

NUMERICAL AND EXPERIMENTAL STUDY ON A
CONTINUOUS SINGLE BUBBLE RISING
BEHAVIOR WITH AND WITHOUT HEAT
TRANSFER EFFECT

by

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Thesis submitted in fulfilment of the requirements for
the degree of
Master of Science

November 2014

ACKNOWLEDGEMENTS

All praises to Allah S.W.T, the most merciful and gracious, and my peace and blessings of Allah upon his messenger, Muhammad S.A.W. Firstly, I would like to thank to Allah, the almighty God who rules the universe for giving me the will power to finish this project. Without His care and love, perhaps I would never finish the work on time.

Secondly, I would like to thank to my parents and family because giving continuous support for me. They provide me with every support either material or moral. I also would like to thank them for their patience in raising me until I am able to study in University Science Malaysia.

I express my special thanks and heartfelt gratitude to my supervisor Prof. Dr. Mohd Zulkifly Abdullah for his patience, guidance, encouragement, support and valuable information on the bubble rising behaviour, during my research.

My special thanks also to all the staff of School of Mechanical Engineering, Universiti Sains Malaysia (USM) for their valuable support and ideas in my research work. Not to forget to my colleagues, Dr. Khalil, Mr. Kamal, Mr. Sofwan, Mr Mior, Mr. Shahrizal, and Mr. Sufian for their support, friendship, and idea for aiding the success in my research goals.

I am grateful to the Universiti Sains Malaysia for giving the opportunity for this postgraduate study and financial support for this study under the RU Grant No. 811027. Last but not least, I also want to thank all of the people who have contributed to help while was finishing my project. Again, thanks a lot to everyone.

Nazmi Bin Che Ismail

November 2014

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LIST OF SYMBOLS

SYMBOL	DESCRIPTION	UNIT
English Symbols		
A	Movement area	m^2
E	Total energy	W
g	Gravitational acceleration	cm/s^2
h	Heat convection coefficient	$W/m^2 \cdot K$
k	Turbulent kinetic energy	m^2/s^2
Nu	Mean Nusselt number	-
P	Static pressure	N/m^2
Q	Power input	W
q	Heat flux	W/m^2
$\dot{q}_h$	Heater heat generation	W/m^3
R^2	Correlation coefficient	-
We	Weber numbers	-
M	Morton number	-
Eo	Eotvos number	-
Fr	Froude number	-
F_g	Gravitational force	$kg.m/s^2$
F_b	Buoyancy force	N
F_d	Drag force	$Pa.m^2$
T_p	Plate surface temperature	$^{\circ}C$
T_b	Temperature of the bulk water	$^{\circ}C$
d_e	Diameter bubbles	mm

S	Source term	-
SD	Standard deviation	-
T	Temperature (Celsius)	°C
T	Temperature (Fahrenheit)	°F
T_{∞}	Ambient temperature	K
t	Time	s
t_h	Heater thickness	mm
$\vec{u}$	Velocity vector	m/s
V	Control volume	m ³
$\vec{v}$	Velocity vector	-
k	Thermal conductivity	W/m.K
x, y	Space coordinates	m
V_T	Terminal velocity	m/s
V	Bubble velocity	m/s
X	Variable value	-
Y	Dissipation coefficient	-
V	Voltage	Watt
f_b	Bubble frequency	bubbles/min
Greek Symbols		
α	Bubble Frequency	bubbles/min
γ	Plate gap	mm
ρ_l	Fluid density	kg/m ³
ν	Kinematic viscosity of air	m ² /s
ω	Ratio of ε to k	-

μ_l	Dynamic Viscosity	Pa.s
σ	Surface tension	N/m
ΔT	Temperature drop	°C
α_g	Gas volume fraction	-
α_l	Liquid volume fraction	-
ρ_p	Density seeding particle	g/cc

LIST OF ABBREVIATION

DOE	Design of experiment	
1-D	One-dimensional	
2-D	Two-dimensional	
3-D	Three-dimensional	
PISO	Pressure-velocity-coupling scheme	
QUICK	Quadratic Upwind Interpolation	
VOF	Volume-of-fluid	
PIV	Particle Image Velocimetry	
LIF	Laser Induced Fluorescence	
IST	Infrared Shadow Technique	
LDA	Laser Doppler Anemometry	
CLSVOF	Coupled level set and the volume-of-fluid	
PTV	Particle Tracking Velocimetry	
HPIV	Hybrid Particle Image Velocimetry	
DPIV	Digital Particle Image Velocimetry	
TLC	Thermochromic Liquid Crystals	
ART	Architecture Resonance Theory	
DAQ	Data acquisition systems	
AC	Alternate current	
DC	Direct current	
CCD	Charge-coupled device	
RS	Response surface	
CCD	Central Composite Design	

CFD	Computational Fluid Dynamics	
ANOVA	Analysis of variance	
SD	Standard deviation	
Re	Reynolds number	
Nu	Nusselt number	
SIMPLE	Semi-implicit pressure-linked equations	

KAJIAN BERANGKA DAN EKSPERIMEN KE ATAS SIFAT KENAIKAN SEBIJI GELEMBUNG UDARA SECARA BERTERUSAN KE PERMUKAAN DENGAN DAN TANPA KESAN PEMINDAHAN HABA

ABSTRAK

Kenaikan sebiji gelembung udara ialah satu proses di mana jisim bulatan gas dikelilingi satu aliran cecair dari dasar ke permukaan atas. Kehadiran satu gelembung udara di dalam cecair yang mana telah melalui pemanas plat boleh meningkatkan pemindahan haba dengan pergerakan gelembung udara melalui permukaan panas tersebut. Pemindahan haba berlaku apabila sesuatu objek yang mempunyai suhu yang berbeza dari suhu persekitarannya atau objek yang lain memindahkan habanya dari satu lokasi ke lokasi lain melalui pergerakan cecair yang telah dibantu oleh gelembung udara. Plat ini ditenggelamkan ke dasar cecair dengan lokasi dan aturan yang berbeza. Tujuan kajian adalah untuk mengenal pasti interaksi dan pergerakan sebiji gelembung udara dengan menggunakan dua cecair yang berbeza kepekatan bersama dengan pemindahan haba ke atas plat pemanas secara kedudukan menegak.

Aliran dimodelkan secara eksperimen dengan melepaskan satu gelembung udara secara berterusan melalui pekatan berbeza sehingganya mencapai satu halaju terminal sebelum sampai ke permukaan. Ia didapati bahawa gelembung udara dalam cecair berkelikatan rendah naik secara memintal seperti gelembung membujur yang terumbang ambing, sementara dalam cecair yang berkelikatan tinggi gelembung udara naik seperti sfera membulat yang naik dalam gerakan melurus. Tambahan pula, gelembung udara berubah bentuk dari gelembung sfera pada awalnya, menjadi membujur setelah melalui plat pemanas.

Satu lapisan nipis di permukaan pemanas terbentuk disebabkan lapisan sempadan terma (haba) dan kenaikan pada permukaan berdasarkan daya keapungan, F_B . Terdapat dua mekanisma utama di mana pemindahan haba boleh ditingkatkan, sebagai contoh; penghasilan gerakan struktur di belakang gelembung udara yang bertindak sebagai agen pengadun, dan frekuensi gelombang f_b udara bertindak sebagai agen penyejuk. Pekali perpindahan haba, h meningkat apabila frekuensi gelembung udara naik ke atas permukaan berubah daripada aliran sebiji gelembung kepada aliran bergelembung.

Siri imej ditangkap menggunakan satu kamera pantas berdasarkan kaedah Particle Image Velocimetry (PIV) untuk memperoleh ukuran medan halaju yang terperinci. Kaedah ini digunakan untuk melihat gerakan struktur-struktur atau pusaran selepas di analisis nanti. Satu gerakan daripada gelembung udara yang naik ke atas permukaan menyebabkan terbentuk satu pusaran di belakang pada setiap gelombang udara yang telah naik ke permukaan. Satu perbezaan besar wujud di antara gerakan pusaran tersebut telah meningkat untuk gelembung frekuensi, $f_b = 40, 60$ dan 80 gelembung setiap minit (bubbles/min). Simulasi telah dijalankan berdasarkan daripada analisis data eksperimen menggunakan perisian komersil, Fluent 6.3.2. Satu perbandingan antara ramalan kajian berangka nampak serasi dengan keputusan hasil uji kaji.

NUMERICAL AND EXPERIMENTAL STUDY ON A CONTINUOUS SINGLE BUBBLE RISING BEHAVIOR WITH AND WITHOUT HEAT TRANSFER EFFECT

ABSTRACT

The behaviors of continuous single bubble rising phenomenon was studied using Particle Image Velocimetry (PIV) in a rectangular bubble column. A single bubble forms when a small amounts of air is released in the bubble column usually gas in a liquid rising from bottom to the upper surface. These processes are most important tools in industrial fluid mixing and oil production. As liquid viscosity changed, the velocity and trajectory of a bubbles change due to the formations of bubble wake structures.

Plate heater with a presence of a single bubble rising in a fluid can enhance heat transfer by bubble motion pass through the heater surface. Heat transfer occurs when an object or physical systems exchange their thermal energy between them. The phenomenon happens when it has a different in temperatures from its surroundings or another object transfer it heated from one place to another by movement of fluids. The plate heater was immersed in the liquid with different locations and arrangements. These present study aim to investigate a single bubble interaction and motion using two different liquid viscosities with associated heat transfer over a vertical plate heater surface.

The flow was modelled experimentally by releasing a single bubble through different viscosities until it achieved a terminal velocity before reaching the top surface of column. It is found that bubble in a low viscosity rise helically as

wobbling ellipsoidal bubble, while at a higher viscosity bubble rise as an ellipsoidal sphere rising in rectilinear motion. Moreover, bubble changes shape from a sphere bubble at initial position to be ellipsoidal after passing through this plate heater. A thin layer on a heater surface is observed to form due to thermal boundary layer (heat) and rising to the top surface based on buoyancy force, F_B . There are two main mechanisms where heat transfer can be enhance, for examples, turbulences (fluid movements) generated behind bubbles act as mixing agent, and the rate of increase of the air bubble rising (bubble frequency) act as cooling agent. Heat transfer coefficient, h increases when the bubble frequency increases in continuous single bubbles rising.

The series of images were captured using a high speed camera based on Particle Image Velocimetry (PIV) method to obtain detailed velocity field measurement. This method allows us to see the wake structures or vortices after analysis. Prior to rising, a wake existed behind each bubble. A major difference existed among the wakes of vortex ring each rising for frequency bubble, $f_b = 40, 60$ and 80 bubbles per minutes (bubbles/min). Simulations were performed based on data analysis from experiments using commercial software, Fluent 6.3.2. Comparisons between experimental studies and simulation predictions have shown good agreement. Based on these researches, the bubbles rising shows the importance of the contribution in heat transfer mechanisms on industrial applications. The turbulence forms behind the bubbles that passing through in bubble column can be useful to reduce the temperature and increase heat transfer rates.

CHAPTER 1

INTRODUCTION

1.0 Overview

In the first sub-chapter, an introduction to a continuous single bubble and its behavior is presented. Issues concerning bubble behavior in different liquids and bubble shapes were discussed. On the second sub-chapter, the bubbles rising in industrial applications are reviewed and the solutions for these applications are highlighted. The third sub-chapter explained the problems that have been established in the current research studies and the scenario of the bubble rising cooling method, objectives and scopes of the present study to fulfil the objectives of the thesis.

1.1 Continuous single bubbles and its behavior

Bubble columns or reactors have a variety of industrial applications in the transport (i.e. gas lift), mixing (i.e. jet mixer), and chemical industrial (i.e. fluidised bed reactors). This is caused by simple construction and low cost to manage their operation in industrial (Degaleesan et. al. (2001)). That is why a lot of company still using this methods until today. The bubbles column used in industrial have different in term of size (i.e. small or large), shape (i.e. rectangular or cylinder) and functions (i.e. reactor, vessel, or tube). Air bubbles naturally exist in this nature and have a shining light surface around it. A bubble is a globule of one substance in another, usually in the form of gas in a liquid. Due to the Marangoni effect, bubbles may remain intact when they reach the surface of the immiscible substance. These effects caused by a surfactant along the bubbles surface of non-uniform concentration distribution. Higher surface tension in a bubble pulls more strongly on the

surrounding liquid compared to the surface tension in the liquids. The presence of surface tension gradient will naturally cause the bubbles to flow away from a region with low surface tensions by Takagi and Matsumoto (2011). In gas-liquid two-phase flows, the bubbles exist show various types of shapes such as spherical, ellipsoid, oblate spheroids, and spherical cap. It also has different flow patterns in rising behaviours such as rectilinear (one-dimensional), zigzagging (two-dimensional), and spiral (three-dimensional) motions based on fundamental studies. Their rising trajectories are greatly associated with the bubble sizes and the properties of the liquid, as asserted by Clift et. al. (1978).

Bubbles form in three conditions. One is the liquid bubble where is a globule of one substance in another, usually gas in a liquid. The second one is the soap bubble usually a very thin film of soap water that forms a sphere with an iridescent surface. The third one is the anti-bubble usually described as a droplet of liquid which forms a bubble sphere upon a liquid medium. Nowadays, these multiphase flows (gas-liquid) are important and widely employed in industrial plants, energy facilities and environmental applications. This application can be found in chemical processes, bio-reactors, environmental plants, and steam power stations. Many industrials seek to use the bubble column due to its cheap installation (low cost), easy operation and high heat transfer rate.

In theory, a single bubble appears in a naturally perfect sphere, and raises straight upwards to the surfaces. Previous studies have shown that a bubble rise in different shapes such as spherical, spherical cap, ellipsoidal and skirted. The bubble term of 'spheroidal' was used by Clift et. al. (1978) to mention the bubble's in asymmetrical shape condition. The bubble's injection mode (the way the bubble exits

or is released), affects bubble's terminal velocity and causes large shape deformation of the bubble at the detachment; this disposition had been concluded by Celata et. al. (2002). In the current study, the investigation will focus on continuous single bubble in the intermediate size range within an equivalent diameter between 3 mm to 5 mm. The bubbles size are depending on needle internal diameter (ID) which is 1.4 mm and gas velocity generated by bubble generator up to 80 bubbles/min. This single bubble lies in the regime where bubbles take the ellipsoidal shape only and also in the secondary motion created by itself such as rocking motion, zigzagging, wobbling, and spiralling. Affected from this secondary motion, it has attracted previous researchers to study areas of bubble trajectories and the rising path in the different liquid media. Interested in this secondary motion, Tomiyama et. al. (2002) have studied the effect of surfactant to bubble oscillation and motion. It have been concluded that the primary cause of widely scattered terminal velocity is not surfactant concentration but its initial shape deformation during the injection of bubbles out from the ID needle.

A single bubble deformed has always been visualised or seen as a perfect sphere inside the liquids condition. However, after decades of researches, bubbles are not only visualised as less spherical, but it also has a cap shape. Aybers and Tapucu (1969) have studies of drag and shape of gas bubble rising through stagnant liquid, mention the names of Peebles and Garber (1953) who have categorised bubble shapes according to Reynolds number, Re (Table 1.1). Nevertheless, the studied have categorised the bubble shape in reference to the Weber numbers, We , by taking into account that Reynolds number is the ratio of inertial forces to viscous forces, while the Weber number is the ratio of inertial force to surface tension.

$$Re = \frac{\rho V d_e}{\mu} \quad (1.1)$$

$$We = \frac{\rho V^2 d_e}{\sigma} \quad (1.2)$$

where, ρ = density of the liquid used (kg/m^3),

V = velocity of the bubbles (m/s),

d_e = diameter of the bubbles (mm),

μ = viscosity of the liquid used (Pa.s), and

σ = surface tension of the liquid (N/m).

Clift et. al. (1978) point out that bubbles have five shapes; spherical, ellipsoidal, wobbling, dimpled ellipsoidal-cap, skirted and spherical cap. The categorisation of bubble shapes has been established to be in accordance to Reynolds number, Morton number, M and Eotvos number, Eo .

$$M = \frac{g \mu^4}{\sigma^3 \rho} \quad (1.3)$$

$$Eo = \frac{g \rho d_e^2}{\sigma} \quad (1.4)$$

where, g = gravitational force (m/s^2),

μ = viscosity of the liquid used (Pa.s),

σ = surface tension of the liquid (N/m),

ρ = density of the liquid used (kg/m^3), and

d_e = diameter of the bubbles (mm).

According to the Clift et. al. (1978), the Morton number is another dimensionless number that has been used by Haberman and Morton (1953) which combines We , Re , and Fr (Froude number). Eotvos number, Eo is the ratio of buoyancy force to surface tension. The wobbling, free oscillating bubbles occur at $Re < 1000$, and $1 < Eo < 100$, whereas the bubbles with spherical-cap, skirted and dimple ellipsoidal shape occur at $Eo > 100$.

Table 1.1: Rising motion by Peebles, Garber, Ayber and Tapucu

Peebles and Garber (1953)		Aybers and Tapucu (1969)	
Shape	Reynolds number	Shape	Weber number
Spherical bubble	< 400	Spherical	0 to 0.62
Oblate spheroids of varying proportion	400 to 1100	Ellipsoid with no surface oscillation	0.62 to 3.70
Oblate spheroids of constant geometric proportion	1100 to 5000	Ellipsoid with increasing surface oscillation	3.70 to 5.35
Mushroom shape with spherical cap	> 5000	Distorted and spherical cap	> 6.35

It is also noteworthy that it is difficult to eliminate surface-active contaminants and control the way the bubbles are released in systems, in terms of the practical and experimental aspects. These problems lead to the study of the effect of fluid properties (e.g. density, viscosity, and surface tension) to the bubble's motion and rising pathlines. Many researchers have correlated bubble terminal velocity to the fluid properties by using dimensionless parameters such as the Morton number, M , Weber

number, We , Reynolds number, Re and Eotvos number, Eo . As bubble rises to the surface, there are three types of forces acting onto a single bubble that must be considered, which are the gravitational force, F_g , buoyancy force, F_b , and drag force, F_d . Figure 1.1 shows the combination of these forces that acting on a single bubble which gives the value for the terminal velocity of the bubble rising in different degrees of liquid viscosity. However, these forces have not given any prediction of bubble trajectories and path lines.

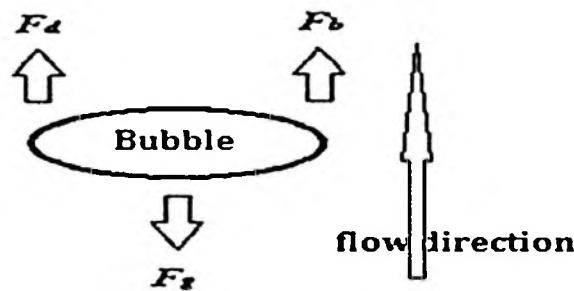


Figure 1.1 Parameters for bubble flow direction

where,

$$F_g = \frac{4}{3}\pi r^3 \cdot \rho_g \cdot g \quad (1.5)$$

where, ρ_g = gas density (kg/m^3),

r = radius of bubble (mm), and

g = gravitational force (m/s^2).

then,

$$F_b = \frac{4}{3}\pi r^3 \cdot \rho_l \cdot g, \text{ and} \quad (1.6)$$

where, ρ_l = liquid density (kg/m^3).

From the Stokes law:

$$F_d = 6\pi \cdot \mu \cdot V \cdot d_e \quad (1.7)$$

where, μ = viscosity coefficient (Pa.s),

V = bubble velocity (m/s), and

d_e = bubble diameter (mm).

1.2 Effect of heat transfer

In our daily lives, a lot of processes that have been dealing with are related to heat. Some examples of heat applications that are very common place are boiling the water using the kettle and cooling the computer heat sink or CPU using a rotary fan. In this vein, examples of practical applications involving single bubble rising enhanced with heat transfer are still abundant. Many end-products in industries like bio-processes, medical, chemical and food industries adopt the bubble rising technique to perform mixing and transport – liquid particles in a continuous liquid medium. Often, it is desirable to generate a new industrial application such as cooling agent in reactor and to fulfil cleaning purposes at the wall surface.

Heat transfer normally entails the transfer of heat from an object with higher temperature to a lower temperature in a fluid movement. “When an object is at a different temperature from its surroundings or another object, the transfer of thermal energy, also known as heat flow, or heat exchange, occurs in such a way that the body and the surroundings reach thermal equilibrium; this means that they are at the same temperature”. It happens when an object has shown different temperature values that move from a high temperature to a cooler temperature based on the second law of thermodynamics. This heat transfer cannot terminate their movement from one to

another until it stays in equilibrium but its slowly decreasing due to heat has been transferred to the environments.

In recent days, researches done on the effect of heat transfers on a plate heater in bubble columns are still lack in studies. In the past few years, a lot of researchers only focus on the bubble rising behaviour in various tanker shapes (bubble columns). Furthermore, there has been evidence that their dedication to the studies is only on the pool boiling effect in the bubble column with different liquids, yet they have yet to focus on the enhanced heat transfer using this bubble rising technique.

The investigation on continuous single bubble rising can be used in industrial applications to enhance heat transfer. This phenomenon is based on three types of heat transfer: i. Conduction, ii. Convection, and iii. Radiation. This present research, as it is, looks into major issues concerning the convection heat transfer inside the bubble column.

Convection is defined as the movement of mass/molecules within fluids such as air or water that is heated, causing the mass/molecules to move away and carrying energy with it. Convection heat transfer increases as the fluid motion increases in a system. The presence of the bulk motion in a column can enhance the heat transfer between the plate heater surface and fluids (cooling liquids).

For example, heating a pot of water under a flame can lead convection to circulation and the effect of heated water can be seen in its expansion and enhanced buoyancy. There are two types of convection that exist:

- i. Natural convection: this occurrence applies in fluid motion, caused by buoyancy forces from density variations due to temperature difference in the fluids without the presence of any external sources.
- ii. Forced convection: this happens when external sources exist such as pumps or fans which force the fluid to flow over the surface by creating an artificially-induced convection.

Based on the experiment or derivation, the convective heat transfer rate is assumed to be:

$$Q = h \cdot A(T_p - T_b) \quad (1.8)$$

where h is heat transfer coefficient that depends on the physical properties of the fluid (temperature) and the physical situation where convection does happen. Q is the power input generated from DC power supply between current, I and voltage, V . A is the surface area of the heat transfer occurrence. Also, T_p is the plate surface temperature and T_b is the temperature of the bulk water. Therefore, this study will focus on finding the heat transfer coefficient, h during a single bubble pass through the plate heater.

$$h = \frac{Q}{A(T_p - T_b)} \quad (1.9)$$

1.3 Single bubble rising in industrial application

Mixing is the key to almost all productions, either mixing chemicals in the pharmaceutical industry or mixing water and pulp in paper production. Poor mixing can cause significant loss. In 1989, the cost of poor mixing was estimated at 1 billion

to 10 billion Dollars in the US chemical industry alone. In one large multinational chemical company, the loss value due to poor mixing was estimated at 100 million per year in 1993 by Paul et. al. (2004).

As mixing significance is appointed with some economical motivation, the study of mixing has its own field of expertise. In previous decades, the mixing technology has transformed rapidly from a traditional static mixing with a centre agitator, to the current jet mixer with bubble diffusion.

Jet mixer is a modern mixer without the rotating equipment i.e.; agitator or rotator located at the centre of the tank.

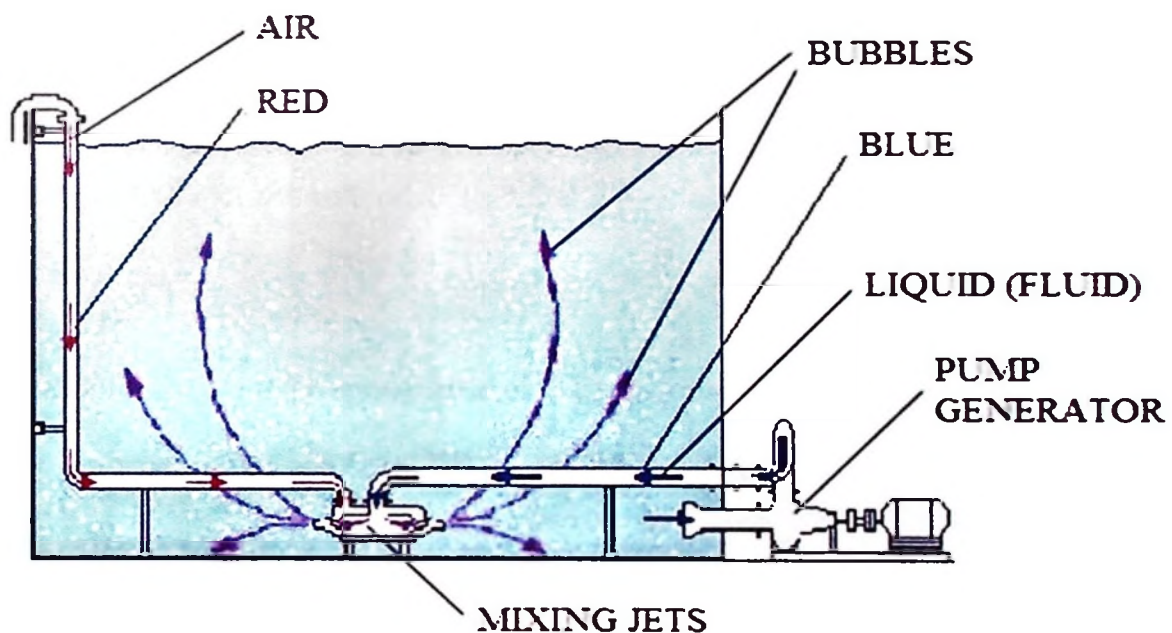


Figure 1.2 Side views of jet mixers (Image from Mixing systems, inc. webpage)

In Figure 1.2, the red arrow is low pressure gas, and the blue arrow denotes pressurised liquid. Located at the centre of the tank is the jet mixer. As the low pressure gas and pressurised liquid come into contact in the mixing chamber, the

resulting mixture (in micro-size bubbles) is pushed through the outer nozzle, creating a high velocity bubble plume, which mixes the tank's content. The movement of bubble creates eddy current in the surrounding liquid, which is thoroughly mixed in the entire tank.

The jet mixer operation does not need any moving part inside the tank that means the maintenance cost can be reduced to operating these systems. Pump located outside the tank will provide easy maintenance for overhaul. As jet mixer gains its reputation in the mixing industry, the studies about the effect of mixing principles in bubble behaviour and its surrounding liquid have a potential in the research fields.

In oil production, gas bubbles are used to transport oil to the surface and its called gas lift. Gas lift is one type of artificial lift, which generally works by increasing the flow rate of the produced fluids to the surface. When there is insufficient pressure in the reservoir to lift the produced fluids to the surface, artificial lift would be used.

There are several types of artificial lift which consist of a pump and a motor. The emerging method of artificial lift is gas lift (Figure 1.3). Gas lift increases the oil production rate through the injection of compressed gas into the lower section of tubing, through the casing-tubing annulus and an orifice installed in the tubing string. Upon entering the tubing, the compressed gas bubbles affect the liquid flow in two ways:

- i. The energy of expansions propels (pushes) the oil to the surface
- ii. The gas aerates the oil so that effective density of the fluid is less, and thus, it is easier to get to the surface.

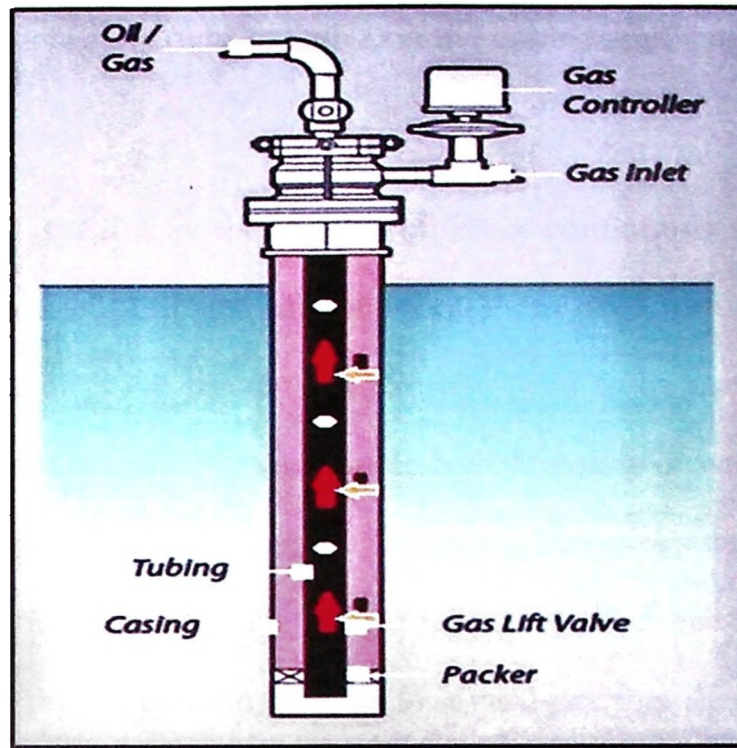


Figure 1.3 Gas lift (Image from Oil and Gas Processing blog page)

Typically, the gases that are injected using a recycling gas produced from the same well. With very few surface units, gas lift is an optimal choice for offshore applications. The examples of industrial applications above shows the bubbles are a key to run the process where the bubbles rising use as the main tools. These two applications are still used to this day in industry and related fields.

1.4 Problem statement

The bubbling flow has become an important tool in industrial fluid such as the mixing purpose, cooling system and oil production. There are a lot of studies made by the researcher on bubble rising behaviours but only limited literatures on heat transfer enhancement due to bubble rise that has been discovered over the past decades. Liu and Zheng (2006) studies on bubble rising behaviour using PIV methods and Sakakibara et al. (2007) using a Dual Camera PIV systems. Many researcher focus on

bubble rising behaviours but didn't studies on the bubble applications to enhance heat transfer rate.

The present research is the first to utilize a continuous single bubble rising behaviour based on small bubbles size between 3 mm to 5 mm in diameters in two different liquid viscosity. All the data and results need to be used to investigate the effect of heat transfer on a continuous single bubble rising in water liquid. The heat plate orientation (γ), γ and bubble frequency, f_b are two parameters investigated while the power, Q is constant. This method will be applied, the vertical plate heater will immerse in the bubble column in order to investigate that the heat transfer can be enhance using bubble rising.

In addition, the research investigate the optimization of heat transfer with respect to plate orientation and bubble frequency using design of experiment (DOE), in order to give higher temperature drop on plate heater surface. Moreover, this present study performs a detailed of two-dimensional (2-D) numerical simulation related to the flow structures and bubble pathlines.

1.5 Objectives of the research

The present study is aimed to achieve the following objectives

- i. To investigate the flow structure of a continuous single bubbles rising behaviour in two different liquid viscosities using particle image velocimetry (PIV) systems.
- ii. To study the interaction with, and without, a heated vertical plate immersing inside the rectangular liquid column using water liquid. This

will focus on the heat transfer coefficient between the plate heater and water solutions and to optimize them by using DOE approach.

- iii. To perform two-dimensional (2-D) numerical simulation to study the flow structures and bubble pathlines with and without heat, and compare with the experimental results.

1.6 Scope of the research

In this research work, the bubble flow behaviour and heat transfer enhancement are investigated as a cooling agents by releasing a continuous single bubble (air) rising through a liquid with different viscosities at room temperature inside a rectangular column. The experimental investigations are then illustrated by the numerical simulations. In the bubble rising behaviour, two different types of liquids are studied with different viscosity. But, in the heat transfer enhancement, plate orientations and bubble frequency are two parameters needed to be investigated in water liquid. These two scopes had been analysed by the Flow Manager V4.60 software (provided by Dantec Dynamic[®], Denmark) through image processing tools. The effect on the surrounding liquid with heat transfer was obtained by using the Particle Image Velocimetry (PIV) method. The numerical simulation is carried out using commercial Computational Fluid Dynamic (CFD) software, Fluent 6.3.26 and Gambit 2.3.16 on flow measurements and data analysis.

1.7 Thesis Outline

This thesis is organized in five chapters. Chapter one deals with the introduction to bubbles flow and its behaviour. It also describes the bubble's background and significance of using it as a mixing and cooling agent. In addition, the problem statement, objectives and scope of research are also established. For chapter two, the literature review explains the application and background of past researchers upon dealing with single bubble rising behaviour and simulations that have been done in liquid solutions. The methodology is highlighted in chapter three. This chapter describe the experimental setup and procedure, the calculation done on bubble rising and provide a table for the Design of Experiment (DOE). Moreover, this chapter will discuss the simulation setup on a single bubble in the bubble column like the computational model, mesh generation, governing equation, turbulence model, and simulation procedure. In chapter four, the results, discussion and analysis done in terms of velocity, vortices and bubble behaviour are presented. Meanwhile, the results for numerical solutions are also supplied in this chapter. Finally, the conclusion and future works are discussed in the chapter five.

CHAPTER 2

LITERATURE REVIEW

2.0 Overview

This chapter seeks to provide a review of the current and past researches on single bubble rising behavior and its applications to mixing and thermal cooling. A brief review of single bubble rising behaviour is first presented. Works on flow visualization hardware and software which help to analyse the bubble rising for the present study are also established next. Afterwards, the experimental studies on the effect on heat transfer in the bubble column are outlined, followed by the computational method on bubble flow and motion in past researches.

2.1 Single bubble rising behavior

Studies made by Aybers and Tapucu (1969) explore into the shape of gas bubbles and drag coefficient rises through stagnant liquid. A new experimental technique was constructed, which consists of phototubes, light beams and an electronic circuit to measure the rises velocity, and drag coefficient by using the notion of buoyancy with the drag equations. From the investigation, five types of motion in bubble rising behaviour were observed such as rectilinear motion, helical path motion, first plane then helical motion, plane motion, and rectilinear motion with rocking. The result has shown that, for bubbles rising with a rectilinear motion, drag theoretical solutions must be compared with the drag coefficient calculated with the maximum rise velocities. In addition, there is no wall effect on the rise velocity of the bubble if the ratio of the medium diameter is equivalent to the bubble diameter (D_{medium}/d_c) which

is greater than 18. The deformation of bubble shapes depends on the Weber number (We) according to the maximum velocity. Therefore, for We number smaller than 0.62, the shape of the bubble is spherical and for $We = 3.70$, the bubble surface starts to oscillate. The results shows if the Reynolds number (Re) is less than 565, the bubbles will rise in the rectilinear motion in stagnant liquid.

Stewart (1995) has investigated the ellipsoidal bubble interaction in low viscosity liquid using aqueous solution of sugar in water. The experiments were conducted using pulsed planar swarms with two dimensionless equations such as Eötvös number and Morton number. For a single bubble rise in an irregular but periodic spiral, it wobbles with a period of 0.2 s just after the release. During the experiments, bubble interaction like coalescence and break-up will tend to happen after the wake-induced collisions. This happens due to one bubble being pulled into the near wake of the other after passing through (vortex shedding). Moreover, there is no coalescence or break-up happening during the actual collision, which means that both of these may occur simultaneously. The same result found in the multi-bubble cluster and is accounted for as turbulent kinetic energy that generates in a bubbly flow.

Katz and Meneveau (1996) study the wake-induced relative motion of bubbles rising in line. The motion of spherical air bubbles rising were measured in a column with stagnant water at Reynolds numbers ranging from $Re_D = 0.2$ to 35. It has been found that the relative velocity is dependent on the distance between bubbles and on their diameter. For larger bubbles, the relative velocities increase with decreasing distance, reaching maximum values just prior to contact. For smaller bubbles, the relative velocity decreases prior to coalescence. The collision between bubbles creates the wake-induced relative motion in Reynolds numbers. These

collisions culminate in coalescence at the present levels of water purity and surface tension. A simple model has been developed, in order to understand the basic features of the measured relative motion based on the known flow field and viscous-wake structure around a single bubble and examines how other bubbles move within this field. They assume Oseen's flow of $Re \ll 1$ and potential flow with a thin wake of $Re \gg 1$. The approximation validity limit of the model was introduced to a distances larger than a few bubble diameters.

A study on bubble column hydrodynamics is carried out by Magaud et. al. (2001). The experiment was conducted in a vertical rectangular channel with liquid velocities approximately about 0.1 m/s and high void fraction. There are two main focal points in their research studies: (1) The experimental result can be used as a database for bubble column in flow modelling or numerical computations. i.e.; void fraction, bubble size, and bubble velocity. (2) The experiment is used to provide information about bubble column hydrodynamics. It state that in the core region, usually characteristics such as the sensitivity of homogeneous bubbly regimes to entrance condition; slip velocity decreasing with bubble concentration; and liquid fluctuation regimes change with the void fraction. In the wall region, the gas velocity increases the local wall shear stress significantly; decreasing the liquid velocity considerably amplifies the gas velocity effect; and space-time correlations are used to calculate integral length scale, coherence time and convection velocity. Results that show the presence of bubbles in the bubble column is known to increase wall-friction.

Javier et. al. (2001) who study bubble shape by using the Particle Tracking Velocity (PTV) technique has confirmed that the shape of bubble is equivalent to the shape of oblate spheroid. The experiments point out that instantaneous bubble shape

and size is a reflection of the dynamic changes of pressure inside the bubbles and in the surrounding fluid. From the experiment, as the agglomeration of contaminant on the bubble hardens the surface, they propose that it diminishes the response of the bubble surface to the pressure changes in the surrounding flow and with a combination of wall effect, yielding the observed oblate spheroid shape, which relate to their test conditions. The difference between bubble shapes in a contaminated and pure system has not been described in the works of Tomiyama et. al. (2002).

Tomiyama et. al. (2002) have investigated theoretically and experimentally the terminal velocity, V_T of a single bubble rising through infinite stagnant liquid in surface tension force dominant regime. The experiments were conducted using air and water to measure bubble trajectories, shapes and velocities. From the results, the experiments have confirmed that the fact that the primary cause of widely scattered, V_T in this regime is not the surfactant concentration, but the initial shape deformation. Furthermore, from the experiments, it proposed that small initial shape deformation results in low V_T and a high aspect ratio, whereas large initial shape deformation results in high V_T and a low aspect ratio.

Celata et. al. (2004) have studied the wake effect on the bubble rising velocity behaviour in one-component systems. The experiment of bubble rising velocity filed was carried out in a bubble column using R-114 and FC-72. Both of them are liquid with different viscosity. The results generated the vapor bubbles at the bottom of the bubble column using a tiny electric heater and their evolution was recorded with high-speed cinematography from the detachment point until the bubbles reached the terminal velocity in the bubble column. The researchers carry out investigations on single bubble and bubble train to ascertain the wake effect on the bubble rising

velocity field in the range of bubble diameters from 0.1 to 0.7 mm. It finds that negligible wake effects are able to be detected on the tested bubbles. The prediction of the bubble terminal rising velocity with available correlations, other than obtaining a reasonable prediction of bubble shapes using available correlations and models, and specifically the Taylor and Acrivos model and the Vakhrushev and Efremov correlation.

Sanada et. al. (2008) have explored experimentally the motion and shape of a single rising bubble in super-purified water. The purity of water by developing an apparatus was evaluated that is equipped with a measurement system for monitoring both the resistivity and amount of total organic carbon of water. The critical Reynolds number were investigated, of which the rising bubble motion changes from rectilinear to zigzag or spiral motion. The critical Reynolds numbers were revealed which is susceptible to the range of observation heights in the experimental tank. Next, the effects of the amount of contaminant are investigated on bubble motion. The results find out that the drag coefficient of bubbles in the case of low Reynolds numbers is greatly affected by a small amount of contaminant. The experimental results of both the terminal rising velocity and drag coefficient were compared with theoretical results for ellipsoidal bubble obtained for high Reynolds number. The results show a good agreement between the experimental and theoretical results for smaller bubbles. However, discrepancies are prominent for larger bubbles.

2.2 Flow visualization techniques

In the past, many researchers have been fast to show interest in water bubbles rising behaviours in gas-liquid two-phase flows by using the PIV system. Chen et. al. (1998) study the turbulent wake induced by a single gas bubble rising in a two-dimensional column using the particle tracking technique (the particle image analyzer technique). Experimental results show three different types of topological features for the integrated streamline flow pattern i.e.; 1. foci, 2. centers, and 3. bifurcation lines. The shear layer vortices will be dispersed, to generate turbulent stresses, or accumulated to form a large-scale Strouhal vortex. The formation of Strouhal vortices are distorted, as the shear layer vortices are mixed with the irrotational free stream. However, when the entrained free stream cuts through one side of the wake boundary, the effect is apparent in the shedding of the Strouhal vortex. The circulation such as foci, centers and bifurcation occurs when the Strouhal vortex is shedding which undergoes change, in both the sign and strength. From the observe show that the descending velocity of Strouhal vortex in the near wake is examined to be less than $1/3$ of the bubble rising velocity.

Tokuhiro et. al. (1998) later studies on turbulent flow past a bubble and an ellipsoid bubble using shadow-image and PIV techniques. The experiments were conducted to investigation on flow around an oscillating bubble and flat bottom ellipsoid bubble. The flow field around an oscillating bubble and its boundary of a turbulent flow around the oscillating bubble were measured, with the application of the PIV system enhanced by Laser Induced Fluorescence (LIF). Also, the experiments record simultaneously the bubble shapes using another camera and the Infrared Shadow Technique (IST).

Delnoij et. al. (1999) develops a new ensemble correlation of multiphase flow called the PIV technique. A straightforward extension of single-phase PIV was discussed and one of the major advantages of the technique is that it employs a single CCD camera. The research focuses on the performance of the PIV technique using synthetic bubble-tracer patterns. Finally, the newly developed PIV technique were tested by studying experimentally the two-phase flow in a pseudo-two-dimensional bubble column

Hassan et. al. (2001) study some three-dimensional measurements of single bubble dynamics in a small diameter pipe using Stereoscopic Particle Image Velocimetry. They use the particle tracking velocimetry combined with the shadow image measurement techniques to study the velocity field produced by the single air bubble passage through a small volume, rising in quiescent water, in a small diameter pipe. The bubble size and shape, together with the velocity field have been imposed by this technique. The Hough transform is introduced and an architecture resonance theory 2 (ART 2) neural networks to track the tracer particles. They also achieve the goal of reconstructing the three-dimensional flow field in the whole measurement volume using a stereoscopic matching technique.

Choi et. al. (2002) conducted yet another study on the measurement of particle/bubble motion and turbulence around it by the hybrid PIV system. The studies focuses on the effect of various factors that have influence on single particle motion, such as particle/bubble size and shape, deformation of bubble, and buoyancy or density difference. The behavior of the interaction between a particle or bubble and the surrounding fluid has been measured using the combination of PIV (Particle

Image Velocimetry) and PTV (Particle Tracking Velocimetry), which is respectively called HPIV (Hybrid Particle Image Velocimetry).

Fujiwara et. al. (2003) study bubble deformation and flow structure using double shadow images and PIV/LIF. The flow structure in the area is studied surrounding the bubble in one plane and its deformation in two planes using the particle image velocimetry (PIV)–laser-induced fluorescence (LIF) and a projection technique for two perpendicular planes, respectively. The velocity of the bubble is measured using a digital high-speed CCD camera for the PIV with fluorescent tracer particles. They also use the second and third CCD cameras to detect the bubble's shape and motion via backlighting from an array of infrared LEDs.

Kitagawa et. al. (2004) investigated experimentally the bubble interactions in a wall-sliding bubble swarm using a Particle Tracking Velocimetry (PTV) technique. The drag coefficient of a single wall-sliding bubble is measured where the distance between the wall and the bubble interface is much shorter than the average bubble diameter and then detect the probability distribution of the nearest bubble around individual bubbles in the bubble swarm in the range from $Re = 1$ to around 20. In order to identify the two-dimensional structure of the bubble–bubble interactions, two kinds of statistical sampling techniques are used. They have also obtained local modification of the drag coefficient by calculating the interactive velocity of an individual bubble.

Brenn et. al. (2006) concentrate on shape oscillations and path transition of bubbles rising in a model bubble column. They investigate experimentally the occurrence of shape oscillations accompanied by path transitions produced periodically by air bubbles rising in the water. The induced velocity is measured to

examine bubble–liquid and bubble–bubble interactions within the bubble formation period. The flow is produced in a small-scale bubble column with square-shaped cross section. A capillary aerator produces bubbles of the size 3.4 mm at a frequency of 5 Hz. They employ high-speed imaging measuring techniques to capture bubble shape oscillations and path geometry. They also use the laser-Doppler anemometry (LDA) to measure the velocity in the liquid near the rising bubbles.

Liu and Zheng (2006) look into the bubble rising behaviors in a rectangular bubble column using the particle image velocimetry (PIV). Bubbles rise in a chain through stagnant liquid. As liquid viscosity reduces, bubble rising trajectory changes from one-dimensional to three-dimensional trajectory. This transition is due to different bubble wake structures. The bubble shapes also show dissimilar characteristics in the liquid of different viscosities. From the measured liquid flow field by the PIV technique, the bubble rise in different paths.

Sakakibara et. al. (2007) developed a new type of Particle Image Velocimetry technique, called the “Dual-Camera PIV System”, in order to achieve higher-accuracy measurement at a high time resolution. The existence of a strong turbulence makes it difficult to measure a complex flow field such as the gas–liquid two-phase flow using the PIV in a precise manner. In the conventionally dynamic PIV, a time interval of two images required for analysis depends, in basic, on a camera frame rate. A time interval of a set of PIV images affects the measurement accuracy significantly. For this specific purpose, they had developed a measurement system composed of two high-speed cameras. The interval of two images obtained from each camera was controlled arbitrarily. Moreover, they adopted a recursive cross-correlation method as the PIV algorithm in order to achieve high spatial resolution.