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Experimental measurements of bubble convection models in two-phase stratified liquids

Hassan Abdulmouti

Department of Mechanical Engineering Division, Sharjah Men's College, Higher Colleges of Technology, P.O. Box 7946, Sharjah, United Arab Emirates

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ABSTRACT

The surface flow generated by a bubble plume is a technique proposed to collect the surface-floating substances. This has a great importance when handling the oil layer formed during large oil spill accidents due to the need to protect naval systems, rivers, and lakes. The motivation of this research is to broaden the understanding of oil flow in the stratified layer of oil on the free surface. Laboratory experiments have been carried out in order to investigate the multi-dimensional motion of water and oil due to bubbles. The flow structure of bubble-induced convection in a stratified liquid is investigated by using particle imaging velocimetry (PIV) measurements and pathline measurements. It is confirmed by this paper that the flow structure is strongly modulated by the gas flow rate and bubble size. The velocity of the surface flow induced by the bubble plume in the vicinity of the oil-water interface is about 50% larger and stronger than that inside the oil layer. Moreover, the surface flow is particularly rapidly generated in the vicinity of the oil-water interface. The highest kinetic energy (which is 0.012 $(m/s)^2$) is generated at a far distance inside the bubble plume and in the vicinity of the oil-water interface. This observation confirms the idea that the bubble plume can indeed generate a strong and wide surface flow over the bubble generation system. The oil layer is easily broken by bubbles, especially with high void fraction and small bubble size and high gas flow rates. The experimental results were compared with the numerical results of our earlier paper. It is confirmed by this paper that the experimental results resemble the numerical results. As a reference, in a thermally stratified liquid, the liquid flow pattern of bubble-induced convection has also been measured by using thermo-sensitive liquid crystal tracer particles in which a color-image processing is combined to measure the temperature field. These results were compared to the immiscible stratified cases.

1. Introduction

Bubble dynamics is of great importance in optimizing the engineering design and operating parameters of various adsorptive bubble system operations, such as dissolved air flotation and dispersed air flotation, for the separation of solids from a liquid. Bubble rise in liquids under different conditions is one of the oldest of scientific investigations [40]. It is of interest as the characteristics of a rising bubble (e.g. size, shape, velocity and trajectory) give insight into the dynamics of a system [12]. Rise velocity is one of the most important characteristics of a rising bubble. Numerous studies have been performed on the motion of single bubbles [26,4]. Flows induced by a bubble plume are observed in various engineering disciplines, e.g. in industrial, material, chemical, mechanical, and environmental applications. That would be situations such as chemical plants, nuclear power plants, applications in naval engineering, for the accumulation of the surface slag in the metal refining process, the reduction of surfactants in chemical reactive processes, waste treatment, gas mixing and resolution, heat and mass transfer, aeronautical and astronautical systems, biochemical reactors as well as distillation plants and so on [20,27,9]. The main features of these kinds of flows are the following: (1) a large scale circulation of the liquid phase can be generated in circulation systems like lakes, agitation tanks, etc. [31]. (2) Strong rising flows can be induced by the pumping effect, as in air-lifting pumps [33]. (3) High speed surface flows are developed at the free surface, by which the density and the transportation of the surface floating substances can be controlled [2,14]. (4) A high turbulence energy can be produced in the two-phase region due to the strong local interaction between individual bubbles and surrounding liquid flow [19,15]. On the other hand, the improvement and development in the performance of oil barriers (oil fences) is required, especially for high values of current velocity, wave height and wind velocity in order to protect the environment and the sea life from oil pollution [11,6,29,13]. Hence, a bubble plume is considered to possibly be an effective way to control

E-mail addresses: habdulmouti@hct.ac.ae, hassanabujihad@hotmail.com

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Nomenclature

A	area of calculation in the injector region, (injector surface of the bubble generator)
D	equivalent (mean) bubble diameter (mm)
H	thickness of the total height or the height of the stratified liquid in the tank (two layers of water and oil) (mm)
$H_{water} = h_1$	thickness (initial height) of the first layer (water) (mm)
$H_{oil} = h_2$	thickness (initial height) of the second layer (oil) (mm)
γ	ratio of the thickness of the second layer (oil) to that of the total height of the immiscible stratified liquid
Q_g	gas volume flow rate (m^3/s)
V_b	rising bubble velocity (m/s)
u_P	particle velocity (m/s)
u_L	liquid velocity (m/s)
u_G	gas velocity (m/s)
x	horizontal coordinate
y	vertical coordinate
α	void fraction
ρ_{L1}	density of the first layer (water) (kg/m^3)
ρ_{L2}	density of the second layer (silicone oil) (kg/m^3)
ρ_P	density of particle (kg/m^3)
d	particle diameter
υ_{oil}	kinematic viscosity of the oil (m^2/s)
υ_{water}	kinematic viscosity of water (m^2/s)
Ke	Kinetic energy calculated per unit mass $(m/s)^2$
β	added mass coefficient for traceability of particles against the flow in the oil layer
F_{DL}	drag force from the liquid
F_{DG}	drag force from the gas
F_{AL}	added inertial force from the liquid
F_{AG}	added inertial force from the gas

the density and transportation of surface-floating substances, and it is expected to be an effective tool to support the function of an oil fence, since it can generate a strong and wide surface flow over the bubble generation system and it can damp the wave motion. Many researchers have carried out extensive modeling experiments by focusing on the flow field using air bubbles as gas injection through a bottom nozzle is the most popular and has wide applications. Since bubble plumes have been used with varying degrees of success more information on these subjects should be accumulated [38,39,1,24,16,17].

There are many applications for bilayer convection; the most important one is the oil fence application. Two-layer systems have been studied theoretically and experimentally by many researchers. Bilayer convection is also an interesting transport process to be studied for both theoretical and application related reasons. Theoretically, a bilayer convection is full of nonlinear dynamics with a wide range of parameters to be investigated. Johnson and Narayanan [8] studied the effects of boundaries on bilayer convection in a cylinder with idealized boundary conditions. Using as examples two bilayer systems, a plot of the Rayleigh number versus aspect ratio (radius-height) was calculated. For certain systems, they found that the type of convection coupling, either thermal or viscous, will change as the width of the container changes, even as the height is fixed. Additionally, the interfacial structure was calculated to help identify the driving force for the convection. Sudden changes in the convection coupling and the dominant driving force of convection were found as the container radius increased. Interfacial tension gradients respond to the temperature field and cause convection of the 'Marangoni' type and this in turn is affected by buoyancy driven convection or Rayleigh convection. Degen et al. [7] experimentally studied two-layers heated from below. Johnson et al. [22] presented a brief review of convective phenomena associated with material processing, and they explained several instability phenomena that can occur in a bilayer of two fluids heated from either the top or the bottom and the effect of laterally and vertically confined geometries. Busse and Sommermann [5], Fujimura and Renardy [10], Johnson and Narayanan [23], Renardy and Stoltz [36], Ozawa et al. [35] discussed Marangoni effects and studied purely buoyancy driven convection for specific two-layer systems. They also investigated the velocity vectors of a water-silicone oil system in thermal convection. The presence of the interface and the coupling between the fluids has received attention by both experimentalists and theoreticians. Beyond that, the interaction between the bubble generated liquid convection and a stratified layer is known to be important for generating large circulation in lakes, rivers, seas, dams and many other processes. It is very important to know the interaction between the surface flow generated by bubbles and an oil layer for application to an actual oil fence. Usually the oil covers the water surface for a long time. However, in the past there were very few reports concerning this interaction mechanism and the bubble convection pattern in immiscible two-phase stratified liquids as an application to an actual oil fence. The motivations then, of the present work is the demand to broaden the knowledge of the separation mechanism of oil due to bubbling and the flow pattern inside the stratified two-phase liquids. In regards to applications, our aim is to focus on the actual oil transportation effect considering an oil layer on a free surface. Laboratory experiments have been carried out in order to investigate the multi-dimensional motion of water and oil due to bubbles. The present paper consists of two kinds of fundamental research. The first type is the experimental measurement of the oil transportation phenomenon due to the bubble plume (the motion of oil-water interface). The flow structure of the bubble-induced convection in a stratified liquid is clarified by using PIV measurements and pathline measurements. The second one is the experimental study of bubble-induced convection in a thermal stratified liquid layer using thermo-sensitive liquid crystal tracer particles, a procedure which has been performed in order to compare the convection pattern with the immiscible stratified cases. It is confirmed by this paper that the experimental results resemble the numerical results that were obtained by our earlier paper [31,32]. The results show that the flow structure depends strongly on the gas flow rate and bubble size. The velocity of the surface flow induced by the bubble plume in the vicinity of the oil–water interface is about 50% larger and stronger than that inside the oil layer. Moreover, the surface flow is particularly rapidly generated in the vicinity of the oil–water interface. The highest kinetic energy (which is 0.012 $(m/s)^2$) is generated at a far distance inside the bubble plume and in the vicinity of the oil–water interface. This observation confirms the idea that the bubble plume can indeed generate a strong and wide surface flow over the bubble generation system. The bubbles break the oil layer easily, especially with high void fraction and small bubble size and high gas flow rates.

2. Experimental apparatus and conditions

An experimental apparatus for investigating the bubble convection pattern in immiscible two phase stratified liquid is con-