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Mixing of thermally stratified water layer by a free rising wobbling air bubble

Iztok Zun [a,*], Matjaz Perpar [a], Jurij Gregorc [a], Kosuke Hayashi [b], Akio Tomiyama [b,1]

[a] Laboratory for Fluid Dynamics and Thermodynamics, Faculty of Mechanical Engineering, University of Ljubljana, Askerceva 6, 1000 Ljubljana, Slovenia
[b] Graduate School of Engineering, Kobe University, 1-1, Rokkodai, Nadaku, Kobe 657-8501, Japan

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ABSTRACT

The purpose of this research was to provide further insights on bubble-induced agitation of heated bulk liquid. Fundamental studies on the bubble disturbance of a stratified thermal layer were carried out for a 6 mm sphere-volume equivalent diameter air bubble suspended in water ($Eo = 1.2$). A video digital image system and thermochromic liquid crystals were used to reproduce the bubble movement as well as the wake drift of the liquid. A three-dimensional interface tracking simulation was used as a numerical tool. The results have revealed a long open wake region that is formed along the fluctuating bubble path. The amplitude of the bubble wake is much larger than that of the bubble path. In addition to longitudinal mixing, strong lateral mixing is also caused by the movement of vortices in the transverse direction. Details of numerical simulations have revealed a wake that tends to form a chain of Omega shaped vortex rings. These "rings" are connected to each other in the near wake region. The coherent effects further downstream lead to more complex vortex patterns in the far wake. The disintegration of the coherent chain of vortices due to bubble surface deformability is highly complex and not clear at this stage. A comparison with liquid crystal temperature response has revealed that the time scale of the mixing is much longer than the ascending bubble residence, approximately 8 s as obtained by several experimental runs. A transverse propagation of entrained cold water has given an estimate of the bubble-induced diffusion to be about 170 times larger than the diffusivity of momentum. The bulk liquid agitation cannot be correctly modeled without taking into account the bubble size dependent wake structure.

1. Introduction

Despite receiving much attention over decades, present knowledge on heat transfer mechanisms in the presence of bubbles is far from complete. The bridges between the system problem solving that involves complex (macroscopic) two-phase structure behavior on the one hand and an inadequate or insufficient understanding of fundamental micro-scale behavior on the other, are in most cases not known. The reasons are rooted in many details which require enormous effort when working on a micro-scale, from both experimental and numerical points of view. A significant portion of heat transfer enhancement can be expected due to the mixing process which exhibits at much smaller time scales than those required by molecular diffusion. This phenomenon occurs due to turbulence, induced or altered by the bubble wake structure.

A striking example of bubble mixing is the artificial thermal destratification of warm surface water by bubble plumes. An air bubble plume in water entrains the continuum from the lower regions and ejects it as a surface jet that propagates outward from the plume center. The negatively buoyant colder water eventually exhibits downdraft which, in a confined basin, may lead to a strong recirculation cell (Schladow, 1993). Many details of the problem of mixing up the bulk liquid due to the presence of bubbles still remain unresolved.

Another example is bubble columns since in many chemical and biochemical processes, chemical reactions are usually accompanied by a heat supply (endothermic) or removal (exothermic) operation. The heat transfer rate in gas–liquid bubble columns is reported to be generally 100 times greater than in single phase flow (Deckwer, 1980). Many hydrodynamic studies investigate heat transfer between the heating objectives and the system flow in order to understand the effects of hydrodynamic structures on heat transfer for improving the design and operation of bubble column reactors (Kantarci et al., 2005).

Heat transfer applications where bubble flow plays an important role also include internal combustion engine block cooling,

* Corresponding author. Tel.: +386 1 4771 403; fax: +386 1 4254 217.
E-mail addresses: iztok.zun@fs.uni-lj.si (I. Zun), tomiyama@mech.kobe-u.ac.jp (A. Tomiyama).
[1] Tel.: +81 78 803 6131; fax: +81 78 803 6155.

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pressurized water nuclear reactors and heat exchangers. For example, Celata et al. (1999) investigated heat transfer enhancement by air injection into a forced convective boiling flow in a vertical pipe. It was confirmed that air injection suppresses the laminarization of the flow and increases the heat transfer coefficient up to a factor of 10. The observation that bubble oscillation may have a dramatic effect on heat transfer enhancement that multiplies the natural convection heat transfer by a factor larger than 2 accords qualitatively with some other investigations as well. In related earlier studies, heat flux measurements were undertaken for a 4 mm bubble by Donnelly et al. (2008). They have shown that the rising bubble and its wake can have a significant effect on heat transfer when the bubble rises close to a heated plate and acts like a bluff body, displacing the heated fluid, increasing local mixing and allowing cooler water to move in. For the bubbles that rise further from the plate, it is the wake of the bubble that enhances heat transfer. Delaure et al. (2003) measured the interaction between bubble wake and convective flows formed along a heated flat plate. The major axes of two different bubbles were about 4 mm and 10 mm, respectively. They pointed out that vortices in the near wake of the bubble successively enhance and hinder heat transfer, and induce temperature fluctuations by bringing colder fluid into contact with the flat plate. Vortices shed by a bubble also play an important role in the enhancement of mass diffusion. It has been recognized that there are two mechanisms in the mass diffusion enhancement: the drift of liquid by a bubble (Darwin, 1953; Lighthill, 1956; Weber and Bhaga, 1982) and the mixing by large-scale vortices in the bubble wake (Koso et al., 2004).

Earlier studies already highlighted the importance of the wake structure for the path instabilities of solid spheroids and speculated that the same holds true for the bubbles. The results of such separate treatment are known to some extent. We believe that the bubble movement, bubble wake structure as well as bubble interface oscillation are coupled phenomena that need to be analyzed at the same time. Deficiencies in obtaining such results are mainly to the intrusive experimental methods used for turbulent transitional phenomena. It is shown in this paper that this problem can be successfully solved using numerical analysis in parallel to laboratory experimentation.

In this research, a laboratory experiment is coupled with a numerical simulation in order to check the relevant time scales and the magnitude of wake disturbances behind a single free rising bubble of 6 mm sphere-volume equivalent diameter. The size of the air bubble suspended in water corresponds to the Eötvös (Bond) number 1.2, which is within the range that has practical importance when using a porous plate as a bubble sparger (Wallis, 1974). An experiment was performed in a rectangular ($160 \times 80 \times 1000\ mm^3$) Plexiglas tank filled with clean (filtered) tap water at 17 °C. Two electric heaters were mounted on top to generate constant heat flux. The bubbles were suspended in water after the temperature stratification reached the range between 19 °C and 36 °C. The bubble shape, its movement and temperature layer destratification were observed simultaneously by video and thermochromic liquid crystals. It is assumed that the change in the rate of mixing is concomitant with the changes of iso-temperature strata. The dynamics of changes (shape changes in space with time) of iso-temperature curves served as the validation criteria for the numerical method. An interface tracking simulation of the free rising bubble was carried out to investigate bubble-induced mixing. Recent developments in numerical simulations (Hayashi et al., 2006; Hayashi and Tomiyama, 2007) and local measurements of wake impact lead toward further insights on bubble-induced agitation of the heated bulk liquid. The phenomenon investigated in this study exhibits Ω shaped vortices shed within the bubble wake and comprises the displacement of heated liquid and the motion of liquid drifted by the bubble movement.

2. Experiment

Experiments of single air bubbles rising through thermally stratified water were carried out to evaluate entrainment capacity A_e defined by the deflection of an isotherm that is caused by bubble agitation. The details of the laboratory experiment are described below.

2.1. Experimental setup and method

The experimental apparatus shown in Fig. 1 enabled simultaneous recordings of temperature field along the solid vertical wall and the bubble motion under free rise conditions. Two electric heaters, 200 W/each, are positioned atop of a rectangular ($160 \times 80 \times 1000\ mm^3$) Plexiglas tank filled with clean tap water at 17 °C. The test volume is bounded by the heaters from two sides and the back wall coated by liquid crystal foil (LC) (Thermochromic standard sheets, TMC Ltd.) and measures $80 \times 65 \times 110\ mm^3$. The initial liquid

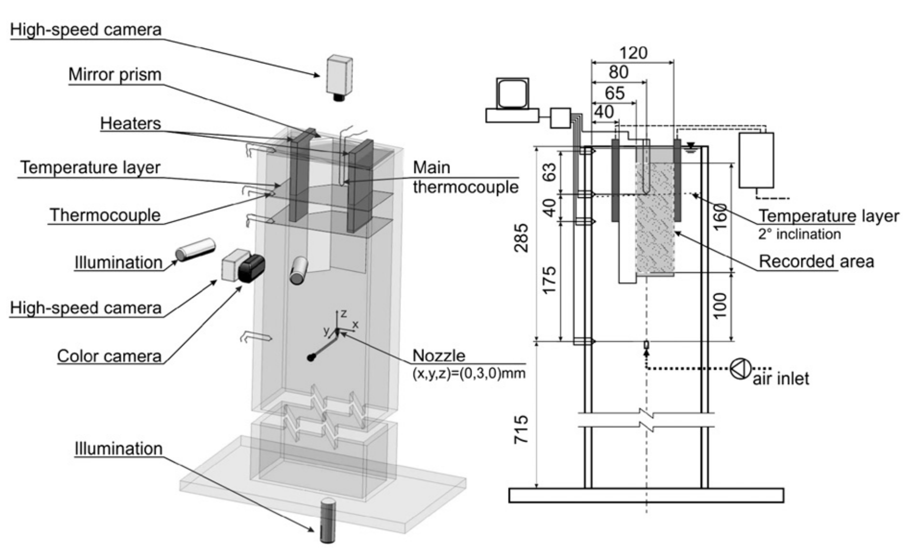

Fig. 1. Experimental setup.