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Flow film boiling collapse and surface rewetting in normal and reduced gravity conditions

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Abstract—In order to study the heat transfer characteristics of flow boiling under reduced gravity conditions, a series of experiments have been conducted on flow quenching of a hot flat surface by Freon-113 aboard the KC-135 parabolic aircraft. The instantaneous heat flux and temperature on the horizontal surface were measured using a heat flux microsensor comprising of two 2-μm thick thermopiles and one resistance temperature sensor. During film boiling, heat transfer from the hot surface to the flowing liquid was found to be reduced under microgravity compared to normal gravity conditions due to the thickening of the vapor layer. Also, the wall superheat and the surface heat flux at the onset of rewetting and the maximum heat flux during quenching of the hot surface were found to increase with the inlet liquid subcooling, mass flux and gravity level. The effect of microgravity was more important for low flow rate results and decreased at high flow rates.

INTRODUCTION

The study of film boiling collapse and rewetting under microgravity conditions is important for a better understanding of a number of thermal processes in space research facilities. The manufacturing processes in space which involve cooling and quenching of hot surfaces, the application of boiling–condensation for more efficient heat transmission in large thermal management systems and the storage and handling of cryogens, all require a knowledge of how stability of film boiling and liquid–wall contact characteristics change from normal to microgravity conditions.

Four tools are available for conducting microgravity experiments. Drop towers make use of the fact that objects in free fall experience no gravity. Relatively jitter-free microgravity conditions can be attained in evacuated and tall drop towers where the effect of air resistance is minimized. However, the duration of experiments is limited by the tower height, and most of the operating drop towers can only provide 3–4 s for experiments. Parabolic flying aircraft like the KC-135 of NASA, can produce periods of microgravity during flight with a duration of about 20 s each. Sounding rockets can provide a few minutes of microgravity at considerably higher costs. Space shuttle and space station can provide the ideal environment for zero-gravity experiments, but of course, are of very limited availability to the researchers.

The short periods of time available during most microgravity experiments require an experimental setting and design best suited to high speed data gathering in unsteady state conditions.

In previous research on boiling heat transfer under reduced gravity conditions, Merte and Clark [1] conducted pool boiling experiments using a 10 m high drop tower with a drop time of 1.4 s. They used a 2.5 cm diameter copper sphere immersed in liquid nitrogen as a transient calorimeter. Fractional gravity down to 0.01 g was obtained using appropriate counter-weights and they concluded that the film boiling heat transfer coefficient was proportional to $g^{1/3}$ and the critical and minimum heat flux followed a $g^{1/4}$ dependence. Siegel and Keshock [2] used a 3.8 m drop tower and a platinum wire of 0.5 mm diameter in horizontal and vertical positions to study the effect of gravity on pool boiling. They found that the heat transfer coefficient increased for two of their three test fluids for the horizontal wire and decreased for the vertical wire orientation with a decrease in the gravity level. The microgravity boiling experiments in Germany started in mid-1970s and made use of parabolic aircraft flights and sounding rocket experiments. Straub *et al.* [3] summarized the results of these experiments as showing a small effect of gravity on nucleate pool boiling, which was contradictory to many pool boiling models which strongly rely on the effect of buoyancy on nucleation and vapor bubble release. They showed that even film boiling can be stabilized in microgravity, with the heat transfer coefficient decreasing with gravity but reaching a nearly constant value for lower g values. Recently, Ervin *et al.* [4] performed drop tower experiments to study nucleation and pool boiling mechanisms in microgravity, using a transparent sputtered gold film on a quartz substrate which worked as both the heating

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NOMENCLATURE

D_H	hydraulic diameter [m]
G	mass velocity [kg m^{-2} s^{-1}]
g	acceleration of gravity [m s^{-2}]
h_{lv}	heat of vaporization [kJ kg^{-1}]
q	heat flux [kW m^{-2}]
T	temperature [°C]
W_e	Weber number.

Greek symbols

ρ	density [kg m^{-3}]
σ	surface tension [N m^{-1}].

Subscripts

CHF	critical heat flux
l	liquid phase
max	maximum heat flux point
v	vapor phase.

element and resistance temperature sensor. They reported an energetic type of boiling spread in microgravity, possibly due to an interfacial instability driven by a large mass flux across the wrinkled liquid–vapor interface.

Most of the microgravity experiments on boiling have been conducted with the intention of clarifying the basic mechanisms of pool boiling, bubble generation and boiling incipience, by changing the level of gravity. On the other hand, flow boiling studies under microgravity are scarce, although the behavior of two-phase flow systems in the absence of gravity under adiabatic conditions has received considerable attention (see for example, Rezkallah [5]).

Westbye *et al.* [6] studied the quenching of a hot, thin-walled tube under microgravity conditions aboard NASA's KC-135 parabolic aircraft and showed how the time required for quenching of the tube considerably increased in microgravity due to a decrease in film boiling heat transfer coefficient and a decrease in rewetting temperature. Lui *et al.* [7] also conducted steady, subcooled flow boiling experiments aboard the KC-135, and found that the heat transfer coefficient for subcooled flow boiling increased during microgravity by 5–20% over the normal gravity conditions. They attributed this to the change in phase distribution and the greater freedom of movement of the vapor bubbles generated on the heated tube surface which could cause more localized turbulence.

For the present study, a test section and a flow loop were designed and fabricated to study flow boiling of Freon-113 under microgravity and normal gravity conditions during film, transition and nucleate boiling on a flat heated surface. The present paper deals with the results of the film boiling collapse and surface rewetting experiments as performed on the ground and aboard the KC-135. A heat flux microsensor was used in the test section to measure the instantaneous heat flux and temperature on the hot horizontal surface, and a condenser, designed to separate liquid and vapor using surface tension effects under microgravity, was incorporated in the flow loop. Flow film boiling and rewetting data were collected during 20-s quenching experiments, using a data acquisition system. The fast response of the measuring devices and direct measurements of surface heat flux and temperature made it possible to successfully acquire heat transfer data during a series of quenching experiments aboard the KC-135.

EXPERIMENTAL SETUP

Figure 1 shows the schematic of the experimental setup. Freon-113 was circulated in a flow loop consisting of the test section, pump, a microgravity-operable two-phase condenser equipped with a cooling water loop, and the connecting Teflon tubing. Three video cameras were used to monitor the flow conditions in the test section and the condenser. Real time data acquisition was implemented using an IBM-compatible 486DX-33, and the flow loop and data acquisition system were installed in two separate aluminum frames for transportation and experiments aboard the KC-135.

R-113 was used in this work because of its several advantageous properties such as low boiling point, inflammability, non-corrosiveness and very low toxicity. Also, R-113 has physical properties characteristic of many fluids which are of interest to the space industry. Clean handling of R-113 was achieved using Teflon tubing in the flow loop and a magnetically driven, speed-controlled, Micropump model 101–415 for Freon circulation with a maximum flow rate of 25 l min^{-1} and a maximum head of 200 kPa. The flow rate of liquid Freon entering the test section was measured by an infrared flow sensor, IR-OP Flow Meter model 502-104, and the measurements were both displayed and converted to 0–5 V analog signals, using a signal conditioner. Two type-T thermocouples and two pressure transducers were used to measure the inlet and outlet temperatures and pressures of the test section. During the experiments, liquid R-113 was partially vaporized in the test section and the resulting two-phase mixture was condensed and cooled to the desired subcooling by the copper cooling coils in the condenser. A closed loop water cooling system was used for the cooling coils including a centrifugal pump, a 25 cm fan and an aircooler heat exchanger.

A major technical difficulty for any microgravity flow boiling experiment is maintaining the liquid–vapor separation in the condenser and preventing the flow of vapor to the suction of the circulation pump.

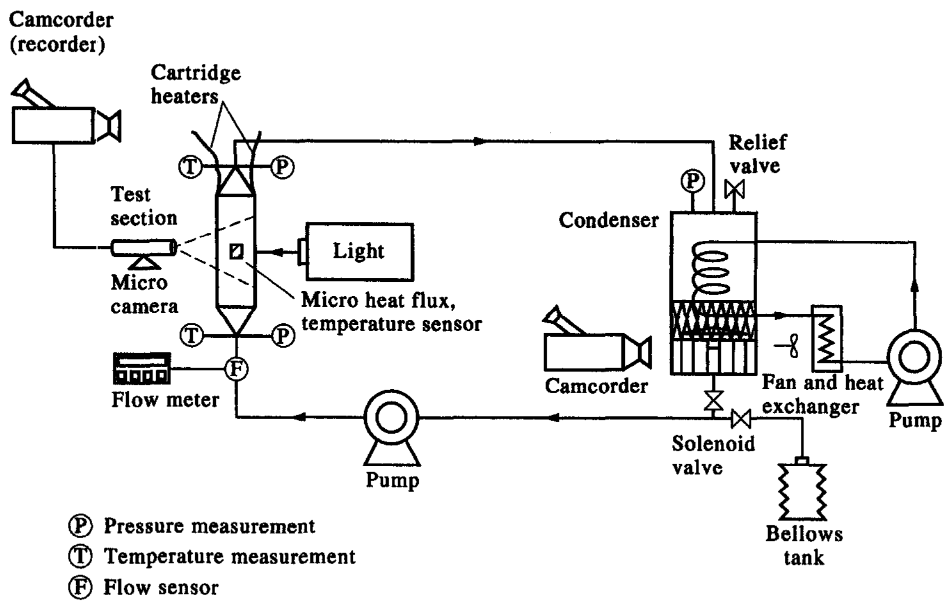

Fig. 1. Schematic of the experimental setup.

Figure 2 shows the design of the condenser which consisted of a transparent cylindrical vessel, 20 cm in diameter and 40 cm in height, made from 6.4 mm thick lucite, and internal components such as inlet spray heads, copper cooling coil, wire mesh, copper cap and bubble ejection fins. A combination of the 10 cm thick bed of wire mesh, perforated copper cap and bubble ejection fins was used to prevent migration of the vapor to the pump suction through the effect of surface tension. The bubble ejection fins consisted of 24 pieces of thin strips of lucite joined at the center to provide 15° radially contracting passages for the fluid toward the pump suction line located at the bottom center of the condenser.

The test section was designed for studying flow boiling of R-113 on a flat surface. It was built in the shape of a 200 mm long flow channel with a 5 mm × 40 mm rectangular cross section comprised of a stainless steel heated wall and an aluminum casing. Figure 3 shows

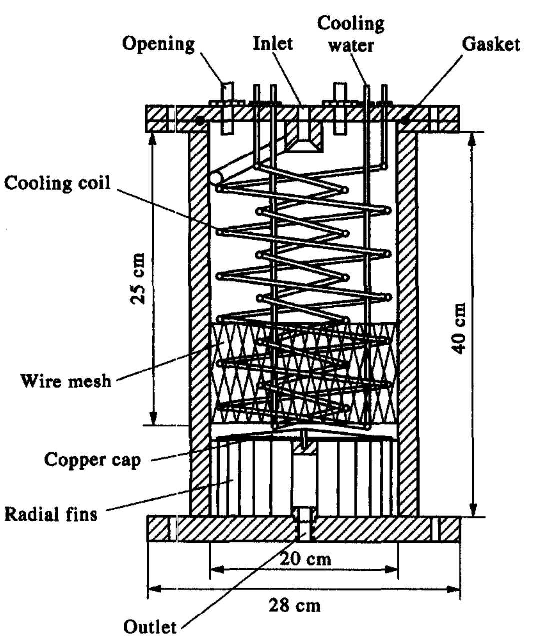

Fig. 2. The condenser and vapor liquid separator.

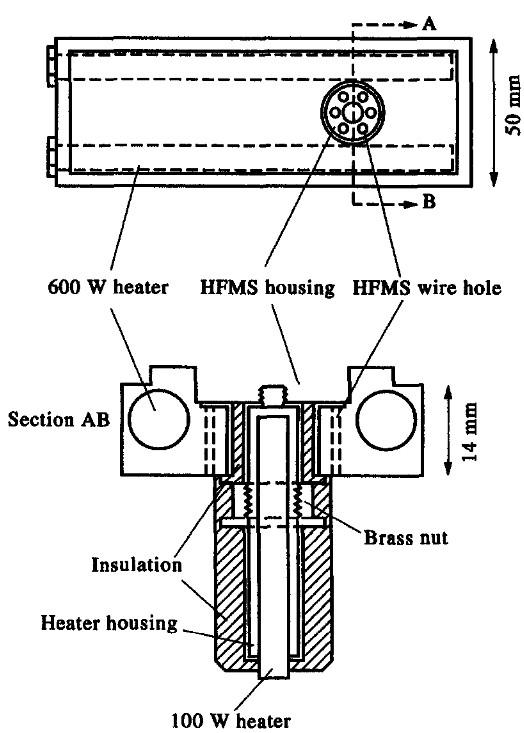

Fig. 3. The heated wall of test section.

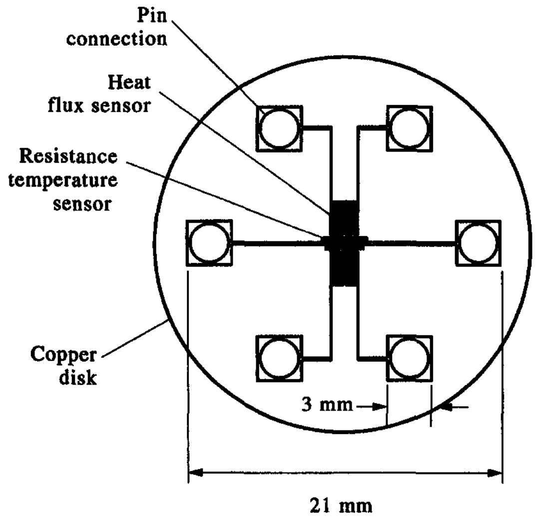

Fig. 4. Top view of the heat flux microsensor.

the schematic of the heated wall which provides housing for a heat flux microsensor (HFMS), three cartridge heaters and four type-T thermocouples. The four thermocouples were mechanically fixed in holes drilled to 1 mm beneath the surface of the heated wall. Two 600 W cartridge heaters were used to heat up the entire heater plate, while a 100 W, 3 mm diameter heater could be used to locally heat the heat flux microsensor (HFMS) region. The test section design allowed different flow boiling and quenching experiments to be performed on the same apparatus, by changing the heating procedure and flow conditions. The cylindrical housing of the small 100 W heater served as both providing heat conduction to HFMS and holding it in its place in the heated wall. A Teflon gasket was used to seal the bottom surface of the disk containing the HFMS against the edge of its housing and six holes provided the passage for the HFMS wiring.

The sensor was a Vatell Corp. heat flux microsensor equipped with two thermopiles and one resistance temperature sensor (RTS), see Fig. 4. The HFMS was fabricated on a 25.4 mm diameter, 6.4 mm thick copper disk with a 100 μm thick plasma sprayed aluminum oxide base insulating layer and a 1 μm overcast of sputtered aluminum oxide providing a moderate abrasion resistance and electrical insulation. The heat flux sensor has been fabricated using a direct deposition technique from the electronics industry, in the form of a 2-μm thick layer containing thermopiles of Platinum/Platinum–10% Rhodium separated by 1-μm thick insulating layer of aluminum oxide (Hager *et al.* [8]). The output of the two heat flux sensors were amplified using two Ectron model-687 differential amplifiers. A Wheatstone bridge was built to convert the change in the resistance of RTS into electric signals.

The resistance temperature sensor (RTS) and the thermopiles of the HFMS were originally calibrated by the manufacturer. After the installation of the HFMS, however, a small drift with time was noted in the resistance of RTS. This aging of a thin film RTS has been observed by other researchers as well [4]. We used the readings of the four type-T thermocouples of the test section for the occasional re-calibration of the RTS. The uncertainty in the surface temperature measurement by RTS was estimated to be ± 1.0°C. The micro heat flux sensors were also calibrated by the manufacturer and the uncertainty in the heat flux measurements was estimated to be ± 5% of the reading. The flow meter was calibrated by measuring the volume of liquid circulated per unit time and the uncertainty was estimated to be ± 2.5% of the flow rate reading.

A flow channel casing provided the other three sides of the rectangular flow channel beside the heated wall. It also provided three glass windows for monitoring the flow inside the test section and was connected to the heated wall using four aluminum clamps. The inlet and outlet ports were connected to the flow channel to provide a smooth expansion and contraction between the circular piping and the rectangular channel cross section. Teflon gaskets were used for sealing all the components of the test section with the exception of the glass windows where high temperature Epoxy was used. Figure 5 shows a schematic view of the assembled test section. The assembled test section was insulated using fiber glass insulation.

Three accelerometers were used to measure the instantaneous acceleration levels during parabolic flights in X (parallel to the wings), Y (normal to the wings) and Z (downward) directions. The output signals from different measuring devices were collected by Keithley Metrabyte Exp-16, expansion multiplexer and signal conditioning boards and fed to the computer via a DAS-1402 analog input board.

For film boiling collapse and rewetting experiments, the temperature of the heated wall of the initially voided test section was increased to about 250°C, using two 600-W heaters. After reaching the desired temperature, heating was stopped and the flow of Freon was initiated. The instantaneous temperature and heat flux on the surface of the HFMS were recorded at a frequency of 100 Hz for the study of film boiling and rewetting. The initial temperature of the heated surface was selected so that film boiling and rewetting could occur during the 20-s long microgravity periods aboard the KC-135. The rate of cooling water circulation in the condenser and a pressure relief valve were used to stabilize the pressure in the condenser at about 100 kPa with an average fluctuation of 7 kPa during the experiments. The same experimental procedure was followed during parabolic flights and under normal gravity conditions.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 6 shows the typical reduced gravity levels provided aboard the KC-135 during the experiments,

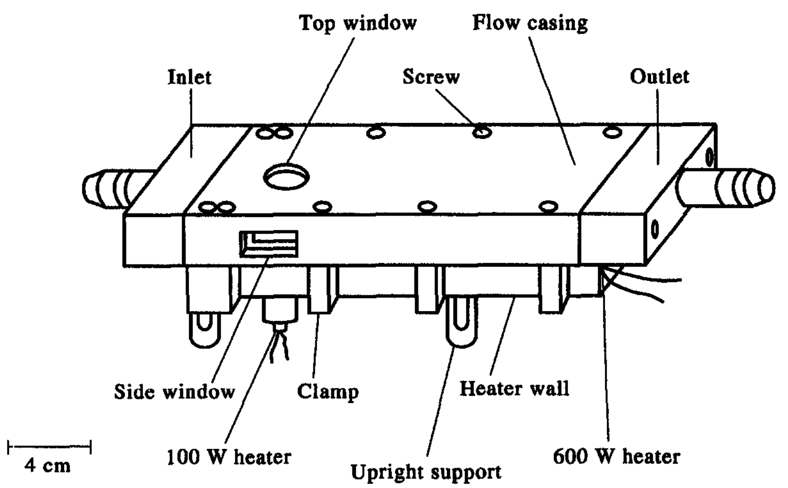

Fig. 5. Schematic of the assembled test section.

as monitored by the X, Y and Z direction accelerometers. The average level of reduced gravity attained aboard the KC-135 was about 10^{-2}g. Experiments were performed during microgravity with subcooled liquid at the inlet for rapid condensation of vapor in the condenser and a better liquid–vapor separation in the separator. Saturated and subcooled inlet liquid conditions were used in normal gravity tests.

The instantaneous heat flux and temperature data, collected at a frequency of 100 Hz during one of the microgravity experiments, are shown in Fig. 7. In order to eliminate the high frequency, low amplitude noise picked up from the surroundings, from the recorded measurements, a five point moving average filter was applied to the raw data. The remaining fluctuations in the data are due to the surface heat flux and temperature fluctuations during different boiling conditions. These fluctuations are characteristic of the wavy liquid–vapor interfacial motion during film boiling, liquid–wall contact during transition boiling and the near wall motion of vapor slugs flowing through the channel during nucleate boiling. Heat flux values can be time-averaged over 1 s intervals in order to eliminate the large scale fluctuations.

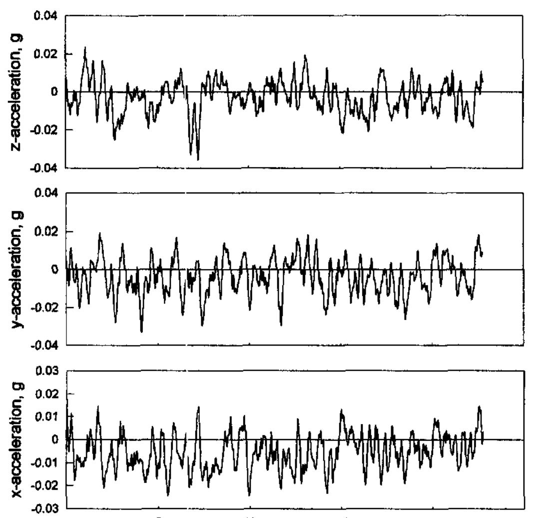

Fig. 6. Typical accelerations during microgravity experiments aboard the KC-135.

The temperature and heat flux measurements were simultaneously obtained at about 3 mm apart from each other on the surface of HFMS, however, the temperature and heat flux data show considerably synchronized behavior, especially during surface rewetting or in the transition boiling region. A magnified representation of heat flux and temperature during this period is shown in Fig. 8 which clearly indicates how each rise in heat flux signal is accompanied by a dip in the temperature data, and vice versa. Therefore, in spite of the fast and transient nature of the experiments, using the fast response of the HFMS, we were able to obtain detailed data during quenching experiments which can be used to elucidate the effects of gravity and subcooling on film boiling collapse and rewetting phenomena.

It is also noted here that the results presented below are strictly valid for a combination of R-113 and copper covered by a thin layer of aluminum oxide, and the thermal behavior of the surrounding stainless steel plate is expected to be somewhat different due to different physical properties such as the thermal conductivity and solid–liquid contact angle. The copper surface was covered by a 100-μm thick aluminum oxide layer having a highly smooth surface and lower thermal conductivity than copper itself, and this two-layer system has certain thermal response characteristics that may become important when large temperature gradients exist. The analysis of the transient, two-dimensional (2D) temperature distribution existing in the heat flux sensor under rewetting conditions will be reported in a separate paper.

The surface heat flux data show a period of film boiling prior to the initiation of surface rewetting.

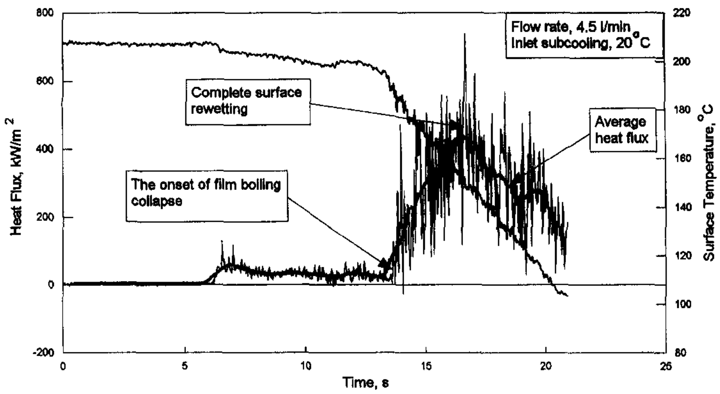

Fig. 7. Surface heat flux and temperature variations during a microgravity rewetting experiment, as measured by the HFMS.

During this period, the film boiling heat flux data show regular and small amplitude oscillations which are due to the fluctuations in the thickness of the vapor film separating the liquid and the hot surface. Surface rewetting is initiated as the surface temperature decreases and the large scale heat flux fluctuations first appear, as indicated in Fig. 7. However, at this point the wall temperature is still quite high and the vapor generated during short periods of direct liquid–wall contact can push the liquid–vapor interface away from the hot surface. Therefore, surface rewetting progresses through successive liquid–wall contacts which further cool the hot wall and possibly increase the contact area.

The period between initial and complete rewetting is characterized by large scale heat flux fluctuations which increase in amplitude and duration until complete rewetting is established. It is commonly believed that before complete rewetting, surface heat flux increases with the decrease in wall superheat and this behavior is known as a unique indication of transition boiling region. This increase in surface heat flux occurs because of the increase in liquid–solid contact area with the decrease in surface superheat. Therefore, the peak point of surface heat flux is commonly considered as the point of complete rewetting; see Fig. 7. In the present study, we follow this accepted view and use the term "complete rewetting" to indicate the point of peak heat flux, but note that the large amplitude heat flux fluctuations in all of our data extended past this peak point to where it is commonly considered as stable nucleate boiling. This has not been observed in previous measurements of heat flux using imbedded thermocouples and inverse conduction calculation.

These fluctuations can be attributed to several possible processes. First, they could be the result of the motion of large vapor pockets that occasionally blanket the sensor surface as bubbles nucleate, grow and are pulled away by liquid inertia. Second, these fluctuations could be the result of incomplete rewetting and an extension of unsteady liquid–wall contact past

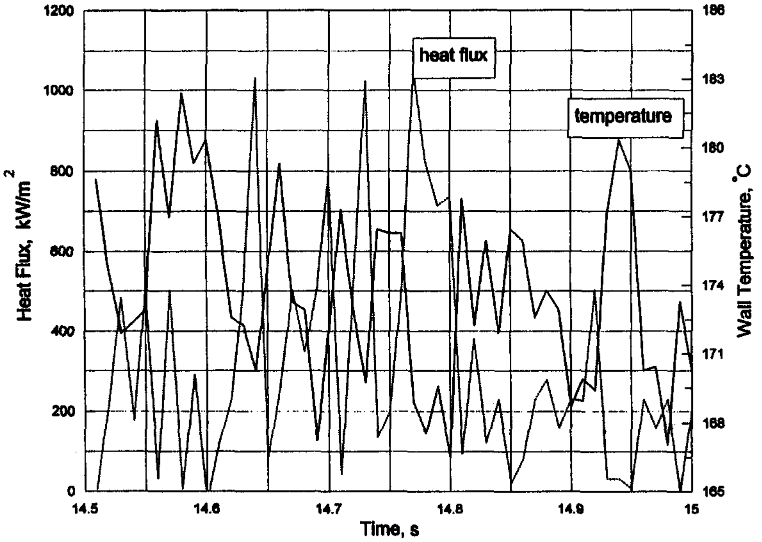

Fig. 8. Details of heat flux and temperature variations during rewetting.

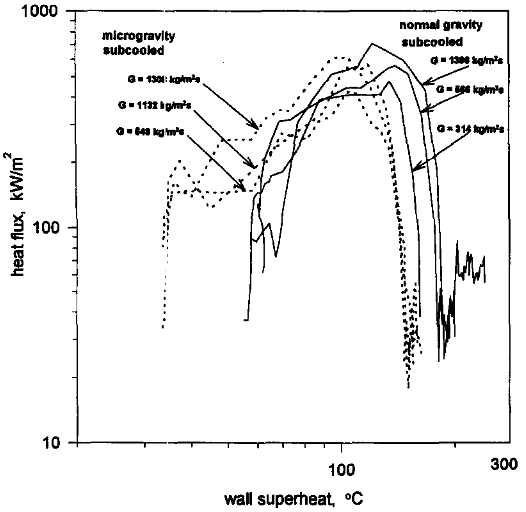

Fig. 9. The effect of gravity on quenching curves, for an inlet liquid subcooling of 20°C.

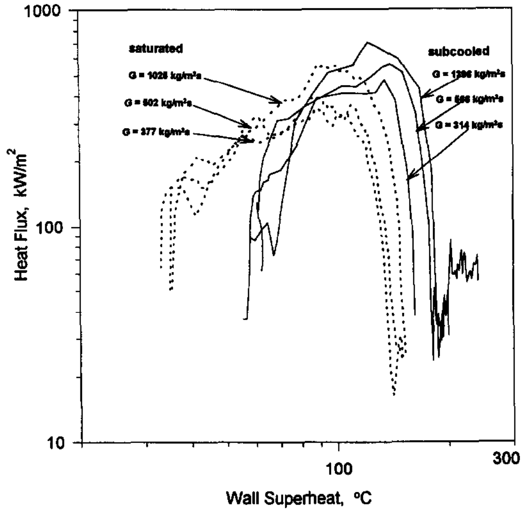

Fig. 10. The effect of inlet liquid subcooling (20°C) on quenching curves under normal gravity conditions.

the peak in the time-average heat flux. As the wall superheat is continuously decreasing, the amount of heat transferred during a direct liquid–solid contact also decreases. The average heat flux is, however, a function of the duration, surface area and frequency of contacts as well as the amount of heat transferred during direct contacts. Therefore, if rewetting is not complete past the point of peak average heat flux as indicated by the large fluctuations, these parameters may be changing in such a way so as to decrease the average heat flux with time. The determination of these parameters, however, is not easy and requires further work.

We leave a more detailed analysis of heat flux and temperature fluctuations observed in these experiments to a future occasion and, here, consider the point of initial rewetting as the point where large scale heat flux fluctuations first start and the point of complete rewetting as the peak point in the time-average heat flux, in order to compare the basic heat transfer characteristics among different experimental conditions.

A plot of the time-average surface heat flux vs wall superheat, or surface temperature less the saturation temperature of Freon, results in quenching curves shown in Figs. 9 and 10 for microgravity and normal gravity conditions, respectively. Heat flux values were time-averaged over one-second intervals in order to eliminate the large scale fluctuations. These figures show the similarity in the general shape of quenching curves between the normal and micro gravity conditions, covering film boiling, transition boiling and nucleate boiling regimes. The curves for subcooled microgravity experiments are shifted towards lower surface superheats and heat fluxes than the curves for subcooled normal gravity experiments. The same behavior is observed for the saturated liquid data as shown in Fig. 10. Flow rate has the same effect as liquid subcooling at both gravity levels, shifting the quenching curves toward higher heat fluxes and surface superheats.

To show the effect of flow rate, gravity level and inlet subcooling on the collapse of film boiling and surface rewetting, different features of the quenching curves are further considered for comparison between different experimental conditions. Figure 11 shows the wall surface superheat at the onset of film boiling collapse for normal gravity conditions as measured by the surface RTS of heat flux microsensor. It is clear that the surface RTS in our experiments has detected the initiation of film boiling collapse for wall superheats well above the previously reported values for Freon-113, for example, by Ueda *et al.* [9]. One explanation for this increase in rewetting temperature could be the difference between surface characteristics of HFMS, due to its very thin aluminum oxide coating, and the metal surfaces usually used in previous experiments. However, there is another difference between the present study and the previous experiments as well. In the previous studies of film boiling collapse and rewetting, thermocouples embedded in the metal wall were usually used to measure the temperatures below the heated surface, and infer the surface temperature and heat flux by inverse conduction algorithms. Those thermocouples could not directly measure the actual surface temperature at the onset of rewetting and could not detect the abrupt change in the heat flux as liquid–wall contact was initiated.

Ueda *et al.* [9] used the data from transient cooling of a copper test section and an inverse conduction calculation routine to find the surface rewet temperature for Freon-113. They reported 60–80°C superheat for saturated liquid rewetting and 120–140°C for subcooled liquid rewetting. Other researchers have also reported an increase in rewetting temperature with liquid subcooling, but there is no general agreement on the effect of mass flux on the initial rewetting temperature. Iloeje *et al.* [10] reported a substantial

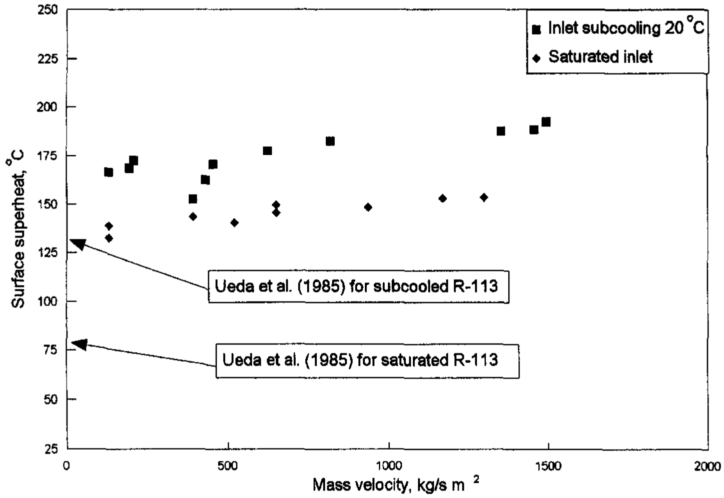

Fig. 11. Surface superheat at the onset of film boiling collapse for normal gravity conditions.

increase, over the expected range, in film boiling collapse temperature with mass flux for water. Their results were not supported by the experiments of Groeneveld and Stewart [11] which indicated an increase in the rewetting temperature for water with liquid subcooling, but no significant effect of mass flux or quality. Cheng *et al.* [12] on the other hand, repeated similar experiments for rewetting of a hot tube by water and concluded that the quench temperature increased with mass flux, inlet subcooling and pressure.

Film boiling collapse and surface rewetting can be viewed as a hydrodynamic stability problem. The driving force for the collapse of flow film boiling comes from Rayleigh–Taylor and Kelvin–Helmholtz instabilities between liquid and vapor flow. During flow film boiling on a flat surface, liquid is supported on a lighter vapor layer which travels at a different horizontal velocity than the liquid. Rayleigh–Taylor instability due to the adverse gravity orientation of the two fluids and Kelvin–Helmholtz instability due to the velocity streaming at the liquid–vapor interface generate interfacial waves which could grow in amplitude and could cause the liquid to directly contact the hot horizontal solid wall. Adham-Khodaparast *et al.* [13] showed that a stabilizing mechanism which can resist the hydrodynamic instabilities present in this system is the vapor thrust or vapor recoil at the vaporizing liquid–vapor interface. The difference between the vapor and liquid density produces an excessive momentum flux at the vapor side of the interface which can only be balanced by a pressure increase in the liquid side of the interface. The stabilizing effect of vapor recoil is proportional to the rate of vaporization and can damp the unstable interfacial waves and establish a stable film boiling condition.

Figure 11 shows a significant increase in the rewetting wall superheat with inlet liquid flow and subcooling. Both of these effects are consistent with the hydrodynamic rewetting model. An increase in fluid flow brings about greater Kelvin–Helmholtz instabilities which in turn results in an earlier collapse of film boiling or higher wall superheat at the onset of rewetting. On the other hand, an increase in subcooling actually decreases the amount of heat used for vaporization at the liquid-vapor interface, which reduces the stabilizing effect of vapor recoil and causes earlier rewetting.

Figure 12 compares the wall superheat at the onset of rewetting for normal and reduced gravity conditions. The rewetting temperatures for microgravity are seen to show the same increase with flow rate, but are 15–25°C lower than those obtained in normal gravity conditions. This decrease in the rewetting temperature can be attributed to the absence of Rayleigh–Taylor instability in microgravity conditions which results in reduced growth rate of interfacial waves and a delay in the vapor film collapse. In the absence of gravity, the vapor film thickness can increase due to the greater stability of the liquid–vapor interface, and therefore, the heat transfer coefficient and film boiling heat flux decrease. These effects are shown in Figs. 13 and 14 where the heat flux and heat transfer coefficient at the onset of rewetting are compared between normal and microgravity conditions. The decrease in rewetting temperature and film boiling heat flux in microgravity is, however, not too drastic which means that even in the absence of gravity and Rayleigh–Taylor instability, there are enough destabilizing mechanisms which give flow film boiling in microgravity the same general characteristics as those under normal gravity conditions.

As we have already shown in Fig. 7, the collapse of a vapor film and the onset of rewetting are followed by intermittent liquid–wall contacts which bring about large scale heat flux fluctuations until the surface rewetting is complete. It is commonly believed that the completion of surface rewetting is accompanied by a maximum in the heat flux on the hot surface, because up to the complete rewetting point, the liquid–

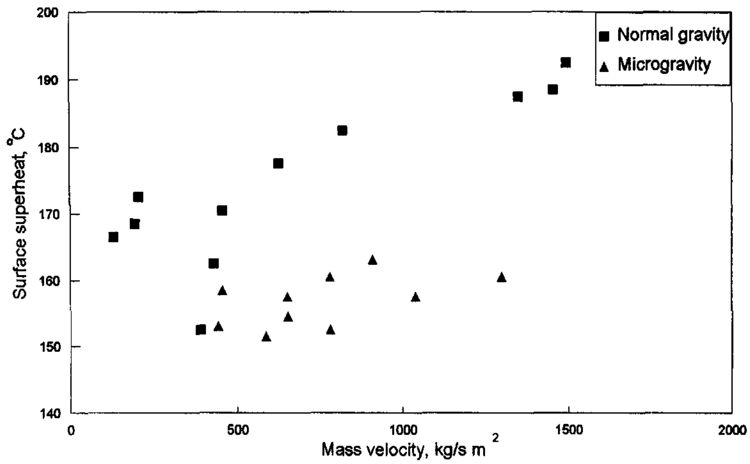

Fig. 12. Surface superheat at the onset of film boiling collapse for inlet liquid subcooling of 20°C in normal and microgravity conditions.

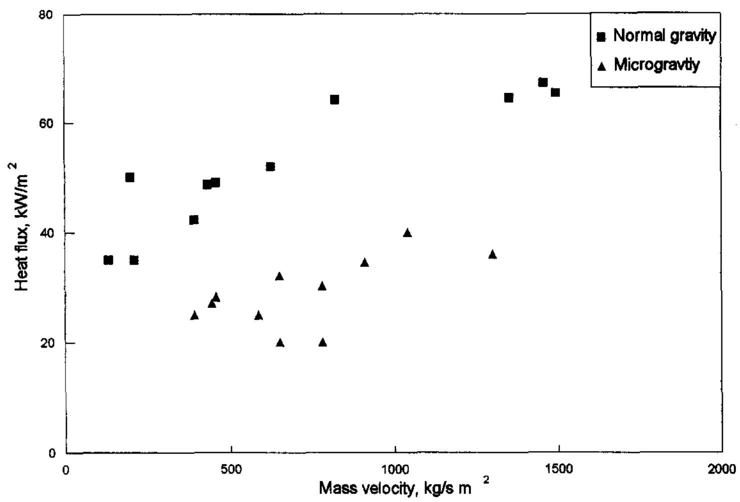

Fig. 13. Heat flux at the onset of rewetting for normal and microgravity conditions.

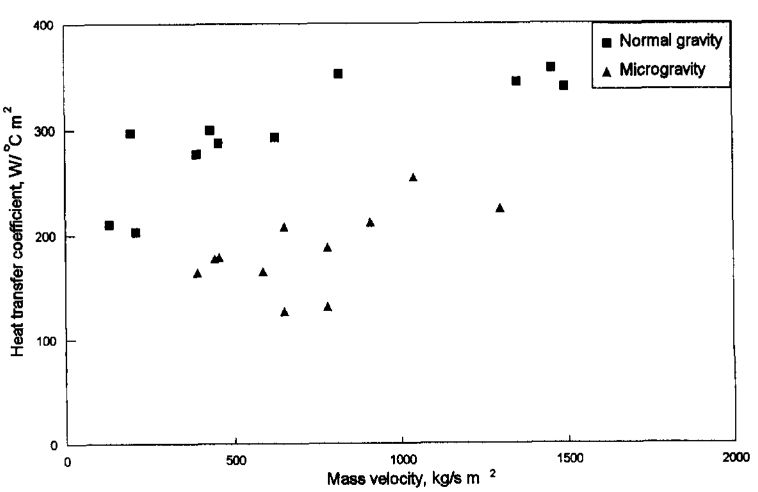

Fig. 14. Heat transfer coefficient at the onset of film boiling collapse for 20°C inlet subcooling in normal and microgravity conditions.

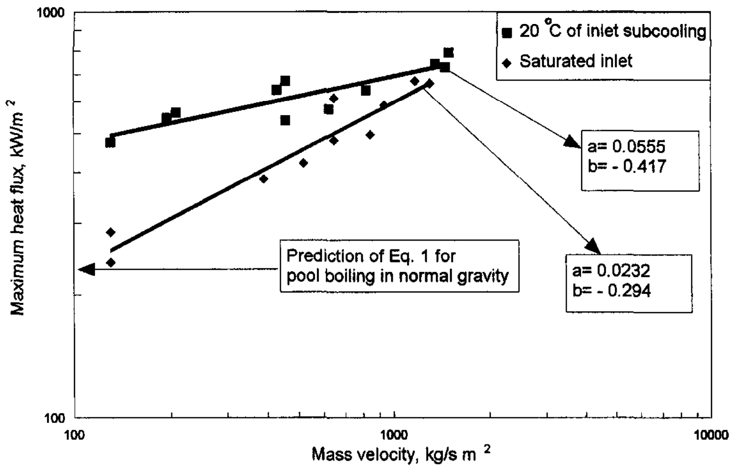

Fig. 15. The maximum heat flux at complete rewetting for normal gravity conditions.

solid contact area and the heat flux should increase with a decrease in surface temperature. After the liquid–solid contact is fully established, the heat flux should decrease with a decrease in wall temperature. Witte and Lienhard [14] showed that the transition boiling curve and maximum heat flux in quenching experiments may not be the same as those obtained in steady boiling experiments. Their view has not been confirmed in all of the previous quenching experiments. For example, Ueda *et al.* [9] showed that the critical heat flux for Freon-113 coincided well with the maximum heat flux obtained by their transient tests. In any case, the maximum heat flux and the wall superheat for complete rewetting can be compared among normal and reduced gravity experiments to see the effects of gravity, flow rate and inlet liquid subcooling.

Figures 15 and 16 show the maximum heat flux during rewetting under normal gravity and microgravity conditions, respectively. The maximum heat flux increased with flow and inlet liquid subcooling, but decreased with reduction in gravity. However, the effects of gravity and inlet subcooling were diminished at higher flow rates. Therefore, the effect of inlet liquid subcooling and gravity are not independent of flow conditions. For comparison, we have also shown in Figs. 15 and 16 the critical heat flux (CHF) for saturated pool boiling of Freon-113 on large flat surfaces as given by the following correlation of Lienhard and Dhir [15].

$$q_{\mathrm{CHF}} = 0.149\rho_v h_{lv}\left(\frac{\sigma(\rho_l-\rho_v)g}{\rho_v^2}\right)^{1/4}. \quad (1)$$

Also drawn in Figs. 15 and 16 are lines representing

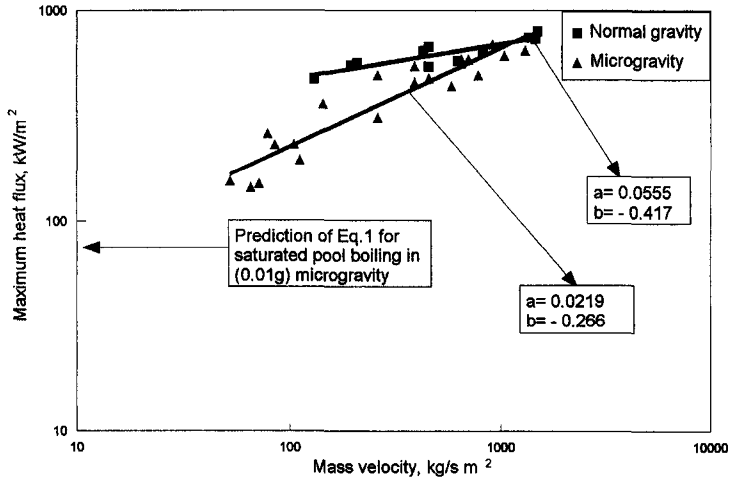

Fig. 16. The maximum heat flux at complete rewetting for 20°C inlet subcooling in normal and microgravity conditions.

the following general form of maximum heat flux correlation,

$$\frac{q_{max}}{Gh_{lv}} = aWe^{b} \quad (2)$$

where $We = (D_H G^2/\sigma \rho_l)$ is the dimensionless Weber number.

Figures 15 and 16 show that the maximum heat flux values during quenching in microgravity with subcooled liquid, and under normal gravity with saturated and subcooled liquid, are proportional to the 0.47, 0.41 and 0.16 power of liquid mass velocity, respectively. The exponent of 0.41 for normal gravity and saturated liquid is in general agreement with the findings of Yilmaz and Westwater [16] who found $q_{max} \propto G^{0.48}$ for their flow boiling experiments with saturated Freon-113 at near atmospheric pressures using a copper tube.

These results show that the boiling curve during rewetting shifts to higher wall superheat and heat flux values with an increase in flow rate, inlet liquid subcooling and gravity level, narrowing the transition boiling region of the boiling curve. The effects of flow and subcooling on flow film boiling and boiling curves during rewetting are, therefore, similar to those for the steady state boiling curve as shown earlier by Yilmaz and Westwater [16]. The effect of gravity on the quenching curves, as expected, seems to be less important for high mass velocity experiments and increases in importance when the flow rate is reduced.

CONCLUSIONS

Flow film boiling collapse was studied by conducting transient quenching experiments under microgravity conditions aboard the KC-135 parabolic aircraft for an inlet flow of Freon-113 with 20°C subcooling, and in normal gravity conditions with both 20°C subcooling and saturated liquid. A heat flux microsensor was, for the first time, used in the boiling experiments to measure the instantaneous surface temperature and heat flux during surface quenching. Also, a new design for a microgravity condenser and liquid–vapor separator was successfully tested during the 20-s long microgravity experiments aboard the KC-135. The following conclusions are derived from this study.

(1) Initial rewetting of the hot surface occurs for surface superheats well above the expected rewetting superheats for Freon-113. The initial rewetting is characterized by sharp and short peaks in heat flux which gradually increase in magnitude and duration until complete surface rewetting is achieved.

(2) The wall superheat at the onset of rewetting increases with mass velocity, inlet subcooling and the gravity level.

(3) Heat transfer coefficient during film boiling is considerably reduced in microgravity due to the thickening of vapor film.

(4) The maximum heat flux during rewetting increases with an increase in mass velocity, inlet subcooling and gravity. The maximum heat flux is correlated by a simple exponential equation (equation (2)) as a function of mass velocity.

Although the quenching results reported here represent the particular combination of liquid (R-113) and sensor material (a copper disc covered by a 100-μm thick layer of plasma deposited aluminum oxide) used in our experiments, they confirm some of the expected trends in quenching under reduced gravity conditions and should provide more confidence in our ability to design and operate equipment under microgravity conditions.

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REFERENCES

1. H. Merte, Jr. and J. A. Clark, Boiling heat transfer with cryogenic fluids at standard, fractional and near-zero gravity, *J. Heat Transfer* **86**, 351–359 (1964).
2. R. Siegel and E. G. Keshock, Nucleate and film boiling in reduced gravity from horizontal and vertical wires, NASA TR R-216, Washington D.C. (1965).
3. J. Straub, M. Zell and B. Vogel, Pool boiling in a reduced gravity field, *Proceedings of the Ninth International Heat Transfer Conference*, Jerusalem, Israel (1990).
4. J. S. Ervin, H. Merte, R. B. Keller and K. Kirk, Transient pool boiling in microgravity, *Int. J. Heat Mass Transfer*, **35**(3), 659–674 (1992).
5. K. S. Rezkallah, Two-phase flow and heat transfer at reduced gravity: a literature survey, *Proc. Am. Nucl. Soc.*, **3**, 435 (1988).
6. C. J. Westbye, M. Kawaji and B. N. Antar, Boiling heat transfer in the quenching of a hot tube under microgravity, *AIAA J. Thermophys. Heat Transfer* **9**(2), 302–307 (1995).
7. R. K. Lui, M. Kawaji and T. Ogushi, An experimental investigation of subcooled flow boiling heat transfer under microgravity conditions, *Proceedings of the 10th International Heat Transfer Conference*, Brighton, U.K., Vol. 7, pp. 497–502 (1994).
8. J. M. Hager, S. Onishi, L. W. Langley and T. E. Diller, Heat flux microsensors, ASME-HTD, Vol. 112, pp. 1–8 (1989).
9. T. Ueda, S. Tsunenari and M. Koyanagi, An investigation of critical heat flux and surface rewet in flow boiling systems, *Int. J. Heat Mass Transfer* **26**(8), 1189–1198 (1983).
10. O. C. Iloeje, D. N. Plummer, W. M. Rohsenow and P. Griffith, An investigation of the collapse and surface rewet in film boiling in forced vertical flow, *J. Heat Transfer* **97**, 166–172 (1975).
11. D. C. Groeneveld and J. C. Stewart, The minimum film boiling temperature for water during film boiling collapse, *Proc. 7th Int. Heat Transfer Conf.*, Vol. 4, pp. 393–398, Munich (1982).
12. S. C. Cheng, P. W. K. Lau and K. T. Poon, Measurements of true quench temperature of subcooled water under forced convective conditions, *Int. J. Heat Mass Transfer* **28**(1), 235–243 (1985).
13. K. Adham-Khodaparast, M. Kawaji and B. N. Antar, Linear stability analysis of a liquid-vapor interface with heat and mass transfer—application to film boiling, *Pro-*

ceedings of the 10*th International Heat Transfer Conference*, Brighton, U.K., Vol. 5, pp. 7–11 (1994).
14. L. C. Witte and J. H. Lienhard, On the existence of two transition boiling curves, *Int. J. Heat Mass Transfer* **25,** 771–779 (1982).
15. J. H. Lienhard and V. K. Dhir, Extended hydrodynamic theory of the peak and minimum pool boiling heat fluxes, NASA CR-2270 (July 1973).
16. S. Yilmaz and J. W. Westwater, Effect of velocity on heat transfer to boiling Freon-113, *J. Heat Transfer* **102,** 26–31 (1980).