Jet Flow Behavior Observed during Microgravity Boiling

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Abstract

A thin wire, subcooled boiling experiment was performed onboard an aircraft flying a parabolic trajectory as a means to provide microgravity conditions. Microgravity allows for improved observation of jet flow phenomena and the ability to investigate their behavior in the absence of buoyant forces. A new mode of jet flows was observed in microgravity which accounts for the high heat fluxes measured on the wire heater. A relative bubble area analysis method was able to quantify vapor production and bubble behavior across multiple frames of video. A cross-correlation calculation similar to particle image velocimetry (PIV) provided velocities of the micro-bubbles in the flow. These micro-bubble jet flows and the convection currents they induce have the potential to allow for sustained boiling to occur in microgravity at high heat fluxes.

1. Introduction

Because of the high heat transfer rates associate with boiling, it is used in many energy production and thermal management systems. Although correlations based on experimental studies have been developed for practical application of boiling heat transfer, these correlations are limited in their scope to thermal systems that are similar to the experiment they were based upon. Additionally, these correlations are unable to provide a prediction of what the boiling behavior would be for a new system and are unable to capture the many nonlinearities and complex interactions that exist in boiling. An example of this is shown in Rohensow’s widely used pool boiling nuclease boiling correlation, Eq. (1) [1,2], which predicts the heat flux dissipated during boiling based on thermal responses of the fluid and buoyant forces.

\[ q''_s = \mu_l hfg \left[ g(\rho_l - \rho_v) \right]^{1/2} \left( \frac{c_p \Delta T_v}{C_{fg} \rho_f} \right)^3 \] (1)

Application of Eq. 1-xx in a microgravity system predicts that the heat flux \( q'' \), heat per unit area, dissipated by boiling heat transfer approaches zero as the gravity force approaches zero. Many experiments [3-5] have shown that this is not the case. Therefore, a predictive model that incorporates the mechanisms involved in boiling would be much more useful than an empirically-based correlation. Dhir [6] has found success in the use of numerical simulations to predict boiling in a few instances [7-12], but he concludes that there is a need for further study to understand the physical processes involved in boiling. This paper examines the behavior of a physical process called jet flows in a microgravity environment, where buoyant forces are removed.

Jet flows are bubble behaviors that often exist during subcooled boiling, where the bulk temperature is below saturation temperature. Surface tension gradients along the bubble face, due to
temperature variations between the heated surface and the subcooled surface, result in flow along the vapor-liquid interface, referred to as Maragoni, or thermocapillary, convection. This flow causes oscillatory, localized destruction of a metastable, superheated boundary layer [13], which can form a jet flow.

Wang has characterized several different modes of jet flows [14]. The high-energy liquid jet occurred when a thin wire was placed in a pool of liquid ethanol at 23 °C (55 K subcooling) and a current of 2.07 A was passed through the wire, resulting in a heat flux of 300 kW/m². Although no bubbles generated from nucleation sites, a flow of high energy liquid was observed to depart from the wire and disappear after 1-3 mm into the bulk fluid. The fog-like jet was observed within liquid ethanol at atmospheric pressure 45 °C (33 K subcooling) and at an applied current of 4.5 A, resulting in a heat flux of 1,000 kW/m². Fog-like jet structures that had no distinct bubble-form generated from active nucleation sites, spraying from site and disappearing at a distance of 7 mm from the wire heater. The cluster-like jet was observed at bulk fluid temperatures near saturation and at a heat flux of 800 kW/m². The jet flow was characterized by small liquid masses that absorbed a significant amount of heat but did not nucleate into vapor bubbles. Additionally because the bulk fluid was near saturation temperature, the flows did not condense like the high-energy liquid jet did.

Further work by Wang’s colleagues [15,16] characterized additional, more stable modes of jet flows. The most significant mode is the bubble-top jet, which forms at the top of small bubbles on the wire. This mode existed when the level of subcooling was greater than 30K and was characterized by a semi-transparent jet of fluid at the top of a bubble that penetrated deep into bulk fluid. This mode of jet flows is caused by the pumping effect of the growing bubble and [17], which causes the bubble to pump the fluid in its vicinity towards the top of the bubble and out into the fluid at velocities of 10-150 mm/s. When the bubble that participated in the bubble-top jet flow grew to a size comparable to the wire, a new multi-jet flow was observed. In this jet flow, two jets flow out from the interface of the wire and the bottom of the bubble, resulting in a butterfly-like structure. Velocities of this mode of jet flow were 30-160 mm/s. [18].

Lu [19] characterized a final mode of jet flow called the small, explosive bubble boiling. This mode was observed at heat fluxes greater than 2,000 kW/m² and was characterized by small vapor bubbles with a diameter of about 10 µm that departed from the wire. As the heat flux was increased, fewer jet flows formed, the diameter of the bubbles increased, and the frequency of departure increased. The current study characterizes a similar jet flow mode, called micro-bubble jet flow, that is characterized by larger vapor bubbles, a different form of the jet flow, and self-organization of the jet into combined flow.

To study fluid velocities, traditional use of particle image velocimetry (PIV) involves a light sheet from a pulsed laser, a high speed camera, and tracer particles to match the motion of the fluid in question. Use of this method in boiling research has resulted in velocity data for bubble growth and departure [20] and the development of bubble-top jet flow [21,22]. Additionally, traditional PIV has been used to verify numerical models of bubble sweeping flows and the jet flows they trail [23,24]. Velocities of the fluid pumped by this jet flow were on the order of 10-140 mm/s [21,25], while the velocity of the bubble sweeping along the wire was lower, 20-50 mm/s [23]. In boiling experiments,
bubbles can be directly visualized instead of additional tracer particles, and the resulting cross correlation computation represents bubble velocities, which may or may not represent fluid velocity depending on the size of bubbles and buoyancy effect. However, little work has been done to investigate the fluid motion of other modes of jet flows by means of traditional PIV or by a bubble image velocimetry. This could be due to the inability of tracer particles to accurately mimic these flows or the sensitivity of different jet flow modes to lighting conditions. The term PIV is used in the remainder of the paper to represent bubble image velocimetry, where the bubbles are cross correlated between frames of video.

The current study discusses a method based on a DaVis 7.2 PIV algorithm for the approximation of jet flow velocities of some of these other jet flow modes, which has not been investigated in the literature. Through the use of PIV, a relative bubble area analysis, and visual observations, the characterization of a new jet flow mode is made.

2. Experimental Setup

Two different sets of experiments, the first being a free float experiment and the second attached to the floor of the plane, were flown on an aircraft flying a parabolic trajectory. Each experiment used identical fluid chambers to provide similar initial conditions for boiling on thin wires. The free float experiment used fifteen of these fluid chambers where one-third contained a single 130 µm diameter platinum wire, another third contained a twist of three 76 µm diameter platinum wires, and the final third contained a twist of four 51 µm diameter platinum wires. The attached experiment used twenty fluid chambers where half contained a single 130 µm diameter platinum wire and the other half contained a twist of three 76 µm diameter platinum wires. All wire geometries are shown graphically in Figure 1a and the diameter of each wire was chosen to produce cross sections with similar areas and comparable resistances (±8%). Each wire was 1 cm long and was connected to the ends of two stainless steel rods by means of electrical terminals, which pinched the wires at the ends. These stainless steel rods protruded into the fluid chamber from the instrument panel and provided electrical power and structural support for the wire heater (Figure 1b). This instrument panel also had a ladder of four Type T thermocouples located below the heating wire to provide initial bulk temperatures and to measure the thermal response of the water away from the wire. Each fluid chamber contained 164 mL of deionized water that was degassed through boiling under a vacuum prior to the filling of the fluid chamber. Polycarbonate walls, an O-ring, and epoxy seals allowed for flexing of the sidewalls to reduce the effects of internal pressure changes because of vapor formation.
During each microgravity parabola, the free float experiment tested three fluid cells, each with a different wire geometry, while the attached experiment tested two fluid cells. Operation of each experiment was the same and followed the schematic shown in Figure 1c. The data acquisition system would select one of eight pre-programmed constant current levels, which would then provide power from separate DC power supplies to each of the wire heaters. Voltage and current measurements of the wire heater were taken at approximately 10,000 Hz, with the average and standard deviation being recorded every 10 ms. Pressure and accelerometer measurements were taken in the same manner and resulted in an ambient pressure of about 82 kPa and an average acceleration near $10^{-2}$ g. Figure 2 shows a typical acceleration profile for the microgravity portion of the plane’s parabolic arc. Thermocouple measurements were taken at 75 Hz. Two orthogonal, high definition cameras provided image capture for each fluid cell, and through use of magnifying lenses, a pixel resolution of 14 $\mu$m x 14 $\mu$m was achieved.
The free floating experiment (Figure 1d) used two diffused red LEDs and one harsh white LED to provide a balance between visibility of both isolated bubbles and jets flows. Additionally, heat fluxes experienced by this experiment are in the low to medium range (500 to 1,200 kW/m²). To compare the effect of lighting on jet flow visualization and to provide higher heat fluxes, the attached experiment (Figure 1e) used a single harsh white LED light and experienced heat fluxes from 500 to 5,100 kW/m², at which point burnout occurs on the single wire. One of the issues with determining the average heat flux of each wire geometry is that the heat flux is not axisymmetric for the twisted wire geometries because of localized heating in the crevices. To take this into consideration, the heat flux for the three-wire geometry was calculated based on the external surface area of the three-wire twist, which is 5/6 of three separate cylinders, to exclude the area in the crevice. Similarly, the four-wire geometry was treated as four separate cylinders and then multiplied by 3/4. The unique surface geometry of the three-wire causes a lower heat flux to be dissipated for the same applied current.
3. Results and Discussion

3.1. Jet Flow Characteristics

Visual observations made by high definition cameras allowed the development of the micro-bubble jet flow to be captured across multiple frames of video. Figure 3 shows the development of several of the micro-bubble jet flows on the top, middle, and bottom of the wire. The micro-bubble jet flow is characterized by the departure of small vapor bubbles, on the order of 100 µm, directly from the wire. Multiple columns of these small bubbles form on a 1-2 mm long region of the wire. Farther away from the wire and as time passes, the columns combine and depart from the wire with a combined jet diameter of 3-4 mm. This combined jet diameter is in contrast to the thin plumes that are seen above bubble-top jet flows observed during this same experiment, which are on the order of tens of microns. It is expected that the velocities of the micro-bubble jet flows are lower than what has been reported for other types of jet flows [21-25] because of the larger diameter of the combined jet flows and the flow consisting of a liquid and vapor cloud. The microgravity environment allows the combination of jet flows into the bulk fluid to be seen when buoyancy effects would obscure these self-organized flows. Additionally, the three-wire geometry is observed to form micro-bubble jet flows more readily than the single wire. During the few instances when micro-bubble jet flows were observed on the single wire, the bubbles were smaller and less visible, similar to Lu’s observations, and the flows did not combine and self-organize like the flows observed on the three-wire.

Figure 3 - Development of micro-bubble jet flow after initiation of boiling
Additionally, visual observations show that at higher heat fluxes, the micro-bubble jet flow mode begins to dominate the bubble behavior on the wire. This behavior is seen in Figure 4a where micro-bubble jet flows are seen to exist along the entire length of the wire, and Figure 4b provides an animation of the jet flow departing in multiple columns of bubbles from a region of the wire and combining into a larger flow. At higher heat fluxes, the departure of vapor bubbles is more frequent and isolated bubbles cease to be present on the wire. However, as the heat flux approaches the critical heat flux of the system and the wire is in danger of burning out, isolated bubbles begin to form again (first frame of Figure 5). These bubbles begin to insulate the wire locally, causing the wire to increase in temperature until the melting temperature of the wire is reached and the wire burns out (middle frames of Figure 5). Burnout occurred on the single wire geometry at a heat flux of 5,100 kW/m² but was not observed on the three-wire geometry. At the highest heat flux experienced by the three-wire (2,800 kW/m²) and near the critical heat flux of the single wire, micro-bubble jet flows and isolated bubbles were both present.

Figure 4 - Image showing micro-bubble jet flow dominant behavior on wire (a) and an illustration of the behavior of the micro-bubble jet flow (b)

Figure 5 - Burnout of wire at critical heat flux after isolated bubbles reappear on the wire
3.2. Bubble Image Velocimetry – Methods and Results

In traditional particle image velocimetry (PIV), the basic setup consists of a pulsed laser to reduce particle blurring between frames, optics to turn the laser beam into a laser sheet to represent a plane of flow, micron-sized tracer particles to visualize but not interfere with the flow of interest, and a high-speed camera to capture sequential images of the flow and tracer particles. The digital images (Figure 6a) are subdivided into smaller interrogation windows (Figure 6b-c), and the interrogation window of the first image is cross correlated with the corresponding interrogation window of the second image. Cross-correlation is a statistical method that basically multiplies the numerical values of each pixel in the images as the two images are “slid” past each other in every direction. The result is a correlation peak (Figure 6d) and the distance and direction this peak is in reference to center of the interrogation window represents the displacement of the tracer particle. This displacement vector is then divided by the amount of time that passed between the two images to represent the velocity of the tracer particle and the fluid flow at that location [26].

Figure 6 - Description of PIV process. Digital image (a), interrogation windows (b), pixel values in interrogation window (c), and correlation peak showing motion of particle (d)
A cross correlation calculation similar to PIV was used to approximate the velocity of the vapor bubbles in the micro-bubble jet flow. In this bubble image velocimetry, the small vapor bubbles become the portions of the images that are tracked across the frames, rather than tracer particles. These bubbles are made visible by use of a harsh LED light, rather than a pulsed laser, lower frame rate cameras, and the microgravity environment. To isolate the vapor bubbles in the image, the frames of video are averaged and the background subtracted. These grayscale images are then analyzed in a two pass pattern of interrogation windows of sizes 128x128 pixels and 32x32 pixels. Although there are issues by assuming planar flow to allow for cross correlation, the results of this method agree within ±2 mm/s according to manual vapor bubble tracking. Typical velocities of these micro-bubble jet flows are on the order of 4 mm/s to 14 mm/s and contour maps of the fluid velocity are able to show the structure of the jet flow at different times (Figure 7). Each structure shows the combined micro-bubble jet flow in the bulk fluid, and this combined flow can cause convective currents in the bulk fluid that would not normally be present. This convective flow in microgravity is important because it can compensate for the lack of buoyant motion and aids in vapor removal from the wire.

Figure 7 - Jet flow structures shown through PIV method. Single, combined jet (a), jet formation after boiling onset (b), symmetric jet (c), two jets (d), dispersed jet (e), and single jet (f)
3.3. Relative Bubble Area – Methods and Results

While many boiling experiments record visual data, this data is often limited to qualitative observations, and there are few analytical methods for this visual data. Typically, relationships between heating element temperature measurements and bubble dynamics would come from bubble diameter or bubble number measurements, which can be difficult and timely to gather for multiple frames of video and multiple tests. Therefore, there exists a need for a method of data reduction to allow for the quick and accurate quantitative analysis of visual data to compare the effects of varying system parameters on bubble dynamics.

A new method of relative bubble area analysis has been developed to provide this quantitative analysis method. The method simply sums the number of pixels in an interrogation window that captures the wire and 2 mm of the surrounding water in a particular greyscale frame that have changed since a designated initial frame, while compensating for any shakiness in the video. This initial frame contains the pixel values for the background of the video and the formation of bubbles changes these values. To balance the presence of false negatives and false positives, a threshold value is used to decide how much a pixel value needs to be changed to be counted in the method. Because this method only counts the number of changed pixels, rather than searching for each bubble, it does not contain information on absolute bubble diameters or bubble counts. Rather it provides a measure of how much bubble area is present relative to other tests and is can be viewed as an approximation of the volume of vapor formed. Equation (2) provides a description of the algorithm used in the relative bubble area analysis, for reference.

\[
[\text{Frame}]_{ij} - [\text{Frame}]_{ij}^{\text{initial}} \begin{cases} > \text{threshold}, \text{count pixel} \\ < \text{threshold}, \text{ignore pixel} \end{cases} \tag{2}
\]

The threshold value for the current study was chosen to be 45 and reduced the number of pixels that are counted along the thermocouples to the left of the wire. Figure 8b shows the changed pixels of a representative frame from the video for a heat flux of 520 kW/m² experienced by the single wire, while Figure 8a shows the initial frame used in the relative bubble area analysis method. Use of this method allows the vapor behavior of an entire video to be represented in a single graph and the effects of system parameters to be compared across different sets of data.
Application of the relative bubble area method to videos from the free floating experiment showed a transition over time, where the dominant form of vapor bubbles transitions from isolated bubbles shortly after boiling was initiated to jet flows after boiling has occurred for about 10 s. This behavior is shown by the slashed line of the single wire in Figure 9, where the percentage of changed pixels decreases as time passes. This is due to the development of jet flows which are not visible due to the diffused lighting of the free floating experiment. Because the flows are not visible, they do not contribute to the relative bubble area, resulting in the drop. In this way, the relative bubble area method is able to capture the time-based transitional behavior of jet flows. However, the length of time that this transition takes means that there is some unknown transient behavior causing this bubble transition. The wire heater’s thermal response cannot explain this transition because it has a relatively short transient behavior. Additionally, Figure 9 shows that the twisted wire geometries can exhibit different bubble behaviors than the single wire.
As mentioned above, the diffused lighting of the free floating experiment decreased the visibility of jet flows on the wire, which affected the relative bubble area. The attached experiment used harsh LED lighting to illuminate jet flows and resulted in a different response in relative bubble area. Figure 10a shows what the relative bubble area of isolated bubbles looks like, while Figure 10b shows what the relative bubble area of jet flows looks like during the attached experiment. Results from the free floating and attached experiments show that lighting can be manipulated to either illuminate or obscure jet flows, and that the relative bubble area method can be used to capture different bubble behavior for both lighting configurations. This aids in the characterization of the micro-bubble jet flow being composed of bubbles about 100 µm in diameter departing in multiple columns from a region of the wire.

Figure 10 - Relative bubble area for attached experiment showing isolated bubbles (a) and jet flows (b)
Additionally, the relative bubble area method’s ability to compare bubble behavior across system parameter variations was able to observe a heat flux-based transition during boiling. Figure 11 shows the relative bubble area results for all microgravity tests performed with the single wire during the free floating experiment. Line 1 represents a heat flux where boiling did not occur and the relative bubble area registered changed pixels for heat distortion caused by superheating of the fluid near the wire. As the heat flux increases, lines 2 shows an increase in relative bubble area as the growth of isolated bubbles is captured, and the relative bubble area reaches a maximum at line 3 where large, isolated bubbles have formed along the entire wire. Due to diffused lighting, the relative bubble area decreases for lines 4 and 5 as jet flows form but are not counted by the method. In this way, bubble behavior is shown to be dominated by isolated bubbles at low heat fluxes (Figure 11, lines 2-3) and by jet flows at higher heat fluxes (Figure 11, lines 4-5).

Figure 11 - Relative bubble area results for increasing heat fluxes 1-5
4. Conclusions

Analysis of both microgravity experiments have led to the following conclusions:

- A new jet flow mode was observed, called the micro-bubble jet flow, which is characterized by small, 100 µm diameter sized bubbles departing in multiple columns from the wire. The columns combine together to form a jet flow with a diameter of 3-4 mm, and penetrate tens of millimeters into the bulk flow with a velocity of 4-14 mm/s.
- Combined micro-bubble jet flows were able to induce fluid motion in the bulk fluid.
- Cross correlation calculations can be made using vapor bubbles as the tracer particles, in a bubble image velocimetry. This method is able to capture and track the development of micro-bubble jet flows and illustrate their effect on the bulk fluid.
- A relative bubble area analysis was developed, which was able to characterize the time- and heat flux-based transitions that occur in boiling systems that exhibit jet flows.

5. Acknowledgements

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Nomenclature

\[ q_s \] = heat flux at surface
\[ \mu_l \] = liquid viscosity
\[ h_{fg} \] = latent heat of vaporization
\[ g \] = gravitational acceleration
\[ \rho_l \] = density of liquid
\[ \rho_v \] = density of vapor
\[ \sigma \] = surface tension
\[ c_{p,l} \] = specific heat of liquid
\[ \Delta T_e \] = temperature difference between surface and bulk fluid
\[ C_{s,f} \] = constant
\[ Pr_l \] = Prandtl number of liquid

References


