International Journal of Multiphase Flow 84 (2016) 145–154

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmultiphaseflow

Flow structures and dynamics in the wakes of sliding bubbles

R. O'Reilly Meehan[a,*], B. Donnelly[b], K. Nolan[b], T. Persoons[a], D.B. Murray[a]

[a] *Department of Mechanical and Manufacturing Engineering, Trinity College Dublin, Dublin 2, Ireland*
[b] *Thermal Management Research Group, Efficient Energy Transfer (ηET) Department, Bell Labs Research, Nokia, Dublin 15, Ireland*

ARTICLE INFO

Article history:
Received 3 December 2015
Revised 4 March 2016
Accepted 12 March 2016
Available online 30 April 2016

Keywords:
Sliding bubble
Wake structures
Particle image velocimetry

ABSTRACT

An experimental investigation is reported for the flow structures in the wake of an air bubble sliding under an inclined surface in quiescent water. Time-resolved particle image velocimetry (PIV) is used to study the wakes of sliding bubbles for a range of measurement planes, bubble diameters and surface inclination angles. Additionally, key aspects of the bubble's motion are measured simultaneously using a novel method that accounts for the motion of the bubble's interface. Thus, vortex shedding may be linked to changes in the bubble shape and path.

Analysis of the measured velocity and vorticity fields reveals a wake structure consisting of a near wake that moves in close proximity to the bubble, shedding vorticity at the inversion points of the bubble path. Downstream of the bubble in the far wake, these structures evolve into asymmetrical, oppositely-oriented hairpin vortices that are generated in the near wake. These hairpin vortices bear similarities to those observed behind freely rising bubbles and near-wall bluff bodies and are found to cause significant motion of the bulk fluid. This bulk fluid motion has the potential to offer significant convective cooling of adjacent heated surfaces, such as submerged electronics components.

1. Introduction

The motion of a bubble through a fluid has attracted considerable scientific attention for many years due to the complex, interesting fluid dynamics in their wakes, coupled to a rich and varied interface motion. Aside from this, understanding the fluid mechanics and how they can affect heat transfer is a major issue for many engineering applications. Although a large body of work exists for bubbles rising in an unbounded medium, that of bubbles rising in constricted geometries has received less attention. The particular case of a gas bubble sliding underneath an inclined surface in a quiescent medium is important to applications such as shell and tube heat exchangers, mineral flotation and oxidation in water treatment. Prior work on sliding gas bubbles has focused on parameters such as the bubble size, shape, initial impingement and terminal velocity (Maxworthy, 1991; Peron et al., 2006; Podvin et al., 2008). Additionally, previous work by the authors has quantified the surface heat transfer enhancement of an air bubble sliding under a heated surface, showing that large heat transfer coefficients are achievable for gas bubbles even at low wall superheats (Donnelly et al., 2015). However, limited research exists on the wake structures that cause these enhancements. This is despite extensive research on the wake structures of freely rising bubbles (Brücker, 1999), and the fact that the bubble wake is key in determining the turbulence production and resulting convective heat transfer (Qiu and Dhir, 2002). Thus, a more complete knowledge of the sliding bubble wake will lead to improved modelling of two-phase phenomena and can provide further insight into wake-driven convective heat transfer. The aim of this study is to achieve this understanding for an ellipsoidal air bubble sliding under an inclined surface in quiescent water by using high speed video and time-resolved particle image velocimetry (PIV).

1.1. Freely rising bubbles

Freely rising air bubbles can take on different shapes depending on the properties of the bubble and the surrounding fluid, with Clift (2005) providing a comprehensive review of the bubble shape regime. The authors found that the bubble's shape can be generally classified as spherical, ellipsoidal or spherical cap, and its motion characterised as rectilinear, zig-zag or spiral. These regimes depend on the dimensionless groups that define the bubble and fluid properties, namely the Reynolds, Eötvös, and Morton numbers. The Weber number, which is a measure of the relative importance of inertia and surface tension, is also relevant for the current study.

* Corresponding author.
E-mail address: ruoreill@tcd.ie (R. O'Reilly Meehan).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.03.010

Nomenclature

$Eo = \frac{g\Delta\rho {d_e}^2}{\sigma}$	Eötvös number
$Mo = \frac{g{\mu_l}^4\Delta\rho}{{\rho_l}^2\sigma^3}$	Morton number
$Re = \frac{\rho_l d_e U_\infty}{\mu_l}$	Reynolds number
$St = \frac{f d_e}{U_b}$	Strouhal number
$We = \frac{\rho {U_T}^2 d_e}{\sigma}$	Weber number
F_b	Buoyancy force [N]
U_b	Bubble velocity [m/s]
$\mathbf{U}$	Bubble velocity vector [m/s]
U_∞	Terminal rising velocity [m/s]
V	Bubble volume [m^3]
V^*_{mag}	Normalised fluid velocity
a	Bubble major axis [m]
b	Bubble minor axis [m]
d_e	Equivalent spherical diameter [m]
e	Eccentricity
f	Path oscillation frequency [Hz]
g	Acceleration due to gravity [m/s^2]
s	Coordinate [m]
t	Time [s]

Greek symbols

α	Surface inclination angle [°]
Ω	Vorticity [1/s]
Ω^*	Normalised vorticity
ϕ	Phase angle [°]
ρ	Density [kg/m^3]
σ	Surface tension [N/m]
μ	Viscosity [kg/ms]

Subscripts

b	Bubble
g	Gas property
l	Liquid property
m	Mean
x, y, z	Coordinate direction

Bubbles in the ellipsoidal regime were found to experience oscillations in shape and path triggered by the bubble wake, which is the region of non-zero vorticity downstream of the bubble. A review of rising bubble wake visualisation methods was provided by Fan and Tsuchiya (1990), who proposed various wake structures, e.g. a closed laminar wake with a stable tail, an open turbulent wake and a wake consisting of a chain of hairpin vortices. The wake structures were found to bear strong similarities to those of bluff bodies, and varied with changing Reynolds, Eötvös and Morton numbers. The authors speculated that for ellipsoidal bubbles, the three-dimensional wake structure likely consisted of an attached vortex in the near wake and a series of interconnected vortex loops in the far wake. This looped structure is commonly referred to as a hairpin, or horseshoe vortex. These findings were supported by the flow visualisations adopted by the dye visualisations of Lunde and Perkins (1997) and Sanada et al. (2007) and the experiments using Schlieren photography of Veldhuis and Biesheuvel (2007) and De Vries et al. (2002). In all cases, these visualisations showed the formation of hairpin vortices in the bubble wake. There were some discrepancies between the number of hairpin vortices shed in each period, with the dye visualisations of Lunde and Perkins (1997) showing a hairpin vortex forming every time the bubble changed its direction, (i.e. twice in each period of path oscillation). However, the numerical study of the unsteady bubble wake provided by Gaudlitz and Adams (2009) observed a chain of up to four connected hairpin loops in the near wake of the bubble per period of oscillation. The authors attributed these differences in results to the influence of surfactants in visualisation experiments, noting that agreement was achieved with the work of Veldhuis et al. (2005), who used highly purified water in their Schlieren experiments.

Flow field measurement techniques can provide further insight into the wake structure, with particle image velocimetry (PIV) among the most ubiquitous, allowing for measurement of the velocity gradient tensor. Brücker (1999) performed 2-D PIV on ellipsoidal rising bubbles. The author found the flow field in a perpendicular plane downstream of the bubble to be the alternate generation of a pair of counter-rotating vortices close to the bubble base, while regions of concentrated vorticity were observed at the locations of maximum surface curvature of the bubble. By combining information acquired in two 2-D planes, the author deduced that the structures in three dimensions consisted of a chain of hairpin vortex loops of alternate circulation and orientation. The author inferred that the zigzagging bubble motion was coupled to a regular generation and discharge of alternate, oppositely oriented hairpin vortices. Zenit and Magnaudet (2009) also used PIV to study the rising bubble wake, performing streamwise measurements of vorticity in a plane downstream of a rising bubble, revealing two swirling regions of vorticity that stretched up to 7 diameters downstream of the bubble. These regions were found to spread outwards in time while reducing in strength.

1.2. Sliding bubbles

Bubbles sliding under an inclined surface differ from rising bubbles in that they only experience the component of the buoyancy force parallel to the surface. This is true until the surface inclination angle is increased above a critical angle, at which bubbles begin to bounce. It is the sliding regime without bouncing that is of interest in the current study. Although previous work had looked at bubbles in channels, Maxworthy (1991) was among the first to study a bubble rising under a flat inclined plate. It was found that the terminal sliding velocity did not scale linearly with Reynolds number or surface inclination angle. A later investigation by Peron et al. (2006) showed that this terminal velocity instead had distinct regimes corresponding to different bubble shapes. Viscosity and surface tension determined the shape for smaller bubbles, while the shape of larger bubbles was determined by inertial effects. The authors also found that sliding bubbles experienced path and shape oscillations as with rising bubbles. Podvin et al. (2008) derived a model based on lubrication theory to describe a bubble impacting an inclined wall, showing that bubbles experienced one of three different behaviours dependent on the surface inclination angle. At low angles, the bubble bounced along the surface several times before sticking to the surface and stopping. At intermediate angles, the bubble slid under the wall, reaching a terminal velocity. At high wall inclinations, the bubble experienced a steady bouncing of constant amplitude.

The current study intends to build on the recent work of Donnelly et al. (2015), who performed measurements on a heated foil to determine the motion and heat transfer enhancement offered by a sliding air bubble in the ellipsoidal regime. In this regime, bubbles were found to undergo a sinusoidal motion linked to vortex generation and shedding in the bubble wake. Local heat transfer enhancement to several times that of natural convection occurred in small regions downstream of the bubble. This was suspected to be a result of fluid advection and vortices impacting the heated surface. In time, these structures formed isolated regions of cooling. This was in agreement with previous work of Cornwell and Grant (1998) and Houston and Cornwell (1996), who showed that the turbulent fluid motion induced by a sliding air bubble