PREDICTION OF BUBBLE VELOCITIES IN AIR-WATER TWO-PHASE FLOW USING VOID FRACTION PROFILES

AHMAD NAJIMUDDIN ISMAIL

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2019

PREDICTION OF BUBBLE VELOCITIES IN AIR-WATER TWO-PHASE FLOW USING VOID FRACTION PROFILES

AHMAD NAJIMUDDIN ISMAIL

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

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2019

UNIVERSITY OF MALAYA

ORIGINAL LITERARY WORK DECLARATION

Name of Candidate: Ahmad Najimuddin Ismail

Matric No: KQK170001

Name of Degree: Master of Mechanical Engineering

Title of Research Project Report ("this Work"): Prediction of Bubble Velocities in Air-Water Two-Phase Flow Using Void Fraction Profile

Field of Study:

I do solemnly and sincerely declare that:

(1) I am the sole author/writer of this Work;
(2) This Work is original;
(3) Any use of any work in which copyright exists was done by way of fair dealing and for permitted purposes and any excerpt or extract from, or reference to or reproduction of any copyright work has been disclosed expressly and sufficiently and the title of the Work and its authorship have been acknowledged in this Work;
(4) I do not have any actual knowledge nor do I ought reasonably to know that the making of this work constitutes an infringement of any copyright work;
(5) I hereby assign all and every rights in the copyright to this Work to the University of Malaya ("UM"), who henceforth shall be owner of the copyright in this Work and that any reproduction or use in any form or by any means whatsoever is prohibited without the written consent of UM having been first had and obtained;
(6) I am fully aware that if in the course of making this Work I have infringed any copyright whether intentionally or otherwise, I may be subject to legal action or any other action as may be determined by UM.

Candidate's Signature　　　　　　　　Date:

Subscribed and solemnly declared before,

Witness's Signature　　　　　　　　Date:

Name:

Designation:

PREDICTION OF BUBBLE VELOCITIES IN AIR-WATER TWO-PHASE FLOW USING VOID FRACTION PROFILE

ABSTRACT

The heat transfer system is the most important application in a power generation plant, particularly in a thermal power plant. With a greater number of pipe bursting accidents happened in thermal power plants due to steam-vapor mixture two-phase flow phenomena, the need for enhancing plant safety level is substantially emerging. Many researchers analyze several parameters such as void fraction, flow rate, temperature and pressure in efforts to improve the plant safety level. Numerous studies on two-phase flow were conducted through simulation, modeling, numerical analysis, theoretical analysis, and comparative study. The present work is basically the investigation and prediction of bubble velocities using the void fraction profiles in air-water two-phase flow via experimental works. The experiment was conducted in an industrial scale vertical two-phase flow rig which consists of a 6.2-m length of transparent pipe with an inner diameter of 20-mm and implanted void sensor on the inner wall. Five different combinations of gas and liquid superficial velocities are designed and used in this experiment. Other variables namely temperature, pressure, pipe diameter and length were kept as constant to simplify the analysis. Experimental results confirmed that bubble velocities can be predicted using the void fraction profiles. Highest void fraction value of 0.40 and the transition of bubbly flow to slug flow occurred easily at high gas superficial velocity at constant low liquid superficial velocity. However, at a higher liquid superficial velocity, the bubbles became unsteady and distorted easily resulting of transition from slug flow to churn flow which is chaotic and unstable. The bubble velocity increased when gas superficial velocity was below 0.05 m/s and void fraction value more than 0.3.

Keywords: Power plant, safety, two-phase flow, bubble velocity, void fraction

RAMALAN HALAJU GELEMBUNG DALAM ALIRAN DUA FASA UDARA-AIR MENGGUNAKAN PROFIL PECAHAN RUANG KOSONG

ABSTRAK

Sistem pemindahan haba merupakan aplikasi yang paling penting pada loji penjanaan kuasa, terutamanya pada loji kuasa haba. Dengan lebih banyak kemalangan paip pecah yang berlaku di loji janakuasa haba yang disebabkan oleh fenomena aliran dua fasa campuran stim-wap, muncul keperluan untuk meningkatkan tahap keselamatan loji. Ramai penyelidik menganalisis beberapa parameter seperti pecahan ruang kosong, kadar aliran, suhu dan tekanan dalam usaha untuk meningkatkan tahap keselamatan loji. Banyak kajian mengenai aliran dua fasa dijalankan melalui simulasi, pemodelan, analisis berangka, analisis teori dan kajian perbandingan. Kerja ini pada dasarnya adalah untuk menyiasat dan meramal halaju gelembung menggunakan profil pecahan ruang kosong dalam aliran dua fasa air melalui eksperimen. Eksperimen ini dijalankan di plantar aliran dua fasa menegak berskala industri yang terdiri daripada paip telus panjang 6.2-m dengan diameter dalam 20-mm dan sensor ruang kosong yang diimplan di dinding dalam paip. Lima kombinasi yang berbeza halaju cetek gas dan cecair direka dan digunakan dalam eksperimen ini. Pembolehubah lain seperti suhu, tekanan, diameter dan Panjang paip dikekalkan sebagai pemalar untuk memudahkan analisis. Keputusan eksperimen mengesahkan bahawa halaju gelembung boleh diramalkan menggunakan profil pecahan ruang kosong. Nilai pecahan ruang kosong yang tertinggi ialah 0.40 dan peralihan aliran berbuih ke aliran *slug* berlaku dengan mudah pada halaju cetek gas yang tinggi dan pada halaju cetek cecair yang rendah dan tetap. Walau bagaimanapun, pada halaju cetek cecair yang lebih tinggi, gelembung menjadi tidak stabil dan herot-berot dengan mudah menyebabkan peralihan dari aliran *slug* untuk menghasilkan aliran *churn* yang huru-hara dan tidak stabil. Halaju gelembung meningkat apabila halaju cetek gas di bawah 0.05 m/s dan pada nilai pecahan ruang kosong yang lebih besar daripada 0.3.

Kata Kunci: Loji kuasa, keselamatan, aliran dua fasa, halaju gelembung, ruang kosong

ACKNOWLEDGEMENTS

I would like to express my gratitude to the Most Gracious and Most Merciful Allah S.W.T. Praiseworthy to Almighty Allah for giving me free will and strength to complete my Research Project.

It is a great pleasure to acknowledge my deepest gratitude to my supervisor, Dr. Mohd Zamri Zainon, from Department of Mechanical Engineering, Faculty of Engineering, University Malaya, for his dedication, support, and guidance during my ups and downs of my Research Project. Big and special thanks also to Assistant Science Officer, Mr. Mohd Asri Ismail for helping me during my project preparations.

To my family especially to my beloved wife, Nurhafizah Abd Rahman, my children, Aimi Nadhirah, Ainan Nabilah, Ahmad Nawfal, and Aida Nasuha, my parents and my in-laws for their endless love and priceless support and it is a great pleasure for me to express my thanks and appreciation to all of you. You all have helped me to focus and strive in pursuing my goal.

I would also like to thank all my fellow course mates who are together supporting each other throughout this Master's Degree journey since Semester 1 2017/2018. With your motivation and valuable insight, that have helped me to finish this course.

Lastly, special thanks to the Ministry of Health for giving me the opportunity to further my study and priceless scholarship to support my study.

May Allah bless you all.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

MW	:	Megawatt
TWh	:	terawatt hour
M	:	Meter
mm	:	Millimeter
LOCA	:	loss of coolant accident
LDV	:	laser doppler velocimetry
PIV	:	particle image velocimetry
CFD	:	computational fluid dynamic
°C	:	degree Celsius
j_G	:	gas superficial velocity (m/s)
j_L	:	liquid superficial velocity (m/s)
S	:	slip ratio
v_b	:	instantaneous bubble velocity (m/s)
v_{Gj}	:	drift velocity (m/s)
v_∞	:	terminal velocity (m/s)
J	:	volumetric flux
Δz	:	bubble traveling distance (m)
Δt	:	time lag (s)
toe	:	tonne of oil equivalent
etc.	:	et cetera
ktoe	:	kilotonne of oil equivalent
WH	:	Water hammer phenomenon
et al.	:	et alia
$\dot{m}_L$	:	Liquid mass flow rate (kg m/s)

$\dot{m}_G$	:	Gas mass flow rate (kg m/s)
ρ_G	:	Gas density (kg/m^3)
ρ_L	:	Liquid density (kg/m^3)
D_C	:	Vertical pipe diameter (m)
z	:	Vertical pipe length (m)
A_C	:	Vertical pipe cross sectional area (m^2)
v_L	:	Liquid mean velocity (m/s)
v_G	:	Gas mean velocity (m/s)
A_G	:	cross-sectional area of the core of the flow channel that filled by the gas phase (m^2)
D_G	:	diameter of the core of the flow channel that filled by the gas phase (m)
α	:	Void fraction
Re	:	Reynolds number
CECM	:	constant electric current method
R_{TP}	:	electrical resistance during the two-phase flow (Ω)
R_G	:	Electric resistance for gas phase (Ω)
R_L	:	Electric resistance for liquid phase (Ω)
η	:	Holdup
V_{TP}	:	voltage drop in a unit length (V/m)
I_0	:	Constant current (A)
V_L	:	voltage output during the sole existence of liquid that occupied whole cross section of the flow channel (V)
σ	:	Electric conductivity (S/m)
S/m	:	Siemens per meter
mA	:	Milliampere

L/D	:	Axial position
D_E	:	Diameter of experimental channel (m)
D_C	:	Diameter of calibration rod (m)
IEA	:	International Energy Agency

CHAPTER 1: INTRODUCTION

1.1 Background

Asia is currently facing a great industrial evolution, particularly in China and India. Asia's manufacturing, industry and services sectors are rapidly growing, and as a result driving increased-on energy demand. Growth in global energy demand lead by Asia is forecasted to intensify for the next 20 years (**Figure 1.1**). Increase in China and India populations also contribute to this increased-on energy demand.

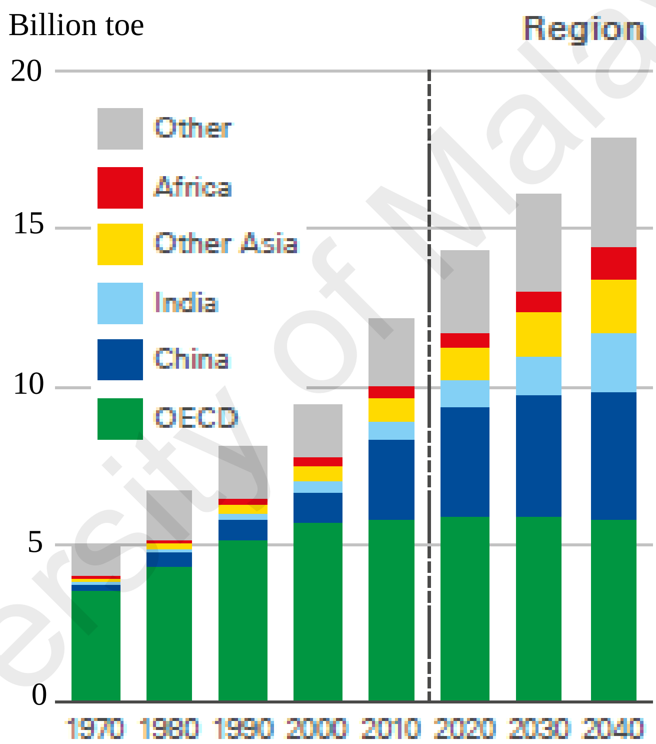


Figure 1.1: Primary energy demand by region (BP, 2019)

Approximately more than 80% of the increase in primary energy demand goes to the power sector (**Figure 1.2**). Building and industry sectors develop robustly, driven by an increase in demand for space cooling, lightings, electrical appliances, and machinery. On the other hand, the transport sector slightly increases in energy demand as a result of the growing technologies on energy efficiency vehicles.

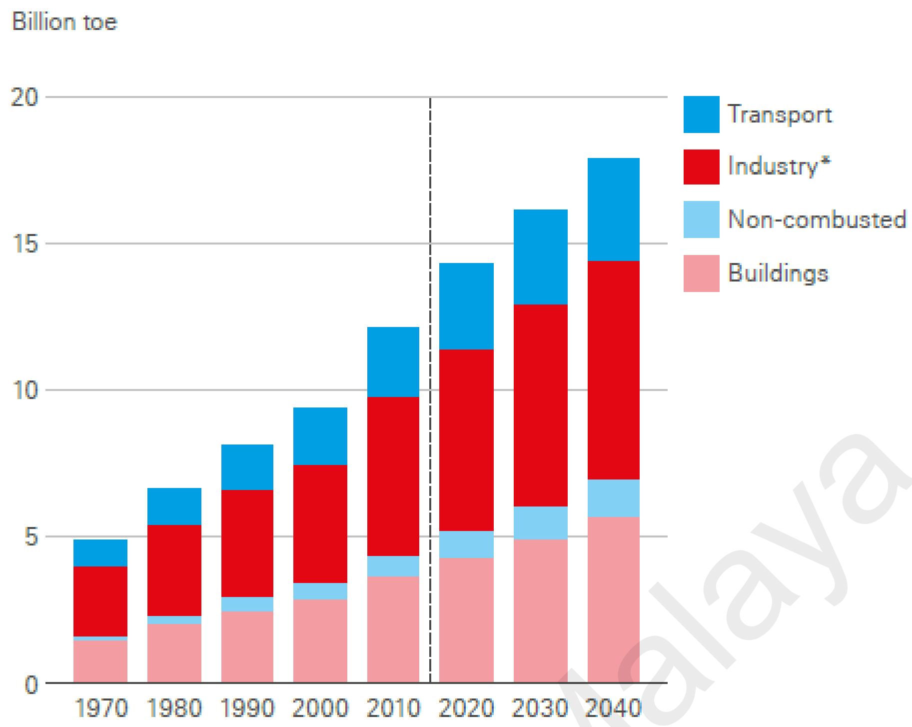


Figure 1.2: Primary energy consumption by end-use sector (BP, 2019)

Accordingly, this situation has encouraged the growth of power generation. Statistically from the point of global electric power sources which are a total of 67% generation by fossil fuel power plant and 13% by nuclear power plant (**Figure 1.3**). This statistic illustrates that approximately 80% of electric power generations are depending on the thermal power plants while the rest of sources are generated from renewable energy such as hydro, geothermal, solar, biofuels, etc.

As a result, the surge in electricity demand will increase the number of the thermal power plant. Thus, India has commissioned new 1000 MW clean coal technologies coal-fired power plant to cater the high energy demand in their railways sector (Bayar, 2017), while in Europe, due to rising carbon costs and coal plant closures, gas-fired power plant has widely constructed in order to produce 117 TWh of electricity demand across Europe (Ross, 2019).

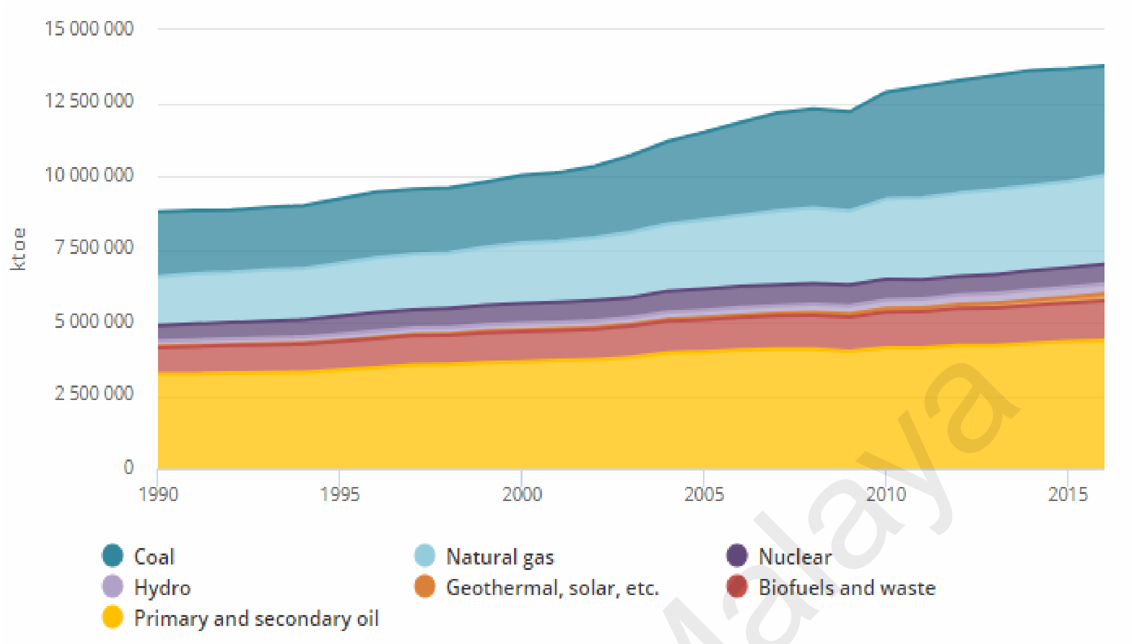


Figure 1.3: World total primary energy supply by source, 1990 ~ 2016, (IEA, 2018)

With the increasing number of thermal power plants, many accidents that occurred during the operations have been reported and eventually resulted in the loss of power generation and casualties. Recent accidents in thermal power plants are such as Zhejiang in China (2017) due to steam pipeline burst, Uttar Pradesh in India (2017) due to pipe in the boiler explosion, and Thoothukudi in India (2016) due to downcomer steam boiler pipe burst. All these accidents mostly due to poor maintenance, failure of equipment, lack of awareness, poor management systems, and human errors.

From the experiences of these accidents, all governments, international authorities, scholars and engineers have put more efforts such as regulations, training, and new sophisticated equipment to ensure high safety assurance level of the thermal power plant in order to maintain the trust of the public in the applications of thermal power plant as the main source of power generation. For most of cases, the same efforts also can be applied for chemical processing plants, oil recovery and refinery plants, and other industries.

Pipe bursting accidents are frequent in thermal power plants, and seriously impacts the safety and economic operation of thermal power plants. These accidents happen mainly due to the long period of superheating (Yue, 2012) and water hammer (WH) phenomenon (Paffel, 2016). These phenomena have mostly happened when two working fluids (i.e. gas-liquid) flow simultaneously in a particular pipe in co-current or countercurrent, which is known as two-phase flow.

Two-phase flow is a crucial phenomenon within various industries such as thermal power plant, chemical processing plant, and oil refineries plant. The most common two-phase flows are Gas-Liquid Flow, Gas-Solid Flow, Liquid-Liquid Flow, and Liquid-Solid Flow. In order to design highly safe heating elements or nuclear reactors, a great understanding of two-phase flow heat transfer is vital. Therefore, it is very significant to understand two-phase flow phenomenon in order to avoid pipe bursting accidents in the thermal power plant or loss of coolant accidents in the nuclear power plant.

1.2 Problem Statement

Rigorous efforts were performed by scholars and equipment manufacturers to understand the two-phase flow phenomenon today in order to improve the safety level of the thermal power plant, particularly in industries to avoid the loss of power generation. One of the methods is by predicting the bubble velocities in gas-liquid two-phase flow using the void fraction profile such as reported by Zubir et al. (2019), via an experiment with a wide range of flow conditions. These studies can also be conducted using simulation, numerical, comparative or theoretical analysis. However, the actual result is the best to be achieved using an industrial scale two-phase flow rig. Therefore, it is necessary to further investigate and predict the bubble velocities on a physical two-phase flow rig using the void fraction profile and analyze the related parameters.

1.3 Objectives of Study

The purposes of this study are:

1. To investigate bubble velocity in a vertical air-water two-phase flow based on different of both phases
2. To compare the experimental value and theoretical coefficient suggested by various scholars

1.4 Scope of Study

In order to achieve such objectives, experimental works were conducted in an industrial scale vertical two-phase flow rig which consists of a 6.2-m length of transparent pipe with an inner diameter of 20-mm and an implanted void sensor on the inner wall. All data were recorded and further analyzed in order to investigate the effect of bubble velocity variations on the two-phase flow. The value of some variables in this experiment was fixed as constant such water temperature, inner diameter, and pipe length.

Several assumptions were made for the current project as follows:

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

1.5 Structure of the Research Project Report

The first part of this report are the reviews on the available literature and studies by other scholars of two-phase flow phenomenon and analysis on flow patterns. It continues with the methodology section that describes the details about the method, experimental apparatus, parameters used in this project.

The next section presents the result from the experiment that has been performed and follows by the discussion section that considers an assessment on the prediction of bubble velocities on air-water two-phase flow using the void fraction profiles. The report ends with the conclusion of this project and recommendation for future studies in the area of two-phase flow.

CHAPTER 2: LITERATURE REVIEW

Complex industrial plant such as power station, chemical processing, oil refineries, and nuclear power plant normally involve a very complicated pipeline arrangement. This pipeline exists for the transport of many types of fluid with various types of flow, especially two-phase flow. The studies on two-phase flow have been conducted since the 1960s (Wallis, 1969). These pipeline arrangements and orientations may differ according to the applications and design of the plants which generally known as horizontal, vertical and inclined. All these types of flow will contribute to many other phenomena which differ from one to another. In the current study, the analysis of two-phase flow will be the focus on vertical orientation. Air and water are used as the working fluids in this two-phase flow system and flow co-currently in an annulus transparent pipe.

Volumetric gas-liquid rate (void fraction), pressure distribution along the pipe, and thickness of the liquid film on the wall of the pipe are the major parameters that significantly affect the safety of the plant or equipment. Prediction and measurement of these parameters are crucial in order to ensure the safety of the plant or equipment and prevent any minor or major accident to happen. Pipe leakage or burst is the common problem happened in the piping system which is due to impropriate treatments of the two-phase flow. This problem may lead to serious disasters to human and the environment if the flowing fluids are hazardous liquid or gas. Leakages due to unpredictable pressure distribution in the pipeline 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 (Reuters, 2011).

In addition, Mishima and Ishii (1984), found that pipe failure in the nuclear reactor occurred due to the two-phase flow-induced vibration. This problem also happens during the fluid hammer phenomena in an ordinary thermal power plant (Bergant et al., 2006).

On the other hand, measurement of liquid film thickness is very important in a high-temperature flow in order to avoid the severe accident such as the Loss of Coolant Accident (LOCA) (Fukano, 1998; Serizawa, 1974). LOCA is a situation when liquids inside the pipe or heating wall dried out causing the meltdown of the heating element. In a big scale such as nuclear reactor, it is termed as core meltdown, Fukushima Daiichi Power Plant in 2011 as such example (Martin, 2019).

Many engineers facing great challenges dealing with the two-phase flow when designing mechanical systems involving high-temperature fluids particularly heating elements such as boiler, condenser, steam generator, and nuclear fuel rods. Besides temperature, other parameters such as heat flux, mass flow rate, pressure, phase velocity also needed to be considered to optimize the design of heating elements. For this purpose, measurement of heat transfer in the two-phase flow of air-water, steam-water, or any mixtures involve, including the air-oil or gas-oil flow is essentially needed (Bergles, 1981). A lot of studies have been conducted on the heat transfer problem in the flow channel, such as temperature measurement using modern or conventional methods. The purpose of these works is to obtain accurate information on pipe internal wall condition. These studies have been conducted by Saha and Zuber (1974), Celata et al. (1997), Kureta (1997) and many more. These experimental measurement results were always compared for pure liquid flow where many of non-heated two-phase flow experimentations are conducted to replicate the case of the heating condition.

In order to get a better understanding about two-phase flow, the flow patterns in the flow channel must be considered firstly. When gas flowing in a stationary or moving liquid in pipes, the two-phase flow is formed with bubbles existence and in many shapes, and hence, the whole flow structure will form various patterns. These patterns can be called with different names depending on the behavior and position of the pipes according to geometrical and parametrical effects. In the vertical pipes, generally used terms of flow pattern known as bubbly flow, slug flow, churn flow, and annular flow. In addition, intermediate flow patterns also frequently encountered. On the other hand, in the horizontal pipes, specifically used terms of flow pattern known as bubbly flow, stratified flow, wavy flow, slug flow, plug flow, and annular flow.

The knowledge of the flow patterns is required in order to model the physical phenomenon as closely as possible and therefore easier to be able to understand the problems of two-phase flow. The determination of flow pattern will lead to the process of prediction of the characteristic in two-phase flow. Hence, in order to conduct the simulation of two-phase flow either by the experimental or computational studies, understanding of the flow pattern and the flow transition is required.

Generally, the two-phase flow will involve the transfer of heat (if any) and mass, and also the inter-phase momentum and energy which are related to the velocity, viscosity and other parameters such as pressure and temperature. On the contrary, the characteristic of heat, mass and momentum transfer in a two-phase flow is strongly depending on its flow patterns. Consequently, the identifications of these regimes are very important because of their significant impact on many phenomena in fluid flow including the heat and mass transfer, flow transition and chaotic behavior. The classification of types of flow is very useful but it is still highly qualitative and often very subjective.

A lot of different regimes have been defined and a various name has been used. The definitions given in the following discussion are chosen for their relative generality of acceptance. Identification of the flow regime can be performed by using the experimental studies; with developing a suitable method and it also provides sufficient information for two-phase flow studies. Because of that, the determination of flow pattern is very important in order to predict the characteristic of the flow, where it may contribute information to solve any problem occur. A lot of considerable factors must be taken into account in the two-phase flow system including the type and size of channels, mass flow rate, phase properties, flow direction, and gravity factors.

The flow patterns or regimes give a significant impact on some behavior of the flow such as velocity profile, pressure fluctuation, and heat transfer conditions. The classification of types of the flow regime is useful but some time will be very subjective to define. Most of the regimes have been defined by many researchers and varieties of names have been given with suitable definitions based on the acceptable behavior of the patterns and shapes of the bubbles in those patterns. A lot of definitions given for each type of flow pattern or flow regime, depending on the flow direction for two-phase flow. Hewitt and Robertson (1969) defined various regimes for the co-current vertical upward flow of gas-liquid in a vertical pipe as below:

(a) ***Bubble flow or bubbly flow***

This is a normal pattern that formed at the lower part of the flow channel. In this case, some spherical and nearly spherical shapes of bubbles exist in the liquid flow when the gas phase is dispersed uniformly. It is always in the form of discrete bubbles at various sizes but is always much smaller than the channel diameter in the continuous liquid phase.

(b) ***Bubbly-slug flow***

At a higher part of the channel, or with an increasing mass flow rate of the gas, more bubbles are formed, distributions become disorder and rapid coalescences occur to form bigger bubbles with a spherical cap. Some of these bubbles will further develop to become bigger and longer.

(c) ***Slug flow***

As the gas flow rate is further increased, the spaces for bubbles to move become very limited and bubbles start to collide and coalesce with each other forming larger in diameter size as well as the length. A new shape of bubble normally called the bullet-shaped is formed with characteristic of the hemispherical nose and various shape of the tail. They are also called the Taylor bubbles and moves up with very thin liquid film surrounded follow by some trailing small bubbles from behind.

(d) ***Churn flow***

With the much higher mass of gas flow in the same channel diameter, the velocity of the gas phase will also increase. During this time the stability of slug flow is disturbed and flow structure will become unsteady in an upward direction. This is due to the effects of gravity and shear stress on the liquid film that try to bring it down. This unstable slug will break off and form the various shape of distorted big bubbles usually dispersed unevenly in the flow channel. The churn flow is also recognized as an intermediate pattern between the slug and annular flow. However, in small diameter tube, churn flow may not be able to develop at all since this intermediate regime is pass by the annular flow that changes directly from slug flow. In many practical applications, churn flow is the pattern to be avoided because of its chaotic and unstable behavior.

(e) ***Annular flow***

With the same flow channel and increasing mass flow rate, the gas velocity become higher enough to surpass the effect of gravitational force on the liquid film, with higher interfacial shear forces. The liquid will be removed from the center flow and it will only flow on the tube wall as a thin layer and formed an annular ring of liquid is then agitated by high ripples and surface frequency waves that make the fraction of liquid to entrain in the core of gas squeeze the droplet from its path. Normally, this flow pattern is stable and for some applications, it may be the desired condition.

f) ***Wispy annular flow***

In the same condition of the annular flow, with an increase, making a higher concentration in the high-velocity gas flow. With this high rate of the entrainment, the droplet will coalesce with each other to form larger droplet or lumps or wisps flowing together in the gas core with a higher rate of droplet deposition rate as well. This is one of the characteristics during the high mass velocity of both phases.

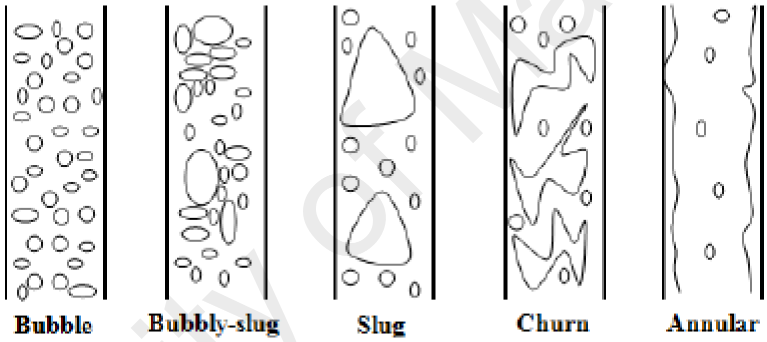


Figure 2.1: Gas-liquid two-phase flow pattern in vertical upward flow (Hewitt et al., 1969)

The transition of the flow patterns is the phenomena which changing condition from one pattern to another pattern. The example of the transition of the flow pattern is the transformation from bubbly to slug in vertical upward of from bubbly to plug flow for the horizontal flow.

This pattern transition depends on a few factors such as flow velocity, the pipe size, length of the pipe and the flow condition such as pressure and temperature. All these aspects give an impact on the flow pattern and also to the flow transition pattern. External factors such as external vibration also can affect the pattern of the flow as well.

Since the transition flow also appears to be significant in some of the flow conditions, some indicator might be very essential in determining this phenomenon. Hervieu and Seleghim (1998) approached a technique for this purpose with an assumption that flow during the transition would be more energetic the established regime.

During higher liquid velocities, the flow in the vertical and horizontal is less affected by the gravitational force, and thus, a considerable analysis can be made in the same manner for both cases. This is particularly in the transition during the bubbly-slug flow transition, where bubbles coalesce together to form bigger bubbles and for sometimes develop a full slug flow.

Lewis et al. (2002) described this transition in internal flow structure using the hot-film anemometry technique within the scope of the intermittent nature of slug flow. They have shown that a single probe can be used for identifying gas and liquid phases and for differentiating the large elongated bubble group from the small bubbles present in the slug flow.

Formation of the slug is one of the most important subjects and being studied in very deep interests in vertical gas-liquid two-phase flow. The slug will be formed by the increase of void fraction waves where more bubbles will congregate and coalesce in the transient bubbly flow (Sun et al., 2002). Violent flow from turbulent effects will, however, slow down the formation of Taylor bubbles and therefore, even in larger diameter pipe with low flow condition, Taylor bubble can be observed, an effect of void fraction waves. Furthermore, in high flow condition, no slug will be formed due to less coalescence of the bubble since have more space to move.

Mi et al. (2001) obtained many characteristics of slug bubbles such as length, formation probabilities, void fraction and velocity using electromagnetic flow meter coupling with impedance void meter. They also developed correlations for slug void fraction from this study.

Void fraction is the volumetric gas rate in the liquid flow and can be considered as the most important parameters in analyzing the two-phase flow. In more detail explanation, this can be described as a ratio of the gas volume (the voids in the flow channel) to the total volume of the flow channel. Considering 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 diameter, D_C, length z, and cross-sectional area, A_C.

Then 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.

According to Figure 2.2, mathematical form can be expressed as following, where the volume or area ratio representing the void fraction,

$$\alpha = \frac{A_G}{A_C} = \frac{1}{\left\{1+\frac{m_G \rho_G v_G}{m_L \rho_L v_L}\right\}} \qquad (2.1)$$

Or simply,

$$\alpha = \frac{A_G}{A_C} = \left(\frac{D_G}{D_C}\right)^2 \qquad (2.2)$$

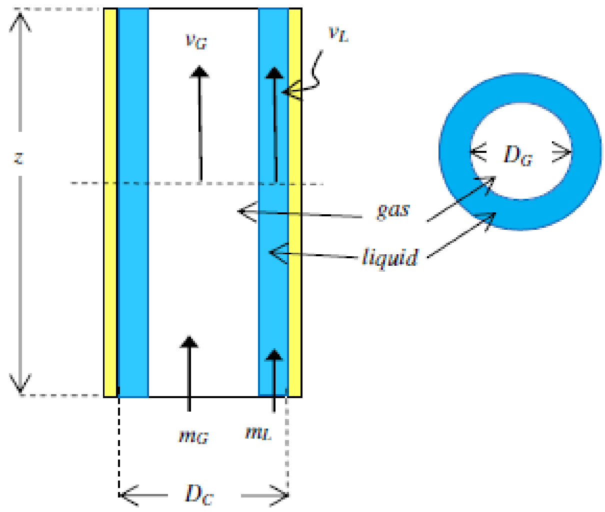


Figure 2.2: Fundamental depiction of void fraction (Zainon, 2013)

In order to investigate the velocity of bubbles in a liquid flow, a lot of analyses are required. This can be carried out by the theoretical, simulation and experimental studies. Jameson and Davidson (1966) proposed the theory on the motion of small bubble in an inviscid liquid which is in forced oscillation. It predicts that the bubble will oscillate at a fixed point with the distance of movement at about three times of the imposed amplitude on the liquid.

Theoretical calculation by Ruckenstein et al. (1970) using the velocity distribution function, shows that at low oscillation frequency, the mass transfer coefficient will decrease proportionally to the decreasing frequency of translational bubble velocity and vice versa.

Most scholars use the Laser Doppler Velocimetry (LDV) to measure the liquid and gas velocity in two-phase flow. This technique offers different amplitudes for the velocities of the two phases. Vassallo et al. (1999) used this technique and found out that the increase of void fraction will reflect the increase of the velocity of gas phase and they confirmed this result using the hot film anemometry and images from high-speed video camera.

Suzuki et al. (2002) carried out the experimental investigation in a vertical counter-current for a void fraction less than 7% to measure velocity profile around the bubble using Ultrasonic Velocity Profile monitor. Using this technique, they can obtain an instantaneous velocity profile along its measuring line across a channel. They plotted the results in the form of non-dimensional velocity profiles with wide ranges of flow conditions. It shows that the velocity field around a bubble has a similar structure to the turbulent boundary layer on a solid wall. This result is discussed with comparison to other scholars' model, that applied an assumption of spherical bubble move steadily while rising in the liquid, and on the relation between these two structures of the boundary layer.

Zhang et al. (2003) developed a mathematical model to predict the interactive spherical bubbles behavior on the velocity while rising in an intermediate Re, based on different forces acting on the bubbles. They compared the prediction results with measurements made by other scholars and found out that the model incorporating both the wake effect and the bubble acceleration effect. It also traced that if both bubbles are kept in distance, the rise velocity of the trailing bubble can be well predicted by adding the mass and Basset force.

In theoretical analysis performed by Hibiki et al. (2003) for large diameter pipe, and based on comparison on experimental data and correlations proposed by many scholars, they recommended that the drift-flux velocity for vertical upward flow for churn and annular flow can be predicted well by using the correlation proposed by Ishii (1977) and for cap bubbly flow the velocity can be predicted using correlations developed by Kataoka et al. (1987).

On the other hand, Hayashi et al. (2012) suggested that the fluid surfactant will also contribute to the rising velocity in the vertical pipe. They used the interface tracking method, a CFD tool to track the rising of the Taylor bubble in a vertical channel occupied with contaminated water at low Morton number and simulations were conducted at various Eötvös number. The results show that the increase of terminal velocity will be affected strongly by reduction of surface tension and at high Eötvös number surfactant effect is found to be quite important.

Shawkat et al. (2008) conducted an investigation on characteristics of bubbly flow in a large diameter vertical pipe by applying the hot film anemometry to measure the turbulent of the liquid phase and optical probe to identify the bubble behavior. With a range of liquid superficial velocities of 0.2 to 0.68 m/s and 0.005 to 0.18 m/s for gas superficial velocity, they gained the void fraction of 1.2% to 15.4% where wall peaks were found at the low void fraction flow and core peaks slowly show up with the increasing void fraction. As the void fraction profile moved from a wall to a core peak, the average liquid velocity and the turbulence intensities will increase when the bubbles are introduced into the flow. With a low void fraction of maximum 1.6%, and at high liquid superficial velocities, turbulence suppression was observed close to the wall. Based on the dimensionless group and the force ratio, a non-dimensional map was proposed for the void fraction in bubbly flow with two conditions of wall or core peak.

Using the Particle Image Velocimetry (PIV) and fluorescent tracer particles, Fujiwara et al. (2004) measured the liquid phase velocity in vertical upward driven bubbly flow to study the effects of dispersed bubble size on turbulence modification. They performed experiments at a low void fraction of 0.5% and 1.0%. They found that bubbles strongly accumulate near the wall (wall peak) that as a result accelerates the liquid phase and fluctuation of liquid velocity intensity is reduced by the high concentration of bubbles.

Velocities of elongated bubbles were studied for various flow rates and pipe diameters by van Hout et al. (2002), using the optical fiber probe and image processing. These measurements were compared with the appropriate correlation. For small elongated bubble, the velocities were well predicted and in continuous slug flow, they were underpredicted.

Clark et al. (1990) performed some alteration in the drift-flux model so that it can be used for prediction in the low velocities and large diameter pipes. Using some data obtained from an experiment in 152mm diameter pipes, computer simulation has been performed to established new values for drift flux profile constant when it is influenced by buoyancy effects. The recommended value can be in the range of <1 to >10 for some outermost cases.

Lucas et al. (2011) applied the four sensor probes to measure the bubbly velocity in the bubbly flow of air-water and oil-water flows. They proposed the arrangement of the new probe and calibration methods and presented that this new technique performed well for the particular purpose. The same approach also was carried out by using a double sensor probe by Wu et al. (2001) for bubbly velocity measurement in a vertical two-phase flow-channel.

Revellin et al. (2008) also measured the length of the elongated bubble but using different fluid, the refrigerant R-134a to study the effect of viscosity and the effect of subcooling in micro-channel. With a small variation of subcooling (2 to 5 °C) and variation of evaporator length (30 to 70 mm), no effects are found on the bubble length. However, bubble length and the bubble velocity both show the increment during the decreasing of saturation temperature, which the effects of decreasing vapor density.

Celata et al. (2007) examined many correlations proposed by many scholars on the terminal velocity of rising bubbles and assess the degree of accuracy of these correlations using a wide range of data set. A simple experimental apparatus for this purpose was constructed and tested and the data of bubbles shapes and velocities are taken from high-speed video camera were compared with available correlations as mentioned. The comparison revealed that shapes of bubbles were well correlated by the Tadaki number and the Weber number and the terminal rising velocity were agreed well with correlations by Tomiyama et al. (2002).

One of the prediction works was carried out by Rivière et al. (1999a) and the result shows that void peaking near wall and velocity profile modification has the capability to induce the wall shear stress and if compared to single phase flow at the same flow rate of liquid, it would be in several folds. The comparison made in other work by experimentation, Rivière et al. (1999b), satisfied this prediction.

Zubir et al. (2019) carried out an experimental works to predict flow patterns using Constant Electric Current Method (CECM) and the result shows that the void values were found to be directly proportional to the percentage of gas and liquid inside the pipe. Each flow pattern corresponds to a unique graph pattern in the void fraction value and can be easily determined from the graph without the need of visual observation.

In addition to this comparison study, prediction of bubble velocities using the void fraction profiles may endeavor a piece of new information on two-phase flow phenomena.

CHAPTER 3: METHODOLOGY

3.1 Introduction

Air-water two-phase flow in pipes is commonly encountered in many engineering applications such as in processing and power plant industries, which comes with heat exchanger such as evaporators and condensers, gas-liquid reactors and also in combustion systems. The two-phase flow is, in fact, a difficult subject principally because of the complexity of the form in which the two-fluid exist inside the flow channel, and they are divided into a scientific term as the regime.

A various phenomenon occurs in the vertical upward air-water two-phase flow such as the change of flow patterns and transition from one pattern to another from the effects of the various parameters and flow conditions. In the two-phase flow, the concept of the holdup is very important 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 indicates 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.

The main purpose of this study is to investigate the bubble superficial velocity of air-water two-phase flow in a vertical annulus pipe. In order to conduct such investigation, a scale down two-phase flow experimental rig was developed and experimentations were carried out for a wide range of vertical velocity parameters. This experimental rig was equipped with a high end of measurement technologies and reliable sensors developed based on previously obtained successful results by other scholars.

3.2 Development of Two-phase Flow Rig

In order to study on bubble velocities in vertical two-phase flow, a vertical two-phase rig was constructed using a model designed by Zainon (2013). It consists of a test sections with length of 1.5~6.2-meter length of transparent pipe with an inner diameter of 20-mm and an implanted void sensor on the inner wall. The construction of the current facilities is shown in Figure 3.1.

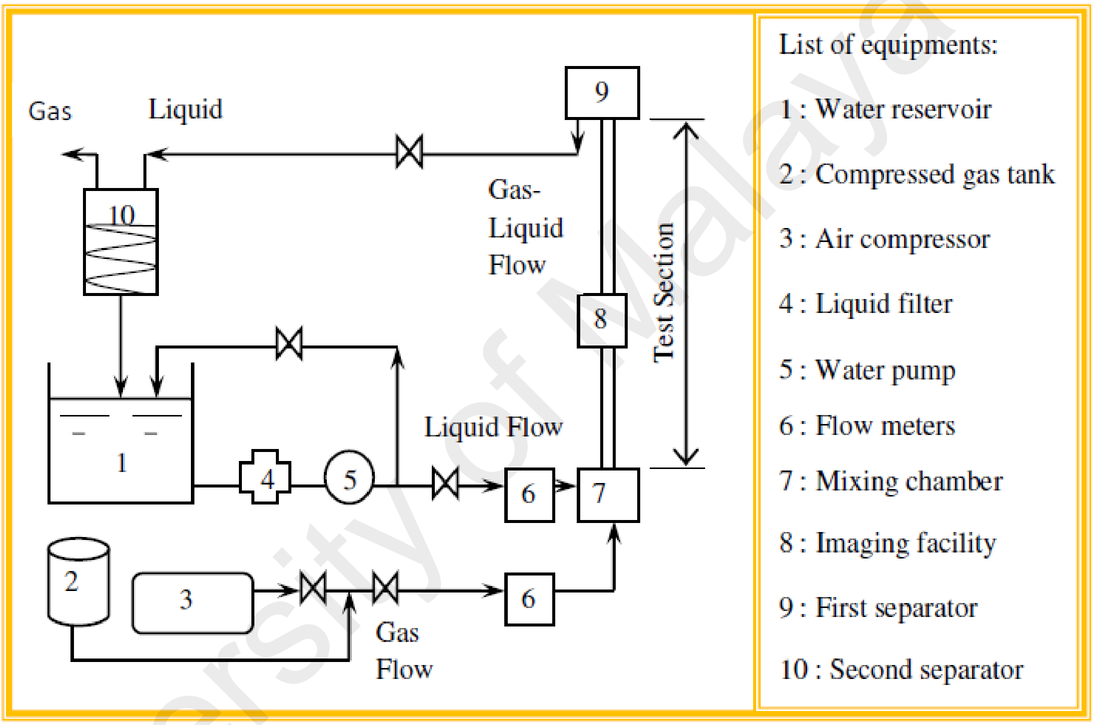


Figure 3.1: Experimental apparatus for vertical upward two-phase flow (Zainon, 2013)

3.2.1 Basic Principle of the Facilities

As shown in Figure 3.1, the working fluids for the current work are air and water. Here, water was supplied from tap source into 500 liters capacity reservoir and filtered before pumped into the loop. The liquid flow rate was measured before it enters the mixing chamber with Kofloc digital water flow meter and based on the 20 mm inner diameter flow channel, the liquid velocity was listed next to it for a reference during the experimentations. The water temperatures were also recorded via digital thermometer placed at the reservoir and throughout the experimentations, it was maintained at 27 to 30 °C.

In order to achieve the two-phase flow, the air is injected into the system from an air compressor and flow through the gas pipe into the mixing section and the flow rate was measured by two different Kofloc, Japan gas flow meters for low and high mass flow rate. The tip of the gas line was covered with a porous cap with very fine holes in purpose to produce very fine small bubbles into the test section. At the mixing section, the gas and liquid mix together and the gas bubbles move upward co-currently with the liquid flow.

The upper-end part of the test section was constructed with a small separator to allow the gas bubble separate from the liquid and connected with the other two-phase flow channel that will deliver both gas and liquid into a bigger separator at the top of the flow loop. The liquid is then channeled back into the reservoir and recirculated again into the flow loop. The actual experimental two-phase flow rig is as shown in Figure 3.2.

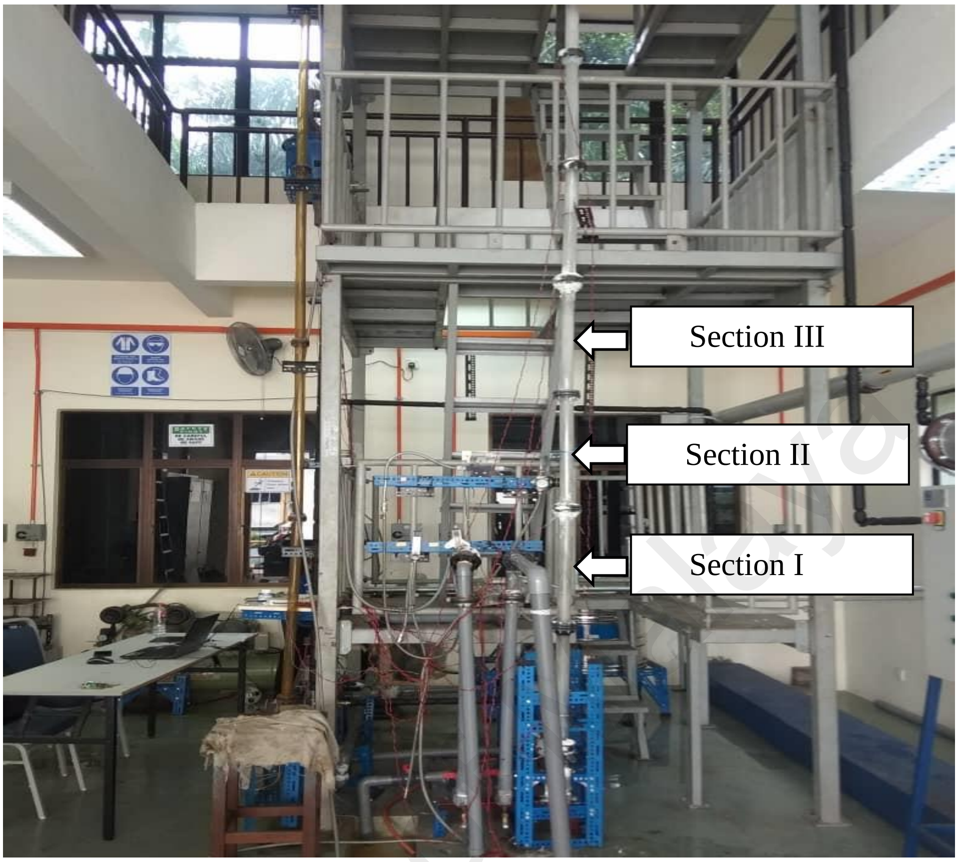


Figure 3.2: Actual photo of experimental two-phase flow rig

3.2.2 Experimental Apparatus

For bubble velocities investigations, systematic observations were conducted using a high-speed camera and proper lighting system of two halogen lamps. The Canon fast-cam Rabbit was used for this purpose. This camera was fixed at the middle of the test section to shoot the bubble shapes and motions as a method to investigate the flow patterns in the two-phase flow channel. After the recorded flow patterns were analyzed, the flow patterns transition at the same location was carefully examined and these data were recorded on the graph sheet, differentiating all the flow pattern according to the variations of both liquid and gas superficial velocities.

The effects of axial location on the void fraction profile were also investigated, and therefore, this flow channel was divided into three sections where at each section the void sensor was installed. The first void sensor was placed in 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 fraction profile 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. The detail configuration for test section is shown in Figure 3.3.

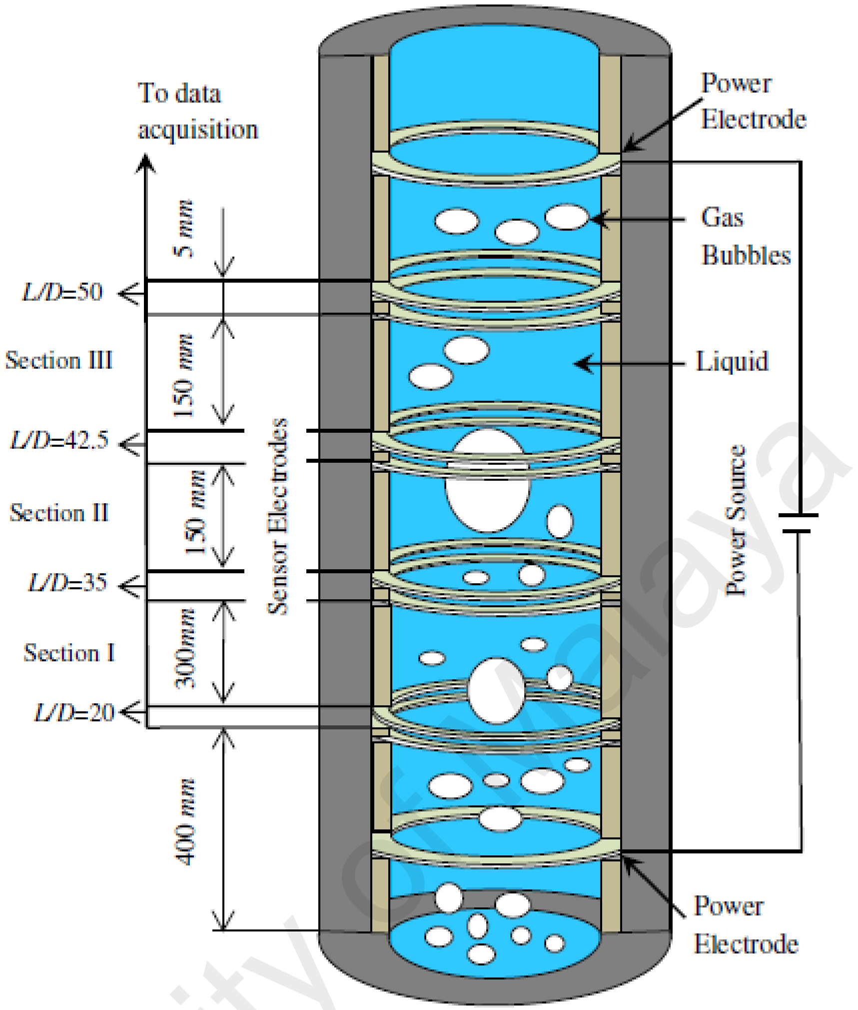


Figure 3.3: Detail configuration of the test section for vertical upward two-phase flow (Zainon, 2013)

3.3 Conceptual Design of Sensor for Two-Phase Flow Measurement

Among all systematic approaches in the measurement of two-phase flow parameters, the electric conductance methods are quite famous, easy to implement and reliable. Therefore, there are many types of electric conductance methods that being practiced such as void impedance meter applied by Mishima and Ishii (1984), Costigan and Whalley (1997), Hibiki et al. (1998), and Cheng et al. (2002) and Costigan and Whalley (1997), and constant electric current method (CECM) designed by Fukano (1998). Fukano method mostly used due to its high reliability in many experimentations carried out by Fukano (1998) and Furukawa and Fukano (2001), and most recently by Zainon (2013). Current work used the existing CECM sensor electrodes developed and calibrated by Zainon (2013), and Zubir et al. (2019) as well.

3.3.1 Constant Electric Current Method (CECM)

Composition of this method is formed by more than four electrodes. A pair of power electrodes are used to supply a constant electric current into the flow and the other pair is called the sensor electrode is used to capture the voltage fluctuation (holdup) when there is a gas bubble flow as gas-liquid two-phase flow. In this application, the position of these pairs of electrodes must be separated, where one piece of power electrode must be placed at the bottom (for vertical) or at the beginning (for horizontal) of the flow channel. The pair of sensor electrode is, therefore, must be placed in between the power electrodes. The distance between sensor electrodes depends on the application or purpose of measurement.

The CECM is the most suitable method to be applied as a two-phase flow sensor since it is independent of the power electrode because of the proper manner of its construction as shown in Figure 3.3, where the power electrodes are far separated, and the sensor electrodes are placed in between them. With this arrangement, the power electrodes can supply sufficient density of the constant electric current, making a uniform distribution along the flow channel. As a result, as a conductance method, the voltage reading will be the same range of value at any location inside the flow channel.

Therefore, there is only one pair of power electrode needed to be installed for a particular flow channel and multi-wiring and power sourcing can be avoided. The voltage output captured by the sensor electrodes transferred to the pre-amplified data acquisition by National Instruments®. This voltage fluctuation data is then digitally transferred into a computer and recorded in the LabView software®. In this case, the increase in voltage output with the increase electrical resistance caused by the existence and increase 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, voltage fluctuation during the measurement of various parameters in different flow patterns in the channel can be avoided.

In addition, the voltage fluctuations also are independent of the sensor electrodes, which each electrode is connected to different ports on the data acquisition. Thus, it is possible for construction of a multiple numbers of sensors along the flow channel, and simultaneous measurement of all sensors can be carried out such as an application to measure the bubble instantaneous velocity based on data from different locations of local void fraction.

The fabrication of the sensors must be very careful procedures and these sensors must be installed at a flush position with the surface of the flow channel. Therefore, flow agitation due to disturbance of coils or probes can be minimized. As a result, the attained data have higher reliability and accuracy.

3.3.2 Basic Equations

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

$$\frac{1}{R_{TP}} = \frac{1-\eta}{R_G} + \frac{\eta}{R_L} \tag{3.1}$$

where the electric resistance; R_G for gas phase and R_L for the liquid phase when each of them solely occupies the whole cross-section of the channel and η is the holdup or the percentage of the liquid volume to the total volume of the channel. 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, $R_G >> R_L$, thus, 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 the whole cross-section of the flow channel.

3.3.3 Fabrication of The Sensor

In the current work, the electrodes were fabricated by using 0.5-mm thickness copper plate, with electric conductivity of a ring shape at $\sigma=5.96x10^7$ S/m. The fabrication of these electrode rings was done carefully to fit and flush to the inner wall of the flow channel at 20-mm. The pair of sensor electrodes were placed at four different locations along the flow channel at 150-mm distance between each other and the gap between the electrodes of each sensor is at 5-mm as shown in Figure 3.3.

A power source by Wells-Gardner Electronics Corp. was used in this work and constant electric current in the range of 0.1~0.3 mA was applied. A low direct electric current was considered in this work to avoid unnecessary chemical reaction on the electrode surface. The output from the four sensor electrodes was sampled using data acquisition and the data were digitized to compute the main parameters such as void fraction, liquid film thickness and bubble instantaneous velocity.

3.3.4 Calibration

In order to validate the reliability of the measurement of this sensor, two types of calibration methods were conducted by Zainon (2013) as follows.

a) Static Calibration

Static calibration is the simplest calibration method 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 the purpose of capturing 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 is longer than the sensor gap (5-mm) were used. Contrarily, for estimation of the group of bubbles passing through the whole channel, longer rods with various diameters were applied. Accordingly, when these rods were placed in the center of the sensor electrodes, the voltage fluctuation was recorded and differ among positions of the sensors.

According to equation 3.2, when V_L=V_{TP}, the holdup is η=1, which implies that only liquid exists in the channel. Hence, the void fraction can be expressed as,

$$\alpha = 1 - \eta = 1 - \frac{V_L}{V_{TP}} \qquad (3.3)$$

Based on equation 3.3, the calibrations for sensor electrodes on the experimental channel were conducted by Zainon (2013) for four times at four axial positions based on the ration of length, (position of the sensor from the two-phase mixer) and diameter of flow channel, L/D using both the long and short cylindrical rods as shown in Figure 3.4. The difference of the symbols signifies the repetition of calibration, and A and B denote the long and short respectively. The results were obtained with good accuracy at 3%, means good data for measurement can be reproduced.

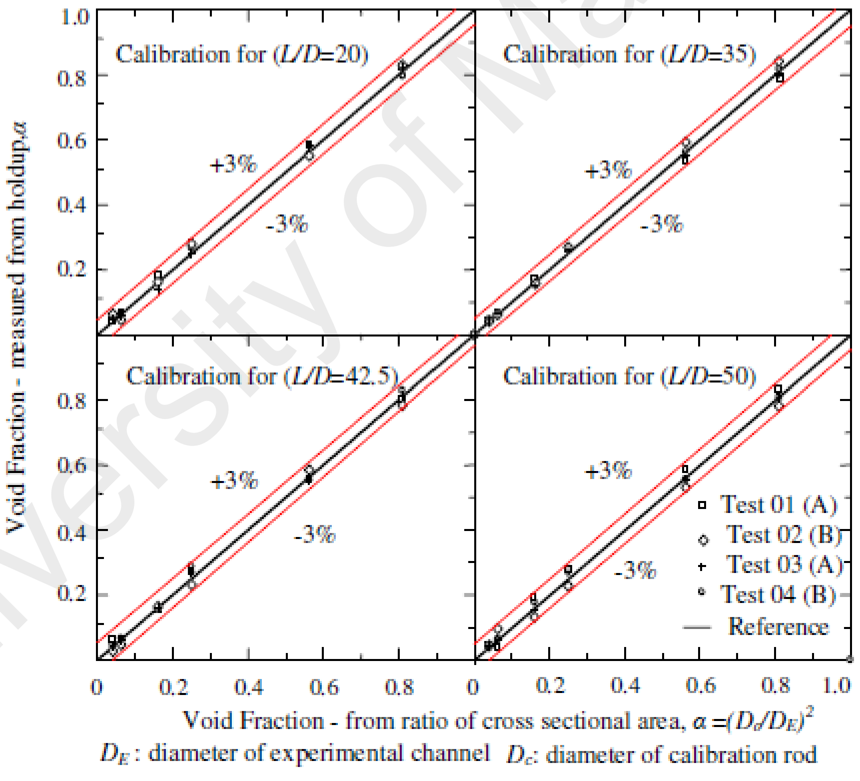


Figure 3.4: Static Calibration for CECM sensor (Zainon, 2013)

b) Dynamic Calibration

Since the static calibration could not give the real picture of the two-phase flow due to the stationary position of the calibration rod, therefore, calibration using the real moving bubble is strongly required. For this purpose, the dynamic calibration was conducted by Zainon (2013) using the method of comparing the visual data from the recorded images and the 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. The image of the bubble was captured by using the high-speed video camera, and at the same time as it passes through the sensor the voltage fluctuation was recorded. Since it was released as a single bubble, there were no trailing bubbles behind it and thus, it can be confirmed that only the captured bubble that passed through the sensor.

For continuous bubble rising, the bubbles were released from a compressor and the average areas occupied by gas bubbles were examined. The images of the captured bubbles were analyzed where the area and diameter sizes were determined with the comparison to the tube diameter. Then, the obtained sizes compared with recorded data from the sensor and the same comparison as shown during the static calibration in Figure 3.4 can be carried out as shown in Figure 3.5.

Furthermore, this dynamic calibration also has been conducted at four different locations of sensors. According to Figure 3.5, dynamic calibration gave an accuracy of 5%, which is slightly different compared to static calibration result. In this figure, the Test 101 and Test 102 denote the calibration using a single bubble of different sizes and Test 103 denotes the calibration using continuous rising bubbles. For this calibration, the liquid superficial velocities, j_L were varied in the range of 0.25 ~ 1.0 m/s. The results show very similar accuracy as discussed above, but for the current work, calibration with j_L=0.25 m/s and j_L=0.5 m/s are presented.

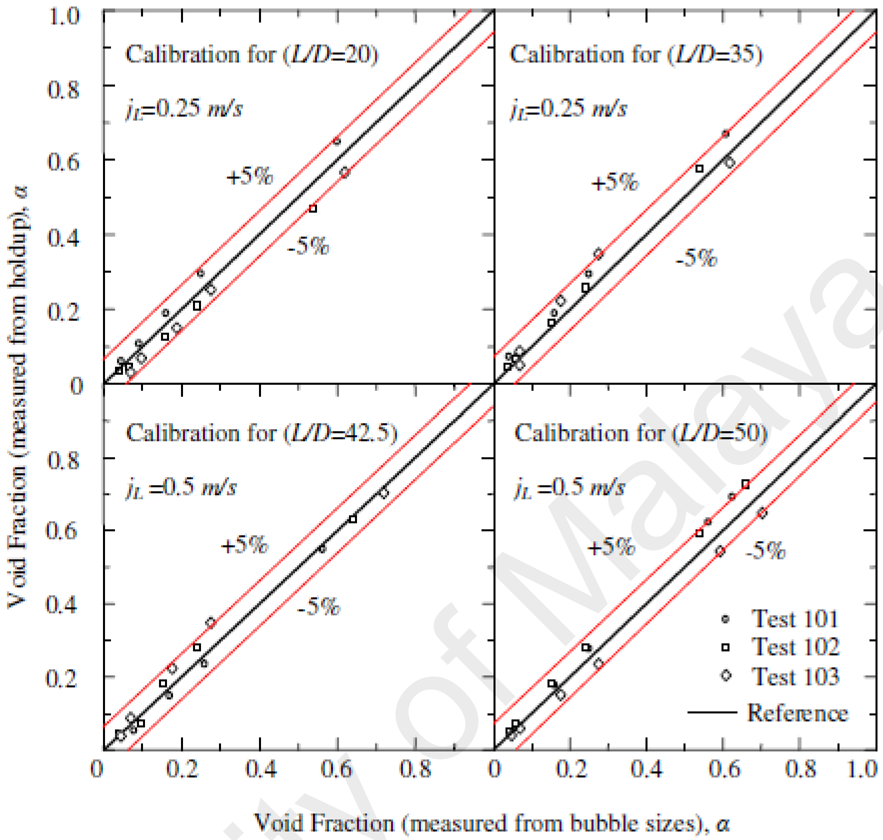


Figure 3.5: Dynamic calibration for CECM sensors (Zainon, 2013)

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Outline of the Analysis

This chapter will present and discuss the results for two categories of investigation on the flow structures of air-water two-phase flow in a vertical upward arrangement in an annulus tube under certain conditions as following:

i) Effect of superficial bubble velocity on flow pattern

ii) Instantaneous bubble velocity

The experiments for each of the category were performed on the steady state condition. The bubble flow patterns were investigated using observation techniques. The details of comparisons are presented in every section of these categories.

As mentioned in the previous chapter that the flow patterns were investigated using the visual observation techniques. The information from the photographic and video-graphic data was analyzed. This investigation was varied by a combination of different gas and liquid superficial velocities. The gas superficial velocities, j_G were ranged in 0.025 to 0.25 m/s and the liquid superficial velocities, j_L were ranged in 0.25 to 2.5 m/s. Thus, the slip ratio of the gas and liquid phases is in the range of 0.01 to 3.0.

Void fractions were measured using the electrical resistance concept at four different locations along flow channel with the axial position, L/D = 20, 35, 42.5 and 50 as shown in Figure 3.2. The first position, (L/D=20) was set as the reference to check the responses of electric current in the flow. The other three positions (L/D=35, 42.5 and 50), which are in Section II of the test section were used in the calculations for void fraction and average void fraction values. Variations of void fraction were carried out accordingly to the combination of gas and liquid superficial velocities.

The instantaneous bubble velocities were analyzed using the information from void fraction data using LabView software. This code has the capability to differentiate the peak values obtained from all the three locations of void sensors in the time domain. Therefore, the distance traveled by the bubbles (the distance of sensors = 150 mm) divided by the time is taken from one location to another produce the values for velocities.

Table 4.1: List of gas and liquid superficial velocities

Liquid superficial velocities, j_L [m/s]	Gas superficial velocities, j_G [m/s]
0.25	$j_G1 = 0.025$
0.50	$j_G2 = 0.050$
0.75	$j_G3 = 0.075$
1.00	$j_G4 = 0.100$
2.00	$j_G5 = 0.150$
	$j_G6 = 0.250$

With the range of liquid and gas superficial velocities as in the above table, the function of slip ratio can be evaluated. From the equation, the range of slip ratio, S = j_G / j_L, will be, 0.0125 to 1.0, which is a good approach for the application on industrial scale gas-liquid two-phase flow.

4.2 Effect of Superficial Bubble Velocity on Flow Pattern

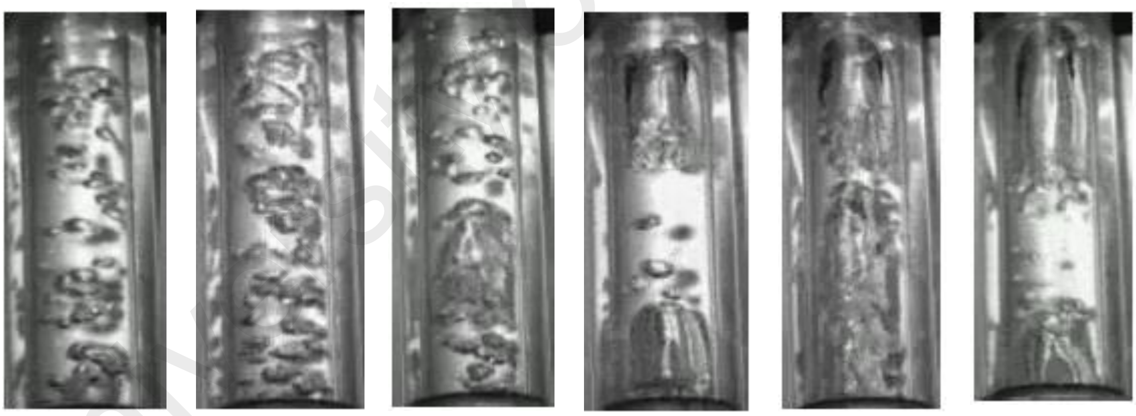
The images of bubble motion in a vertical two-phase flow channel has been captured by a high-speed video camera, and these photographic data have been analyzed frame by frame using the image processing software, the Pinnacle Studio. The observation took place at the center of the flow channel and referring to experimental apparatus in Figure 3.1 and channel configuration in Figure 3.2, it is at section II with two axial positions; which is between L/D = 35 and L/D = 42.5.

Flow conditions were varied by changing the combination of gas and liquid superficial velocities as listed in Table 4.1. Selection of flow patterns in these analyses were based on the most extreme changes shown during the entire flow for steady state condition. The effect of superficial bubble velocities will be discussed in this section with the image of flow patterns are projected in the series of velocities. This investigation also including the slip ratio in the flow channel.

4.2.1 Effect of Gas Superficial Velocity, j_G

The investigation on the effect of gas superficial velocities in the flow patterns were conducted at constant low liquid superficial velocity for this experimental facility at j_L = 0.25 *m/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*.

As shown in Figure 4.1, the bubbly flow was developed at lower gas superficial velocities, j_G1 = 0.025 m/s and j_G2 = 0.050 m/s. As the velocity increase to j_G3 = 0.075 m/s, the bubbly flow started to change to bubbly-slug flow. More bubbles were formed, distributions become disorder and rapid coalescences occurred to form bigger bubbles with a spherical cap. At higher velocity, j_G4 = 0.10 m/s, the bubbly-slug flow changed to slug flow resulting the spaces for bubbles to move become very limited and bubbles started to collide and coalesce with each other, forming bullet shaped bubbles with hemispherical nose and followed by some trailing small bubbles from behind. The slug flow became unstable and changed to churn flow when the velocity increased to j_G5 = 0.15 m/s. During this time, the stability of slug flow is disturbed and flow structure became unsteady in an upward direction due to the effects from gravity and shear stress on the liquid film that try to bring the slug down. The slug flow became fully formed and longer shape when velocity reached j_G6 = 0.25 m/s. From this investigation, the transition from bubbly flow to slug flow occurred easily with the increasing of gas superficial velocity at low liquid superficial velocity was observed in the region of slip ratio, S = 0.1 to 1.0. Slug flow was firmly developed in the region of slip ratio, S = 0.3 to 1.0. Thus, at constant low liquid superficial velocity, when the gas superficial velocity increase, the void fraction also increases proportionately.



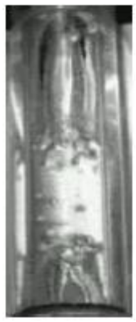
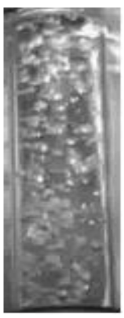
0.025 m/s   0.05 m/s   0.075 m/s   0.1 m/s   0.15 m/s   0.25 m/s

Figure 4.1: Effect of Gas Superficial Velocities on flow patterns, for j_L = 0.25 *m/s*

4.2.2 Effect of Liquid Superficial Velocity, j_L

For investigation on the effect of liquid superficial velocity, the same procedures as in the previous section were repeated with combinations of superficial velocity as shown in Table 4.2. As the gas superficial velocities were set as a constant parameter, the transitions of bubbly flow to slug flow were getting difficult with the increase of liquid superficial velocities was observed in the region of slip ratio, S = 0.125 to 0.5. Due to the high velocity of the liquid phase, a solid formation of the slug was not allowed since it was distorted easily. These phenomena occur due to low air bubble density compared to water which forced the bubble to be dragged away from its trailing path and could not stand the shear force from the liquid phase and failed to develop to slug. Accordingly, at constant gas superficial velocity, when the liquid superficial velocity increase, the void fraction decreases proportionately. This current flow pattern almost well agreed with the works by Furukawa et al. (2001) and Zainon et al. (2014).

Table 4.2: Effect of Liquid Superficial Velocity

j_G (m/s)	0.025	0.05	0.075	0.1	0.15	0.25
$j_L = 0.25$ (m/s)						
$j_L = 0.50$ (m/s)						
$j_L = 0.75$ (m/s)						
$j_L = 1.0$ (m/s)						
$j_L = 2.0$ (m/s)						

4.3 Instantaneous Bubble Velocity

4.3.1 Analysis of Instantaneous Bubble Velocity

The instantaneous bubble velocity, v_b is one of the important parameters in the two-phase flow where it will contribute to the transition in flow patterns. There are many factors that affect the value of this parameter as well. It is a function of average volumetric flux, j, the pipe geometry, the fluid properties, and the body force field. In almost every case, the bubble length is not found to be an important variable since the dynamics of the nose and tail of the bubble govern the motion entirely. Another form of describing the velocity of the bubble is the drift velocity, v_{Gj} which is actually the average velocity of the phase or also referred as axial drift velocity since the phase of the fluid defined are assumed to be moving along a pipe. It is the difference between bubble velocity and the overall volumetric flux, where these three parameters are in the relationship as following.

$$v_{Gj} = v_b - j \qquad (4.1)$$

Hence the drift velocity is also independent of void fraction and depends on overall volumetric flux, j and not on j_G and j_L independently. Figure 4.2 shows the depiction of a unit cell for slug flow analysis proposed by Zainon (2013), which illustrates the relationship of bubble velocity and the average volumetric flux, j.

On the other hand, if the bubble velocity and the gas flux are known, the void fraction, α can be simplified as

$$\alpha = \frac{j_G}{v_b} \qquad (4.2)$$

However, for one-dimensional flow with no wall shear effects, the drift velocity is independent of j but is a function of void fraction, α. The only way these conditions can be both satisfied is for v_{Gj} to be a constant. This constant can be evaluated by choosing the special case of a single bubble in stagnant liquid for which the drift velocity having the same value as the terminal velocity, v_∞ for which,

$$v_{Gj} = v_\infty \quad (4.3)$$

Therefore, for all value of α,

$$j = \alpha v_\infty \quad (4.4)$$

And thus, the bubble velocity where there is net flow is,

$$v_b = j + v_\infty \quad (4.5)$$

From the relationship as the above, and the void data as obtained, a simple method can be derived to calculate the instantaneous bubble velocity. This measurement is very important in order to predict the bubble velocity changes in the flow channel.

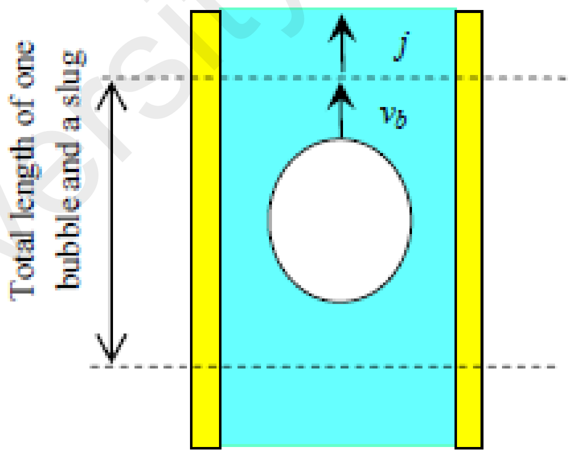


Figure 4.2: Unit cell for bubble and slug flow analysis (Zainon, 2013)

4.3.2 Evaluation of Bubble Instantaneous Velocity using the Void Fraction Profile

Bubble velocities during the steady state condition are determined by using the time-varying void fraction fluctuation. A time lag, Δt of the bubble to travel between two different sensors can be measured shown as the difference of time between the two peaks. Since there are four different locations of sensors placed on the flow channel wall, the distance of the traveling bubble, Δz can be determined using the two different axial positions, which are at L/D = 42.5 and L/D = 50 with 150 mm gap. Thus, the bubble velocity can be generated as the following:

$$v_b = \frac{\Delta_z}{\Delta_t} \tag{4.6}$$

The calculated results from equation 4.6 were then compared to the theoretical results using equation 4.2 since the void fraction value also directly available from this relationship. In this analysis, the selections of peaks were carried out by a very thorough inspection of the pattern of void fluctuation spectrum. These peaks were selected based on the same pattern demonstrated for spectrum at the two different locations of sensors with the purpose of ensuring the same bubble to be analyzed. Thus, the peak selections were scaled down to a very brief time, which the analyses were carried out to evaluate the bubble velocities within the range of 2 seconds.

Based on Table 4.2, the void fraction is increasing proportionately with the increase of gas superficial velocity at constant low liquid superficial velocity, j_L = 0.25 m/s. Therefore, evaluation of the instantaneous bubble velocity will be focused on this condition. From Figure 4.3, the time lags are mostly constant at around 0.27 seconds, and the bubble velocity to be around 0.6 m/s under the condition gas superficial velocity, j_G = 0.05 m/s. Comparison of this value with the theoretical value which is 0.56 m/s shows the difference is below 5%, hence, this result is acceptable.

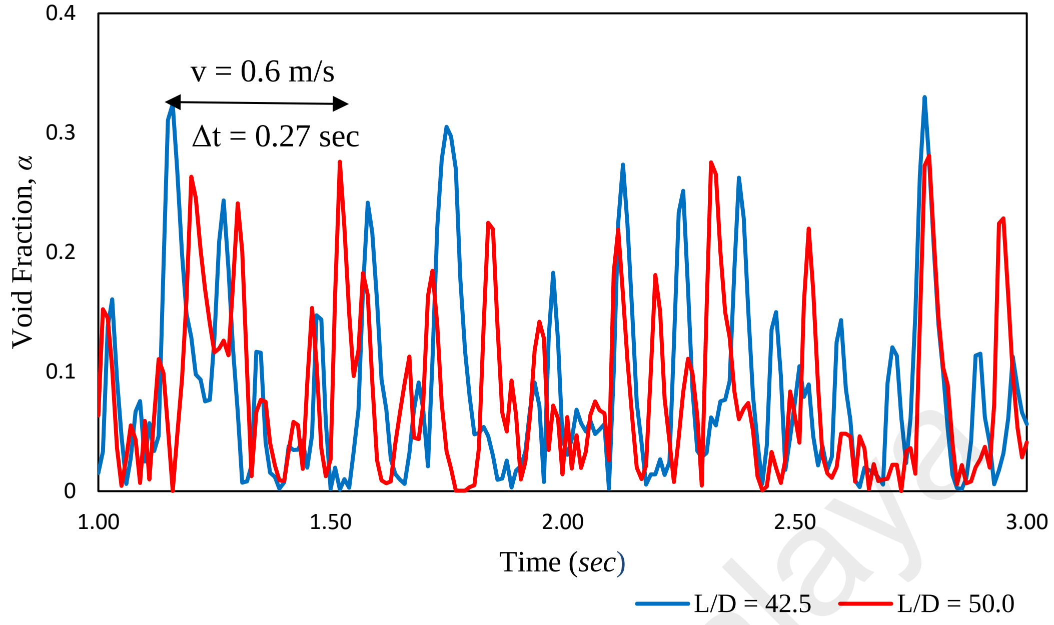


Figure 4.3: Evaluation of bubble instantaneous velocity using the void fraction profile with flow condition at j_L = 0.25 m/s, j_G = 0.05 m/s

The experimental value of instantaneous bubble velocity can be compared with theoretical value by using equation 4.2 and the result as shown in Figure 4.4. The different of these two values is below 7%. The instantaneous bubble velocity increased when gas superficial velocity increased from 0.025 m/s to 0.05 m/s. On the other hand, the bubble velocity decreased when gas superficial velocity increased from 0.05 m/s to 0.1 m/s. The bubble velocity decreased due to limited moving area and formation of larger bubbles or slug formation.

Furthermore, theoretically, Bergles (1981) postulated that the higher amount of gas flowing in a stagnant or at a constant velocity of liquid in a particular channel, the higher the void fraction will be. In Figure 4.4, as the gas velocity increased at which a higher volume of gas injected into a flow channel diameter, more gas bubbles exist in the flow channel, as well as shown in Table 4.2 for j_L = 0.025 m/s. Generation of more bubble, therefore, resulted in higher void fraction and gas bubbles rushing upward in the channel. However, when bubble generation increase, coalescence between bubbles becomes more rapidly, and thus, slow down the velocity of the bubbles as they move up for some time with increasing gas superficial velocity. During this concise period, the coalescence of bubble resulted in the formation of slugs.

At a higher rate of gas superficial velocity, as in this case, around j_G = 0.075 m/s, the void fraction increases again a result of slug formation. This reveals that the slugs flow has enough momentum to flow upwards with a steadily increase of its velocity. This result also shows that the instantaneous bubble velocity strongly affecting the change of flow patterns or vice versa, as can be reflected Table 4.2 and Figure 4.5, also reported by van Hout et al. (2002).

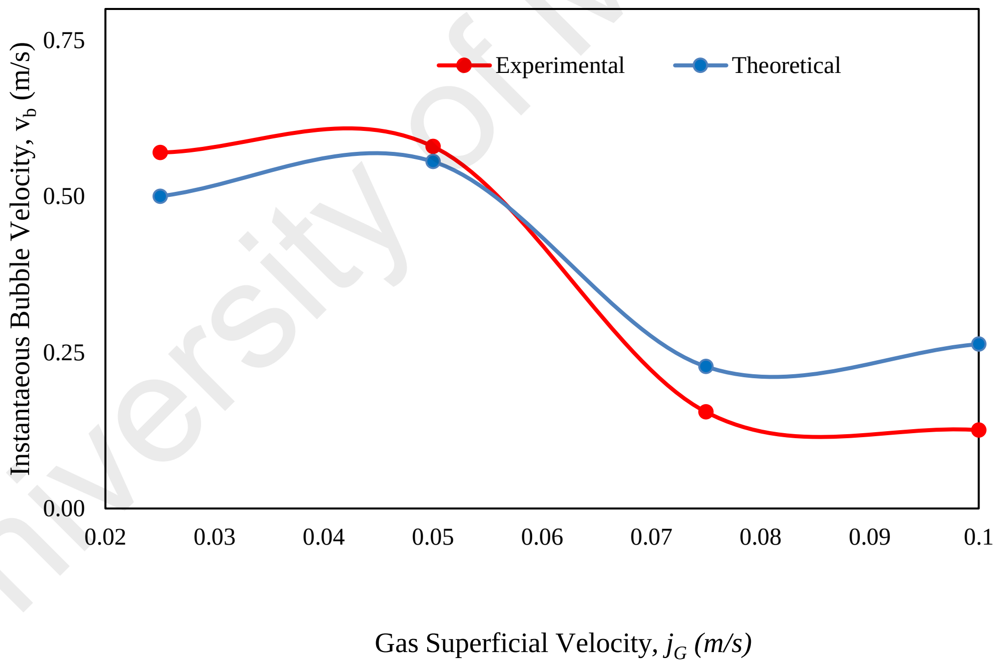


Figure 4.4: Evaluation of instantaneous bubble velocity with comparison to theoretical calculation under flow condition of j_L = 0.25 m/s

As shown in Figure 4.5, void fraction increased proportionately when gas superficial velocity increased at constant low liquid superficial velocity condition due to low dragging effect from the liquid phase. As a result, more bubbles were formed and rapid coalescence occurred to form slug, which is higher void fraction value.

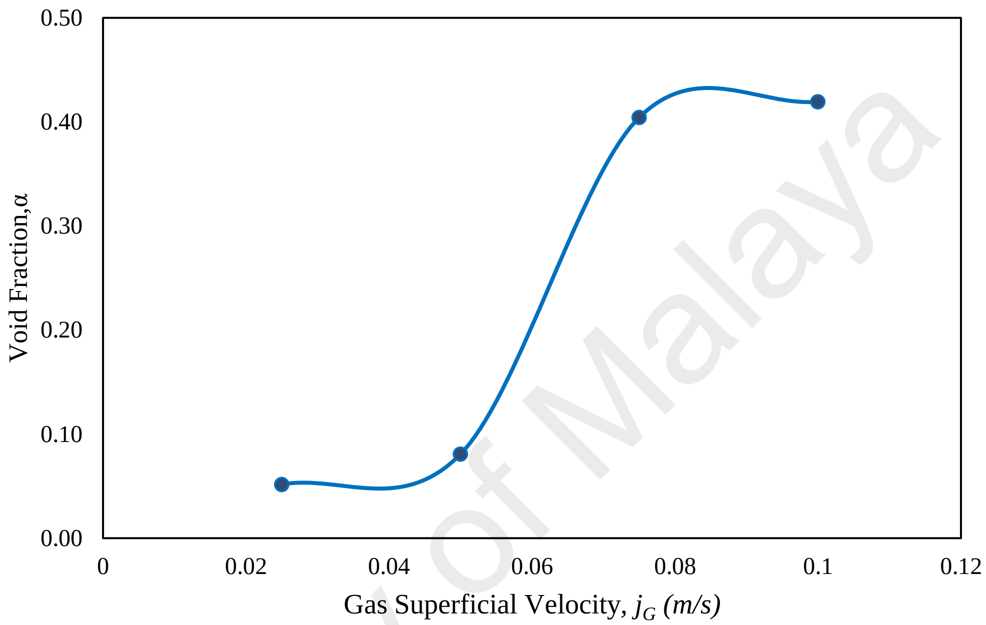


Figure 4.5: Evaluation of void fraction under flow condition of j_L = 0.25 m/s

Based on Figure 4.4 and Figure 4.5, using equation 4.2, the relationship between instantaneous bubble velocity and void fraction can be expressed as in Figure 4.6. The instantaneous bubble velocity decreased proportionately along with void fraction until they reached the value of 0.30. The experimental value and theoretical value showed the same trend with different below 7%. This result further proved that an increased volume of the gas phase, which is shown as increased in a void fraction which also reflects a flow pattern changes in the channel will affect the instantaneous bubble velocity. As discussed previously, a higher void fraction shows that the gas phase has higher momentum and therefore moving upward at a higher velocity, which is also due to the thinner liquid film that enable the bubble to travel easier with lower density. The theoretical value shows that the bubble velocity slows down for a while during void fraction, α = 0.1 ~ 0.3 but later travel with increased velocity. The experimental value, however, does not show this phenomenon but still follow the same trend.

During this period, it can be postulated that the flow experienced some sort of pattern change before stabilized at a slug, or probably annular flow condition since the void fraction is above 0.3 and with this condition the flow steadily moving up with higher velocity. The behavior of annular flow and its condition has been well described by Mishima and Ishii (1984).

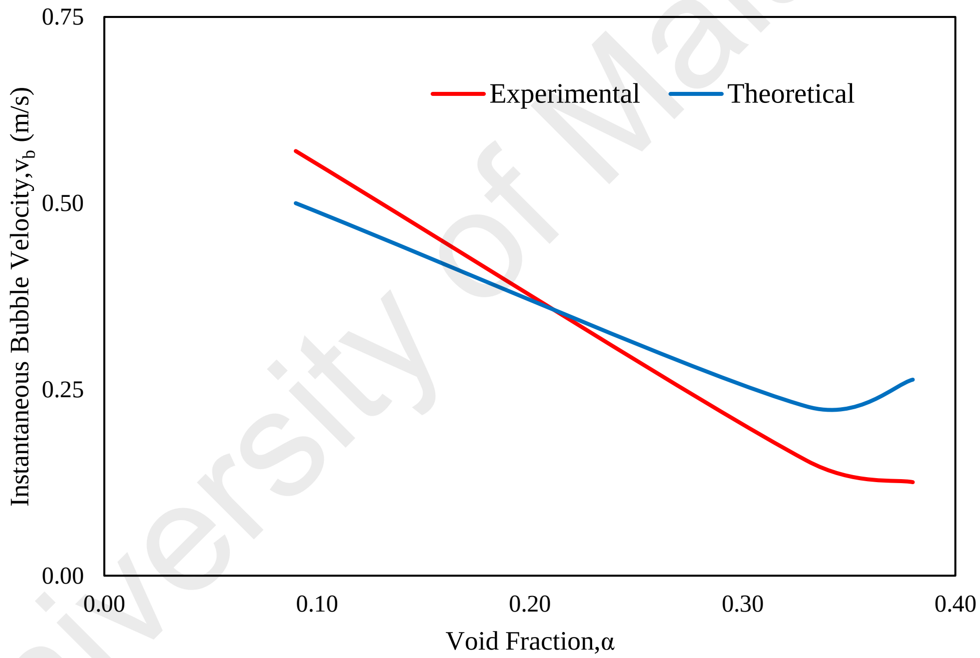


Figure 4.6: Evaluation of instantaneous bubble velocity with comparison to theoretical calculation using the void fraction profile under flow condition of j_L=0.25 m/s

CHAPTER 5: CONCLUSION

Experimental work has been carried out on an industrial scale gas-liquid two-phase flow loop. Based on the experimental results and analysis, the following conclusions have been achieved:

1. The air-water two-phase flow showed a significant change in terms of flow pattern, from bubbly flow to slug flow with the increasing of gas superficial velocity at constant low liquid superficial velocity.
2. The bubbles became unsteady and distorted easily when liquid superficial velocity increased accordingly due to the effect of drag and shear force. At higher liquid superficial velocity, churn flow occurred easily.
3. Void fraction increased when gas superficial velocity increased at constant low liquid superficial velocity. The highest void fraction value was nearly 0.4.
4. The instantaneous bubble velocity increased when gas superficial velocity was below than 0.05 m/s and decreased after gas superficial velocity more than 0.05 m/s.
5. The instantaneous bubble velocity decreased proportionately with the void fraction value below than 0.3 and increased steadily after void fraction value more than 0.3.

Recommendations for future works are listed below:

1. Perform numerical study or simulation analysis for current work by including all parameters involved namely pressure, temperature, gravity, and shear force.
2. Include losses and reduce noise into the analysis to improve the analysis accuracy as these factors have a direct influence on the analysis.

REFERENCES

Bayar, T. (2017). Coal-fired power down in west but strong in east, survey finds, *Power Engineering International*. Retrieved from https://www.powerengineeringint.com/articles/2017/10/coal-fired-power-down-in-west-but-strong-in-east-survey-finds.html

Bergant, A., Simpson, A., & Tijsseling, A. S. (2006). *Water hammer with column separation: A historical review* (Vol. 22).

Bergles, A. E. (1981). *Two-phase Flow and Heat Transfer in the Power and Process Industries*: McGraw-Hill Education.

BP. (2019). BP Energy Outlook 2019 edition.

CBS. (2017). Huge blast at India thermal power plant leaves 26 dead, *CBS News*. Retrieved from https://www.cbsnews.com/news/india-explosion-uncharhar-thermal-power-plant-new-boiler-pipe-blows/

Celata, G. P., Cumo, M., & Mariani, A. (1997). Experimental evaluation of the onset of subcooled flow boiling at high liquid velocity and subcooling. *International Journal of Heat and Mass Transfer, 40*(12), 2879-2885. doi: https://doi.org/10.1016/S0017-9310(96)00345-6

Celata, G. P., D'Annibale, F., Di Marco, P., Memoli, G., & Tomiyama, A. (2007). Measurements of rising velocity of a small bubble in a stagnant fluid in one- and two-component systems. *Experimental Thermal and Fluid Science, 31*(6), 609-623. doi: https://doi.org/10.1016/j.expthermflusci.2006.06.006

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

Clark, N. N., Van Egmond, J. W., & Nebiolo, E. P. (1990). The drift-flux model applied to bubble columns and low velocity flows. *International Journal of Multiphase Flow, 16*(2), 261-279. doi: https://doi.org/10.1016/0301-9322(90)90058-Q

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

Fujiwara, A., Minato, D., & Hishida, K. (2004). Effect of bubble diameter on modification of turbulence in an upward pipe flow. *International Journal of Heat and Fluid Flow, 25*(3), 481-488. doi: https://doi.org/10.1016/j.ijheatfluidflow.2004.02.018

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

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

Hayashi, K., & Tomiyama, A. (2012). Effects of surfactant on terminal velocity of a Taylor bubble in a vertical pipe. *International Journal of Multiphase Flow, 39*, 78-87. doi: https://doi.org/10.1016/j.ijmultiphaseflow.2011.11.001

Hervieu, E., & Seleghim, P. (1998). An objective indicator for two-phase flow pattern transition. *Nuclear Engineering and Design, 184*(2), 421-435. doi: https://doi.org/10.1016/S0029-5493(98)00213-1

Hewitt, G. F., Roberts, D. N., Establishment, A. E. R., Group, U. K. A. E. A. R., & Division, A. E. R. E. C. E. (1969). *Studies of Two-phase Flow Patterns by Simultaneous X-ray and Flash Photography*: Chemical Engineering Division, Atomic Energy Research Establishment.

Hibiki, T., & Ishii, M. (1998). Effect of flow-induced vibration on local flow parameters of two-phase flow. *Nuclear Engineering and Design, 185*(2), 113-125. doi: https://doi.org/10.1016/S0029-5493(98)00241-6

Hibiki, T., & Ishii, M. (2003). One-dimensional drift–flux model for two-phase flow in a large diameter pipe. *International Journal of Heat and Mass Transfer, 46*(10), 1773-1790. doi: https://doi.org/10.1016/S0017-9310(02)00473-8

IEA. (2018). IEA World Energy Balances 2018.

Ishii, M. (1977). One-dimensional drift-flux model and constitutive equations for relative motion between phases in various two-phase flow regimes (pp. 77 ~ 47). United States: Argone National Laboratory Reports.

Jameson, G. J., & Davidson, J. F. (1966). The motion of a bubble in a vertically oscillating liquid: theory for an inviscid liquid, and experimental results. *Chemical Engineering Science, 21*(1), 29-34. doi: https://doi.org/10.1016/0009-2509(66)80004-0

Kataoka, I., & Ishii, M. (1987). Drift flux model for large diameter pipe and new correlation for pool void fraction. *International Journal of Heat and Mass Transfer, 30*(9), 1927-1939. doi: https://doi.org/10.1016/0017-9310(87)90251-1

Kureta, M. (1997). *A study on forced convective boiling in a small pipe under atmospheric pressure.* (Doctor of Engineering Thesis), Kyoto University.

Lewis, S., Fu, W. L., & Kojasoy, G. (2002). Internal flow structure description of slug flow-pattern in a horizontal pipe. *International Journal of Heat and Mass Transfer, 45*(19), 3897-3910. doi: https://doi.org/10.1016/S0017-9310(02)00107-2

Lucas, G., Zhao, X., & Pradhan, S. (2011). Optimisation of four-sensor probes for measuring bubble velocity components in bubbly air–water and oil–water flows. *Flow Measurement and Instrumentation, 22*(1), 50-63. doi: https://doi.org/10.1016/j.flowmeasinst.2010.12.004

Martin, J. (2019, March 4, 2019). A rare look at the meltdown inside Fukushima Daiichi Nuclear Power Plant, *CNET*. Retrieved from https://www.cnet.com/news/inside-fukushima-daiichi-nuclear-power-station-nuclear-reactor-meltdown/

Mi, Y., Ishii, M., & Tsoukalas, L. H. (2001). Investigation of vertical slug flow with advanced two-phase flow instrumentation. *Nuclear Engineering and Design, 204*(1), 69-85. doi: https://doi.org/10.1016/S0029-5493(00)00326-5

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

Paffel, K. (2016). Four causes of water hammer, and how to prevent damage. *Plant Engineering*.

Reuters. (2011, July 11, 2011). Analysis: Study warns of leak risks of Canada-U.S. oil pipe, *Reuters*. Retrieved from https://www.reuters.com/article/2011/07/11/us-usa-pipeline-analysis-idUSTRE76A67R20110711WNA

Revellin, R., Agostini, B., Ursenbacher, T., & Thome, J. R. (2008). Experimental investigation of velocity and length of elongated bubbles for flow of R-134a in a 0.5mm microchannel. *Experimental Thermal and Fluid Science, 32*(3), 870-881. doi: https://doi.org/10.1016/j.expthermflusci.2007.10.006

Rivière, N., & Cartellier, A. (1999a). Wall shear stress and void fraction in Poiseuille bubbly flows: Part I: simple analytic predictions. *European Journal of Mechanics - B/Fluids, 18*(5), 823-846. doi: https://doi.org/10.1016/S0997-7546(99)00127-2

Rivière, N., Cartellier, A., Timkin, L., & Kashinsky, O. (1999b). Wall shear stress and void fraction in Poiseuille bubbly flows: Part II: experiments and validity of analytical predictions. *European Journal of Mechanics - B/Fluids, 18*(5), 847-867. doi: https://doi.org/10.1016/S0997-7546(99)00128-4

Ross, K. (2019). Gas now the dominant fossil fuel in Europe says report, *Power Engineering International*. Retrieved from https://www.powerengineeringint.com/articles/2019/04/gas-now-the-dominant-fossil-fuel-in-europe-says-report.html

Ruckenstein, E., & Muntean, O. (1970). Mass transfer between a bubble and an oscillating liquid. *Chemical Engineering Science, 25*(7), 1159-1166. doi: https://doi.org/10.1016/0009-2509(70)85005-9

Saha, P., & Zuber, N. (1974). *Point of net vapor generation and vapor void fraction in subcooled boiling* (Vol. IV).

Serizawa, A. (1974). *Fluid-Dynamic Characteristics of Two-Phase Flow*. (D Eng Thesis), Kyoto University.

Service, E. N. (2016). 2 die in Thoothukudi thermal plant accident, *The New Indian Express*. Retrieved from http://www.newindianexpress.com/states/tamil-nadu/2016/oct/17/2-die-in-thoothukudi-thermal-plant-accident-1528687.html

Shawkat, M. E., Ching, C. Y., & Shoukri, M. (2008). Bubble and liquid turbulence characteristics of bubbly flow in a large diameter vertical pipe. *International Journal of Multiphase Flow, 34*(8), 767-785. doi: https://doi.org/10.1016/j.ijmultiphaseflow.2008.01.007

Suzuki, Y., Nakagawa, M., Aritomi, M., Murakawa, H., Kikura, H., & Mori, M. (2002). Microstructure of the flow field around a bubble in counter-current bubbly flow. *Experimental Thermal and Fluid Science, 26*(2), 221-227. doi: https://doi.org/10.1016/S0894-1777(02)00130-9

Tomiyama, A., Celata, G. P., Hosokawa, S., & Yoshida, S. (2002). Terminal velocity of single bubbles in surface tension force dominant regime. *International Journal of Multiphase Flow, 28*(9), 1497-1519. doi: https://doi.org/10.1016/S0301-9322(02)00032-0

van Hout, R., Barnea, D., & Shemer, L. (2002). Translational velocities of elongated bubbles in continuous slug flow. *International Journal of Multiphase Flow, 28*(8), 1333-1350. doi: https://doi.org/10.1016/S0301-9322(02)00027-7

Vassallo, P. F., & Kumar, R. (1999). Liquid and gas velocity measurements using LDV in air–water duct flow. *Experimental Thermal and Fluid Science, 19*(2), 85-92. doi: https://doi.org/10.1016/S0894-1777(99)00002-3

Wallis, G. B. (1969). *One Dimensional Two-phase Flow* (1st ed.). London, United States: McGraw-Hill Education - Europe.

Wu, Q., Welter, K., McCreary, D., & Reyes, J. N. (2001). Theoretical studies on the design criteria of double-sensor probe for the measurement of bubble velocity. *Flow Measurement and Instrumentation, 12*(1), 43-51. doi: https://doi.org/10.1016/S0955-5986(00)00041-8

Xinhua. (2017). Four dead in China power plant accident, *Xinhuanet*. Retrieved from http://www.xinhuanet.com/english/2017-12/23/c_136847743.htm

Yue, Z. (2012). Analysis of Coated-after Superheater Pipe Bursting Accident in Utility Boiler. *Procedia Engineering, 43*, 594-599. doi: https://doi.org/10.1016/j.proeng.2012.08.105

Zainon, M. Z. (2013). *Effects of vibration onto the flow structures and dynamics of gas-liquid two-phase flow.* (PHD Thesis), University Malaya.

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. *Advanced Materials Research, 881-883*. doi: 10.4028/www.scientific.net/AMR.881-883.721

Zhang, J., & Fan, L.-S. (2003). On the rise velocity of an interactive bubble in liquids. *Chemical Engineering Journal, 92*(1), 169-176. doi: https://doi.org/10.1016/S1385-8947(02)00189-4

Zubir, M. A., Ramli, R., & Zainon, M. Z. (2019). Determination of Flow Patterns in Vertical Upward Two-Phase Flow Channel via Void Fraction Profile. *Journal of Applied Fluid Mechanics*, *12*(2), 474-483. doi: 10.29252/jafm.12.02.28351