Bouncing bubble dynamics and associated enhancement of heat transfer

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Abstract. Heat transfer enhancement resulting from the effects of two phase flow can play a significant role in convective cooling. To date, the interaction between a rising gas bubble and a horizontal surface has received limited attention. Available research has been focused on bubble dynamics, although the associated heat transfer has not been reported. To address this, this study investigates the effect of a single bubble bouncing against a heated horizontal surface. Local heat transfer measurements have been performed for four orifice to surface distances, with a bubble injection orifice of 1 mm in diameter. High-speed photography and infrared thermography have been utilized to investigate the path of the bubble and the associated heat transfer.

1. Introduction

Two phase flow can play an important role in convective heat transfer processes. Developments in two phase flow technology have allowed for ever more effective and compact heat exchangers. A study by Yoon et al. [1] estimated that, in two phase bubbly flow with phase change, the bubble dynamics were responsible for up to 80% of the total heat transport in the nucleate boiling regime. Cornwell [2] experimented on horizontal tube arrays in R113 and demonstrated that small bubbles nucleated from the lower tube surfaces. It was observed that when the upper tubes were at too low a temperature for the possibility of nucleation, large heat fluxes were observed; this was primarily due to a stream of bubbles passing over the tubes. These bubbles initiated from lower tubes and caused a local increase in the liquid velocity. This phenomenon of enhancement due to bubble movement was further investigated by Houston & Cornwell [3], by means of air bubbles rather than vapour bubbles. Golobic et al. [4] conducted an experimental study on spatio-temporal temperature variation underneath growing bubbles on a thin platinum heating foil in saturated and sub-cooled nucleate pool boiling of water. Two different modes of bubble growth were found; both fast and slow growth and detachment under equal conditions. For fast growing bubbles an initial spike in the local heat flux followed by a reduction crater was detected. Following a bubble’s detachment, no indication of wall quenching was found. A similar study was conducted by Golobic et al. [5] who hypothesised that a fast-growing bubble pushed superheated liquid underneath slow-growing bubbles.

A number of studies have focused on bubbles sliding along inclined surfaces. Qiu & Dhir [6] utilised holographic interferometry to visualize both the near and far wake of a bubble sliding...
along an inclined plate, with angles of plate inclination of 15° and 75° from the horizontal. At 15°, vortices were observed to form downstream of the bubble, detach, and move into the bulk fluid where they dissipated. This resulted in an increase in local heat transfer as heated fluid is moved away from the surface and cooler fluid replaces it.

Donnelly et al. [7] preformed an experimental study on the flow dynamics and related heat transfer for a bubble sliding along a heated inclined surface. The authors noted that the majority of the heat transfer enhancement resulted from the bubble’s wake effect rather than the direct motion of the bubble. Similar enhancement levels to these encountered for inclined surfaces were also found for bubbles rising against vertical surfaces, as investigated by [8, 9].

Work on bouncing bubble dynamics has been investigated by numerous authors [10, 11, 12, 13], although currently, to the authors’ knowledge, no experimental data have been reported for heat transfer enhancement associated with a rising bubble bouncing on a heated surface. Therefore the primary objective of this research is to contribute to the current understanding of convective heat transfer from a heated horizontal surface subject to a bouncing bubble. For the present study a single orifice diameter of 1 mm has been investigated along with four orifice to surface spacings: 10 – 40 mm. A single surface temperature of 50°C has been chosen.

2. Experimental Set-up
The experimental apparatus shown in Figure 1 consists of a tank of 110 × 95 × 195 mm³, constructed from 3 mm thick glass, with a horizontal test surface placed at the top. The tank contains an adjustable bubble injection orifice and a controllable heated surface. Aluminium structural elements support the tank, allowing a high speed infrared camera to be mounted directly above the test surface, while two CCD cameras are mounted horizontally at the sides of the test section as illustrated.

![Diagram of experimental setup](image)

**Figure 1.** Experimental set-up. High-speed camera (b) is located perpendicular to camera (a).

The injection orifice is on a movable platform, which allows the injection point to be adjusted to varying distances from the test surface. The test surface measures 50 × 90 mm² and consists of an electrically heated foil insulated on the upper surface by a 3 mm air gap. The air gap is maintained by a Calcium Fluoride (CaF2), 1 mm thick IR transparent viewing window. This polished glass window has a very high percentage transmissibility, approximately 95% for a depth of 1 mm. The bubble is injected from a point 30 mm (z coordinate) away from the heated surface, which is centred at (0, 0) in the x and y direction, respectively.

The foil is a 10 µm thick Constantan Alloy Cu55/Ni45 rolled foil supplied by Goodfellow Ltd. The foil is bonded between two bus bars using silver based electrically conductive epoxy
(Loctite 3888 silver infused epoxy). The rear face of the foil is sprayed with a matt black paint with a high emissivity; it was determined that the depth of paint was $10.3 \pm 0.1 \mu m$. The disadvantage of using a thin foil technique is that the limited thermal capacity of the wall may alter the actual heat transfer processes under investigation by causing large local variations in wall temperature. To account for this a correction term to account for stored energy has been employed and will be discussed.

To capture high speed movement of the bubble, high intensity lighting is required to enhance the visibility of the bubble. This is provided by three high intensity light emitting diode (LED) strips (15 bulbs per strip) mounted behind each camera. A diffusive screen allows for a uniform light sheet. Two NAC Hi-Dcam II digital high-speed colour cameras are used in these experiments (max resolution 1280 x 1024 pixels, dependant on frame rate).

A FLIR SC6000 high resolution, high frame rate infrared camera is used for the surface temperature measurements. It is used in conjunction with a high speed data recorder (HSDR) and FLIR’s SC6000 camera controller and ExaminIR frame grabber software to acquire the data. The camera has a 640 x 512 pixel focal plane array (FPA), InSb 3-5 μm sensor which is vacuum sealed in a cooler assembly. The camera is set to record a zone that is 160 x 160 pixels in size, with an offset from the centre of the lens; this offset reduces camera reflection from the IR window. The field measured by the IR high-speed camera was 34.5 x 34.5 mm$^2$, corresponding to a spatial resolution of 216 μm/pixel. The SC6000 is set to acquire frames at a frequency of 1000 Hz with an exposure time of 0.85 ms. To achieve this, a Thurlby Thandar TG300 series function generator produces a square wave signal at 1000 Hz. When the InSb sensor is active, a square wave signal is sent from the camera to the PCI controller card for the first (master) Hi-Dcam camera, which in turn triggers the second (slave) camera. The Hi-Dcam cameras record at a frequency of 1000 Hz with an exposure time of 0.5 ms. The uncertainty of this method is one frame i.e. 1 ms. This exposure time allows the bubbles detailed movements to be fully captured.

An accurate bubble injection rate is achieved by using a kdScientific model 200 infusion pump in conjunction with a Hamilton GASTIGHT 1002 2.5 ml syringe.

3. Experimental Procedure
The tank is filled with ultra-pure water which is maintained at $22 \pm 0.5^\circ\text{C}$. An air injection rate of 100 ml/hr was chosen for the experiment, with a single injection orifice diameter of 1 mm. The foil is electrically heated using a Lambda d.c. power supply, with a constant current of 30 A. Once the power is switched on, conditions are allowed to stabilise for 3 minutes until a constant surface temperature has been achieved. This also allows the 3 mm air gap to reach a stable temperature. Once both the infrared and high speed cameras are armed and synchronised, a single bubble is injected into the test section and the instrumentation is triggered. Once the images have been acquired the test section is allowed to return to $22^\circ\text{C}$, before repeating the test.

4. Analysis
The foil is Joule heated, which approximates a uniform heat flux surface. In order to calculate the heat convected from the foil to the fluid, an energy balance has been utilised. To complete the energy balance three assumptions are required, namely that a uniform heat flux is generated in the foil, that the temperature is uniform through the foil thickness and that the air between the foil and IR glass is stagnant so that one dimensional conduction across the air gap may be assumed.

To validate the assumption that the upper surface temperature and the lower surface temperature are equivalent, the Biot number criterion is utilised. If the Biot number is much less than one, then it can be assumed that the temperature is uniform within the solid at any time
during the transient process. \( Bi = \frac{h L_c}{k} < 0.1 \), where \( h \) is the heat transfer coefficient, \( k \) is the conductivity of the solid and \( L_c \) is the characteristic length of the surface. This characteristic length reduces to half-thickness, \( L \) for a plane wall of thickness \( \delta \) cooled from both sides \((2L = \delta)\).

For the current set-up, the Biot number is estimated to be \( Bi \approx 1.025 \times 10^{-3} \) for the foil and \( Bi \approx 36.14 \times 10^{-3} \) for the paint.

A secondary way to assess the validity of measuring surface temperature on the back face of the foil is by means of its characteristic time constant for thermal diffusion across the thickness of the foil and paint. The characteristic conduction time in the thickness direction \( (\delta) \) is shown in Equation 1 (Golobic et al. [4, 5] and Maranzana et al. [14]).

\[
\tau = \frac{\delta^2 \rho C_p}{k} = \frac{\delta^2}{\alpha}
\]  

where all the values relate to the properties of the wall.

Figure 2. Illustration of heat transfer through a single element with a surface area of \( dx \times dy \), where, \( \delta_{foil}, \delta_{paint} \) is the thickness of the foil and paint layer.

Figure 3. Surface temperature 75 ms after bubble impact. The black line shown represents a slice through the surface, illustrated in succeeding figures, in which the origin is the point marked A.

For the present study, the paint layer was found to have the higher time constant, of \( \tau \approx 5.05 \times 10^{-4} \) s, whereas the time constant for the foil was found to be much less, with a value of \( \tau \approx 1.78e \times 10^{-5} \) s. This analysis shows that the foil can be considered as having a uniform temperature through its thickness, for both steady state and transient regimes. This is because the camera integration time, \( t \), is \( 8.5 \times 10^{-3} \) s and therefore (as \( t > \tau \)), the camera is the limiting factor for the current set-up.

### 4.1. Element Energy Balance

In order to approximate the energy convected to the fluid, an energy conservation method is applied. This conservation of energy is defined in Equation 2.

\[
\dot{E}_{in} + \dot{E}_{gen} - \dot{E}_{out} = \dot{E}_{st}
\]  

A differential control volume for both the foil and paint layer is illustrated in Figure 2. The final energy equation employed is as follows:
\[ q''_{\text{conv}} = q''_{\text{gen}} - q''_{\text{cond}} - q''_{\text{rad,total}} + \left( k_f \delta_f + k_p \delta_p \right) \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) - (\rho_f C_p f \delta_f + \rho_p C_p p \delta_p) \frac{\partial T}{\partial t} \]  

where \( q''_{\text{conv}} \) is the flux convected to the fluid, \( q''_{\text{gen}} \) is the generation term, \( q''_{\text{cond}} \) is the linear conduction through the 3 mm air gap, \( q''_{\text{rad,total}} \) is the total radiation from both surfaces and the last two terms are the lateral conduction and energy storage terms, respectively. A finite difference approach was applied to both the lateral conduction and energy storage terms. For the present set-up a preliminary uncertainty analysis was preformed. The maximum uncertainty in the heat transfer coefficient is estimated as 35% at a 95% confidence level, depending on the temperature difference between the bulk and surface temperature, using methods describes by Coleman & Steele [15].

5. Results and Discussion

Results are presented for an injection orifice diameter of 1 mm, with a variation in release height of 10 – 40 mm from the heated impact surface. This injection orifice produced a bubble with an equivalent diameter of 3.5 mm. A constant current of 30 A was found to provide a corresponding surface temperature of approximately 50 ± 0.1°C. Only detailed results for a release height of 30 mm will be presented here.

Once the bubble detaches from the 1 mm orifice, it rises 30 mm to the solid surface, in approximately 97 ms, with a maximum velocity of 320 mm/s. The bubble was found to rise with a rectilinear path up to a height of approximately 14 mm, beyond this point the bubble began to tilt in the positive x and y directions. More detailed analysis of bubble dynamics, prior to impact, have been are presented by Donoghue et al. [16].

![Figure 4](image_url)  
**Figure 4.** Non-dimensional wall temperatures, with 0 ms being the time at which the bubble impacts the surface.

![Figure 5](image_url)  
**Figure 5.** Bubble movement associated with wall temperature reduction, as illustrated in Figure 4, one bounce has occurred.

5.1. Surface Temperature

To illustrate the extent of cooling, resulting from the motion of the bubble, surface temperature plots will be presented using Equation 4.
\[
T_s = \frac{T_w - T_0}{T_{w,t = 0} - T_0}
\]  

(4)

where \(T_{w,t = 0}\), \(T_0\) are the surface temperature prior to the bubble impact and the constant bulk water temperature, respectively. \(T_w\) is the local time varying surface temperature.

Figure 6. Non-dimensional wall temperatures up to 140 ms after impact, with 0 ms being the time at which the bubble impacts the surface, along with the bubble position at \(t = 60\) ms.

As the bubble approaches the heated surface, the surface temperature begins to drop. This reduction in temperature was found to occur as early as 4 ms prior to the bubble impacting the surface, with the upper surface of the bubble being approximately 1.4 mm away from the surface. Once the bubble impacts the surface, at 0 ms, a temperature drop of 1°C was observed. This can be seen in Figure 4, in which the temperature profiles along the solid line shown in Figure 3 are presented as a function of time. The bubble was found to drift away from its initial injection point (0, 0) in the \(x\) and \(y\) plane, resulting in the bubble tilting. The bubble motion at the surface is shown in Figure 5.

Prior to the bubble impacting the surface, the front surface of the bubble deforms, creating a dimple. This dimpling phenomenon has been observed by both Donoghue et al. [16] and Zapryanov & Tabakova [17]. This dimple is a result of viscous action, “trapping” fluid between the bubble and the rigid boundary. The effect of this dimple on surface temperature is evident 5 ms after the initial impact, as seen in Figure 4, where the extremities of the bubble are 10% cooler than the centre of the bubble.

Once the bubble has dissipated its kinetic energy by means of bouncing, the bubble attaches to the surface, forming a triple contact line. Once formed, the local surface temperature beneath the bubble rises. This is illustrated in Figure 6, where from 60 ms onwards the bubble is fully attached to the surface. This local dry out causes the foil temperature to rise to a maximum of 82°C, thereby reducing local heat transfer. As no phase change occurs, no high increase in heat transfer at the foot occurs as seen by Sodtke et al. [18].

5.2. Heat Transfer Coefficient

For the present study, a surface temperature of 50°C was found to provide a corresponding natural convection heat transfer coefficient of approximately 200±10 W/m²K. Once the bubble
impacted the surface, an immediate increase in heat transfer was detected, with a value of 2000 W/m²K being observed. After 10 ms, the surface heat transfer enhancement \( (\varepsilon = h/h_{\text{nat.conv.}}) \), rose to a value 68 times greater than natural convection alone. This enhancement is illustrated in Figure 7 for the release height of 30 mm.

Figures 8 and 9 provide a detailed representation of the extent of enhancement, 30 ms after the bubble’s initial impact. At that moment in time the bubble has rebounded from the heated surface, as seen in Figure 5. The bubble initially impacted the foil approximately 1 mm away from its release point of (0, 0), in both the positive x and y direction. After the initial bounce the bubble continued to move, before settling at 2.4 mm, 3.3 mm.
It is evident that the strongest heat transfer enhancement occurs in a region that is opposite to the direction of bubble motion, i.e. (-2 mm, -2 mm). This demonstrates that the wake of the bubble may be responsible for the majority of the enhancement, which is similar to the conclusions by Donnelly et al. [7] for a sliding bubble and Donoghue et al. [9] and Donnelly et al. [8] for a bubble rising past a vertical surface.

Figures 10 and 11 demonstrate the area affected by the bubble’s wake 196 ms after its initial impact. A feature of particular interest is that the local dryout associated with the bubble attaching to the surface, described previously, can be seen to reduce the heat transfer coefficient to below the natural convection levels for water. This reduction is of the order of 60%. The general enhancement in heat transfer was found to begin diminishing after 1.5 s, while being fully diminished after 6 s. Although not presented here it was observed that the area of enhancement was significantly reduced for lower release heights. This may be primarily due to the motion of the bubble, with only mild deviation from a rectilinear path being noted for low release heights.

6. Conclusion
From the results obtained in this preliminary study, is it clear that a bouncing bubble significantly increases the heat transfer from a horizontal surface, when compared to that of natural convection alone. It was also determined that the area of maximum cooling was always slightly displaced from and in the opposite direction to the motion of the bubble along the surface.

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