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Surface Geometry and Heat Flux Effect on Thin Wire Nucleate Pool Boiling of Subcooled Water in Microgravity

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The motivation of this nucleate boiling research is to understand the effects of surface geometry and heat flux as applied to a thin wire heater. This will further the understanding of the fundamental behaviors of boiling onset, steady state heat transfer, and bubble dynamics with respect to nucleate boiling with the goal of creating efficient thermal management systems for future space applications. Using three different thin platinum wire geometries and five different power levels, subcooled water was boiled over a period of approximately 30 seconds for 15 parabolic arcs to simulate microgravity. To represent the trends in bubbles behavior across hundreds of frames of video in a single graph, a new method, named relative bubble area analysis, is introduced and used to analyze the results of the experiment. It was determined that the efficiency of steady state heat transfer via nucleate boiling in microgravity is comparable to, and in some cases more efficient than, steady state heat transfer in terrestrial applications. The three-wire geometry reduced the heat flux necessary to initiate boiling. Bubble dynamics show a transition from isolated bubbles to jets of small bubbles as heat flux increases. This can be confirmed both visually and with relative bubble area analysis. The implications of this research are that sustained convective heat transfer with subcooled water is possible in microgravity. A three-wire surface geometry was shown to initiate boiling at lower heat fluxes, which would provide minimal super heating of the surface, which is a result of the lack of convection, before boiling heat transfer could begin.

Nomenclature

$h_{\mu g}$	=	convection heat transfer coefficient in microgravity period
h_{1g}	=	convection heat transfer coefficient in 1-g period
T_{wire}	=	average wire temperature
T_{fluid}	=	bulk temperature of fluid
T_{sat}	=	saturation temperature of fluid
$\Delta T_{\text{sat,wire}}$	=	average wire temperature above fluid saturation temperature
ΔT_{sub}	=	subcooled temperature (bulk temperature of fluid below saturation temperature)
ΔV_{wire}	=	voltage difference across wire

I. Introduction

NUCLEATE boiling is used in a variety of terrestrial heat transfer applications due to its associated high heat transfer rates. The phase change process and the generation of highly dynamic, buoyancy-based, natural convection provide the ability to transfer more heat from smaller surface areas in relation to other forms of heat transfer. Currently large-scale power production utilizes boiling to transfer heat from an energy source to an

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electricity generating turbine. The use of boiling to cool electronic components is also becoming increasingly popular as electronics become denser and more capable. However, the current limited and empirically-based understanding of nucleate boiling dynamics in the absence of the dominant buoyant force prevents the development of systems with predictable boiling dynamics for space applications. Previous microgravity boiling research has produced apparently contradictory conclusions on boiling dynamics due to the use of a variety of working fluids, surface geometries, levels of subcooling, and heat flux. The main findings of these microgravity experiments are summarized below.

A. Onset of Nucleate Boiling (ONB)

The transition from natural convection (1-g) or conduction (0-g) to nucleate boiling is often studied to demonstrate the benefits of operating in the nucleate boiling regime. The dominance of conductive heat transfer in microgravity environments results in high surface temperatures according to Fourier's law until the onset of boiling is reached. It is therefore desirable for a microgravity thermal management system to operate in the nucleate boiling regime. The relations between working fluid, heat flux, surface geometry, gravity, and onset temperature are observed in order to predict when this transition will occur for various combinations of these parameters and what type of heat transfer conditions will exist.

Straub [1] studied the heat transfer efficiencies associated to various heat flux densities while boiling subcooled degassed R113 with a 0.2 mm diameter platinum wire aboard the TEXUS 3b sounding rocket. Under the lowest heat flux (17 kW/m²), the 0-g experiment boiled after reaching an onset temperature of $\Delta T_{\text{sat,wire}} = T_{\text{wire}} - T_{\text{sat}} = 34$ K and then dropped to $\Delta T_{\text{sat,wire}} = 18$ K after boiling was initiated. For the 1-g experiment under the same heat flux, natural, buoyancy-based convection adequately cooled the wire, preventing the transition to nucleate boiling. At the median heat flux density (39 kW/m²), the 0-g experiment continued to boil with a 5 K wire temperature increase from the previous heat flux level, resulting in a $\Delta T_{\text{sat,wire}} = 22$ K. The 1-g experiment still did not boil but the $\Delta T_{\text{sat,wire}}$ increased to 30 K, a 20 K increase from the previous level. The final heat flux density (77 kW/m²) produced boiling in both the 0-g and 1-g experiments. The 0-g experiment however showed a 6% increase in heat transfer coefficient when compared to the 1-g experiment. This experiment has shown that at certain heat flux densities, 0-g heat transfer can be more effective than the 1-g equivalent.

Straub [2] also performed an experiment on the TEXUS 5 sounding rocket. This experiment also boiled subcooled degassed R113 with a 0.2 mm diameter platinum wire. The onset superheated temperatures of the wires ($\Delta T_{\text{sat,wire}}$) varied heavily with gravity. The 0-g onset temperature was 25% more than the 1-g equivalent. This onset temperature difference was conjectured to be due to the fact that the fluid in proximity to the wire in the 0-g experiment was quite transient in its temperature prior to the onset of nucleate boiling. The 1-g experiment, however, had reached a steady state wire temperature due to the effects of natural convection well before boiling.

Zhao [3] utilized a temperature controlled pool boiling device to boil subcooled, degassed R113 with a 60 μm diameter platinum wire. The onset of nucleate boiling was noted by explosive boiling which occurred as soon as the heater temperature (T_{wire}) was increased to a higher set-point. This temperature set-point was the same for 1-g and 0-g, leading Zhao to conclude that the onset of boiling temperature is weakly dependent, or independent, of gravity.

These previous studies show that the ONB in microgravity is distinctly different than ONB in 1-g and often results in an enhancement to the heat transfer. However, they fail to specify the conditions and system parameters that determine the ONB. The current experiment aims to study the effects of wire geometry and power input on the onset of boiling by observing the heat flux required to transition from natural convection to nucleate boiling in 0-g and 1-g, the decrease in average wire temperature (T_{wire}) after the transition into boiling, and its associated explosion of bubbles along the heating element.

B. Heat Flux Effect on Steady State Heat Transfer

Once the threshold heat flux input is provided to initiate boiling, the efficiency of heat transfer can vary with the magnitude of the input heat flux and surface geometry, and is quantified in the heat transfer coefficient, h , given by Newton's law of cooling.

Straub [1] discovered that under a given heat flux, where both 0-g and 1-g experiments boiled, the 0-g wire temperature (T_{wire}) was actually lower than that of the 1-g. This lead Straub to conclude that the 0-g boiling was 6% more efficient than 1-g boiling. This is highly unexpected since the 0-g experiment is missing the seemingly major driving force of buoyancy.

In another experiment by Straub [4, 5], the enhancement of heat transfer in 0-g appears to be a function of heat flux and wire diameter. In this experiment, two platinum wires of 0.05 and 0.2 mm were used to boil saturated R134a. The 0.2 mm wire showed heat transfer enhancements of up to 10% for lower power levels which decreased with increasing heat flux. The 0.05 mm wire showed a nearly constant reduction of about 10% and eventually

burned out. Straub's [4] results also showed that 0-g boiling is either slightly enhanced or the same as a 1-g experiment for a given wire superheat temperature ($\Delta T_{\text{sat,wire}}$) but the efficiency did not seem to relate to power input.

Although Straub studied the effect of wire diameter and gravity level on steady state heat transfers with a set heat flux, there is still a need to confirm these results across different operating conditions. The current experiment seeks to resolve these issues by studying the effects of heat flux on the steady state heat transfer efficiency by observing the heat transfer coefficient for various power levels and surface geometries during steady state boiling of subcooled water.

C. The Effects of Surface Geometry on Heat Transfer

The surface characteristics of the heating element affect bubble generation and departure dynamics which, in turn, affects the heat transfer coefficient. As previously mentioned, Straub [4] showed that a smaller diameter wire was constantly more efficient at dissipating heat in 0-g than in 1-g, but a larger diameter wire was less able to withstand higher heat fluxes without wire burnout.

Fukada [6] studied the effects of calcium carbonate fouling on platinum wires of various diameters ranging from 0.01 mm to 0.2 mm. Saturated water was boiling with both bare wires and wires with a coating of calcium carbonate. The scaling on the wires created large discrete nucleation sites which prevented the coalescence of bubbles widely seen on the single wire. The bubble departure diameters from the scale wire were also relatively smaller. The bubble coalescence on the bare wires eventually led to the development of large engulfing bubbles which resulted in burnout. Therefore critical heat flux (CHF) was effectively increased due to the scale on the wires.

Chyu and Mghamis [7] investigated the heat transfer enhancement achieved by connecting two hollow, stainless steel tubes in line contact. They determined that the restricted region between the tubes had low wall super heats and provided a restricted geometry that was favorable to vapor bubble formation. Because of the operation of this experiment in a terrestrial laboratory, buoyancy effects prevented the heat transfer enhancement from existing anywhere except on the upward face of the twisted tubes. A microgravity environment could allow that enhancement to be experienced by the entire wire surface.

Past research has concluded that surface geometry plays a role in boiling dynamics but has not answered the questions about specific surface characteristic effects on microgravity boiling. The current experiment seeks to fill that gap by testing the effect of two unique wire geometries (a three-wire and a four-wire twist) and by specific surface features, including a notch on the heating element.

This study aims to add to the understanding of 0-g boiling dynamics by examining the effects of heat flux, surface geometry, and gravity on the boiling of highly subcooled water utilizing thin wire heating elements focusing mainly on the transition into boiling, steady state heat transfer coefficients, and bubble dynamics.

II. Experiment

A. Boiling Chambers and Heating Elements

Figure 1 shows a schematic diagram of the fluid chambers used to boil the heavily subcooled ($\Delta T_{\text{sub}} = T_{\text{fluid}} - T_{\text{sat}} = 66 \text{ K}$) deionized, degassed water. Three types of 1 cm long platinum wire heating elements were used: a single 0.005 in (0.13 mm) diameter wire, a twist of three 0.003 in (0.076 mm) diameter wires, and a twist of four 0.002 in (0.051 mm) diameter wires. Using these three configurations allowed for the three distinct cross sections shown in Fig. 1c. The fluid cells also contained four type T thermocouples (TC 1-4) at varying radial distances from the heating element as well as wire probes to measure the voltage drop across the heating element (Fig. 1b).

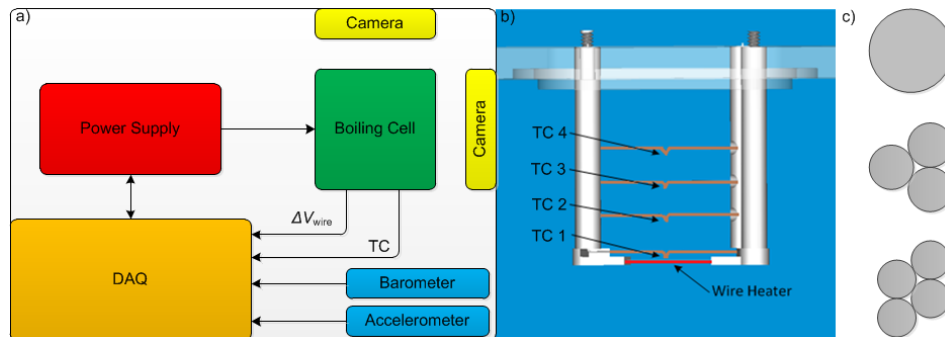


Figure 1. a) System schematic; b) Boiling cell layout; c) Heating element cross-sectional geometries

B. Electronics

Three power supplies provided constant current sources to each of the three heating elements. The output current was measured and recorded by a National Instruments CompactRio data acquisition (DAQ) system (Fig. 1a). The DAQ also measured the voltage drop across the heating elements (ΔV_{wire}), the voltage output from the thermocouples, the outputs from an accelerometer and a pressure transducer, as well as the digital signals used to operate the experiment. Measurements of the wire voltage were effectively taken at approximately 10,000 Hz and the mean and standard deviation were recorded at 100 Hz. The thermocouple measurements were taken at 75 Hz. Visual recordings of the experiment were taken by two Kodak Zi8 HD video cameras located 90° relative to each other in order to give a three dimensional view of each cell. Each camera had a resolution of 1920 x 1080 pixel resolution at 30 frames per section. A pixel resolution of 14 μm x 14 μm was achieved through the use of 4X magnifying lens.

C. Procedure

The experiment was performed on Zero-G's Boeing 727 microgravity simulator. The airplane flew 30 parabolic trajectories comprising of an approximately 20 second 0-g free-fall followed by a 40 second 2-g climb. Each of the three different wire geometries boiled water with 5 constant power levels. The fluid cells used to boil the subcooled water were placed in a free floating structure to reduce the effect of vibrations from the aircraft. Table 1 contains the resulting average power and heat flux based on the wire geometry and input current.

Geometry	"Power Level"	Input Current (A)	Average Power (W)	Average Heat Flux (kW/m ² K)
Single Wire	5	2.13	2.48	599
	6	2.37	3.11	750
	7	2.60	3.36	786
	8	2.81	4.40	1031
	9	3.01	4.93	1168
Three-Wire	5	2.20	2.35	397
	6	2.46	3.17	503
	7	2.71	3.32	559
	8	2.91	4.41	670
	9	3.12	4.48	777
Four-Wire	5	1.69	2.47	512
	6	1.91	3.04	639
	7	2.09	3.66	689
	8	2.26	4.44	930
	9	2.42	4.70	992

Table 1 - Average input current, power, and heat flux supplied to experiment

The barometer measured a cabin pressure of 82.9 kPa, which resulted in a saturation temperature of approximately 94°C. The average net acceleration measured is approximately 0.01 g's with several small spikes corresponding to positioning maneuvers of the free floating structure which contained the boiling cells. While these accelerations are relatively large for microgravity simulation, gravitation effects on bubble dynamics are rarely noticed and will be assumed to be negligible for the majority of the analysis [8].

III. Results and Discussion

The wire temperature (T_{wire}) as a function of time of a single wire experiment is shown in Fig. 2 with $t=0$ representing the moment that power was supplied to the wire. In analyzing nucleate pool boiling, it is important to note that there are four distinct regions that occurred during the boiling process of the current experiment, as shown in Fig. 2.

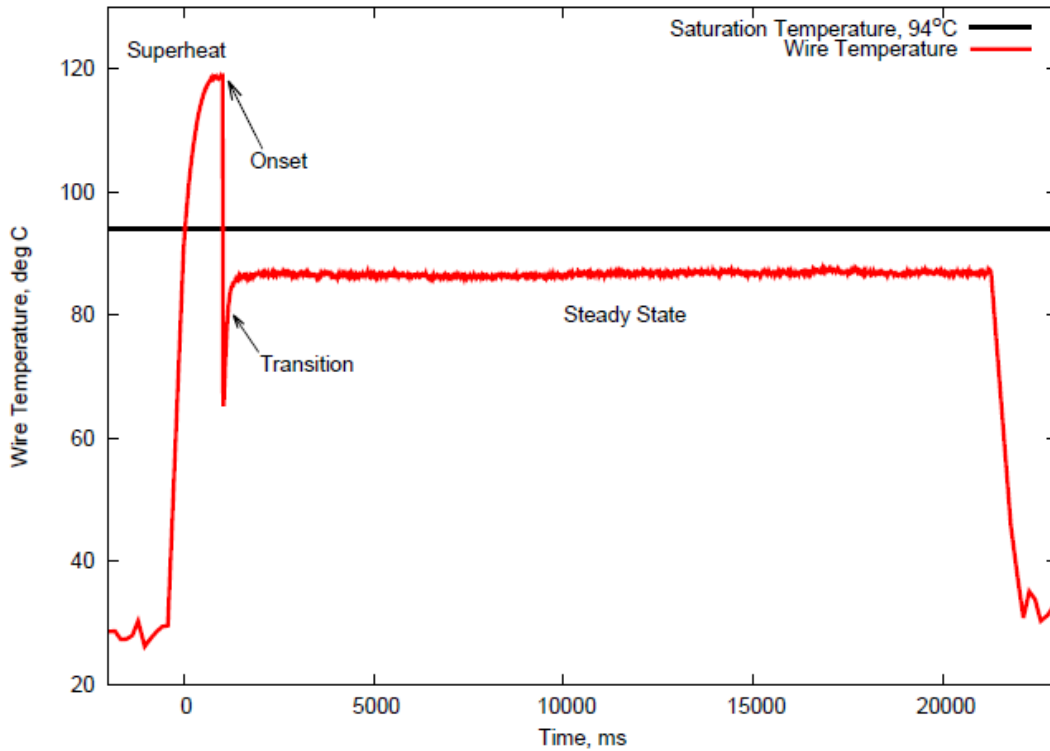


Figure 2. Wire temperature of single wire showing superheat, onset, transition and steady state regions.

These regions are superheating, boiling onset, a transition state, and steady state boiling. The superheating region is noted at lower heat flux levels as having extremely high wire temperatures (T_{wire}), resulting in a high $\Delta T_{\text{sat,wire}}$. After the necessary heat flux is dissipated by the wire, boiling begins. This onset condition is characterized by a rapid cooling of the wire, and at low heat fluxes, an explosion, as bubbles are seeded for the first time. This cooling behavior is similar to Straub’s observations [2], but a greater cooling effect was observed in the current experiment due to the larger degree of subcooling. The transition state is characterized by a large amount of nucleated bubbles. These bubbles grow and depart until equilibrium of bubble nucleation, growth, and departure is reached. The regions of greatest interest are boiling onset and boiling steady state and will be analyzed below.

A. Relative Bubble Area Analysis

Because of the large amount of visual data collected, a computerized relative bubble area analysis was developed in an effort to quantify the change of bubble area from one picture frame to next. In general, this method determines and measures the area of the picture covered by bubbles. This allows for bubble nucleation, growth and departure to be summarized for an entire frame.

In order to create the graphs shown in Fig. 3, the images were first cropped so that only the wire is seen. The images were then put through an image stabilization program. A few of the cells had mounting problems that created movement during flight. After the images were stabilized, one image was selected as a base from which to measure changed pixels from. Each successive image was then taken and, effectively, had the base image subtracted from it. The effect was the ability to count the number of pixels changed from the reference frame. The number of changed pixels was then plotted against the frame number, or effectively changed pixels over time.

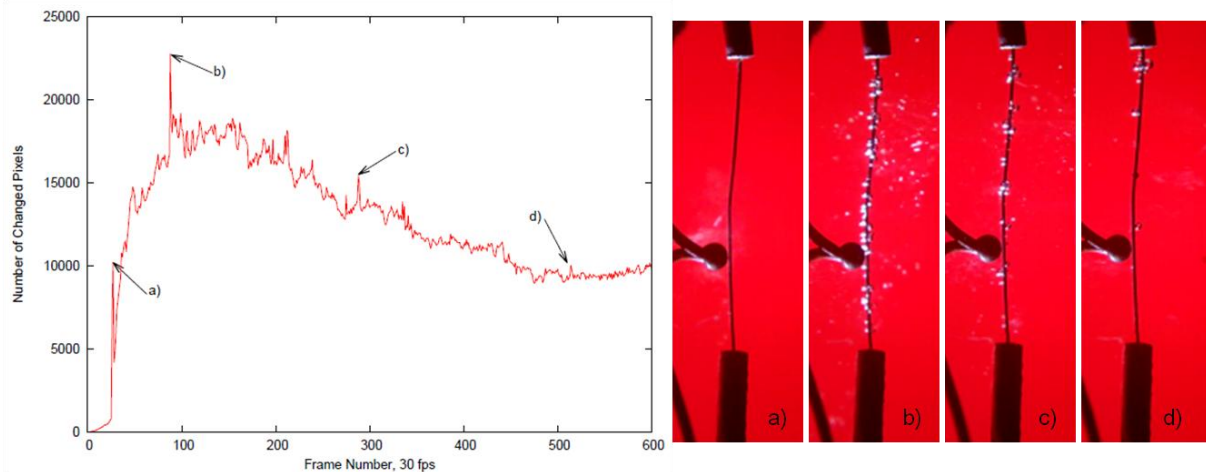


Figure 3. Relative bubble area analysis plot of single wire geometry at power level seven (786 kW/m^2), showing corresponding images.

Figure 3 shows the change in area occupied by bubbles as a function of elapsed heater time of a single wire geometry. Images in Fig. 3a-d are associated with the indicated point in time and represent the viewing area tracked in the relative bubble area analysis after the images have been stabilized. These images show an evolution as bubbles nucleate and transition to steady state boiling. Even though some noise can be seen over the plotted graph the trends indicated on the graph give accurate summaries of the bubble dynamics observed during the 30 seconds of video. The comparison of bubble area for different experimental conditions is discussed in the sections below.

B. Onset of Nucleate Boiling

The onset of nucleate boiling can be easily seen in Fig. 4, which depicts the three different wire geometries as they transition from conduction to nucleate boiling. The onset of boiling can be seen as a large drop in wire surface temperature (T_{wire}). This temperature drop is caused by sudden increase in the convection coefficient as boiling begins with an explosion of bubbles, as previously observed by Zhao [3]. This bubble explosion is seen as a spike in the number of changed pixels as evident in the first peak of Fig. 3 (image Fig. 3a), and is one of the key features of boiling onset. After the initial explosion, bubbles begin to form along the majority of the wire (Fig. 3b). Such explosions occur with all three wire geometries. It seems that this explosion is the conduit in which bubbles are seeded onto the nucleation site that allows the bubble growth to follow. These explosions are observed mostly at lower power levels that still produce boiling, but at higher power levels, this pattern does not occur.

Superheating before boiling begins is caused by the lack of natural convection in microgravity. Once boiling begins, more heat can be transferred away from the wire and thus causes the decrease in wire temperature. The values used to determine onset temperature, heat flux, power, and heat transfer coefficient were taken at the last point before the drop in temperature. If this spike was not observed, as is the case in many of the 1-g experiments, the onset of nucleate boiling was determined to be the first data point for the first power level where boiling was present. In comparing the values of boiling onset heat flux, we see that the three- and four-wire geometries lower the heat flux required in boiling. The single wire required a heat flux of 823 kW/m^2 , while the four-wire geometry required a value of 586 kW/m^2 . The three-wire geometry's onset condition was found to be a range between 396 kW/m^2 and 519 kW/m^2 . The reason for this range is that both the single wire and four-wire geometries reached a steady state superheating condition before transitioning into boiling (Fig. 4). The three-wire geometry did not boil in the lowest power and did not have a steady state superheating region in the next power level up. This indicated that the transition into boiling occurred between these two power levels.

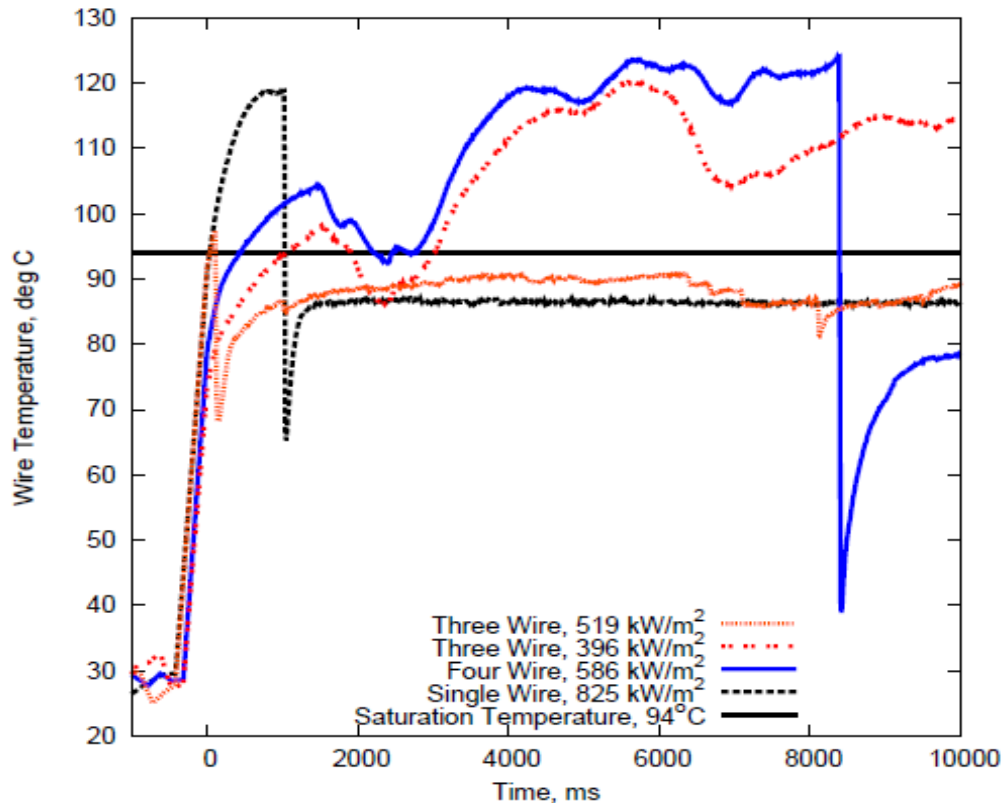


Figure 4. Wire temperatures at onset of boiling.

Even though the three-wire geometry has a range for its onset condition, the entire range remains below that seen in the single and four-wire geometries. This geometry can thus effectively lower the onset heat flux for boiling. It is proposed that the reason for this lowering of onset heat flux is due to the area of enhanced temperatures in the cavity between the three wires which causes local superheating. This area would allow for an even larger amount of superheating within that would be able to seed bubbles. These bubbles would then be allowed to seep to the outside surface of the wire and continue to dissipate heat from the wire. The four-wire geometry also has this superheated region, but it seems that it is not as effective, because the two cavity situation in the four-wire case needs more power to generate the same effect as the one cavity of the three-wire case. The bubble dynamics seem to suggest that it more closely approximates the single wire. It would be interesting to see whether adding more wires would in turn create an even closer approximation to the single wire. The ratio of area within the superheated region to area outside of the superheated region may be related to the ability for the combination of wires to approximate the single wire geometry.

C. Steady State Nucleate Boiling

After the initial onset of boiling, the system reached a steady state region characterized by a nearly constant wire temperature (T_{wire}). This behavior can be seen in the steady state region shown in Fig. 2. The slight dips in wire temperature seen on the three-wire geometry correspond to departures of large bubbles from the heater, resulting in a lower wire temperature as the departing bubble is replaced by the subcooled water. It was also observed that as the heat flux dissipated by the wire increased, the steady state temperature of the wire also increased, similar to the trend observed by Straub [1]. The current experiment's large amount of subcooling, however, dropped the wire temperature below that of saturation ($\Delta T_{\text{sat wire}} < 0$).

In order to compare the efficiency of boiling in microgravity to terrestrial tests, the same conditions found on the Boeing 727 were reproduced in a 1-g environment. The values computed for heat flux and the heat transfer coefficient were averaged over this steady state region, and the heat transfer coefficient, h , was calculated by Newton's law of cooling. Figure 5 shows the ratio of the heat transfer coefficient in microgravity to heat transfer coefficient in 1-g versus the power that the heat transfer coefficient was achieved at.

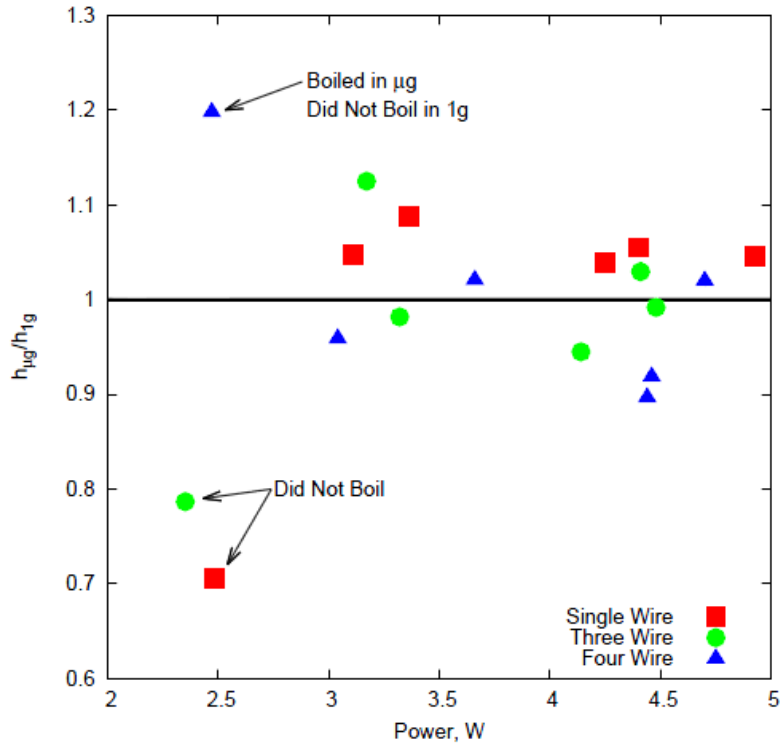


Figure 5. Comparison of heat transfer coefficient in microgravity and on earth for different power inputs.

When the ratio is greater than 1, heat transfer is more efficient in microgravity, and is less efficient when the value is less than 1. This plot shows that gravity plays an independent role in influencing the effectiveness of heat transfer, and, in many instances, a reduction in the buoyant force results in an enhancement of heat transfer. This result is a confirmation of Straub's observations [1].

Two exceptions to the observation that heat transfer efficiency is independent of gravity exist; however these instances are special cases. The first is the four-wire geometry at 2.5 W. This condition boiled in microgravity but did not boil on earth. This resulted in a much higher heat transfer coefficient in microgravity, thus showing the benefit of using boiling over natural convection. The other cases (single and three-wire geometries at 2.5 W) are characterized by a lack of boiling in both 1-g and 0-g tests. This resulted in conduction dominant heat transfer in microgravity compared to the natural convection dominant heat transfer in the terrestrial test.

D. Bubble Dynamics

Although steady state boiling characteristics are independent of gravity, the bubble dynamics are different. As a general rule, larger bubbles are able to form on the wire in microgravity because of the lower frequency at which bubbles depart due to lack of buoyancy, as compared to running terrestrial experiments. As heat flux increases, there is a transition from the formation of isolated bubbles to the formation of bubble jets. These jets were similar in appearance to fog-like liquid-vapor jets seen by Wang [10, 11] which had been observed in subcooled alcohol. This transitional behavior can be seen on Fig. 6 as relative bubble analysis shows a decrease in the number of changed pixels as time goes by. The larger values represent large isolated bubbles and the smaller values represent the dominant behavior of jets. The reason for this discrepancy between changed pixels is due to the small size of the jets relative to the bubbles and the inability of the system lighting to show all of the jets along the wire. Some jets are visible because they are contained in the stream of light; however, many remain invisible and can only be seen through their influence on other bubbles.

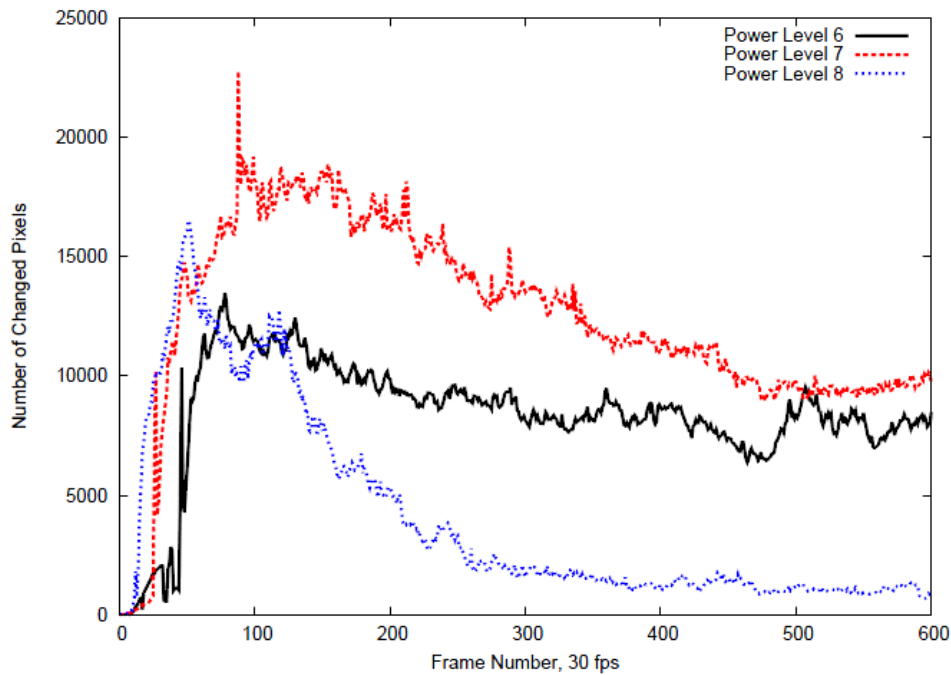


Figure 6. Relative bubble area analysis results for 3 different power levels of the single wire showing transition from isolated bubbles to jets.

Our observations suggest that in microgravity, these jets provide a more efficient way for a large amount of heat to be transferred from the wire in as opposed to isolated bubbles removing the heat. This is due to the formation of convection currents that have a pumping effect [12, 13] of pushing the hot liquid-vapor water away from the wire in the absence of a dominant buoyancy force. This behavior allows the temperature of thermocouple 2 to be greater than thermocouple 1, which is closer to the heating element as seen in Fig. 1b, as heat is transferred by the convective jet in its proximity.

As the heat flux dissipated by the wire increases, the transition from isolated bubbles to jets occurs. At the highest heat fluxes, jet behavior dominates bubble dynamics and there is virtually no observation of transitions from isolated bubbles occurring. This behavior is probably due to the presence of Marangoni effects in the subcooled water which is a dominant factor on the formation of these jets [13]. The geometry of the wire heater also affects the tendency of the boiling system to form jets. The bubble dynamics of the three-wire geometry have a tendency to form large, isolated bubbles that either coalesce into larger bubbles or depart. The single and four-wire geometries had very similar behavior with the initial formation of smaller isolated bubbles and the transition to jets. This transition was more rapid for the four-wire than the single wire.

The platinum wires used in this experiment were magnified 100X under an optical microscope after testing had been performed with the wires to investigate the nucleation sites from which these convective jets originate. Of special interest is a single wire that experienced a jet in both microgravity and terrestrial experiments. In all configurations (microgravity – Fig. 7c, horizontally oriented – Fig. 7e, and vertically oriented – Fig. 7d), a jet formed on the same location of the wire (shown in Fig. 7a). The ability to associate the formation of this jet with a specific nucleation site on the wire helps to resolve Wang’s [14] observation that these jet flows are random and unpredictable. Further work to predict the formation of these jet flows, specifically with the twist of three-wires, is needed and is the subject of an ongoing microgravity nucleate boiling experiment.

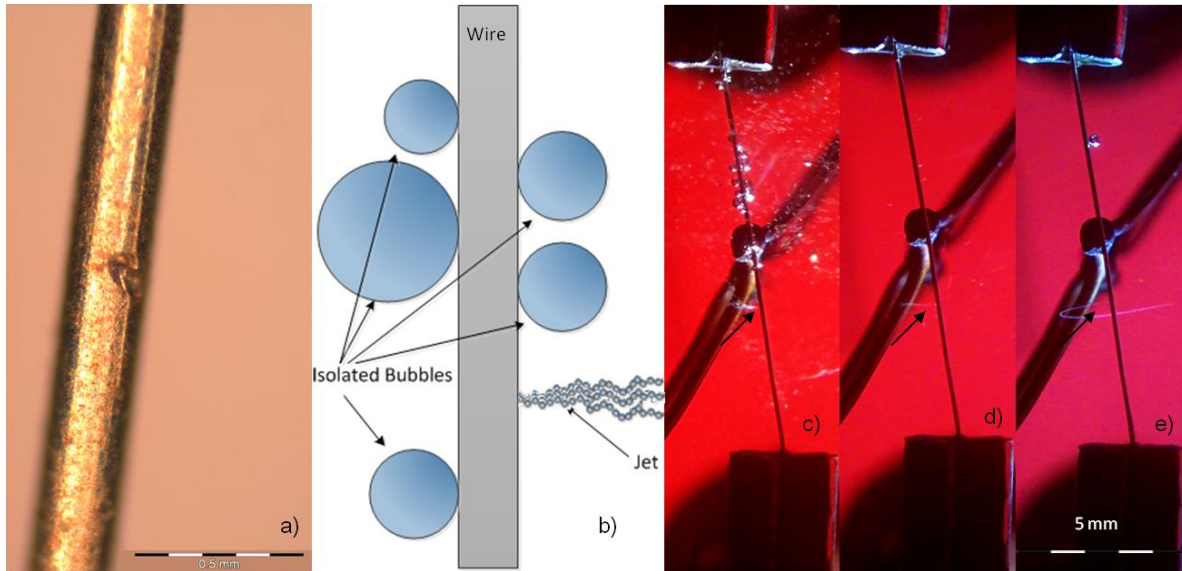


Figure 7. a) Nucleation site of jet on single wire; b) Diagram of jet bubble dynamics; c) Jet in microgravity; d) Jet in Earth gravity (vertical orientation); e) Jet in Earth gravity (horizontal orientation);

IV. Conclusions and Recommendations

Based on the results of this microgravity experiment, nucleate boiling can be an efficient means of transferring heat in microgravity under certain conditions. This observation is based on the following conclusions:

- In many instances, steady state heat transfer is enhanced in microgravity in the range of 5-10%.
- The unique twist of three-wires provides a surface geometry that reduces the required heat flux for onset boiling. This behavior is favorable because more heat is transferred at smaller ΔT_{sat} .
- As heat flux increases, there is an increased tendency to form jets, which provide convective currents normally absent in microgravity.

It appears that the heat flux dissipated by the wire is the primary parameter in determining the mode of heat transfer experienced in microgravity, whether it is pure conduction, boiling with isolated bubbles, or boiling with convective jets.

Further work includes: determining the onset heat flux of the three-wire geometry, determining the heat transfer performance of the wire geometry near CHF, predicting jet formation and performance, and applying the results from previous experiments to design an array of microheaters to provide heat transfer enhancement by creating seed bubbles.

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