Experimental study of flow fields around small gas bubbles under the combined action of buoyancy and thermocapillarity

E. Koukan, G. Wozniak, K. Wozniak, J. Siekmann

Abstract Due to the combined action of buoyancy and thermocapillarity, the flow around a moving or stationary bubble, surrounded by a liquid matrix, exhibits a relative complex structure. The results of recent experiments show two different cases. First the buoyancy force is stronger than the thermocapillary force, secondly, the reverse relationship holds.

List of symbols

- $a$ thermal diffusivity
- $g$ gravitational acceleration
- $r$ radius
- $t$ time
- $x, y, z$ spatial Cartesian coordinates
- $D$ bubble diameter
- $G$ parameter [Eq. (2)]
- $H$ distance
- $R$ bubble radius
- $T$ temperature
- $U$ bubble speed
- $VT$ temperature gradient
- $\sigma$ interfacial tension
- $\sigma_T$ constant rate of change of interfacial tension with temperature
- $\mu, \mu'$ dynamic viscosity of the continuous (liquid) phase and the gaseous phase (bubble), respectively
- $v$ kinematic viscosity of the continuous phase
- $\rho, \rho'$ density of the continuous (liquid) phase and the gaseous phase (bubble), respectively
- $\psi$ stream function
- $\theta$ angle
- $Re$ Reynolds number
- $Mg$ Marangoni number

1 Introduction

In the present work, our objective is to illustrate some interesting features of flows around small gas bubbles generated by the combined action of buoyancy and thermocapillarity (Marangoni convection). Bubbles occur in many domains in nature and engineering. Hence the influence and behaviour of these bubbles is of fundamental interest in the applied sciences. For example the removal of gas bubbles is a basic requirement in problems of fluid handling and management and, particularly, materials processing, e.g. crystal growth, since bubbles within crystals represent grave defects. This process is especially complicated for very small bubbles because of the extremely small influence of buoyancy. Concerning the investigation of the Marangoni convection, a test cell was utilized for the observation of the particle motion. The cell was equipped with vertical glass windows. Horizontally, two copper plates form the boundary of the cell. The high heat conductivity of the copper guarantees constant temperatures at the horizontal boundaries of the liquid matrix. The hardware was designed so, that extremely small bubbles with diameters $D \leq 150 \mu m$ could be investigated. This required a special construction of the bubble injection system and an illuminating optics.

Concerning the injection of the bubbles with diameters of approximately $D \leq 100 \mu m$ conventional micro-pipettes are not sufficient. Thus a new micro-pipette was developed to get bubble diameters of about 40 $\mu m$. By means of a fine micrometre screw a fine adjustment of the desired bubble diameter was achieved. Next the bubble was injected through the plexiglas window into the matrix liquid. A vertical temperature gradient, controlled by thermoelements, was adjusted in the continuous fluid phase in the test chamber.

Regarding the visualization of the fluid motion by means of tracer particles, backlit and depth of field technique using a “Long Distance Microscope” were utilized. This procedure is in contrast to the system known hitherto, where an image plane was generated by a laser light sheet. However, on the one hand the new method has the advantage that considerably less light power is required, and on the other hand the contour of small bubbles can be recorded. For the illumination of the tracer particles within the measuring plane LED’s were applied. The diameter of the particles is about 5 $\mu m$. To map and to observe the measuring plane, the latter was enlarged first with a microscope and afterwards recorded by a CCD camera. The flow pictures were evaluated by virtue of a

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PIV programme, which works by the principle of cross-correlation.

2 Experimental apparatus and procedure
Since details regarding the test cell, bubble injection and positioning, etc. have been documented by Koukan elsewhere [1], we shall only provide a brief summary here. Figure 1 shows a sketch of the experimental set-up. To visualize the fluid motion around very small bubbles and to study the thermocapillary bubble motion, a special test cell was designed (Fig. 2). The rectangular cavity with the inside dimensions 40 mm \( \times \) 40 mm \( \times \) 6 mm consists of vertical plexiglas windows to observe the particle motion. Horizontally the cavity is bounded by copper plates. Thus constant temperatures at the horizontal boundaries of the liquid matrix are guaranteed, whereby a controllable heat exchange within the liquid matrix by heating or cooling, respectively, can be realized. In the middle of the plexiglas window and perpendicular to the direction of observation is a capillary drill hole with a diameter of 2 mm for the bubble injection.

Figure 3 displays the bubble injection system, designed for the injection of micro-bubbles. By means of a micro-pipette system, bubbles with a diameter of about 30 \( \mu \)m could be generated. The micro-pipette is located outside the cavity. A bubble of the desired size is generated within the liquid matrix by the drill hole through the plexiglas window. Application of this injection method ensures a minimal disturbance of the temperature field of the liquid matrix.

In this study exclusively silicone oil AK 1000 (Firma Wacker Chemicals, Munich, Germany) was employed. Table 1 compiles the physical data of the applied silicone oil and air at room temperature and a pressure of one bar. The fluid properties of air as viscosity, density, and thermal diffusivity are negligible in comparison with those of silicone oil. The test fluid has to meet a number of demands occurring in thermocapillary investigations. They are

1. The fluid should be a newtonian liquid.
2. The fluid should be transparent for optical reasons.
3. The refraction index of the fluid should have the same order of magnitude as the plexiglas of the walls of the cavity in order to minimize refraction.
4. The kinematic viscosity and the heat conductivity of the fluid must be large enough to allow experiments in the higher temperature ranges. Hence the melting temperature and the boiling temperature should be far from the working temperature.
5. The order of magnitude of the fluid density and the particle density should be the same to avoid sedimentation.
6. The surface tension of the fluid should be unaffected by contamination.
7. The test fluid should be nontoxic and nonpolluting.

Polymer Microspheres (Duke Scientific Corporation, Palo Alto, U.S.A.) having a density of 1.05 g/ml and a diameter of 3–5 \( \mu \)m, as well as liquid crystals of the type TCC 1001 (BDH Chemical Ltd, London) with a diameter of 10–12 \( \mu \)m were used as tracers. In order to check the sensitivity of the surface tension and its variation with temperature of the pure test fluid to the tracer seeding we have measured its surface tension with and without the presence of the

![Fig. 1. Schematic of experimental set-up](image1)

![Fig. 2. Schematic of the test cell](image2)

![Fig. 3. Bubble injection system](image3)

<table>
<thead>
<tr>
<th>System</th>
<th>( \rho ) (kg/m(^3))</th>
<th>( \mu ) (kg/ms)</th>
<th>( \gamma ) (m(^2)/s)</th>
<th>( a ) (m(^2)/s)</th>
<th>Pr</th>
</tr>
</thead>
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<tr>
<td>Silicone oil</td>
<td>970</td>
<td>0.97</td>
<td>( 10^{-4} )</td>
<td>( 0.99 \cdot 10^{-7} )</td>
<td>10023.4</td>
</tr>
<tr>
<td>Air</td>
<td>1.169</td>
<td>18.2 ( \cdot 10^{-6} )</td>
<td>15.6 ( \cdot 10^{-6} )</td>
<td>22.5 ( \cdot 10^{-6} )</td>
<td>0.696</td>
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