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Bubble-wake interactions of a sliding bubble pair and the mechanisms of heat transfer

R. O'Reilly Meehan [a,*], B. Donnelly [a], K. Nolan [a], D.B. Murray [b]

[a] Thermal Management Research Group, Efficient Energy Transfer (ηET) Department, Nokia Bell Labs, Blanchardstown Business & Technology Park, Snugborough Rd, Dublin 15, Ireland
[b] Dept. of Mechanical & Manufacturing Engineering, Trinity College Dublin, Dublin 2, Ireland

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ABSTRACT

An experimental investigation is reported for the bubble-wake interactions that occur between an in-line air bubble pair sliding under an inclined surface in quiescent water. Three experimental techniques are utilised to study this flow: time-resolved particle image velocimetry (PIV), a new edge-based bubble tracking algorithm incorporating high speed video and high speed infrared thermography. These techniques allow for a novel characterisation of sliding bubble-wake interactions in terms of their associated fluid motion, the fluid-induced changes in the trailing bubble interface and the resulting surface convective heat transfer. As these interactions are ubiquitous to multiphase flows, such knowledge is pertinent to many industrial applications, including the optimisation of two-phase cooling systems.

This work has revealed that for an intermediate bubble size, in-line bubble pairs adopt a configuration in which their paths are 180° out of phase. Upon entering the fluid shed from the near wake of the leading bubble at each local extremum, the trailing bubble is accelerated both in the direction of buoyancy and in the spanwise direction corresponding to that of the shed fluid structure. This causes significant, high-frequency changes in the interface of the trailing bubble, which recoils and rebounds during this interaction. Surface heating adds further complexity to the bubble-wake interaction process due to the disruption of the thermal boundary layer at the surface. It is found that the trailing bubble can momentarily decrease local convective heat transfer levels by displacing the cool fluid introduced to the surface by the leading bubble. However, the amplified fluid mixing and local heat transfer enhancement of 7–8 times natural convection levels observed at the trailing bubbles mean that the net effect of the trailing bubble is to enhance convective heat transfer.

1. Introduction

The dynamics of bubbles moving through a fluid are rich, complex and multi-layered. Considering that they also have applications in diverse fields such as chemical engineering, water treatment and thermal management, it is no surprise that there has been considerable recent research into these flows. Despite this, the current understanding of two phase flows remains incomplete, particularly in terms of the coupling between the bubble dynamics, fluid mechanics and convective heat transfer enhancement [1]. To date, both vapour and gas bubbles have been found to enhance the convective heat transfer rate between the fluid and an adjacent heated surface [2]. A significant portion of this enhancement results from the turbulent disruption of the surrounding fluid induced by the bubble wake structure. Indeed, much of the behaviour of these flows stems from the bubble wake [1,3,4].

Extensive work exists on freely rising bubbles describing the bubble shape [5,6], path [7,8], dynamics [9], wake structures [10–12] and bubble–bubble interactions [13,14]. Bubbles in more constricted geometries, however, have received comparatively less attention. One configuration of interest is the interaction between a gas bubble and a heated inclined surface, which is pertinent to applications such as two-phase shell and tube heat exchangers. At intermediate surface inclination angles, gas bubbles have been observed to slide under the surface, resulting in significant convective heat transfer enhancement [2]. Much of the literature on the heat transfer associated with these sliding bubbles does not address the underlying fluid motion that causes this enhancement. Furthermore, the majority of studies on sliding bubbles to date have been limited to a single bubble, whereas the aforementioned industrial applications will involve the interactions between multiple bubbles. The current study will seek to address these issues by exploring the dynamics of bubble-wake interactions for

* Corresponding author.
E-mail address: rudi.oreilly_meehan@nokia.com (R. O'Reilly Meehan).

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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
U_b	bubble velocity [m/s]
T	temperature [K]
V_{mag}	fluid velocity [m/s]
a	bubble major axis [m]
b	bubble minor axis [m]
c_p	specific heat capacity [J/kg K]
d_e	equivalent spherical diameter [m]
e	eccentricity
k	thermal conductivity [W/mK]
q	convective heat flux [W/m^2]
s	coordinate [m]
t	time [s]

Greek symbols

α	surface inclination angle [°]
δ	foil/paint thickness [m]
ϵ	eccentricity
Ω	vorticity [1/s]
ϕ	phase angle [°]
ρ	density [kg/m^3]
σ	surface tension [N/m]
θ	orientation [°]
μ	viscosity [kg/ms]

Subscripts

b	bubble
f	foil
g	gas property
∞	bulk fluid property
l	liquid property
m	mean
p	paint
x, y, z	coordinate direction

an in-line pair of air bubbles sliding under an inclined surface in quiescent water, along with the resultant effects on convective heat transfer.

The motion of a bubble and its associated wake is strongly dependent on its shape. Freely rising bubbles adopt different shapes depending on the properties of the bubble and the surrounding fluid. Various dimensionless numbers can be used to characterise bubble shapes, although most studies tend to focus on the Reynolds, Morton and Eötvös numbers. Using these three dimensionless numbers, Bhaga and Weber [6] developed a shape regime for freely rising bubbles, while Fan and Tsuchiya [5] discussed the nature of the bubble wake for each of these shapes. The bubble wake, defined as the region of non-zero vorticity downstream of the bubble, was found to bear strong similarities to bluff bodies. However, the changing bubble shape and path and different boundary conditions (zero normal stress for a bubble versus zero slip for a bluff body) added further complexity to the bubble wake. Indeed, the bubble and its wake were found to have a symbiotic relationship, with instability in the bubble wake causing bubbles to undergo path oscillations and vica versa [5]. At intermediate bubble diameters (approximately 4–7 mm), air bubbles rising in water were classified as ellipsoidal, undergoing path and shape oscillations with a three-dimensional wake structure that consisted of an attached vortex in the near wake and a far wake consisting of interconnected vortex loops. This structure is referred to as a hairpin vortex, and has been observed both numerically [10,15] and experimentally for rising bubbles using techniques such as dye visualisation [12,16], particle image velocimetry [11,17] and Schlieren photography [18,19].

Bubbles can interact with a surface in a number of ways. Upon impingement, a bubble will typically bounce at first, reducing in kinetic energy due to viscous dissipation during this collision. The subsequent motion of the bubble is determined by a variety of factors, including the roughness of the surface and the contact angle, but is mostly dependent on the surface inclination angle, α. At low inclination angles, the bubble will stick to the surface. As the inclination angle increases, the bubble will slide continuously under the surface until some critical angle, α_{crit}, at which it will begin to bounce while traversing the surface. It is the second, sliding regime that is of interest in the current study, typically encountered between $\alpha = 10^\circ$ and 50°. The presence of the inclined surface, along with the liquid film that exists between the bubble and the surface [20], fundamentally alters the bubble mechanics, meaning the shape regime defined for freely rising bubbles cannot be directly extended for this case. The mechanics of such bubbles were studied by Maxworthy [21] in terms of the terminal sliding velocity and Peron et al. [22] in terms of the sliding bubble shape.

In a recent study, the motion and wake structure of a single sliding air bubble were characterised by O'Reilly Meehan et al. [1] using high speed video and PIV. Intermediate sized bubbles ($d_e = 5$–7 mm) were found to take an undulating path, with a wake structure consisting of a near wake that moved in close proximity to the bubble, separating from the bubble at the inversion points of its path. Downstream of the bubble in the far wake, these structures evolved into asymmetrical, oppositely-oriented hairpin vortices that spread laterally into the bulk fluid. This vortical structure bore similarity both to those of freely rising bubbles and that of near-wall bluff bodies, e.g. the near wall sphere studied by Stewart et al. [23].

As an air bubble slides under a heated surface, it disrupts the thermal boundary layer, altering the mechanism of heat transfer from free to forced convection. Houston and Cornwell [2] showed that this liquid disturbance could account for significant heat transfer at low wall superheats, even in systems without phase change. Qiu & Dhir [24] showed that the sliding bubble wake structure to the rear of the bubble enhanced heat transfer by introducing cooler liquid from the bulk to the surface. Bayazit et al. [25], and more recently Hollingsworth et al. [26], performed experiments on a vapour bubble sliding under a heated surface in FC-87, a dielectric perfluorocarbon fluid. The effect of the sliding bubble on surface heat transfer was found to be substantial, accounting for a third of the total temperature change between the wall and bulk fluid. The bubble was found to grow rapidly due to evaporation, with a triangular thermal wake forming to its rear. Within the wake, thin shear layers were observed shedding from the sharp edges of the bubbles, which corresponded to regions of maximum local heat transfer.

Recent work by Donnelly et al. [4] and O'Reilly Meehan et al. [3] measured the change in surface temperature and convective heat flux associated with single sliding air bubbles of 5–7 mm diameter using high-speed infrared thermography. Surface cooling plots matched the flow structures observed by PIV, with an affected