this method.

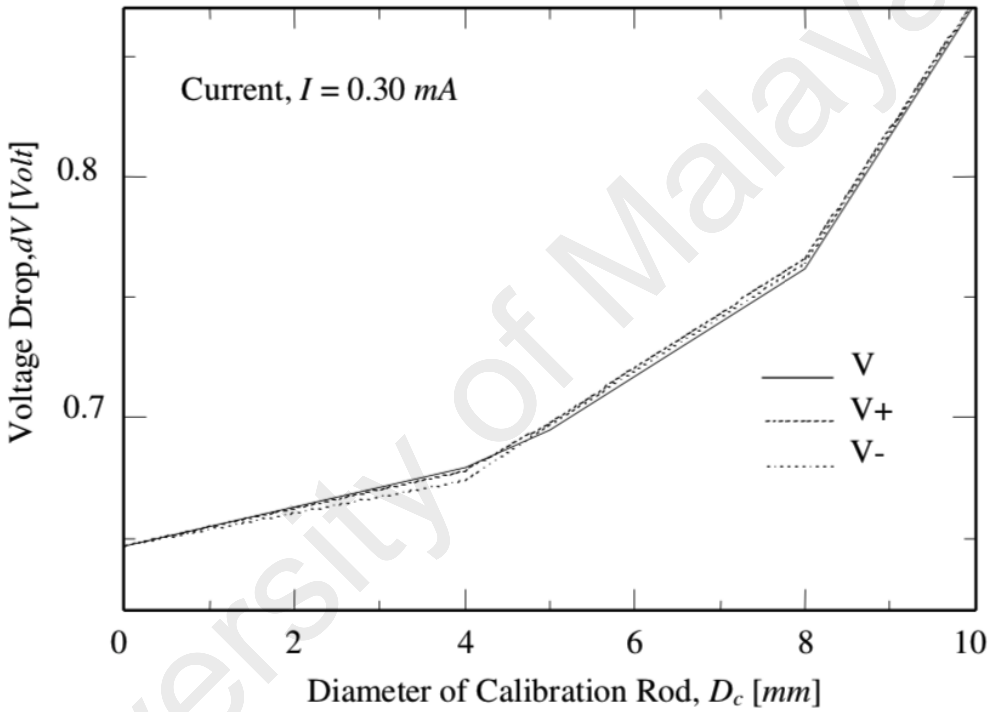

Figure 3.5 Voltage drop by radial location

Using the same date from Figure 3.4 and Figure 3.5, the effect of the radial position of the rod during the calibration to the holdup can be pulled out and this is shown in Figure 3.6. With 1% different, the accuracy is found to be very good and this reflected that the CECM method would be a reliable tool where electric resistance caused by the bubble at any radial position of the flow channel can be detected.

The calibration for sensor electrodes on the experimental channel were conducted for four times at four times at four axial positions based on the ratio of length, (position of

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the sensor from the two-phase mixer) and diameter of flow channel, L/D using both the long and short cylindrical rods and they are shown in Figure 3.7. The difference of the symbols signifies the repetition of calibration, and A and B denotes the long and short cylindrical rod respectively. The similar results were obtained with good accuracy at 3%, meaning the good data measurement can be reproducible as well.

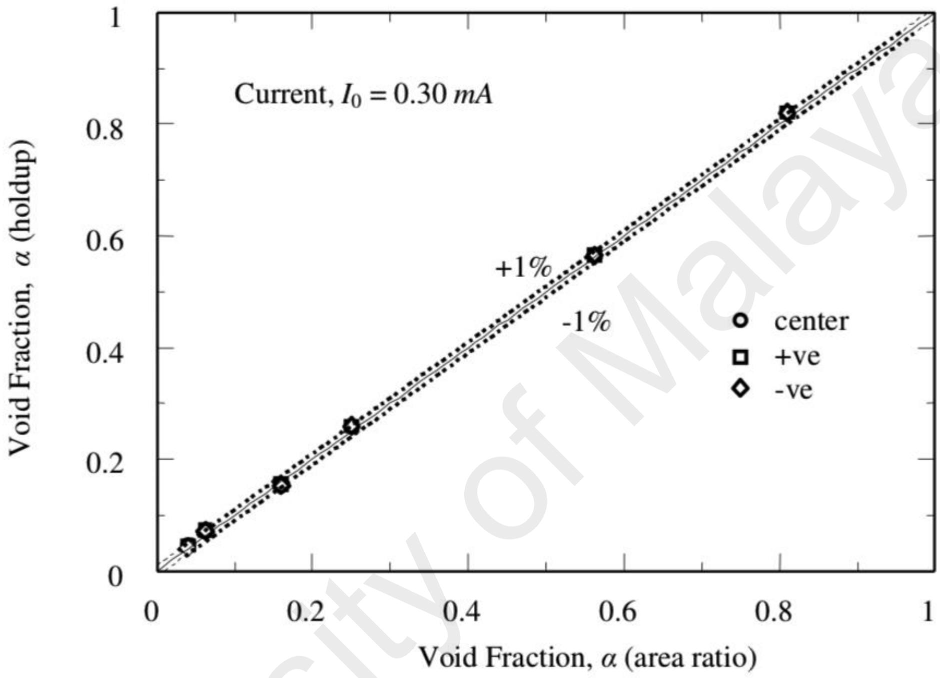

Figure 3.6 Radial location effect on holdup

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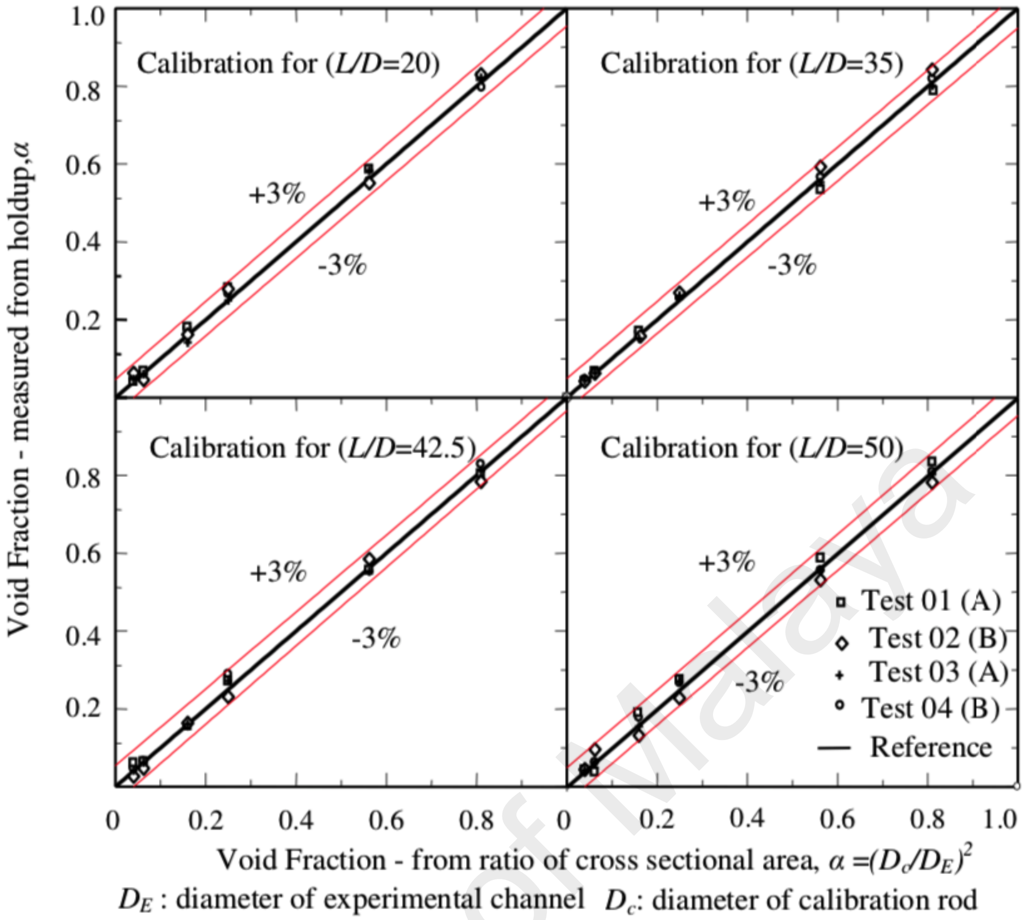

Figure 3.7 Static calibration for CECM sensors

3.3.2 Dynamic calibrations

Dynamic calibration was conducted to give the real picture of the two-phase flow by using the real moving bubbles. This was done by comparing the visual data from the recorded images and measurement by the sensors. In these tests, a single air bubble was injected through the bottom of the liquid filled with water via a syringe with six different needle sizes to produce different sizes of bubbles. Then, the image of the bubble was captured by the high-speed video camera and the voltage fluctuation was recorded by the sensor simultaneously. As only a single bubble is released, it can be confirmed that only the captured bubble has passed through the sensor without presence of trailing bubbles.

On the other hand, for continuous bubble rising, the bubbles were released from a compressed gas tank. Then, the average areas occupied by gas bubbles were assessed.

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The area and diameter sized of captured bubbles were analysed with comparison to the tube diameter and were then compared with the recorded data from the sensor. The same comparison as shown during the static calibration in Figure 3.7 were carried out and plotted as shown in Figure 3.8.

The calibration was conducted at four different locations. Test 101 and Test 102 denote the calibration using single bubble of different sizes while Test 103 using continuous rising bubble. For this calibration, the liquid superficial velocity (j_L) where varied in the range of 0.25~1.0 m/s. A slight difference from the static calibration results was recorded where the dynamic calibration gives an accuracy of 5% as shown on Figure 3.8 which is still in range of acceptable tolerance. For the current report, calibration with j_L=0.25 m/s and j_L=0.5 m/s are presented.

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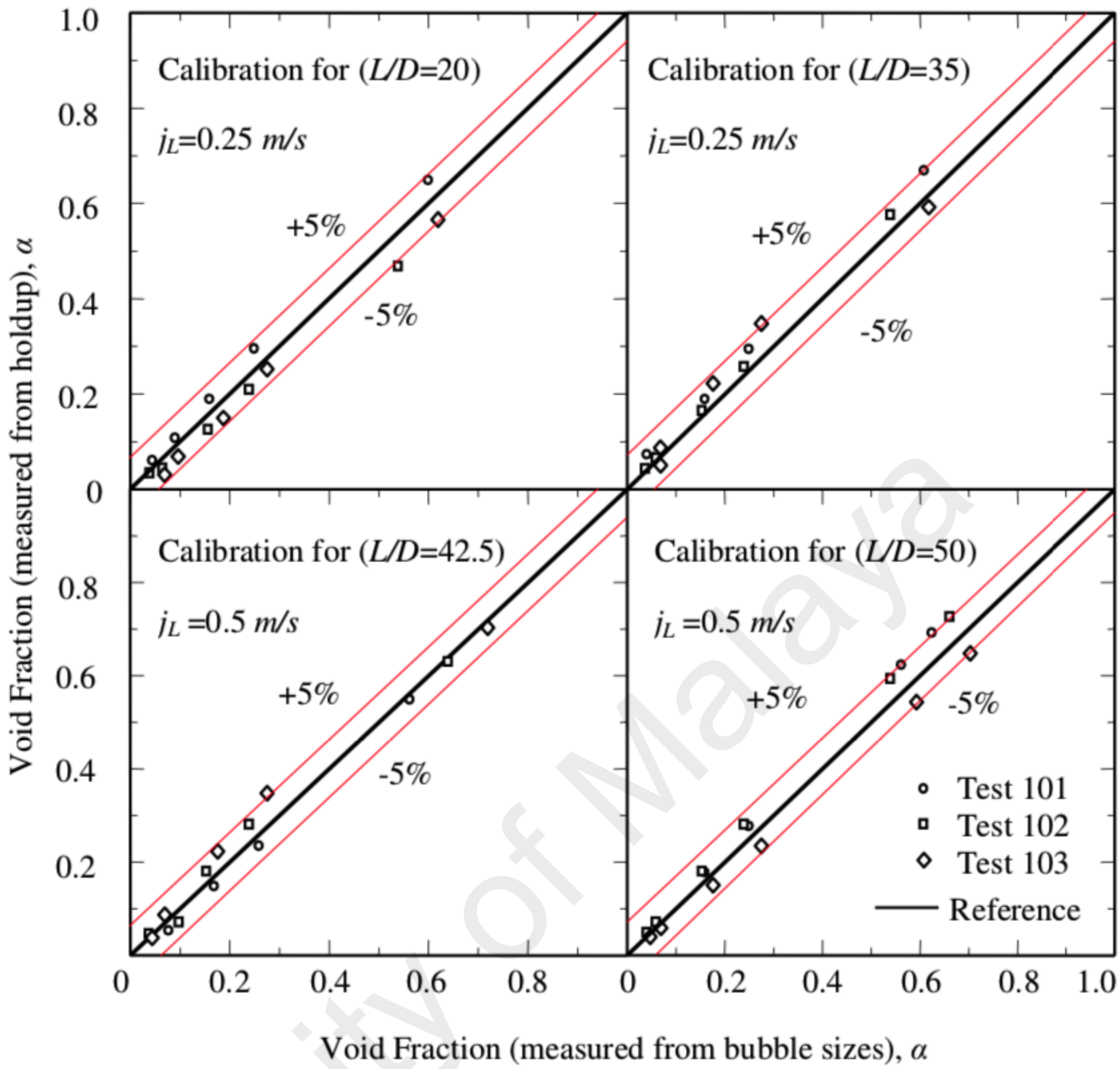

Figure 3.8 Dynamic calibration for CECM sensors

3.4 Reliability Test

The fluctuations of void fraction were measured in the case of vertical upward air-water two-phase flow and their time mean values were calculated using the data obtained in a long period. Figure 3.9 shows the example of voltage fluctuation that was used to compute to measure the void fraction. Here, V_L represents the voltage during a liquid single phase occupied fully in the cross-sectional area of the flow channel and V_{TP} is the voltage fluctuation during the two-phase flow. Referring to equation (3-4), with a fixed V_L and varied V_{TP}, the void fraction along the channel can be calculated for variation of flow condition.

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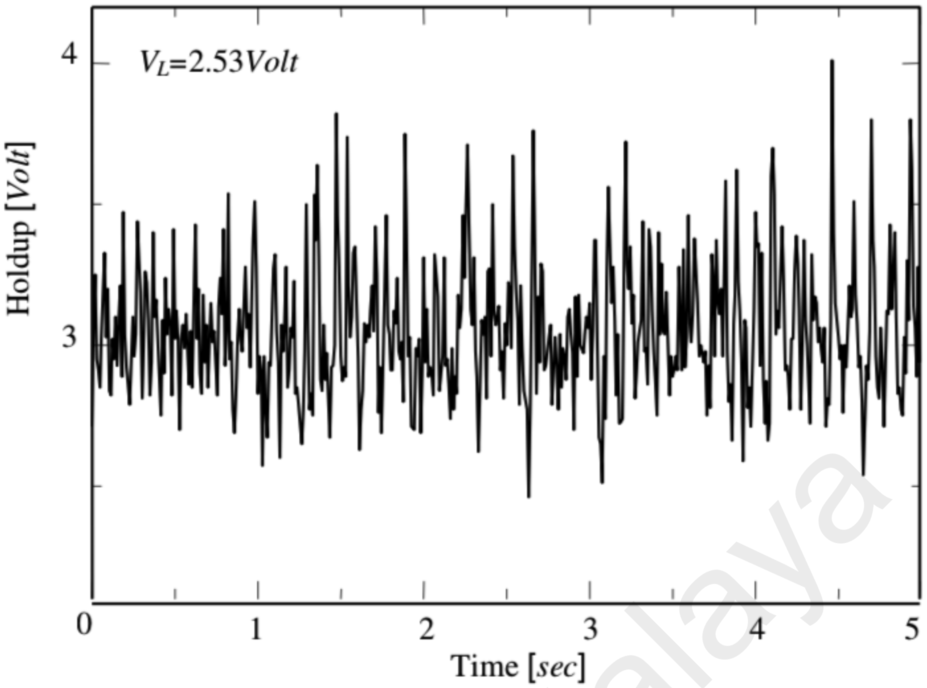

Figure 3.9 Example of voltage fluctuation for holdup to measure void fraction

3.4.1 Comparison of Void Fraction

The reliability of the current sensor is assessed by comparing time mean values with three other data obtained by other scholars from 1960s that has been used widely in the studies of two-phase flow. This is done by measuring the void fractions fluctuations of vertically upward air-water two-phase flow for a fixed liquid superficial velocity, j_L =0.1, 0.75, 1.0, 2.0 and 2.5 m/s and gas superficial velocity, j_G in the range of 0.025~0.25 m/s. Based on Figure 3.10to Figure 3.14, the current result shows very similar patterns with other scholars and value of void fraction is within acceptable range.

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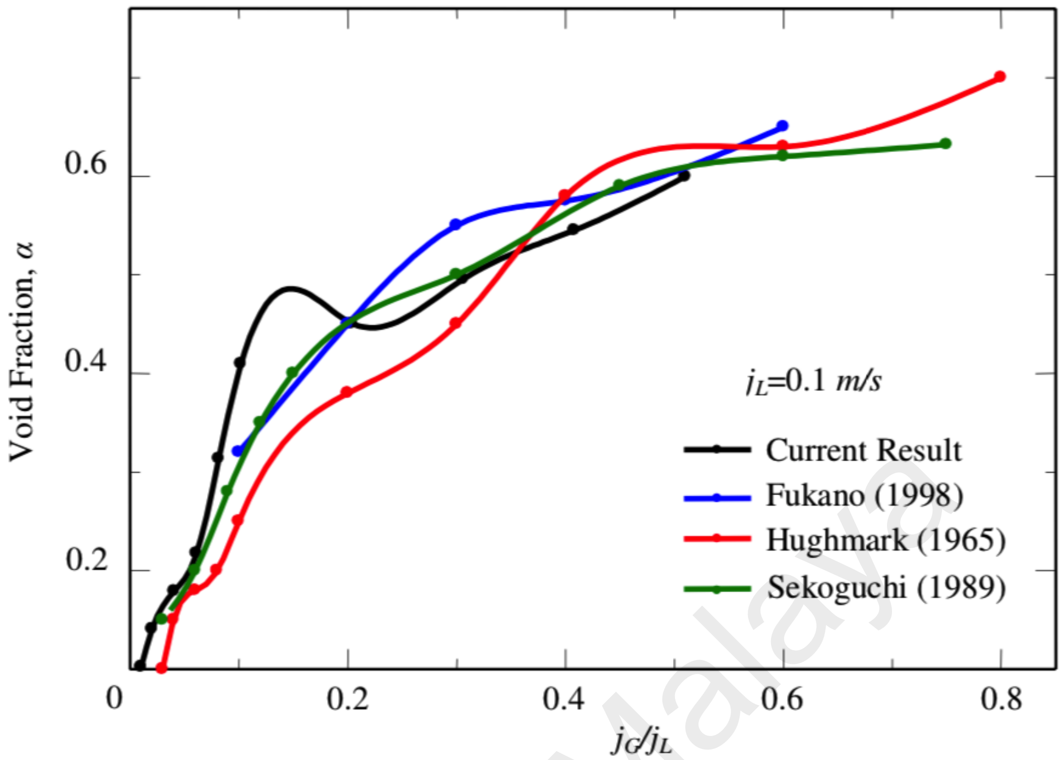

Figure 3.10 Comparison of measured void fraction with other scholars' for j_L=0.10 m/s

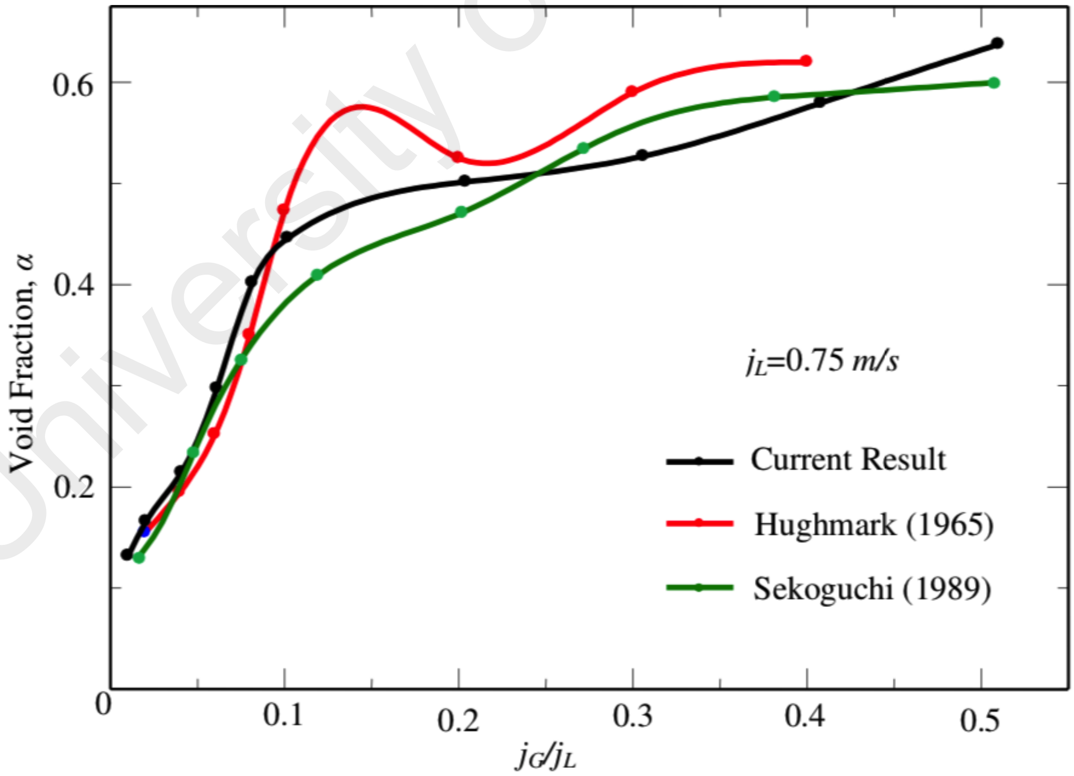

Figure 3.11 Comparison of measured void fraction with other scholars' for j_L=0.75 m/s

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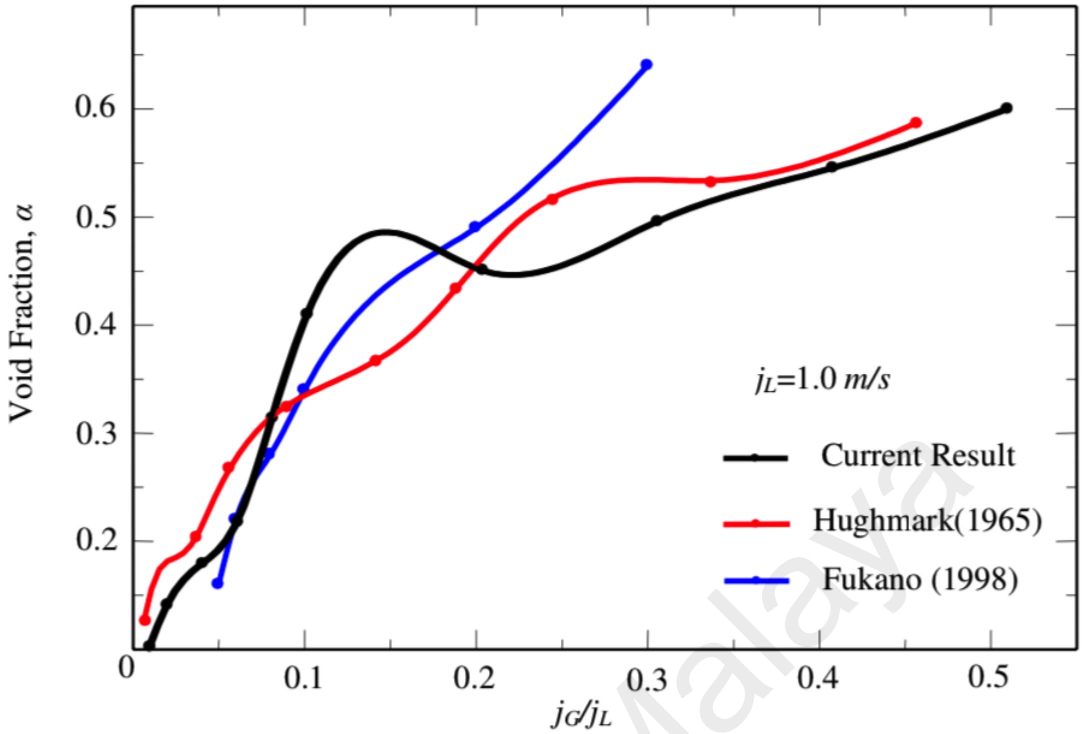

Figure 3.12 Comparison of measured void fraction with other scholars' for j_L=1.0 m/s

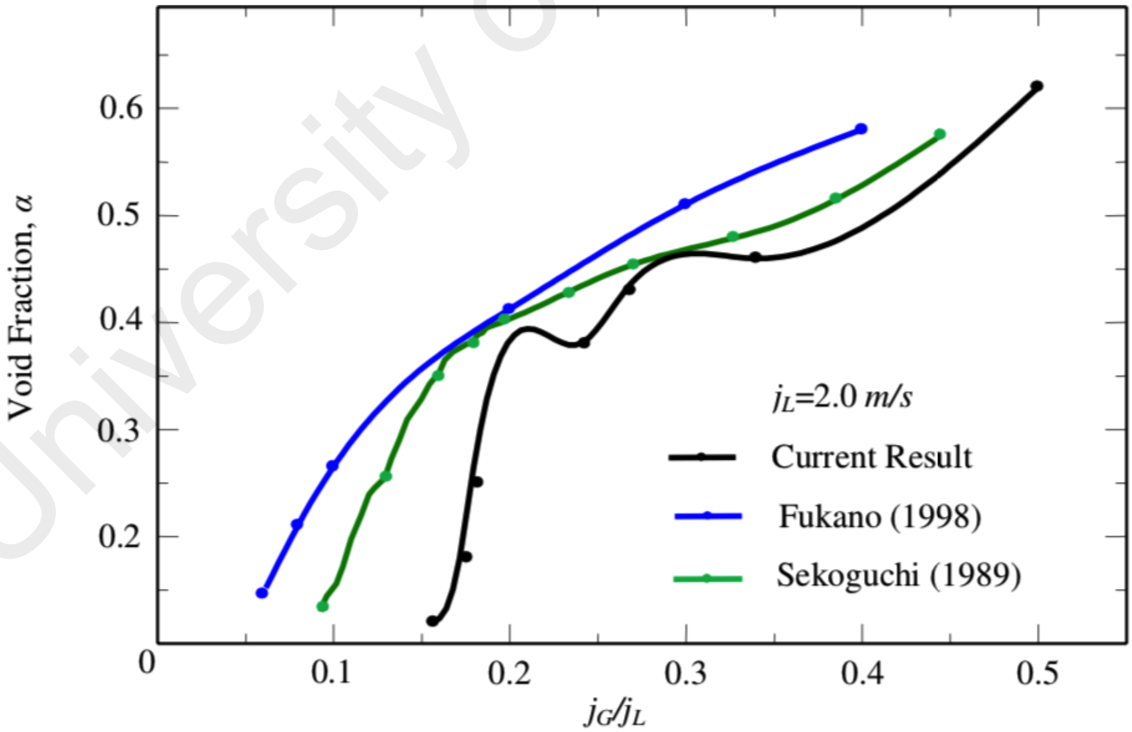

Figure 3.13 Comparison of measured void fraction with other scholars' for j_L=2.0 m/s

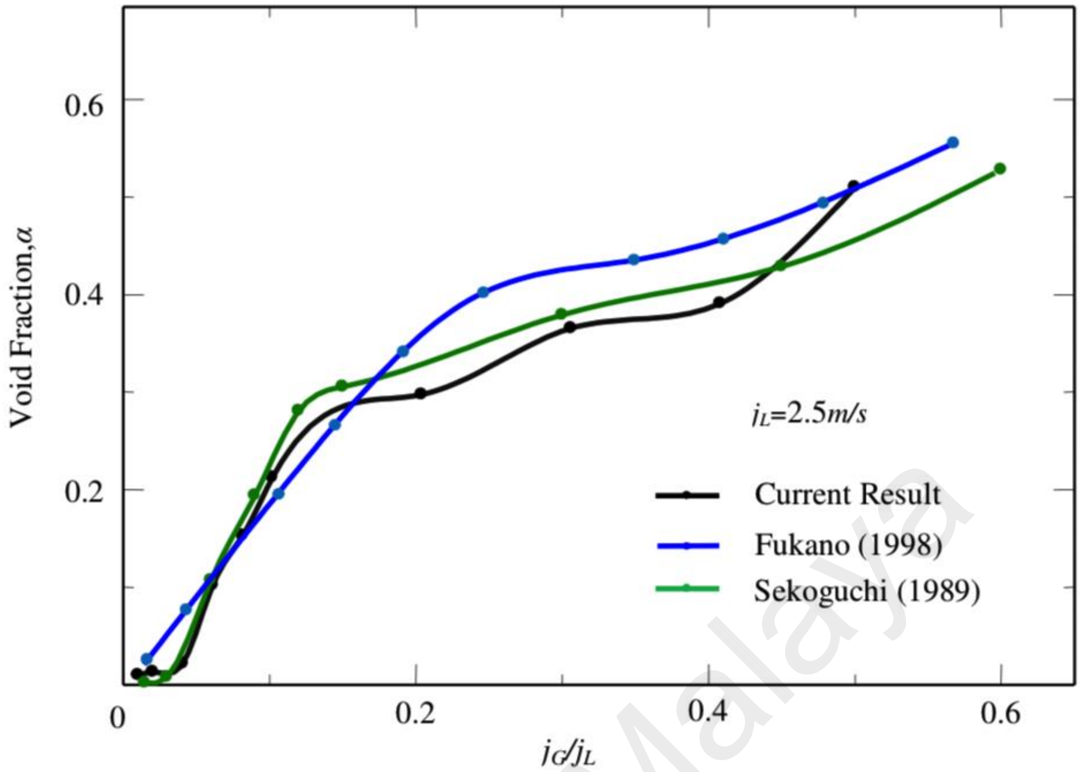

Figure 3.14 Comparison of measured void fraction with other scholars' for j_L=2.5 m/s

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CHAPTER 4: RESULTS AND DISCUSSIONS

Vertical upward two-phase flow is a very important subject to be studied since they are widely used in many engineering practices, analyses and design of equipment. The dynamics of two-phase flow can be more exclusively expressed by the direct measurements of the parameters involved. During the experimentations, the gas and liquid superficial velocities can be determined using the relation of volumetric or mass flow rate and the channel diameter, but these parameters has limitation to draw the characteristic of the two-phase flow. Therefore, the actual rate of gas existence in the flow channel or systematically termed the void fraction is the best parameter that would fill in the hole of this incomplete event.

This chapter will present and discuss the results of the experiment on the flow structures and dynamics of gas-liquid two-phase flow in a vertical upward arrangement in an annulus tube.

4.1 Flow Pattern

4.1.1 Changes of flow pattern at j_L=0.25 m/s

The first investigation in the flow patterns was conducted for the lowest liquid superficial velocity for this experimental facility at j_L=0.25m/s. The investigations were varied with six different gas superficial velocities at j_G= 0.025, 0.050, 0.075, 0.10, 0.15 and 0.25 m/s. Referring to Figure 4.1, the bubbly flow were developed at j_G= 0.025 to 0.05 m/s, with formation of bigger bubbles with spherical caps at j_L=0.075m/s and slugs started to form at j_G= 0.10 m/s. When the gas superficial velocities being increased to 0.15 m/s and 0.25 m/s, a fully developed slug flow were formed with bigger sizes and longer lengths.

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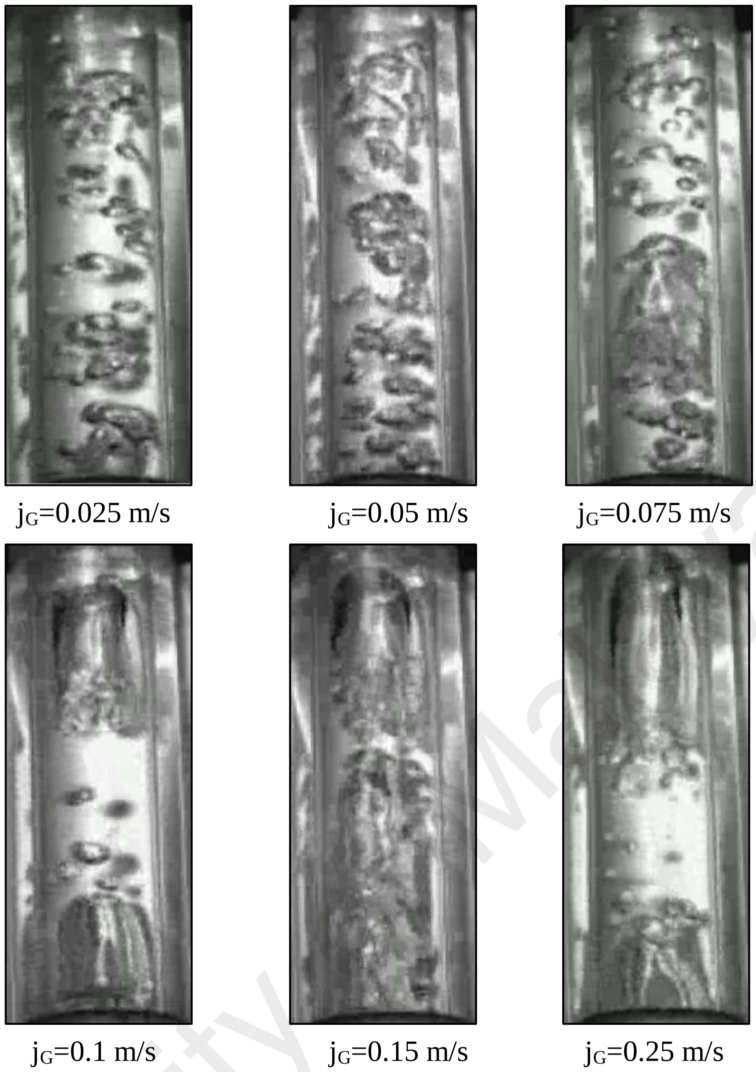

Figure 4.1 Changes of flow pattern at j_L= 0.25 m/s

4.1.2 Changes of flow pattern at j_L=0.50 m/s

For liquid superficial velocity, j_L=0.5 m/s, the same procedures as in the previous were repeated. At gas superficial velocities of j_G=0.025 m/s and j_G=0.050 m/s as shown in Figure 4.2, a steady bubble flow was formed. Further increase of gas superficial velocity to, j_G=0.075 m/s, resulted a flow pattern with very steady bubble flow, with bigger bubbles sizes and some of them were flapping like a bird wing as observed by Krishna and van Batten (1999). With higher gas superficial velocity at j_G=0.1 m/s, the flow pattern started with formation of slugs.

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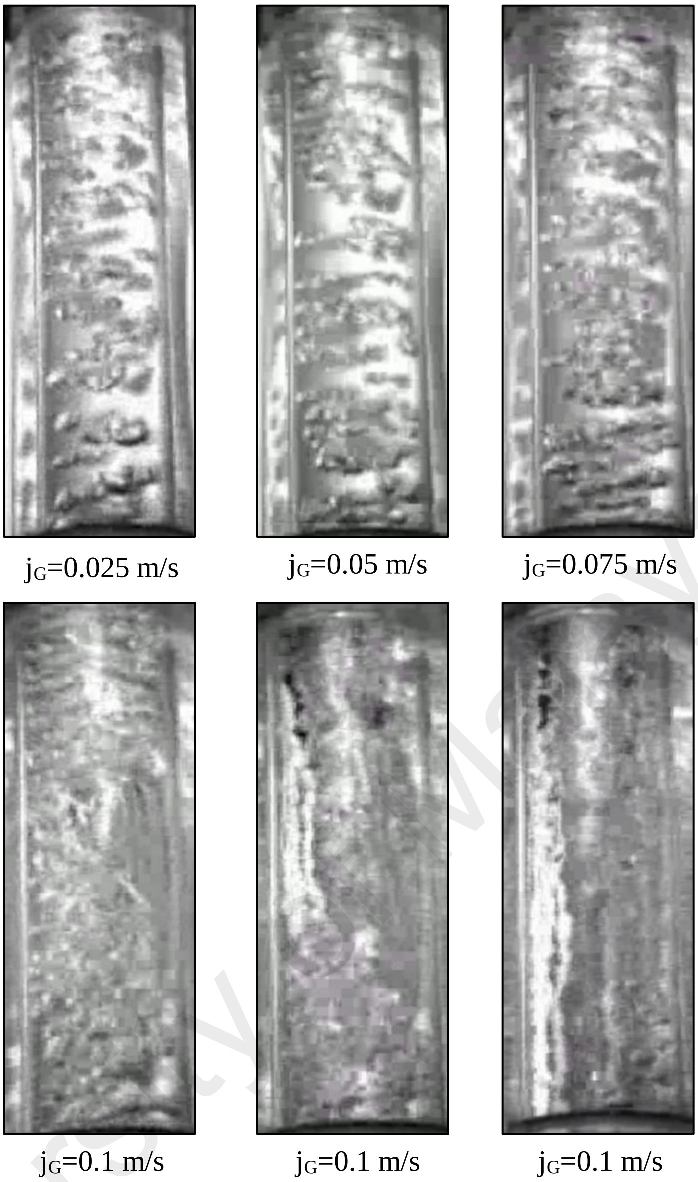

Figure 4.2 Changes of flow pattern at j_L= 0.5 m/s

4.1.3 Changes of flow pattern at j_L=0.75 m/s

Under the condition of liquid superficial velocity at, j_L=0.75m/s, very stable bubble flow was formed in most of the condition for wide range of gas superficial velocities, j_G=0.025 m/s to 0.1 m/s. The flow pattern still shows the bubble flow for gas superficial velocity of j_G=0.25 m/s, during the steady state condition with formation of slugs in between the bubbles. However, for gas superficial velocity of j_G=0.5 m/s, no more bubble flow characterization can be made since bigger slugs were formed in a turbulent flow.

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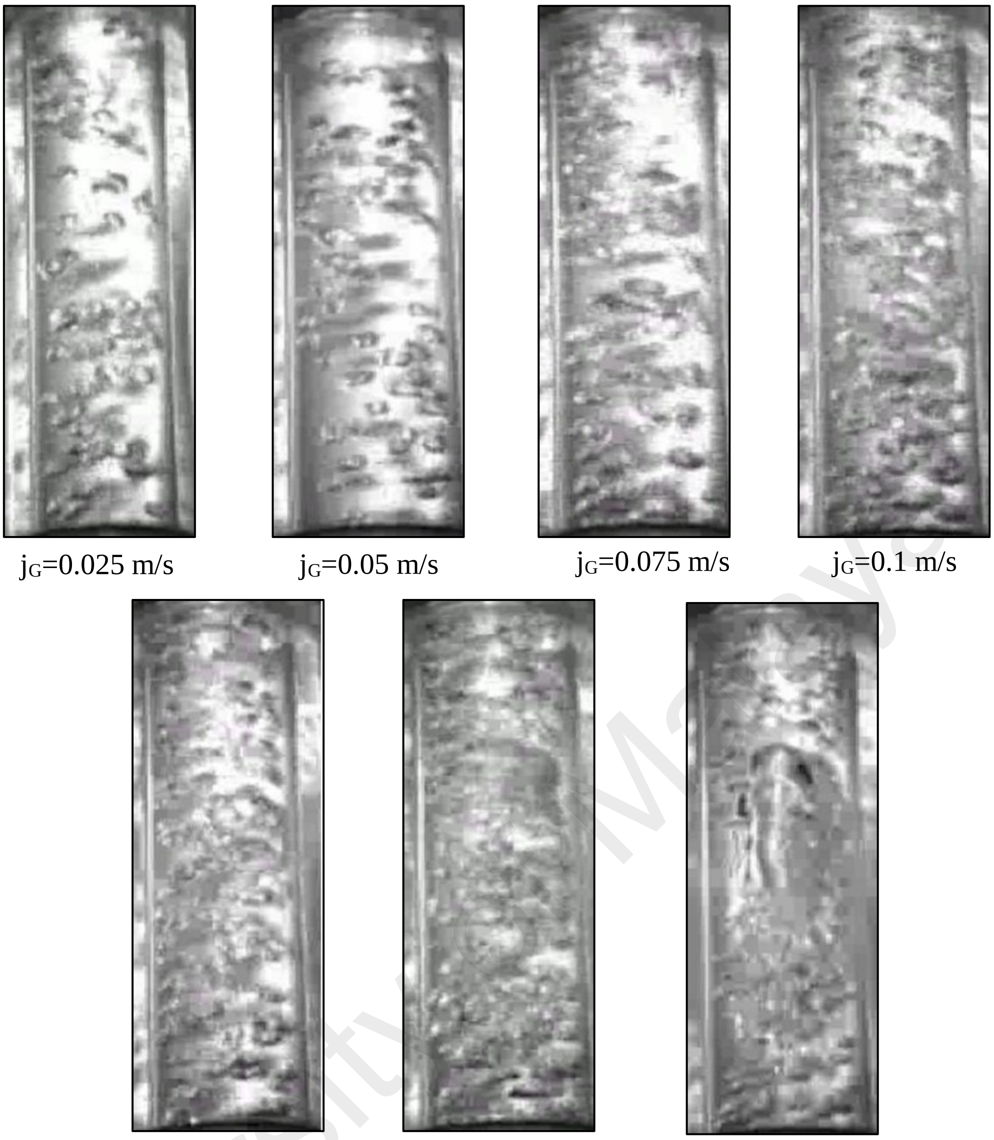

j_G=0.025 m/s j_G=0.05 m/s j_G=0.075 m/s j_G=0.1 m/s

j_G=0.15 m/s j_G=0.25 m/s j_G=0.50 m/s

Figure 4.3 Changes of flow pattern at j_L= 0.75 m/s

4.1.4 Changes of flow pattern at j_L=1.0 m/s

In this condition, bubble flow was observed in most of the gas superficial velocity, ranging from 0.025 ~ 0.25 m/s with discrete and continuous flow in those ranges. Coalescences of bubbles and grouping of bubble were more rapidly seen for gas superficial velocities in the range of j_G= 0.15 m/s ~ 0.25 m/s. The bubble rising was more stable due to their sizes and high liquid superficial velocities. Therefore, throughout these conditions, it can be concluded that the flow patterns remain as bubbly flow. When the gas superficial velocity increased to 0.5 m/s, transitions of bubbly to slug flow were observed and this is very well match with the work by Furukawa and Fukano (2001). For

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more higher gas superficial velocities at j_G=0.75 m/s and j_G=1.0 m/s, the flow pattern appeared as slug flow at the beginning and after some time when more slugs were formed, coalescences become more often, and they started to break up. Hence, the transition from slug to churn flow was observed.

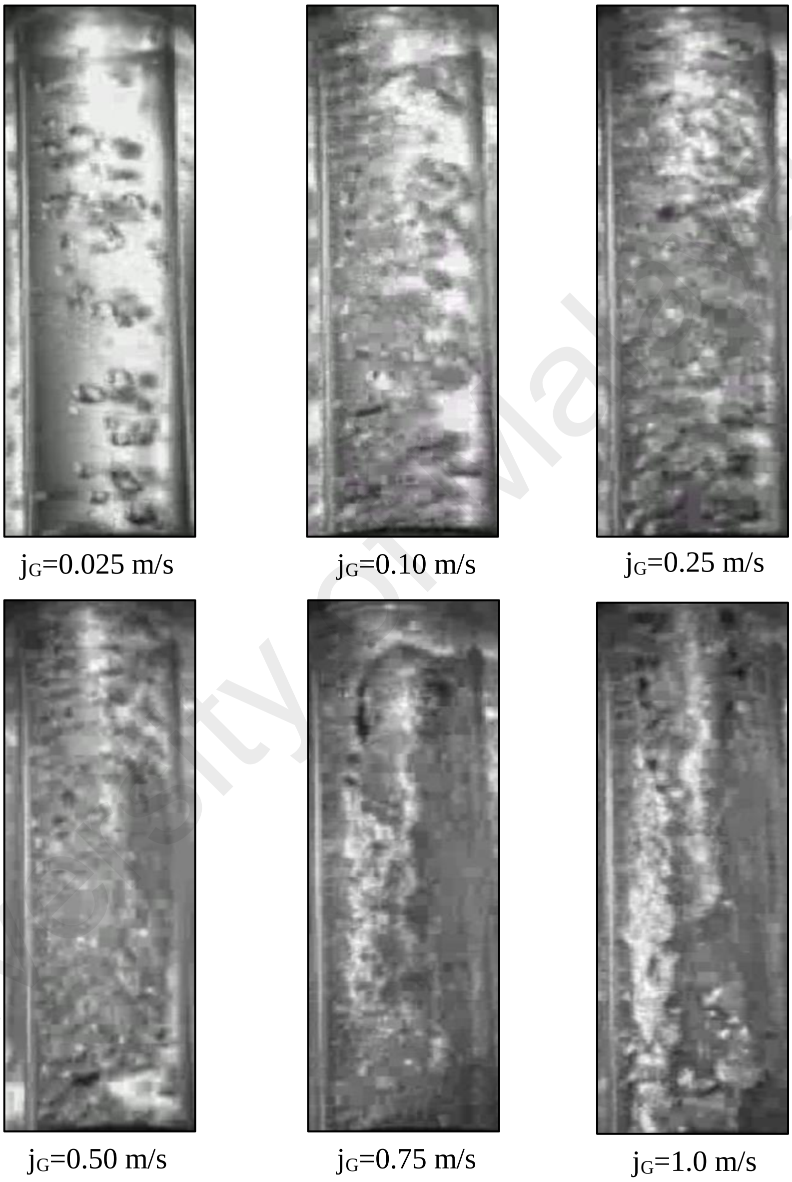

Figure 4.4 Changes of flow pattern at j_L= 1.0 m/s

4.1.5 Changes of flow pattern at j_L= 2.0 m/s and 2.5 m/s

Up to this point, the flow patterns were discussed for liquid superficial velocities in the range of 0.25 ~ 1.0 m/s. For the current size of liquid superficial velocity at 2.0 m/s, the flow patterns are only in the form of bubbly flow as shown in Figure 4.5. The steady

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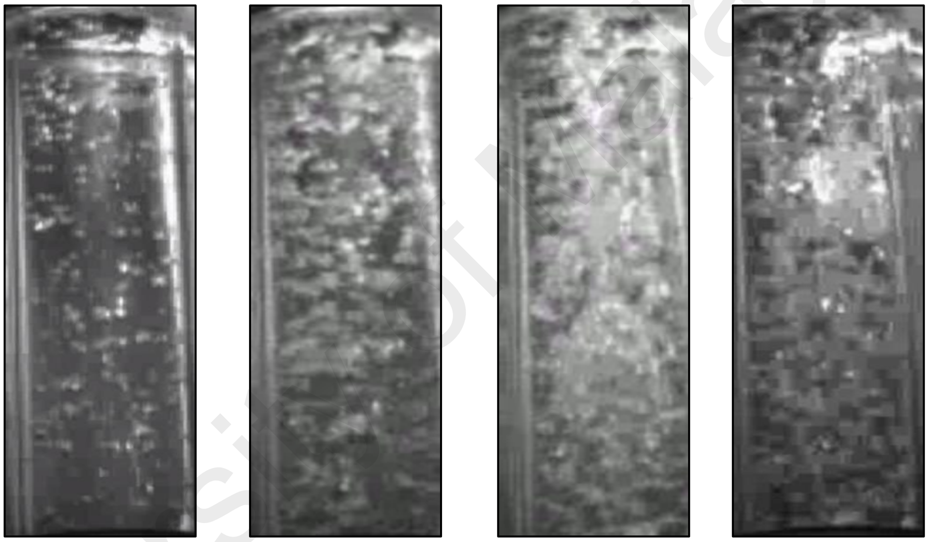
flow due to high liquid superficial velocity is obvious for very low gas superficial velocity at 0.025 m/s where bubbles flow in very good manner with only very little coalescences. Bubble congregations were observed to be better with the increasing of gas superficial velocities at 0.15 m/s. At j_G= 0.50 m/s, close gap congregations took place and lead to coalescences where as a result forming more slugs. These slugs also travel within the bubbles and easily distorted to form smaller bubbles but does not show any transition into the churn flow. Therefore, at these conditions, they remain as bubbly flow. Transition from bubble to slug flow was displayed at j_G= 0.75 m/s.



j_G=0.025 m/s j_G=0.15 m/s j_G=0.50 m/s j_G=0.75 m/s

Figure 4.5 Changes of flow pattern at j_L= 2.0 m/s

For the highest liquid superficial velocity obtained in this work j_L=2.5 m/s, the flow patterns remain bubbly throughout ranges of the gas superficial velocity. Therefore, a short conclusion can be addressed here is to confirm that this is the level that limit change of flow pattern for gas superficial velocity in the range of 0.025 ~ 0.25 m/s or translate in the form of slip ratio as 0.01 ~ 0.1.

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Figure 4.6 Flow pattern at j_L= 2.5 m/s

4.2 Total Average Void Fraction

Total average void fraction, α_{avg} is the average void fraction or sometimes refers as mean void fraction between position L/D = 42.5 and L/D = 50. Figure 4.7 to Figure 4.13 represent total average void fraction at different liquid superficial velocity ranges from 0.25 m/s to 2.5 m/s. Individual figure of the graph is presented here first to discuss in detail the effect of increasing gas superficial velocity at constant liquid superficial velocity on void fraction. Then, these data will be presented in single graph to discuss the effect of increasing liquid superficial velocity on void fraction as shown in Figure 4.14.

The first result for average void fraction is for liquid superficial velocity, j_L=0.25 m/s as shown in Figure 4.7. For very low liquid superficial velocity at j_L=0.25 m/s, the range of void fractions were recorded as high as 0.4. The plot shows that the average void fraction increases linearly with an increase gas superficial velocity for a constant liquid superficial velocity at j_L=0.25 m/s. This phenomenon show that when the gas superficial velocity increases during very low liquid superficial velocity, more bubbles collide and coalesce to form bigger bubble and as a result forming slugs and bigger slugs and longer lengths as shown in Figure 4.1. With these formations the volume of gas will be higher

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and therefore increase the value of void fraction. At liquid superficial velocity of j_L=0.50 m/s and j_L=0.75 m/s as shown in Figure 4.8 and Figure 4.9 also show the same relation.

However, it is also observed that the void fraction increases at lower superficial gas velocities (j_G/j_L=0.1~0.3) sharper than that at higher superficial gas velocities (j_G/j_L = 0.3 ~0.4). As such, the void fraction becomes less sensitive to gas flow increases at higher air flow rates where slug flow was formed than that at lower air flow rates.

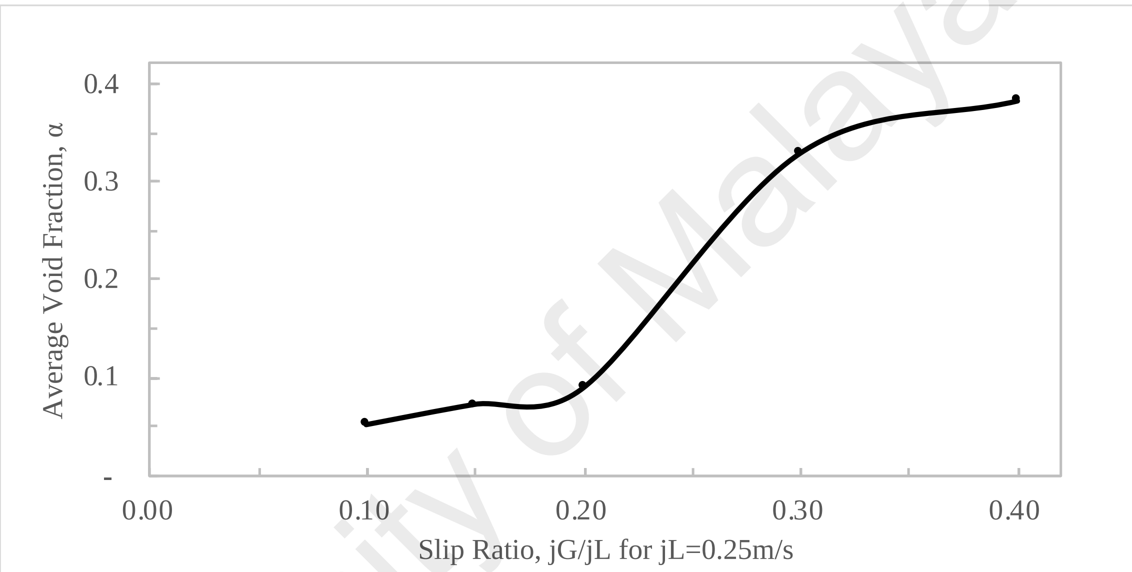

Figure 4.7 Average void fraction for j_L=0.25 m/s

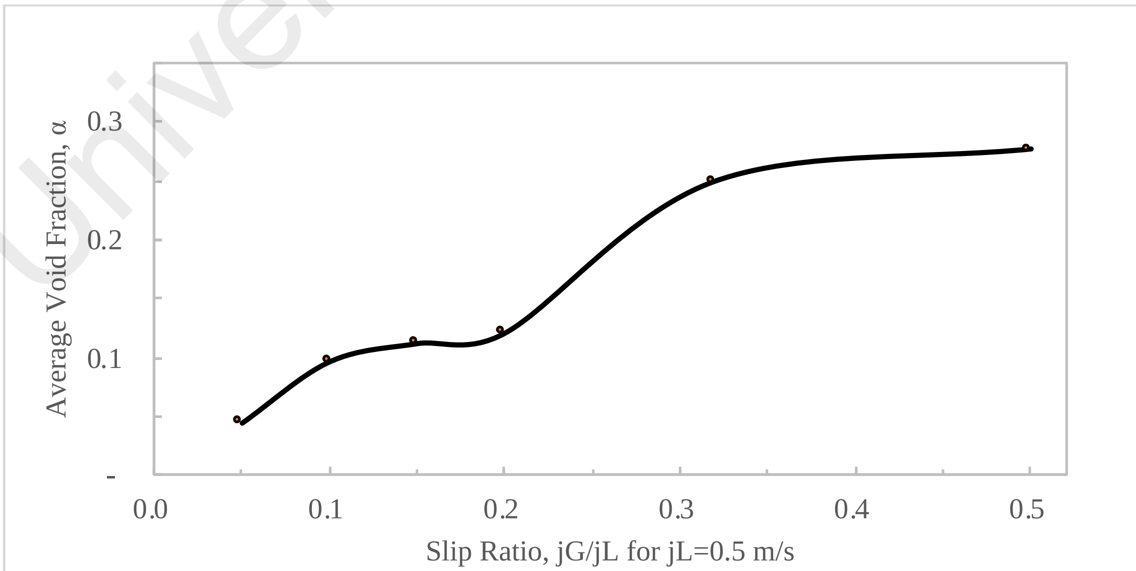

Figure 4.8 Average void fraction for j_L=0.5 m/s

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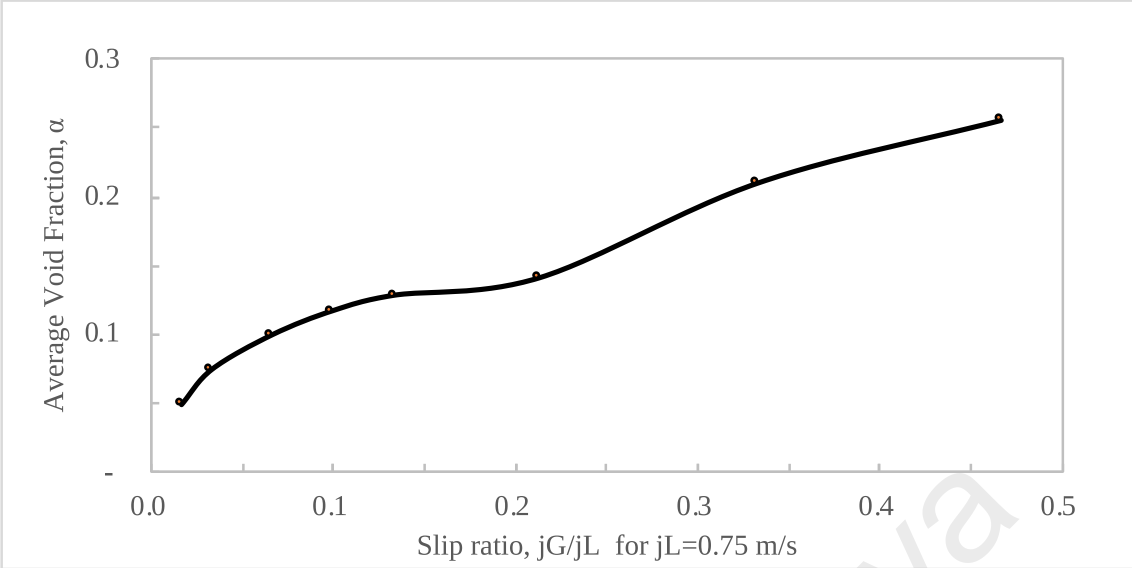

Figure 4.9 Average void fraction for j_L=0.75m/s

On the other hand, for liquid superficial velocity of 1.0 ~ 1.5 m/s, there is little difference in the average void fraction at the lower and higher gas superficial velocities with the range of only 0.2 as shown in Figure 4.10 and Figure 4.11.

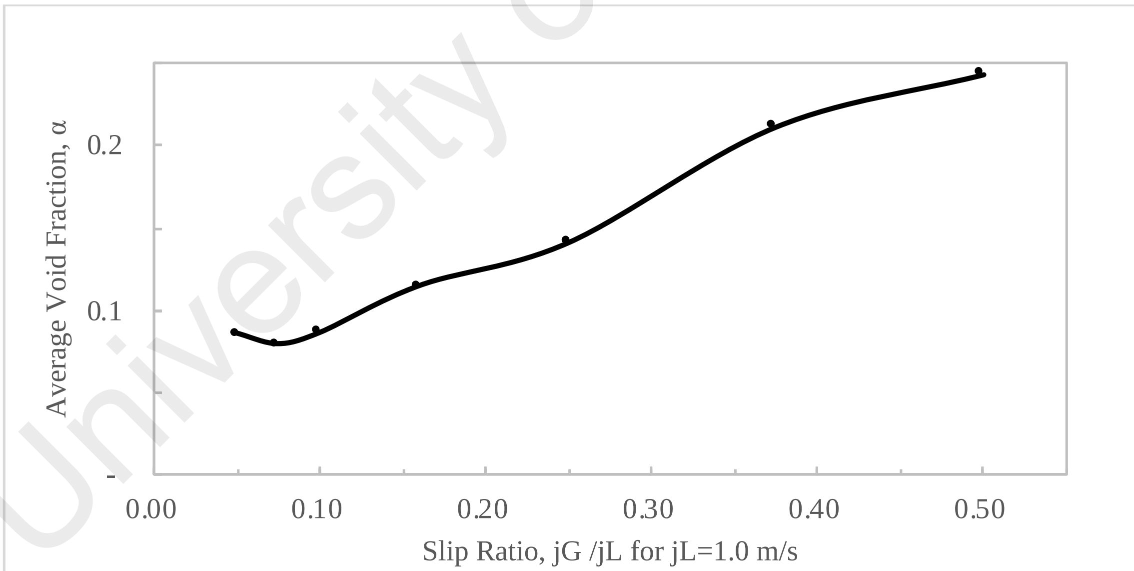

Figure 4.10 Average void fraction for j_L=1.0 m/s

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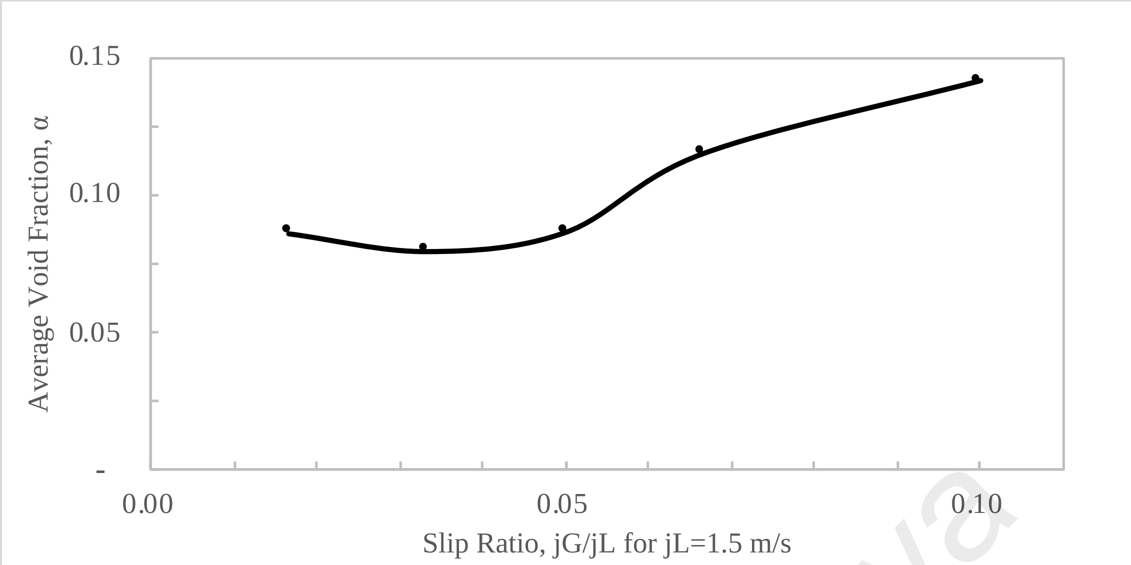

Figure 4.11 Average void fraction for j_L=1.5 m/s

Figure 4.12 shows total average of void fraction for j_L= 2.0 m/s. After slip ratio of 0.05 the average void fraction drops linearly. This may happen due to the pressure build up in the liquid phase in the test section, as a result of higher velocity and hence higher volume of liquid in the flow channel. However, different phenomena are observed at a local position and they are presented in Section 4.3.

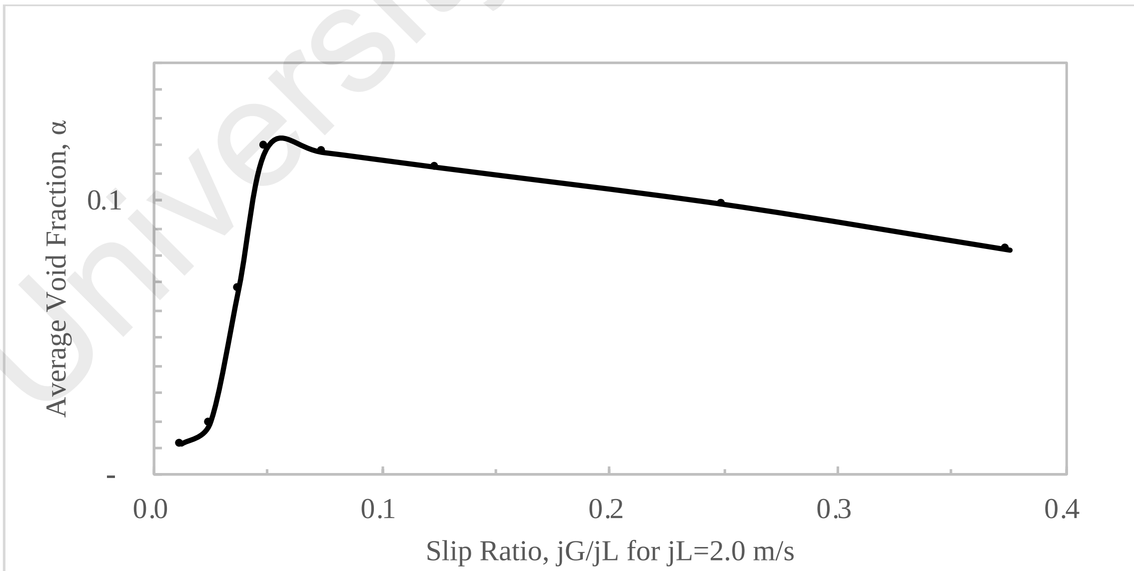

Figure 4.12 Average void fraction for j_L=2.0 m/s

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Figure 4.13 shows total average void fraction at 2.5 m/s liquid superficial velocity. In this case, the average void fraction fluctuates up and down as the gas superficial velocity increases. Here, with combination of high gas and liquid superficial velocity, the flow is very chaotic and pressure distribution along the channel also disrupted, therefore resulted in different amount of volume of both phases as they travel upward in the channel. Again, referring to section 4.1.5, the flow patterns during this flow condition are almost unchanged regardless of the increasing gas superficial velocities.

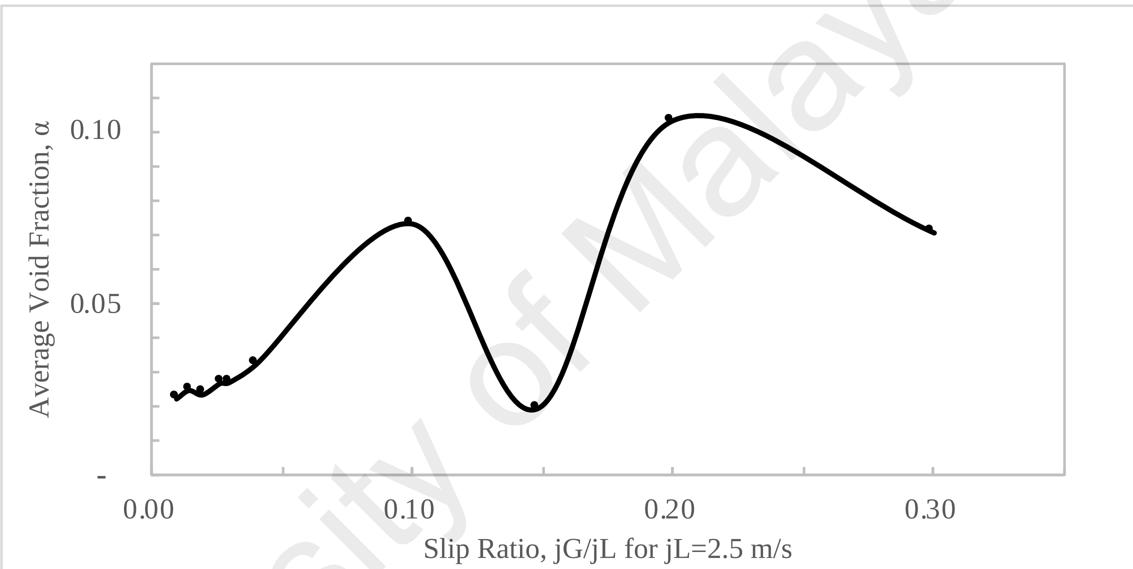

Figure 4.13 Average void fraction for j_L=2.5 m/s

Figure 4.14 shows average void fraction at different liquid superficial velocities, j_L. The plot implies that void fraction values decrease as superficial liquid velocity increases which is physically consistent. It can hence be inferred that void fraction is well correlated with gas and liquid velocities when they are expressed in dimensionless form. At higher velocity of liquid phase, the bubbles could not stay longer in a local position in the flow channel as they were push away along with the liquid to the upper part of the flow channel and therefore contribute to the decreasing void fraction.

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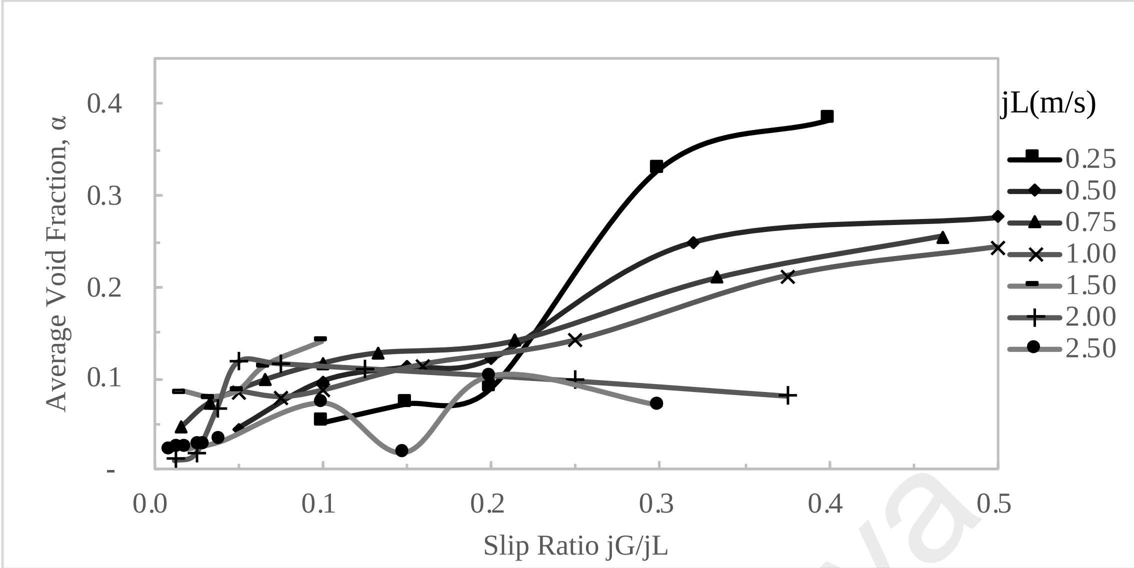

Figure 4.14 Average void fraction at different liquid superficial velocities, j_L

In conclusion, it is confirmed that the velocity of both phases strongly influences the value of void fraction in gas-liquid two-phase flow and particularly for this case, the air-water flow. This effect is extremely very important to be analysed using the ratio of both phases which is termed here as slip ratio.

4.3 Local Average Void Fraction

Figure 4.14 illustrates the local average void fraction at various liquid superficial velocity, j_L=0.25 to 2.5 m/s. The averages void fraction for a pair of flow condition (j_G and j_L) refers to the average of all the void faction values measured during the 10 seconds period. For all the plots, the void fraction at the two axial positions (35 and 50 L/D) increases as slip ratio increases. However, the void fraction at the upper position (at L/D = 50) shows different behaviour at j_L greater than 2.0 m/s.

In detail, at comparatively low liquid superficial velocity, j_L = 0.25 ~ 1.0 m/s, the average local void fractions at axial position, L/D=50 are higher than local void fraction at axial position L/D=35. In general, it can be concluded that the void fraction at the upper side of flow channel is higher than the lower position. This implies that the gas phase dominated the flow as it travels upward in the channel under this flow condition, with range of slip ratio, S= 0.1 ~ 0.5. Here, the occupation of gas phase at both parts is around 30 ~ 40%, which reflect that there is not much change of gas volume along the channel. In other word, it can be described that the gas phase flows smoothly upward in the channel. The increased void fraction indicates that the bubbles congregate and coalesce easily and therefore it can be postulated that the possibility of flow patterns transition and formations are much easier under this condition. This conclusion is supported by the discussion on flow patterns transitions in section 4.1 and they are presented in Figure 4.1 ~ Figure 4.4.

When the volume of liquid increases in a channel with fixed diameter, a comparatively higher liquid superficial velocity can be supplied and for the current work, they are in the range of, j_L = 1.5 ~ 2.5 m/s. Under this condition, results in Figure 4.15 show that average local void fraction at axial position, L/D=50 are lower than local void fraction at axial position L/D=35. This contrast results indicate that the liquid phase took over as dominating phase as the gas-liquid travel up in the flow channel. Under very low slip ratio, the bubbles generations at both positions (L/D=35 and L/D=50) are almost the same, with very low void fraction, $\alpha < 0.1$. As the two phases move up together, it can be noticed that the void fraction at the higher position is still showing higher value than the lower position, as for j_L=2.0 ~ 2.5 m/s until they reach a situation where the gas dominating 20% of the flow channel (α =0.2) with slip ratio, S=0.1.

However, with the increases of the velocity in the gas phase, as in this figure, which is indicated by higher order of slip ratio (S>0.1), the void fraction at higher position does not increase accordingly. Here, it can be predicted that the coalescences of bubbles did not succeed and the further collapsed to form smaller bubbles with churning behaviour and therefore the void fraction does not increase.

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Again, as the gas superficial velocity increases, congregation of bubbles were developed and destroyed, which is shown by changes of void fraction in Figure 4.15. In this case, the maximum occupation of gas phase at higher position is below 10% and only about 35% at the lower position when it travels together with liquid at higher superficial velocities, j_L=2.0 ~ 2.5 m/s. Under this condition, the liquid phase dominates the flow channel, and when the gas superficial velocity is further increased, the flow become chaotic and a rough turbulent condition has developed, and therefore void fraction can be seen fluctuating up and down at the higher position, L/D=50, and occupation of gas phase at this position is very hard to go beyond 10%. Some visual evidence of the current results can be referred in Figure 4.5 and Figure 4.6.

The current work only concentrated on the shorter test channel of 2-m length due to limitation of generating higher gas superficial velocity. Therefore, the results presented in this report are only for gas superficial velocity with the range of 0.025 ~ 1.0 m/s and within this scope, they agreed well with Ishii (1977).

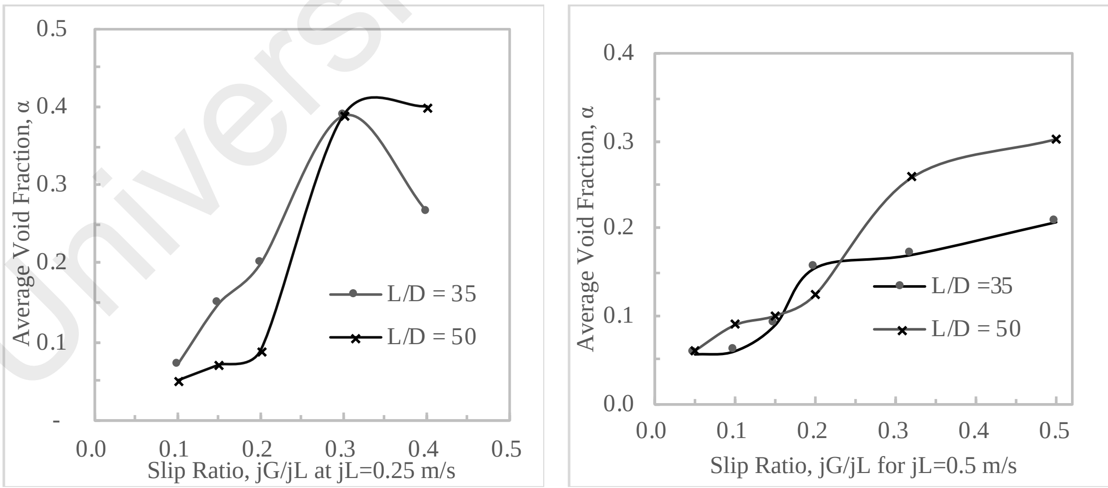

Figure 4.15 Local average void fraction at jL = 0.25 ~2.5 m/s

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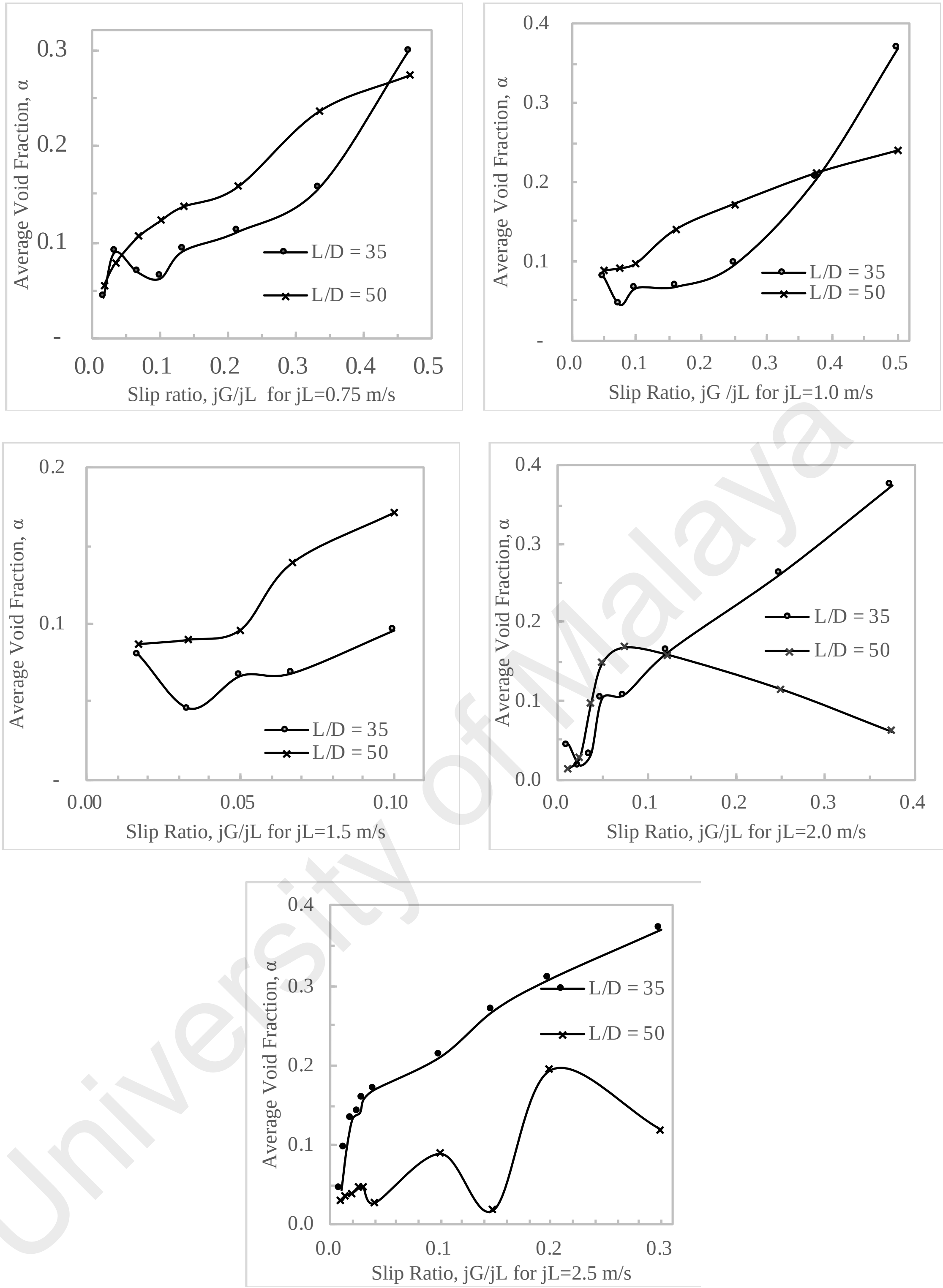

Figure 4.15 Continued

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CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

An industrial scale of air-water two-phase flow experimental rig has been constructed for measurement of various parameters in gas-liquid two-phase flow. A special sensor has also been developed to perform measurement of those paraments using CECM. The performance of this sensor has been validated by the calibration conducted both for the static and dynamics methods. The static calibration shows that the sensor has a good accuracy with 3% of overall error while the dynamic calibration gives a diversion of accuracy around 5%. The reliability of this sensor has been tested to measure the volumetric gas rate in the two-phase flow (void fraction) in wide range of flow conditions. The results show that all the measured parameters agreed well with previously obtained data from various scholars.

In this report, the void fraction measurements have been conducted for a vertically upward air-water flow with ranges of velocities of gas-liquid phases in 20-mm inner diameter flow channel and were compared with other scholars' results. It was found that the results agree well to some extent, but some discrepancies were unavoidable. due to different experimental condition, Furthermore, the obtained results revealed that the velocities of both phases strongly contribute to the fluctuations of void fractions, particularly for the current study in two different ways. Firstly, as a natural phenomenon, at a fixed liquid velocity, and increasing velocity of the gas from j_G= 0.025 ~ 0.5 m/s due to increase of mass flow rate will increase the value of void fraction. This condition will contribute to congregation of gas bubbles that as a result promote coalescences of these bubbles that lead to formations of bigger and longer bubbles such as slugs along the flow channel. With these formations the volume of gas will be higher and therefore increase the value of void fraction. Secondly, at higher velocity of liquid phase, the bubbles could not stay longer in a particular local position in the flow channel as they were push away along with the liquid to the upper part of the flow channel and therefore contribute to the decreasing void fraction. This result should be confirmed by the investigated of flow patterns of the same flow conditions. The final case study was conducted for flow condition with liquid superficial velocity of 2.5 *m/s* with the fluctuations of average void fraction value are very obvious as they seem cannot be settled at any fixed point.

Furthermore, at comparatively low liquid superficial velocity, j_L = 0.25 ~ 1.0 m/s, the average local void fractions at axial position, L/D=50 are higher than local void fraction at axial position L/D=35. It can be concluded that the void fraction at the upper side of flow channel is higher than the lower position. This implies that the gas phase dominated the flow as it travels upward in the channel under this flow condition, with range of slip ratio, S= 0.1 ~ 0.5. However, at higher liquid superficial velocity, j_L = 1.5 ~ 2.5 m/s, average local void fraction at axial position, L/D=50 are lower than local void fraction at axial position L/D=35. This contrast results indicate that the liquid phase took over as dominating phase as the gas-liquid travel up in the flow channel.

5.2 Recommendation

In addition, it is suggested that, void fraction on horizontal and incline air-water flow channel could also be investigated in the future as they are also very important in practical applications in industries. Apart from that, further assessment of many correlation related to void fraction such as drift-flux model is very important in order to predict the void fraction in wide range of flow conditions. Therefore, more progresses in this area are desired in the effort to gain a better understanding of the complexities involved in two-phase flow. It is very important to take this issue seriously for the safety design and analyses of various equipment, machineries and for benefit of future generation.

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APPENDIX A

Close-up of test section and measurement facilities

APPENDIX B

Example of Datasheet for Local Average and Total Average Void Fraction

jL	jG	SLIP RATIO	L/D=35	L/D=50	TOTAL AVERAGE
0.25	0.025	0.100	0.054	0.051	0.053
0.25	0.038	0.150	0.075	0.071	0.073
0.25	0.050	0.200	0.090	0.090	0.090
0.25	0.075	0.300	0.271	0.390	0.330
0.25	0.100	0.400	0.366	0.401	0.384
0.50	0.025	0.050	0.028	0.061	0.045
0.50	0.050	0.100	0.103	0.091	0.097
0.50	0.075	0.150	0.123	0.101	0.112
0.50	0.100	0.200	0.116	0.125	0.121
0.50	0.160	0.320	0.240	0.259	0.249
0.50	0.250	0.500	0.250	0.303	0.277
0.75	0.013	0.017	0.042	0.056	0.049
0.75	0.025	0.033	0.070	0.079	0.074
0.75	0.050	0.067	0.093	0.106	0.100
0.75	0.075	0.100	0.111	0.123	0.117
0.75	0.100	0.133	0.119	0.138	0.128
0.75	0.160	0.213	0.124	0.158	0.141
0.75	0.250	0.333	0.184	0.236	0.210
0.75	0.350	0.467	0.238	0.274	0.256
1.00	0.050	0.050	0.085	0.087	0.086
1.00	0.075	0.075	0.069	0.090	0.080
1.00	0.100	0.100	0.077	0.096	0.086
1.00	0.160	0.160	0.091	0.139	0.115
1.00	0.250	0.250	0.111	0.171	0.141
1.00	0.375	0.375	0.212	0.210	0.211
1.00	0.500	0.500	0.247	0.239	0.243
1.50	0.025	0.017	0.085	0.087	0.086
1.50	0.050	0.033	0.069	0.090	0.080
1.50	0.075	0.050	0.077	0.096	0.086
1.50	0.100	0.067	0.091	0.139	0.115
1.50	0.150	0.100	0.111	0.171	0.141
2.00	0.025	0.013	0.008	0.015	0.011
2.00	0.050	0.025	0.009	0.029	0.019
2.00	0.075	0.038	0.037	0.098	0.068
2.00	0.100	0.050	0.090	0.148	0.119
2.00	0.150	0.075	0.066	0.168	0.117
2.00	0.250	0.125	0.065	0.159	0.112
2.00	0.500	0.250	0.081	0.116	0.098
2.00	0.750	0.375	0.102	0.061	0.082
2.50	0.025	0.010	0.016	0.029	0.022
2.50	0.037	0.015	0.013	0.036	0.025
2.50	0.050	0.020	0.008	0.039	0.023
2.50	0.067	0.027	0.007	0.046	0.027
2.50	0.075	0.030	0.008	0.046	0.027
2.50	0.100	0.040	0.037	0.026	0.032
2.50	0.250	0.100	0.058	0.088	0.073
2.50	0.370	0.148	0.021	0.018	0.019
2.50	0.500	0.200	0.013	0.193	0.103
2.50	0.750	0.300	0.023	0.118	0.070

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REFERENCES

Acuña, C. A., & Finch, J. A. (2010). Tracking velocity of multiple bubbles in a swarm. *International Journal of Mineral Processing, 94*(3), 147-158. doi:https://doi.org/10.1016/j.minpro.2010.02.001

Amaya-Bower, L., & Lee, T. (2010). Single bubble rising dynamics for moderate Reynolds number using Lattice Boltzmann Method. *Computers & Fluids, 39*(7), 1191-1207. doi:https://doi.org/10.1016/j.compfluid.2010.03.003

Barcozy, C. J. (1966). A systematic correlation for two-phase pressure drop. *Chemical Engineering Program Symposium*(62), 232 ~ 249.

Bergant, A., Simpson, A. R., & Tijsseling, A. S. (2006). Water hammer with column separation: A historical review. *Journal of Fluids and Structures, 22*(2), 135-171. doi:https://doi.org/10.1016/j.jfluidstructs.2005.08.008

Boccardi, G., Bubbico, R., Piero Celata, G., & Di Tosto, F. (2008). Geometry influence on safety valves sizing in two-phase flow. *Journal of Loss Prevention in the Process Industries, 21*(1), 66-73. doi:https://doi.org/10.1016/j.jlp.2007.07.002

Cha, J.-E., Ahn, Y.-C., & Kim, M.-H. (2002). Flow measurement with an electromagnetic flowmeter in two-phase bubbly and slug flow regimes. *Flow Measurement and Instrumentation, 12*(5), 329-339. doi:https://doi.org/10.1016/S0955-5986(02)00007-9

Cheng, H., Hills, J. H., & Azzopardi, B. J. (2002). Effects of initial bubble size on flow pattern transition in a 28.9 mm diameter column. *International Journal of Multiphase Flow, 28*(6), 1047-1062. doi:https://doi.org/10.1016/S0301-9322(02)00013-7

Chun, M.-H., & Ryu, Y.-H. (2000). Thermal analysis of a simulated CANDU 37-element spent fuel bundle with air backfill. *Nuclear Engineering and Design, 199*(1), 85-99. doi:https://doi.org/10.1016/S0029-5493(99)00072-2

Costigan, G., & Whalley, P. B. (1997). Slug flow regime identification from dynamic void fraction measurements in vertical air-water flows. *International Journal of Multiphase Flow, 23*(2), 263-282. doi:https://doi.org/10.1016/S0301-9322(96)00050-X

Ebrahimi-Mamaghani, A., Sotudeh-Gharebagh, R., Zarghami, R., & Mostoufi, N. (2019). Dynamics of two-phase flow in vertical pipes. *Journal of Fluids and Structures, 87*, 150-173. doi:https://doi.org/10.1016/j.jfluidstructs.2019.03.010

Fossa, M. (1998). Design and performance of a conductance probe for measuring the liquid fraction in two-phase gas-liquid flows. *Flow Measurement and Instrumentation, 9*(2), 103-109. doi:https://doi.org/10.1016/S0955-5986(98)00011-9

University of Malaya

Fukano, T. (1998). Measurement of time varying thickness of liquid film flowing with high speed gas flow by a constant electric current method (CECM). *Nuclear Engineering and Design, 184*(2), 363-377. doi:https://doi.org/10.1016/S0029-5493(98)00209-X

Fukano, T., & Ousaka, A. (1989). Prediction of the circumferential distribution of film thickness in horizontal and near-horizontal gas-liquid annular flows. *International Journal of Multiphase Flow, 15*(3), 403-419. doi:https://doi.org/10.1016/0301-9322(89)90010-4

Furukawa, T., & Fukano, T. (2001). Effects of liquid viscosity on flow patterns in vertical upward gas–liquid two-phase flow. *International Journal of Multiphase Flow, 27*(6), 1109-1126. doi:https://doi.org/10.1016/S0301-9322(00)00066-5

Gardner, G. C. (1980). Fractional vapour content of a liquid pool through which vapour is bubbled. *International Journal of Multiphase Flow, 6*(5), 399-410. doi:https://doi.org/10.1016/0301-9322(80)90002-6

Gardner, T. (2011, July 11, 2011). Analysis: Study warns of leak risks of Canada-U.S. oil pipe. *Reuters*. Retrieved from https://www.reuters.com/article/us-usa-pipeline-analysis/analysis-study-warns-of-leak-risks-of-canada-u-s-oil-pipe-idUSTRE76A67R20110711

Gregory, G. A., Nicholson, M. K., & Aziz, K. (1978). Correlation of the liquid volume fraction in the slug for horizontal gas-liquid slug flow. *International Journal of Multiphase Flow, 4*(1), 33-39. doi:https://doi.org/10.1016/0301-9322(78)90023-X

Harvel, G. D., Hori, K., Kawanishi, K., & Chang, J. S. (1999). Cross-sectional void fraction distribution measurements in a vertical annulus two-phase flow by high speed X-ray computed tomography and real-time neutron radiography techniques. *Flow Measurement and Instrumentation, 10*(4), 259-266. doi:https://doi.org/10.1016/S0955-5986(99)00008-4

Hibiki, T., Ishii, M., & Xiao, Z. (2001). Axial interfacial area transport of vertical bubbly flows. *International Journal of Heat and Mass Transfer, 44*(10), 1869-1888. doi:https://doi.org/10.1016/S0017-9310(00)00232-5

Hibiki, T., Situ, R., Mi, Y., & Ishii, M. (2003). Local flow measurements of vertical upward bubbly flow in an annulus. *International Journal of Heat and Mass Transfer, 46*(8), 1479-1496. doi:https://doi.org/10.1016/S0017-9310(02)00421-0

Hirt, C. W., & Nichols, B. D. (1981). Volume of fluid (VOF) method for the dynamics of free boundaries. *Journal of Computational Physics, 39*(1), 201-225. doi:https://doi.org/10.1016/0021-9991(81)90145-5

Hughmark, G. A. (1965). Holdup and heat transfer in horizontal slug gas-liquid flow. *Chemical Engineering Science, 20*(12), 1007-1010. doi:https://doi.org/10.1016/0009-2509(65)80101-4

Huq, R., & Loth, J. L. (1992). Analytical two-phase flow void prediction method. *Journal of Thermophysics and Heat Transfer, 6*(1), 139-144. doi:10.2514/3.329

University of Malaya

Ishii, M. (1977). *One-dimensional drift-flux model and constitutive equations for relative motion between phases in various two-phase flow regimes*. Retrieved from United States: https://www.osti.gov/servlets/purl/6871478

Ismail, I., Gamio, J. C., Bukhari, S. F. A., & Yang, W. Q. (2005). Tomography for multi-phase flow measurement in the oil industry. *Flow Measurement and Instrumentation, 16*(2), 145-155. doi:https://doi.org/10.1016/j.flowmeasinst.2005.02.017

Kataoka, I., & Ishii, M. (1987). Drift Flux Model for Large Diameter Pipe and New Correlation for Pool Void Fraction. *30*, 1927–1939. doi:10.1016/0017-9310(87)90251-1

Krishna, R., & van Baten, J. M. (1999). Rise characteristics of gas bubbles in a 2D rectangular column: VOF simulations vs experiments. *International Communications in Heat and Mass Transfer, 26*(7), 965-974. doi:https://doi.org/10.1016/S0735-1933(99)00086-X

Lenzinger, M., & Schweizer, B. (2010). Two-phase flow equations with outflow boundary conditions in the hydrophobic–hydrophilic case. *Nonlinear Analysis: Theory, Methods & Applications, 73*(4), 840-853. doi:https://doi.org/10.1016/j.na.2010.03.040

Ma, Y.-P., Chung, N.-M., Pei, B.-S., Lin, W.-K., & Hsu, Y.-Y. (1991). Two Simplified Methods to Determine Void Fractions for Two-Phase Flow. *Nuclear Technology, 94*(1), 124-133. doi:10.13182/NT91-A16228

Michiyoshi, I., & Serizawa, A. (1989). Two-phase flow studies in Japan. *International Journal of Multiphase Flow, 15*(5), 679-733. doi:https://doi.org/10.1016/0301-9322(89)90036-0

Mishima, K., & Hibiki, T. (1996). Quantitative limits of thermal and fluid phenomena measurements using the neutron attenuation characteristics of materials. *Experimental Thermal and Fluid Science, 12*(4), 461-472. doi:https://doi.org/10.1016/0894-1777(95)00181-6

Mishima, K., & Ishii, M. (1984). Flow regime transition criteria for upward two-phase flow in vertical tubes. *International Journal of Heat and Mass Transfer, 27*(5), 723-737. doi:https://doi.org/10.1016/0017-9310(84)90142-X

Mukherjee, H., & Brill, J. P. (1983). Liquid Holdup Correlations for Inclined Two-Phase Flow. *Journal of Petroleum Technology, 35*(05), 1003-1008. doi:10.2118/10923-PA

Nayak, A. K., Lathouwers, D., Hagen, T. H. J. J. v. d., Schrauwen, F., Molenaar, P., & Rogers, A. (2006). A numerical study of boiling flow instability of a reactor thermosyphon system. *Applied Thermal Engineering, 26*(5), 644-653. doi:https://doi.org/10.1016/j.applthermaleng.2005.05.019

Okawa, T., Kataoka, I., & Mori, M. (2002). Numerical simulation of lateral phase distribution in turbulent upward bubbly two-phase flows. *Nuclear Engineering*

University of Malaya

and Design, 213(2), 183-197. doi:https://doi.org/10.1016/S0029-5493(01)00512-X

Pozos, O., Giesecke, J., Marx, W., Rodal, E. A., & Sanchez, A. (2010). Experimental investigation of air pockets in pumping pipeline systems. *Journal of Hydraulic Research, 48*(2), 269-273. doi:10.1080/00221681003726262

Rahmani, A., Bouchami, T., Bélaïd, S., Bousbia-Salah, A., & Boulheouchat, M. H. (2009). Assessment of boiler tubes overheating mechanisms during a postulated loss of feedwater accident. *Applied Thermal Engineering, 29*(2), 501-508. doi:https://doi.org/10.1016/j.applthermaleng.2008.03.008

Revankar, S. T., & Ishii, M. (1992). Local interfacial area measurement in bubbly flow. *International Journal of Heat and Mass Transfer, 35*(4), 913-925. doi:https://doi.org/10.1016/0017-9310(92)90257-S

Rzasa, M. R. (2009). The measuring method for tests of horizontal two-phase gas-liquid flows, using optical and capacitance tomography. *Nuclear Engineering and Design, 239*(4), 699-707. doi:10.1016/j.nucengdes.2008.12.020

Serizawa, A. (1974). *Fluid Dynamic Characteristics in Gas-Liquid Two-Phase Flow.* Kyoto University,

Sharma, S. L., Ishii, M., Hibiki, T., Schlegel, J. P., Liu, Y., & Buchanan, J. R. (2019). Beyond bubbly two-phase flow investigation using a CFD three-field two-fluid model. *International Journal of Multiphase Flow, 113*, 1-15. doi:https://doi.org/10.1016/j.ijmultiphaseflow.2018.12.010

Song, C.-H., Chung, M. K., & No, H. C. (1998). Measurements of void fraction by an improved multi-channel conductance void meter. *Nuclear Engineering and Design, 184*(2), 269-285. doi:https://doi.org/10.1016/S0029-5493(98)00202-7

Sterman, L. S. (1956). The generalization of experimental data concerning the bubbling of vapor through the liquid,. *Technical Physics USSR 1*, 1479 -1485.

Taitel, Y., & Dukler, A. E. (1976). A model for predicting flow regime transitions in horizontal and near horizontal gas-liquid flow. *AIChE Journal, 22*(1), 47-55. doi:10.1002/aic.690220105

Takenaka, N., Asano, H., Fujii, T., & Matsubayashi, M. (1998). Three-dimensional visualization of void fraction distribution in steady two-phase flow by thermal neutron radiography. *Nuclear Engineering and Design, 184*(2), 203-212. doi:https://doi.org/10.1016/S0029-5493(98)00197-6

Talaia, M. (2007). *Terminal Velocity of a Bubble Rise in a Liquid* (Vol. 28).

Tan, C., Dong, F., & Wu, M. (2007). Identification of gas/liquid two-phase flow regime through ERT-based measurement and feature extraction. *Flow Measurement and Instrumentation, 18*(5), 255-261. doi:https://doi.org/10.1016/j.flowmeasinst.2007.08.003

University of Malaya

Uesawa, S., Kaneko, A., & Abe, Y. (2016). Measurement of void fraction in bubbly-slug flow with a constant electric current method. *Journal of Nuclear Science and Technology, 53*(1), 48-60. doi:10.1080/00223131.2015.1021284

Wallis, G. B. (1969). *One-dimensional two-phase flow*: McGraw-Hill.

Wang, P., Cilliers, J. J., Neethling, S. J., & Brito-Parada, P. R. (2019). The behavior of rising bubbles covered by particles. *Chemical Engineering Journal, 365*, 111-120. doi:https://doi.org/10.1016/j.cej.2019.02.005

Yang, H. C., Kim, D. K., & Kim, M. H. (2003). Void fraction measurement using impedance method. *Flow Measurement and Instrumentation, 14*(4), 151-160. doi:https://doi.org/10.1016/S0955-5986(03)00020-7

Zainon, M. Z. (2013). *EFFECTS OF VIBRATION ONTO THE FLOW STRUCTURES AND DYNAMICS OF GAS-LIQUID TWO-PHASE FLOW.* (ENGINEERING). UNIVERSITY OF MALAYA, MALAYSIA.

Zainon, M. Z., & Serizawa, A. (2002, July 29 -31). *Behavior of a rising bubble during a class of heavy disaster shakes.* Paper presented at the Proceedings of Japan Society of Multiphase Flow Annual Meeting, Nagoya, Japan.

Zainon, M. Z., Zubir, M., & Ramli, R. (2014). *Transition of Bubbly to Slug Flow in a Short Vertical Channel of Gas-Liquid Two-Phase Flow* (Vol. 881-883).

Zboray, R., & Trtik, P. (2018). 800 fps neutron radiography of air-water two-phase flow. *MethodsX, 5*, 96-102. doi:https://doi.org/10.1016/j.mex.2018.01.008

Zhao, Q., & Hibiki, T. (2019). One-dimensional drift-flux correlation for vertical upward two-phase flow in large size concentric and eccentric annuli. *International Journal of Multiphase Flow, 113*, 33-44. doi:https://doi.org/10.1016/j.ijmultiphaseflow.2018.12.016

Zuber, N., & Findlay, J. A. (1965). Average Volumetric Concentration in Two-Phase Flow Systems. *Journal of Heat Transfer, 87*(4), 453-468. doi:10.1115/1.3689137

Zubir, M., Ramli, R., & Zainon, M. (2019). *Determination of Flow Patterns in Vertical Upward Two-Phase Flow Channel via Void Fraction Profile* (Vol. 12).

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