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SURFACE HEAT TRANSFER DUE TO SLIDING BUBBLE MOTION

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Abstract:

The presence of a rising bubble in a fluid can greatly enhance heat transfer from adjacent heated surfaces such as in chemical reactors or solar energy collectors. This is especially true if the bubble impacts and slides along the surface. Two main factors influence this: the wake generated behind the bubble and the bubble itself acting as a bluff body, displacing fluid as it moves. The current research is concerned with measuring the heat transfer from a submerged heated surface that is subject to a sliding bubble flow. An ohmically heated 25 micron thick stainless steel foil, submerged in a water tank, forms the test surface. This approximates a uniform wall flux thermal boundary condition. The angle of the foil can be varied relative to the horizontal. An air bubble is injected onto the lower surface of the test plate, it slides along its length and the effects are monitored by two methods. Thermochromic liquid crystals (TLC's) are used in conjunction with the high speed camera to obtain a time varying 2-D temperature map of the test surface. A second synchronised camera mounted below the foil records the bubble trajectory, size and velocity. The heated plate is tested at angles of 10, 20 and 30° to the horizontal. The current research reports on the enhancement of the heat transfer due to the bubble flow. It has been found that the angle made between the heated surface and the horizontal influences heat transfer by changing the behaviour of the bubble. In general, a steeper angle leads to a higher bubble velocity which results in greater heat transfer enhancement.

INTRODUCTION

It is known that the presence of bubbles in a system can lead to increased heat transfer from adjacent heated surfaces. In applications such as shell and tube heat exchangers bubbles are created at nucleation sites on the liquid-solid boundary during boiling. In other applications such as chemical reactors gas bubbles may be introduced to the flow to increase heat transfer. These bubbles, whether gas or vapour, grow and detach and can, in some cases, come in contact with a downwards facing heated surface. Bubbles of this nature are known as sliding bubbles. Heat transfer between the impacted surface and the bubble depends on the interaction at the surface which is influenced by bubble size, surface inclination angle and temperature difference.

In an investigation performed by Cornwell [1] it was found that vapour bubbles created on the upstream tubes in a shell and tube heat exchanger impacted and slid around the downstream tubes. The interaction between the bubbles and downstream tubes was found to significantly increase the heat transfer coefficient in that region. Bubble induced heat transfer is achieved by several mechanisms such as vapour bubble nucleation and detachment, the behaviour of the wake of the bubble, the fluid flow around the bubble and evaporation of the micro-layer between the bubble and the heated surface. There has been much debate in identifying the relevance of each individual mechanism and its contribution to the overall heat transfer.

It is important to understand how the bubble interacts with the fluid it moves in to appreciate how this influences heat transfer. In a study by Qui and Dhir [2], holographic interferometry is used to visualize both the near and far wake of the bubble for 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 results in an increase in heat transfer as heated fluid is moved away from the surface and cooler fluid replaces it. In a study by Brucker [3], PIV (Particle Image Velocimetry) and high speed photography were used to obtain the temporal evolution of the flow field in the near wake of single rising bubbles of 5-7 mm diameter in water. The existence of hairpin vortices was confirmed by DPIV performed in a plane perpendicular to the bubble flow direction. This showed the alternate generation of a pair of counter-rotating vortices close to the bubble base. Qiu and Dhir [2] also used PIV to observe the flow field around a sliding bubble moving under a heated inclined plate at 30° to the horizontal. The resulting data showed that liquid at the front of the bubble is pushed outwards, away from the heater surface. Towards the rear of the bubble, liquid is pulled inwards creating a vortical structure in the wake. Fluid velocities in this vortical region are comparable with the overall bubble velocity. The effect of plate inclination angle on bubble rise velocity and the volumetric growth of bubbles have been investigated by Chen et al. [4] and Maxworthy [5]. For vapour bubbles moving under a submerged surface in water they concluded that bubble terminal velocity increases with bubble volume and plate angle, reaching a maximum at an angle of 50° to the horizontal. In a numerical study by Yoon et al. [6] investigating boiling heat transfer from a flat surface it was concluded that fluid agitation caused by bubble development and detachment contributes to 80% of the overall predicted enhancement of heat flux. In an experimental study Thorncroft & Klausner [7] conclude that sliding bubbles can account for as much as 52% of the total energy transfer, outweighing the contribution of bubble nucleation.

Manickam and Dhir [8] used holographic interferometry to visualize the variation in fluid temperature surrounding a sliding vapour bubble. The heat transfer to and from the bubble was quantified. It is known that a liquid layer exists between the bubble and the heated surface but its thickness and contribution to heat transfer is much debated. They concluded that the vapour bubble continues to grow as it slides along the heated surface and provided a power law equation to calculate the growth rate, which is achieved by evaporation of the thin liquid layer. In the study performed by Qui and Dhir [2] into sliding bubbles, the existence of a wedge-like liquid gap in front of the bubble (determined by the angle made with the surface) is confirmed. The apparent wedge angle is seen to increase as the heater inclination angle increases and the wedge length increases with bubble size. In magnified photography the wedge is seen to almost penetrate to the down stream side of the bubble, thus it is connected to the thin liquid film which exists beneath the bubble. The relative contribution of the liquid layer evaporation to the total heat transfer rate was found to be small in their work. Cornwell & Grant [9] also report the existence of a thin evaporating liquid layer beneath a bubble sliding under a horizontal tube. Both water and Flutec (a commercial refrigerant) were used in the study. High speed photography and thermo chromic liquid crystal paints were used to evaluate the contribution of the evaporation of this layer to the overall heat transfer. Results indicated that the liquid layer evaporation can cause 'dry out' (a dry spot between the bubble and surface) which is quenched by the surrounding fluid after the bubble moves away. They conclude that neither the bubble motion nor the liquid layer evaporation is dominant under all conditions. The existence of 'dry out' was also confirmed by Yan et al. [10]. Sliding bubbles were observed under inclined plane and curved surfaces with heat transfer enhancement factors of 3-5 reported close to the trailing edge of the bubble compared to the undisturbed state. For large, slow moving bubbles, liquid layer evaporation was found to be the dominant heat transfer mechanism, whereas for smaller bubbles the reduction in evaporation was compensated by the higher velocity and therefore higher wake turbulence. In a study carried out by Kenning et al. [11] where heat transfer to a sliding bubble moving through saturated water was analyzed it was concluded that, for a micro layer thickness of approximately *60 μm*, micro layer evaporation could account for only a small fraction of the heat energy transferred from the hot surface to the bubble. In a similar investigation by Qiu and Dhir [2], it was concluded that the heat transferred to the bubble via micro layer evaporation was small in comparison to the heat transfer resulting from induced liquid agitation caused by bubble motion, with micro layer evaporation contributing only *17%* of the overall heat transfer.

The primary objective of this research is to contribute to the current understanding of heat transfer enhancement from a heated inclined surface subject to a bubble flow. This is done for surface inclination angles of 10, 20 and 30° degrees to the horizontal with a bubble of 4 mm in diameter. Whole field temperature measurement of the test surface is achieved using Liquid Crystal Thermography combined with high speed photography. From this, heat transfer enhancement is calculated. Bubble dynamics are analysed using a second camera synchronised with the first in order to observe both bubble dynamics and heat transfer on an accurate time line.

NOMENCLATURE

A	area of the foil (m^2)
A_{aff}	area affected by the bubble (m^2)
α	plate angle to horizontal (°)
ε	enhancement factor (-)
h	heat transfer coefficient (W/m^2K)
I	current (amps)
P	power supplied to the foil (W)
q''	heat flux (W/m^2)
T	temperature (°C)
ΔT	temperature difference, foil to bulk water (°C)
V	applied voltage (volts)
v_{avg}	average bubble velocity (mm/s)

EXPERIMENTAL SETUP

The experimental apparatus (figure 1) consists of a tilting test tank which can be set to any angle between 0 and 45 degrees by rotating a winding jack. The tank is constructed from 6 mm thick plate glass of dimensions 420 x 420 x 420mm and is supported by aluminium structural members. An inclinometer mounted on the tank provides angle of inclination. Additional structural elements connected to the tank allow cameras to be mounted above and below the test surface.

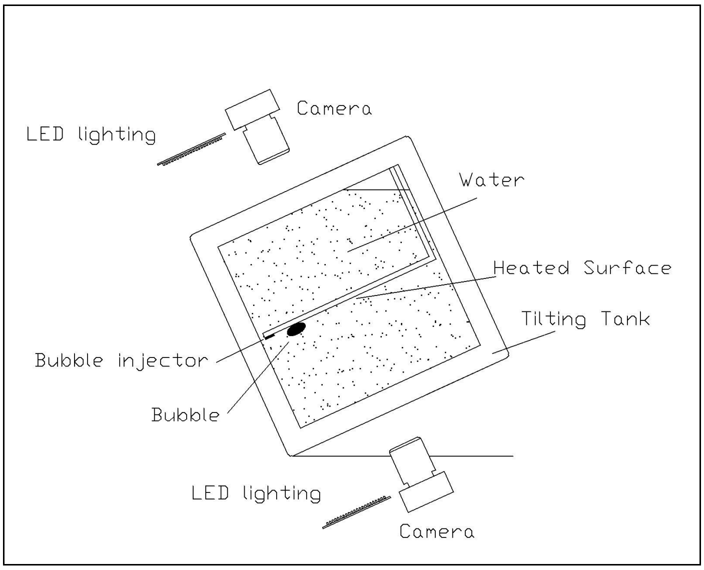


Figure 1: Schematic of tilting test tank

The test surface for this experiment measures *300mm x 100mm* and consists of a liquid crystal layer backed by black paint applied to a thin electrically heated foil mounted on a *10 mm* thick Perspex sheet. The foil used is

25 micron thick AISI 321 stainless steel supplied by Goodfellow Ltd. Both the black paint and the liquid crystal (Hallcrest: BM/R28C12W/S40) layers are applied using an Aztek A4702 artists airbrush in conjunction with a compressed air supply at 1.5 bar. The foil is bonded to the surface and electrical contact is made by two machined copper bars at each end as can be seen in figure 2 below.

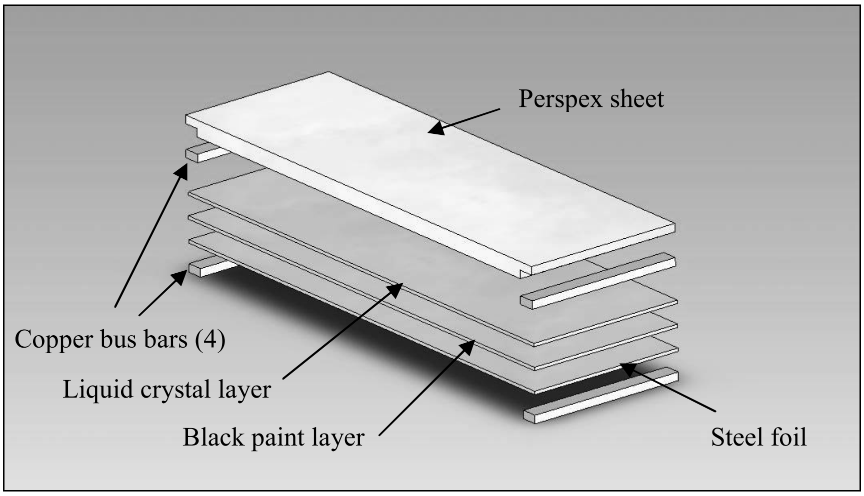


Figure 2: Exploded view of test surface

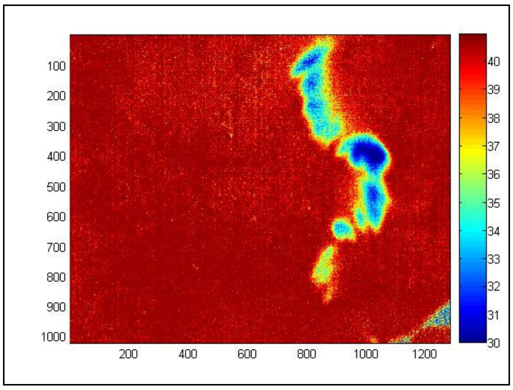
The test surface requires high intensity lighting both to enhance the visibility of the liquid crystal layer from above and to image the bubble flow from below. This is provided by 4 high intensity light emitting diode (LED) strips mounted on the tank which illuminate the test surface. Each strip contains 15 LED bulbs angled to provide maximum light intensity at the test surface. This method of lighting provides ample uniform light at low temperatures so as not to interfere with the liquid crystal's colour play. Mounting both the cameras and the lighting to the tilting tank ensures consistency in results obtained for all angles of the tank.

Bubble generation is achieved by use of a surgical syringe machined to remove the tip. It is mounted as shown in figure 1 directly onto the test plate surface. The bubble is released by pressing a plunger connected to the syringe via rubber tubing.

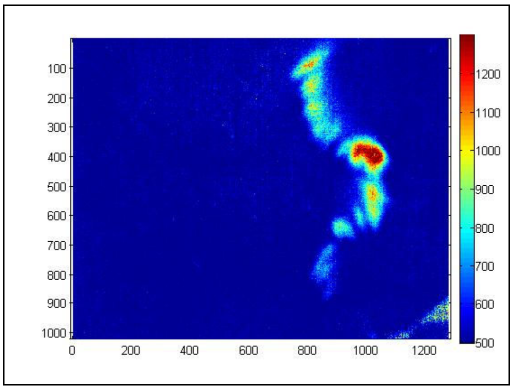
Two NAC Hi-Dcam II digital high-speed colour cameras capable of recording at frame rates of up to *20000 fps* and at image resolutions of up to *1280 x 1024* pixels per frame were used in these experiments. One camera observes the liquid crystal layer, the other the bubble motion. Both cameras are PC controlled via the manufacturer's PCI card which allows synchronisation of the recordings meaning both heat transfer and bubble flow can be analysed simultaneously. Although each camera is capable of recording images at very high frame rates, for these experiments frame rates of *125 fps* were deemed suitable for both the liquid crystals and the bubble motion due to the dynamic response of the system.

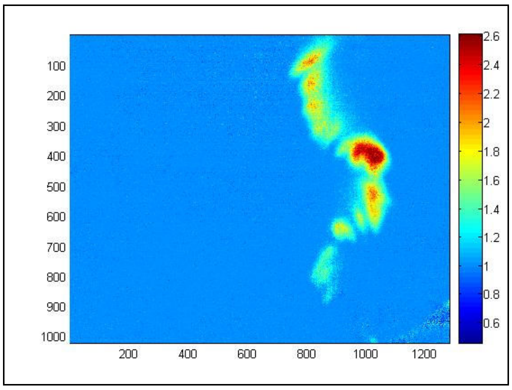
ANALYSIS

The foil is heated to the clearing point of the liquid crystals, *40°C,* through resistive heating. The supplied power required to keep the foil at this temperature is dependent on the natural convection flow conditions and therefore on the angle of the surface. The bulk water is maintained at approximately *25°C* throughout the tests. A bubble is introduced to the flow at the plate surface and slides along the plate through the test area (see figure 1). This causes local regions on the plate surface to cool and thus the liquid crystals change colour passing through the full colour range before the lower temperature limit is reached. Any temperature measurement above or below the limits, or bandwidth, is not possible and the temperature in such regions is replaced with a minimum or maximum value of *28°C* and *40°C* respectively. Images of the liquid crystal layer are recorded at *125 fps* with an exposure time of *0.017s*; they are then stored for further analysis. Figure 3 (a)-(d) below illustrates the conversion of the raw images to temperature maps using hue based calibration curve.



(a) Photographic image of test surface **(b) Conversion to temperature map**





(c) Conversion to heat transfer coefficient map **(d) Conversion to enhancement map**

Figure 3 (a)-(d): Data Conversion

These temperature maps are then used to calculate the heat transfer coefficient maps, calculated by dividing the heat dissipated from the foil by the surface to bulk water temperature difference.

$$h = \frac{q''}{\Delta T} \tag{1}$$

The heat transfer enhancement factor, ε is defined as the ratio of the forced convective heat transfer coefficient measured during bubble passage to that measured under natural convective conditions for each angle of inclination of the plate.

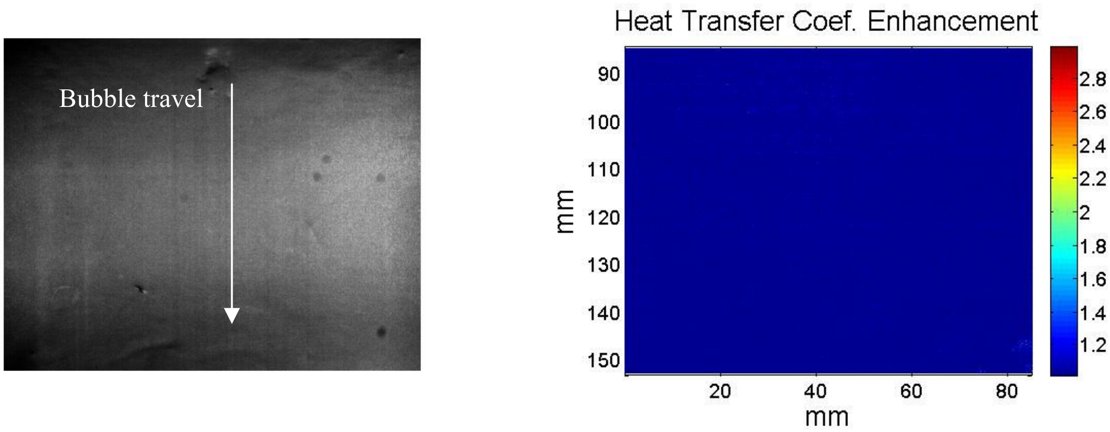
$$\varepsilon = \frac{h_{bubble}}{h_{NatConv}} \tag{2}$$

RESULTS AND DISCUSSION

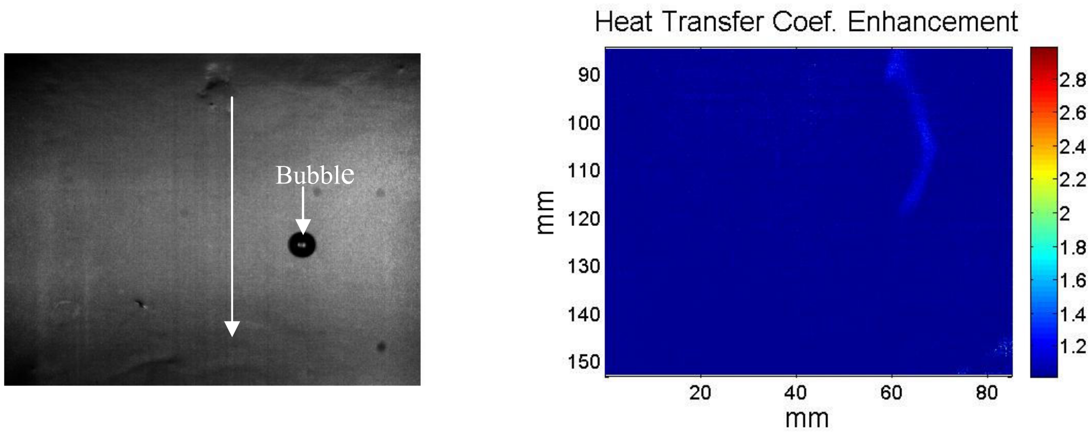
Results are presented of bubble position synchronised with heat transfer coefficient enhancement maps of the same surface area for plate angle, α, of 10, 20 and 30°. The bubble size in each test is approximately 4mm. The reference time, t, is measured from when the bubble first enters the image frame.

Plate inclination angle: 10°:

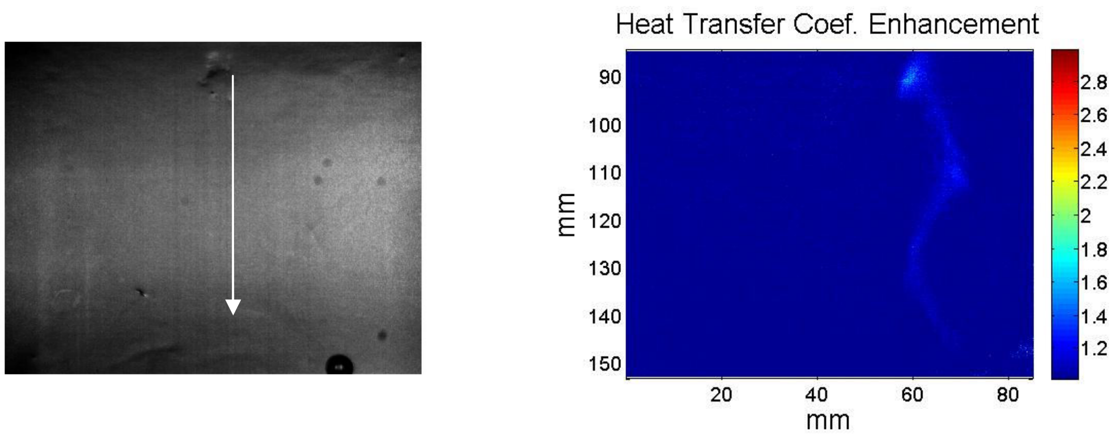
The test plate angle is set to 10° with respect to the horizontal. The foil is dissipating 130 W of power which heats the foil surface to 40°C, the clearing point of the liquid crystals. A bubble is released onto the surface of the inclined plate and travels approximately 85mm before entering the frame. The bubble travels from top to bottom of the recorded image. Bubble position and subsequent heat transfer enhancement plots are presented below (see figure 4 (a)-(e)).



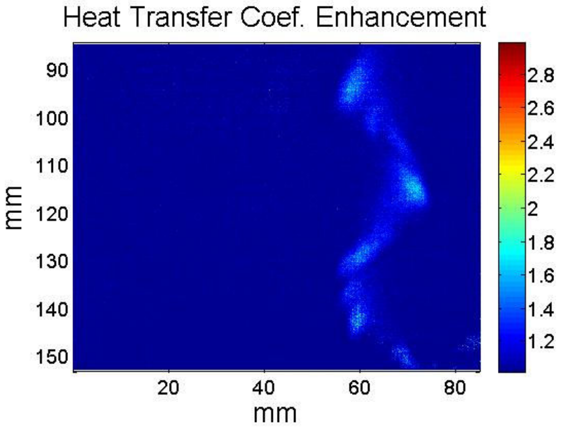
(a) t = 0 s



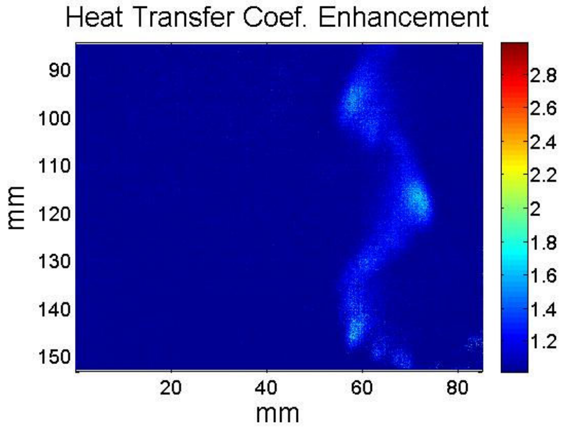
(b) t = 0.32 s



(c) t = 0.48 s



(d) t = 1.04 s



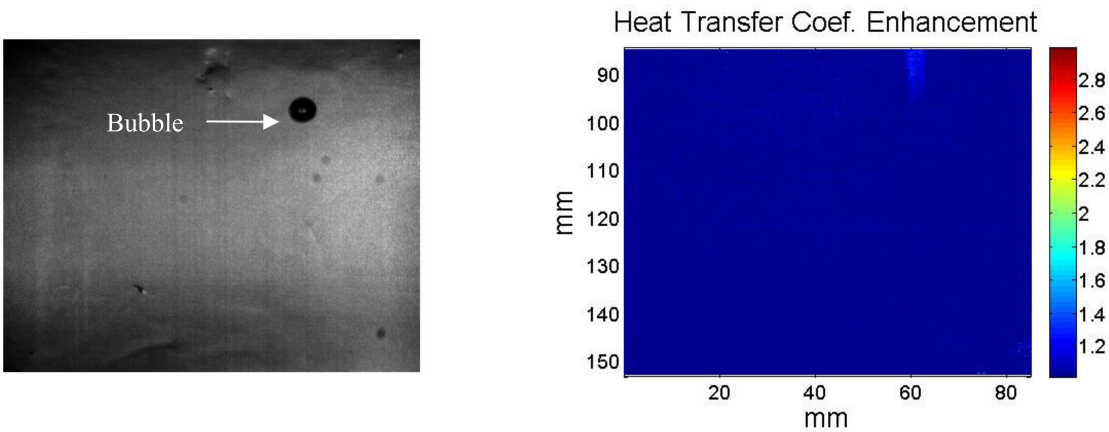
(e) t = 1.54 s

Figure 4 (a)-(e): Heat transfer and bubble flow plots for plate inclination angle of 10°

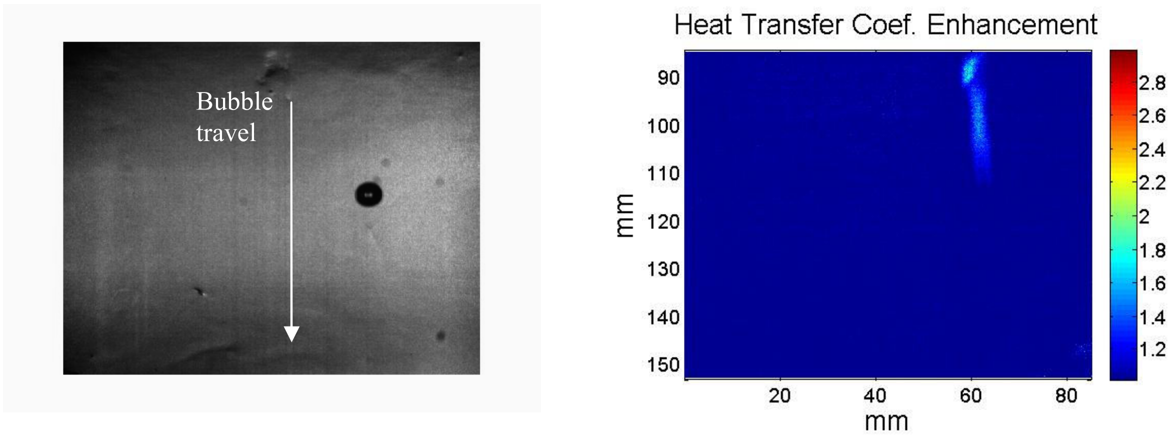
Before the bubble enters the frame the foil is transferring heat by natural convection alone, therefore enhancement factors of 1are shown for the entire test area (figure 4 (a)). At t = 0.32 s the bubble has travelled approximately 40 mm along the foil. The corresponding heat transfer coefficient enhancement map reflects this (see figure 4 (b)), indicating that the bubble immediately begins to cool the plate directly below where it has travelled. Enhancement factors of approximately 1.5 can be seen in figure 4 (b) concentrated in a small area directly below where the bubble has travelled. Figure 4 (c) shows the bubble as it is about to leave the frame. The corresponding heat transfer plot clearly shows the zig-zag motion of the bubble which is expected for low angles of plate inclination, as will be discussed in a later section. Once the bubble has left the frame, the extent of heat transfer enhancement and the area over which it is observed increases (figure 4. (d)&(e)). Since the bubble has left the area of interest, the heat transfer enhancement observed can be attributed to the wake of the bubble, the motion of which is described by Manickam and Dhir [8]. Heated water on the surface is moved away by the bluff body motion of the bubble and replenished by cooler water drawn in from the surroundings by wake of the bubble. Enhancement factors of approximately 1.8 can be seen in localised regions with the majority of the bubble wake at 1.5. The area over which this enhancement can be seen is larger now than when the bubble was in frame. This indicates that the turbulent mixing within the bubble wake is responsible for most of the heat transfer enhancement. The duration of these effects is discussed and compared in a later section.

Plate inclination angle: 20°:

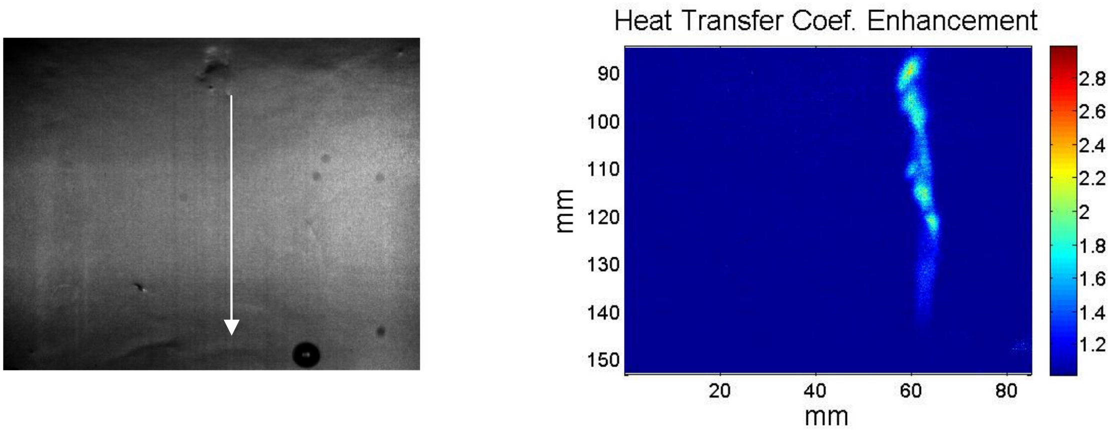
The test plate angle is increased to 20° to the horizontal and the power adjusted to maintain a surface temperature of 40°*C*. Bubble position and corresponding heat transfer plots are presented below (see figure 5 (a)-(g))



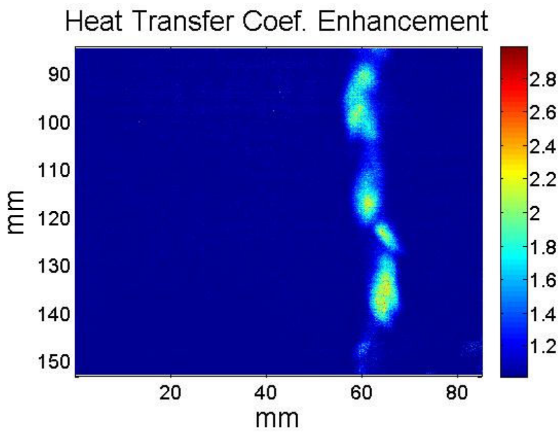
(a) t = 0.08 s



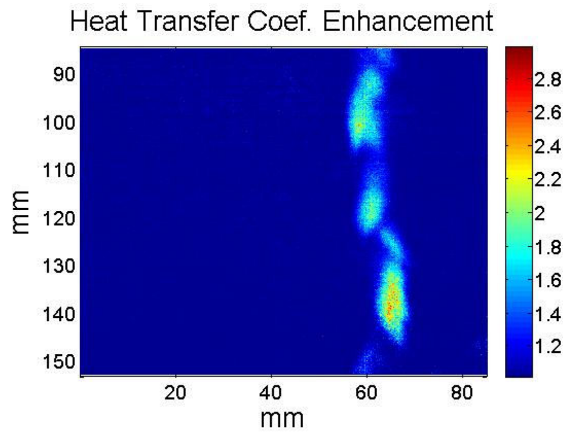
(b) t = 0.16 s



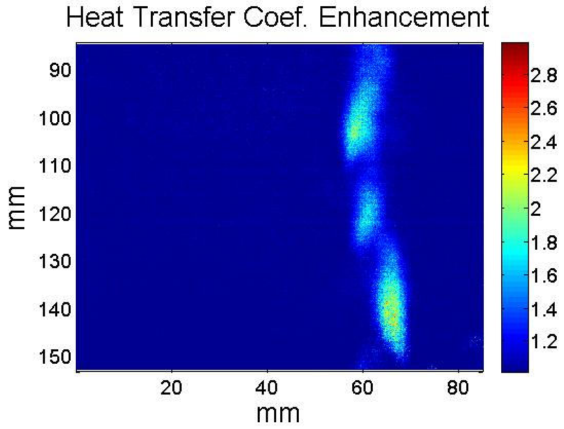
(c) t = 0.32 s



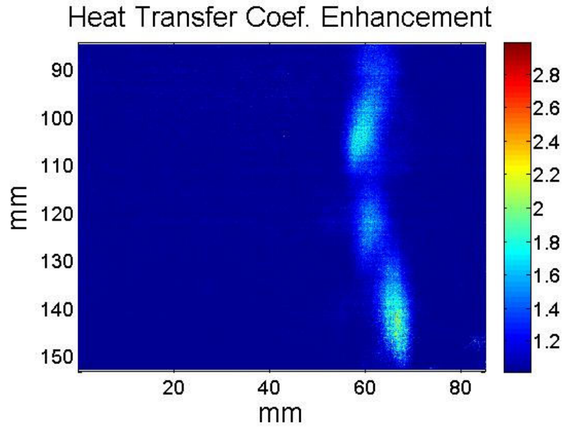
(d) t = 0.64 s



(e) t = 0.88 s



(f) t = 1.36 s



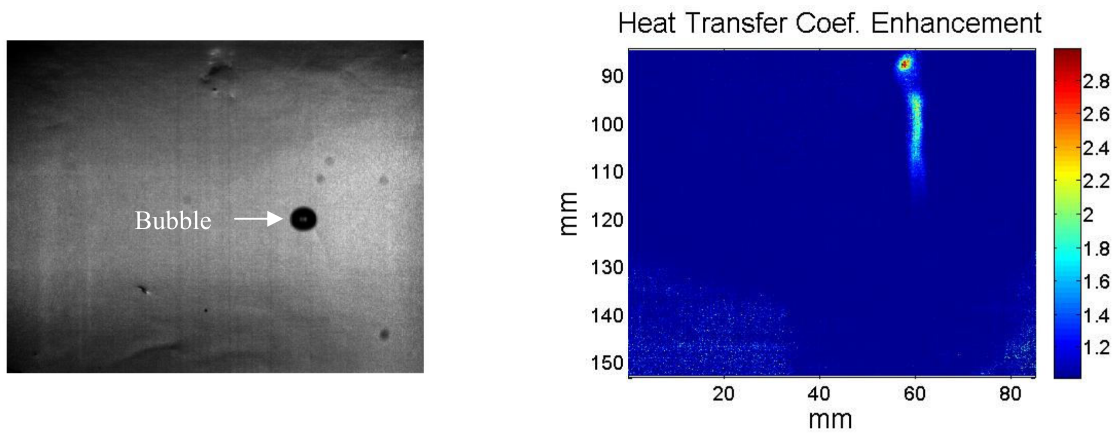
(g) t = 1.84 s

Figure 5 (a)-(g): Heat transfer and bubble flow plots for plate inclination angle of 20°

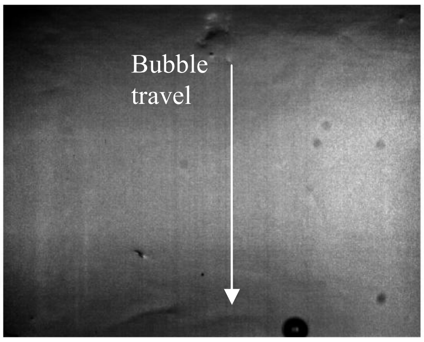
Figure 5 (a)-(c) show similar results to the 10° tests where heat transfer enhancement is confined to the area directly below where the bubble has travelled but, in this case, enhancement factors of approximately 2.2 can be seen in localised regions. These areas of relatively high enhancement factors expand over time as seen in figure 5 (d)&(e) reaching a maximum of approximately 2.4. Once again the bubble has already left the test area and the enhancement observed can be attributed to the elevated mixing in the wake of the bubble. The bubble has a much straighter trajectory than that of the 10° bubble, as reflected in the heat transfer plots presented above where the enhancement zone follows a straight path (see figure 5 (d)). The bubble in this case is travelling faster than in the 10° test due to the increased angle of the plate. This elevated velocity causes more vigorous mixing of the water resulting in higher heat transfer enhancement factors and longer duration of effects. Approximately 1.2 seconds after the bubble enters the frame enhancement effects begin to recede back to natural convection levels (see figure 5 (f) and (g)), although some enhancement persists for several seconds (see Table 1)

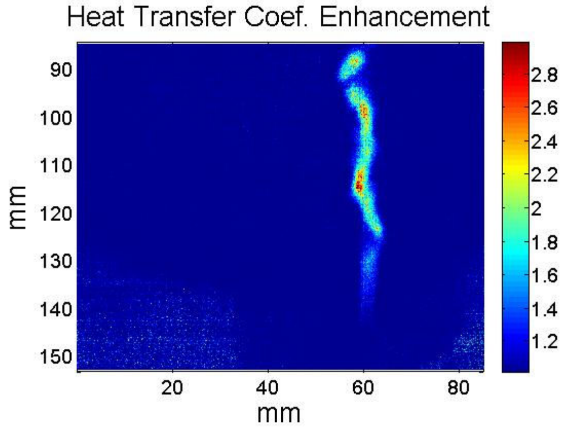
Plate inclination angle: 30°:

The test plate is elevated to an angle of 30° to the horizontal and again heated to 40*°C*. This requires 244 *W* of power. Presented below are the results for 30° (figure 6 (a)-(d)).

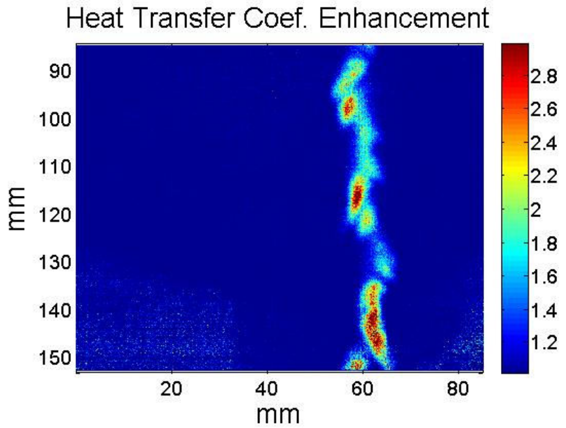


(a) t = 0.12 s

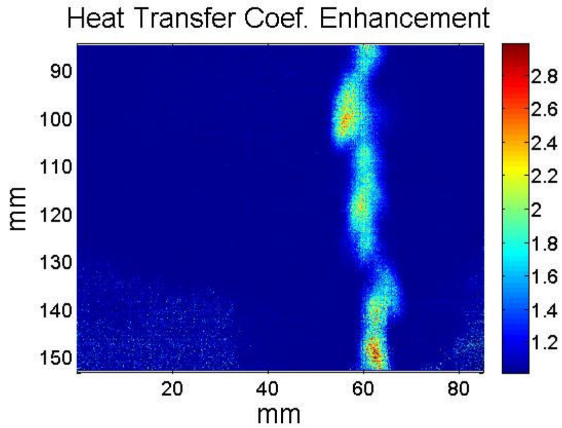




(b) t = 0.24 s



(c) t = 0.52 s



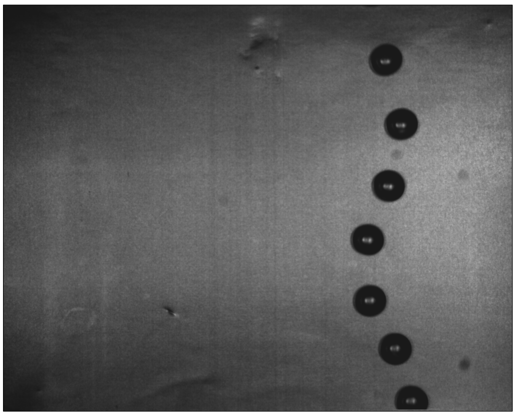
(d) t = 1.00 s

Figure 6 (a)-(d): Heat transfer and bubble flow plots for plate inclination angle of 30°

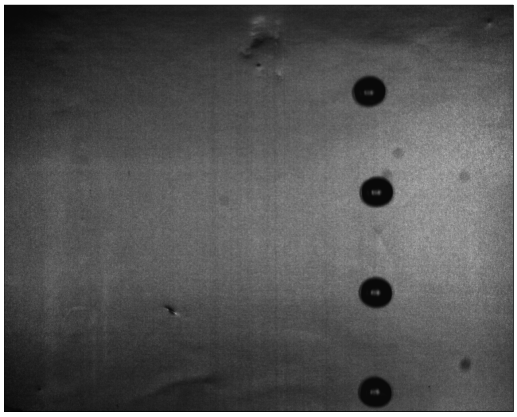
Figure 6 (a)&(b) follow the same general trend as before (with the 10° and 20° tests) but far higher enhancement factors can be seen. Small localised areas show factors of 2.7 with the surrounding area generally at 1.8. This much higher heat transfer can once again be attributed to the velocity of the bubble. The path of the bubble is relatively straight, as in the 20° tests. With increasing test plate angle, both the extent of heat transfer enhancement and the area over which it acts increases. Figure 6 (c) shows three localised areas with an enhancement factor of 3 or greater (restricted by the lower temperature limit of the liquid crystals) surrounded by a much larger area with an enhancement factor of approximately 2. Around 1.0 s after the bubble enters the frame the larger enhancement effects begin to recede back to natural convection levels but the overall duration lasts longer than the tests at lower angles (see Table 1).

Bubble Dynamics:

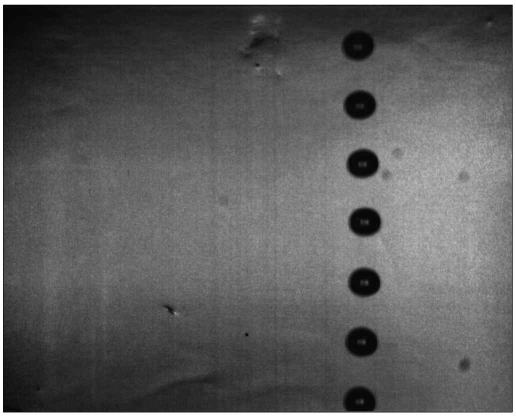
Compiled images of the bubble motion over the test area are presented below (see figure 7 (a)-(c)). These images are obtained by overlapping successive images of the bubble maintaining a constant time separation for each individual composition. They aid in understanding the velocity and path of the bubble.



(a) Bubble dynamics for 10° plate inclination angle



(b) Bubble dynamics for 20° plate inclination angle



(c) Bubble dynamics for 30° plate inclination angle

Figure 7 (a)-(c): Bubble Dynamics

In all images the bubble travels from top to bottom of the frame. A time separation of 0.04 s is used for the 30° test and 0.08 s for the 20° and 10° tests. The effects of increasing angle on both bubble path and velocity can clearly be seen from these images (figure 7 (a)-(c)). At low angles, such as the 10° test, the bubble can be seen to follow a wavy zig-zagging path. Due to this low angle the bubble travels relatively slowly compared to the 20° and 30° tests (see Table 1). This lower velocity can be linked to the lower enhancement factors observed above (figure 4 (d)); at slower velocities the bubble causes less mixing with the bulk fluid. When the plate angle is increased to 20° there is a marked increase in the average velocity of the bubble, this is evident from the larger spacing between bubble images in the 20° test compared to 10°.

Table 1: Plate angle vs. enhancement duration, in frame time, average velocity and enhancement zone

Plate Angle, α (°)	10	20	30
Duration of bubble enhancement, (s)	4.72	6.16	6.47
Bubble ‘in frame’ time, (s)	0.496	0.24	0.216
Bubble Avg. Velocity, (mm/s)	96	184	204
Enhancement Zone, (m^2)	$1.94x10^{-4}$	$2.89x10^{-4}$	$5.07x10^{-4}$

It can also be seen that the path of the bubble becomes straighter as the angle increases. This trend continues for the 30 degree test as shown in figure 7 (c) with both the average velocity increasing and the bubble path straightening further. Average velocities for the bubble in each test are presented in Table 1. This is calculated by summing the individual distances between bubbles in each compilation and dividing by the ‘in frame’ time (i.e. the time from when the centroid of the bubble first enters frame to when it leaves). From these tests it is clear to see that the increase in angle leads to a substantial increase in the bubble velocity and heat transfer enhancement.

As mentioned previously, increasing the plate angle leads to an increase in the duration of the enhancement effects (see Table 1 above). The results shown were obtained by calculating the average duration of enhancement from three tests at each of the three different angles. The enhancement duration is defined as the time it takes from first signs of enhancement to when the plate returns to natural convection heat transfer alone. The duration of enhancement is strongly dependent on the velocity of the bubble, therefore at higher plate angles, longer enhancement duration can be expected.

Although the enhancement level and the duration of enhancement are important parameters, the area over which the enhancement effects are observed is also important. The combination of these three factors determines the increase in thermal energy transferred to the fluid due to the bubble. For each angle, an image was chosen which contained the highest affected area for that test; the extent of the enhancement zone was then calculated. The results are tabulated in Table 1 above. A threshold value of a minimum of 10% increase over natural convection levels was maintained.

From Table 1 it is clear that increasing the plate angle leads to an increase in the area over which enhancement can be seen. Thus, for the same energy input (bubble generation and injection in this case), the interaction with a slightly different geometry can lead to very different heat transfer enhancement. This finding may help in exploiting bubble induced heat transfer enhancement in the future.

CONCLUSIONS

An experimental study has been conducted of flow dynamics and heat transfer for a bubble sliding along a heated inclined surface. The main conclusions of this research are detailed below:

- Increasing plate angle leads to higher sliding bubble velocities. Bubble velocity fluctuates significantly at low angles of inclination (10°)
- The oscillating motion of the bubble path reduces with larger angles of inclination
- The bubble wake is responsible for most of the heat transfer enhancement
- The area showing elevated heat transfer increases with higher inclination angle as does the duration and extent of the enhancement

The next phase of this research will focus on whole field fluid velocity measurements in order to gain better understanding of this heat transfer enhancement mechanism.

Acknowledgments

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