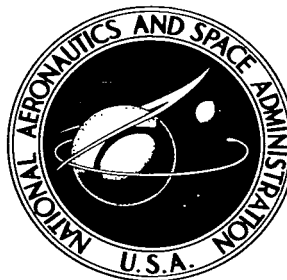


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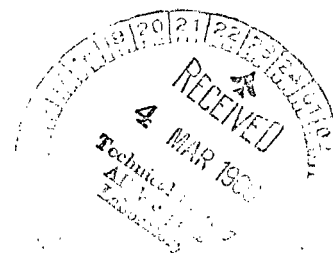


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by S. Stephen Papell and Otto C. Faber, Jr.

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SUMMARY

Gravitational effects on the heat-transfer characteristics of a pool-boiling system were examined by means of a novel gravity simulator technique. Magnetic body forces were used to counteract the influence of Earth gravity on a stable colloidal magnetic fluid. The weight of the fluid was reduced in a magnetic gradient oriented parallel but opposed to the Earth-gravity vector. Proper control of the magnitude of the gradient subjected the fluid to discrete values of effective accelerations between nearly zero and Earth gravity. Steady-state, saturated nucleate pool-boiling data were obtained at the various body force loadings.

Changes in the boiling curves, attributed to buoyancy force effects, were observed in the critical-heat-flux region and the boiling incipience region. The critical heat flux dropped 15 percent when the acceleration field was changed from Earth gravity to nearly zero gravity. At the same time, the temperatures of the heat-transfer surface at the incipience boiling point dropped about 5° F (2.78° C). Explanations for this phenomenon were made in terms of the sensitivity of the thermal-layer thickness to the gravity field.

Comparisons made with critical-heat-flux data, including the present and reference data, showed a divergence of 68 percent at nearly zero gravity. Because of the differences in the various experiments, it was suggested that these comparisons be made with strong reservations.

INTRODUCTION

Investigations into gravitational effects on pool-boiling heat transfer can be divided into the multigravity and reduced- or zero-gravity body force regimes. The availability of centrifuge devices has permitted the generation of

*Much of the material presented herein was presented at 55th National Meeting, AIChE, Houston, Texas, February 7-11, 1965, under the title "Simulation of Zero, Reduced, and Multi-g Pool Boiling Using a Magnetic Colloid."

much multigravity data as, for example, that reported in references 1 to 6. Electrostatic forces have also been used to simulate acceleration forces on pool-boiling systems (refs. 7 and 8). Results of these multigravity experiments are well documented in the literature.

Zero- and reduced-gravity pool-boiling experiments, on the other hand, are not as numerous because of the relative difficulty in obtaining gravity fields of this nature that are suitable for the heat-transfer studies. Although experiments have been run in airplanes flying parabolic trajectories, most of this type of data has been obtained in drop towers of various heights.

The first drop-tower experiments reported were performed by Siegel and Usiskin (ref. 9), who demonstrated the technique of subjecting a pool-boiling apparatus to gravity forces less than Earth gravity. A later study (ref. 10) by the same authors showed photographic evidence of gravitational effects on bubble growth rate and final size before departure. Critical-heat-flux data were obtained by a transient burnout technique. The data showed that the critical heat flux was lower as the gravity force was reduced. A great deal of scatter in the data was attributed to the limited time available in the gravity field for the data runs.

Steinle (ref. 11) employed a drop-tower technique for obtaining zero-gravity pool-boiling data for Freon 114. The results also showed that the transition from nucleate to film boiling occurred at lower power levels when the gravity force was reduced.

Clark and Merte (ref. 12) obtained saturated liquid-nitrogen pool-boiling data at nearly zero-gravity conditions in a 32-foot (9.75-meter) drop tower. Comparative heat-flux data obtained in Earth gravity showed very little difference in the nucleate-boiling regime except for the power level requirements of the critical heat flux. The data appeared to follow a semitheoretical relation defining the critical heat flux as a $1/4$ -power function of the acceleration force.

Sherley (ref. 13) presented liquid-hydrogen pool-boiling heat-transfer data obtained in both drop towers and an airplane flying parabolic trajectories. Comparisons made with Earth-gravity data showed insignificant differences in the nucleate-boiling regime except for the critical heat flux. Although the airplane data were inconclusive, the drop-tower data showed that the transition to film boiling occurred at 12 000 to 18 000 Btu per hour per square foot (3.79 to 5.67 W/sq cm) as compared to 25 000 Btu per hour per square foot (7.88 W/sq cm) at Earth gravity.

Clodfelter (ref. 14) used a 1.8-second drop tower to show the effect of gravity and geometry on the critical heat flux of a water pool-boiling system. A brief description of some experiments run in an aircraft was also presented. Results obtained with three data points seemed to indicate that a longer zero-gravity time of 2 to 3 seconds results in lowering the value of the critical heat flux.

The time dependency inherent in drop-tower and aircraft techniques for ob-

taining reduced-gravity fields has raised questions concerning the steady-state nature of pool-boiling heat-transfer data obtained in this manner. However, it would be expected that lower critical heat fluxes would result from steady-state low-gravity conditions. The purpose of the present investigation was to obtain zero and reduced-gravity saturated pool-boiling heat-transfer data in an apparatus capable of permitting the establishment of steady-state conditions. A novel gravity simulation technique, operating independently of time, was introduced. The technique used magnetic body forces to counteract the effect of Earth gravity on a fluid that exhibited magnetic properties in addition to being suitable as the working fluid for the heat-transfer experiments. A fluid of this nature was produced by suspending ferromagnetic submicron particles as a colloidal dispersion in normal heptane. A pool-boiling apparatus was designed to be run in a vertically mounted solenoid type magnet at a position where the magnetic gradient was quite uniform and produced a magnetic body force acting in opposition to Earth gravity.

Proper control of the magnetic flux permitted the fluid to be subjected to accelerations such that the effective gravity forces on the fluid ranged between nearly zero and Earth gravity. Steady-state saturated nucleate-boiling heat-transfer data were obtained up to the critical heat flux in the various effective gravity fields. These data showed gravitational effects on boiling incipience and on the upper limit of nucleate boiling. The critical-heat-flux data were compared with published data through a semitheoretical relation that describes the heat flux as a function of gravity forces raised to the $1/4$ power.

An evaluation of the gravity simulation technique was also made to determine the validity of the heat-transfer data.

GRAVITY SIMULATION TECHNIQUE

Experimental Apparatus

A fluid susceptible to magnetic forces could be made weightless by subjecting it to magnetic body forces acting equal and opposite to the direction of Earth gravity. This technique was used as the basis for the gravity simulation reported herein. The validity of such a simulation depends on the properties of the magnetic fluid and the characteristics of the field that supplies the magnetic body forces. The fluid chosen for this investigation must also have fluid properties suitable for use in pool-boiling heat-transfer studies. A description of the apparatus that includes both the fluid and the electro-magnet follows.

Magnetic colloid. - The availability of fluids that could be subjected to magnetic body forces was a requirement of the gravity simulation technique. A fluid of this nature was produced by dispersing submicron particles of magnetic iron oxide (Fe_3O_4) in a medium of normal heptane. An extremely stable, low-viscosity magnetic colloid system containing a 6.83-weight-percent particle concentration was prepared in this manner. A description of the particles obtained from electron-microscope pictures showed that they were essentially spherical in shape, uniformly distributed throughout the liquid, and approxi-

mately 3.94×10^{-6} inch (0.1μ) in diameter. The clear normal-heptane liquid became brownish black and opaque upon the addition of the ferromagnetic particles. No significant changes were observed in its boiling point, nor was the apparent viscosity of the fluid altered markedly. The stability of the colloid system was also unaffected by Earth gravity or applied magnetic forces in fields of 50 kilogauss, which yield magnetic gradients of 9.1 kilogauss per inch (3.6 kG/cm). Under these forces the particles remained dispersed throughout the liquid even for extended periods of time; that is, times long in comparison with that required for data acquisition in the heat-transfer study.

The apparent stability of the colloid system allows an assumption to be made concerning an equivalency between magnetic body forces and gravitational forces. Justification for this statement lies in the nature of the action of these forces on the solid-liquid system. A comparison between these two forces could best be examined in terms of the manner in which they act on a microscopic volume of the colloid system consisting of a magnetic particle surrounded by a volume of liquid. The influence of the magnetic body force on the colloid system is essentially limited to the magnetic particle itself. Under the influence of a magnetic field, the particle experiences a force in the direction of the magnetic gradient. Each particle influences a specific volume of fluid by some adsorption mechanism so that the magnetic force is transmitted to the liquid through the particle itself. The apparent stability of the system suggests that the applied forces are smaller than the forces that hold the solid-liquid system together, even though calculations show that the distance between particles is about five times the diameter of the particles themselves. The microscopic colloid volume can, therefore, be considered to act as a continuum with the magnetic force acting through its center of mass.

Gravitational forces, on the other hand, are thought of as acting equally on every elemental particle of the microscopic colloid volume, which includes solid and liquid alike. The weight of the colloid volume is the summation of all the parallel gravity forces acting as a resultant force through the center of gravity of the system. Therefore, on a macroscopic scale, resultant magnetic and gravitational forces can be considered to act in a similar manner on the colloid system provided the system remains stable.

It is significant to note that the vapor phase of the liquid in the colloid system cannot be influenced by magnetic fields since the bonding forces between the solid and the liquid are broken when the liquid vaporizes. The vapor is, therefore, always subject to Earth gravity, and its effect on the heat-transfer data obtained for this investigation will be discussed.

Electromagnet facility. - The magnetic-force field requirements for the investigation were supplied by a 100-kilogauss, water-cooled, solenoid-type magnet located at the Lewis Research Center. The orientation of its longitudinal axis parallel to Earth gravity makes this particular magnet ideally suited for the gravity simulation study. A 4-inch-diameter throat (10.16 cm) also provides sufficient room to work within the magnet.

Figure 1 is a highly schematic sectional view of the magnet showing directions of the magnetic force field with respect to Earth gravity. A magnetic

particle positioned in the upper portion of the magnet would experience a body force in the direction of Earth gravity. At the bottom of the magnet the direction of the body force would be directly opposed to Earth gravity. The experiments described in this report were run in the lower portion of the magnet so that the direction of the magnetic forces could be used to negate the effect of Earth gravity on the fluid. A recent work appearing in the literature (ref. 15) describes a similar though not parallel investigation that used magnetic gradients to subject liquid oxygen to various acceleration forces. The paramagnetic properties of liquid oxygen made this study possible.

Since Earth gravity is uniform in the region occupied by the test apparatus, a good gravity simulation using magnetic body forces requires a field possessing a uniform magnetic gradient. Solenoid-type magnets are, therefore, well suited for this study because their fields can be designed to contain uniform axial gradients along a portion of their longitudinal axis. The magnetic field characteristics for the particular solenoid used were calculated by a method reported by Brown et al. (ref. 16). Figure 2 is a plot of the calculations showing the distribution of the axial component of the magnetic field. The ratio of the local axial field at axial position Z to the field at the center of the magnet B_z/B_0 was plotted against the axial position Z measured from the center of the magnet. The position $Z = 10$ inches (25.4 cm), at the inflection point of the curve, was chosen as possessing the optimum desired properties for the study. The axial distance between $Z = 8$ and $Z = 12$ represents 4 inches (or 10.16 cm) of essentially uniform magnetic gradient; therefore, the testing procedure was standardized to that particular position within the magnet.

Calculations were also made to determine the magnitude of the radial component of the magnetic field at the position $Z = 10$ inches (25.4 cm) for field requirements that produce weightlessness. The results showed a radial magnetic gradient varying from zero along the longitudinal axis of the magnet to 1 percent of the axial gradient at the maximum radial position required for the heat-transfer tests that are described in the following section. It is suggested that these radial forces did not appreciably affect the validity of the gravity simulation technique because the heat-transfer data obtained were found not to be a function of radial position within the magnet.

The presence of ferromagnetic particles in the colloid system can distort the magnetic field produced by the solenoid magnet if magnetic interaction (dipole-dipole) takes place between the particles. The magnitude of this distortion is a function of the particle concentration, which has a limiting value of the order of 1 percent by volume (ref. 17), below which this effect is insignificant. Since the colloid system used for this study has a particle concentration of less than 1 percent by volume, the possibility of magnetic field distortion was not considered serious.

Calibration Procedure

A calibration was run at the predetermined position in the lower half of the magnet to relate effective gravity on the fluid to magnetic field measure-

ments in the center of the magnet. The apparatus consisted of a glass bottle suspended from a sensitive strain-gage-type load cell that was capable of measuring a 2.2×10^{-3} -pound (1-gram) change in weight. The millivolt signal output was fed to a digital voltmeter that was calibrated to read in grams. The bottle was filled with 6.10 cubic inches (100 cu cm) of the magnetic colloid and placed in the uniform magnetic gradient between $Z = 8$ inches (20.32 cm) and $Z = 12$ inches (30.48 cm). The weight of the fluid in Earth gravity, independent of its container, had previously been recorded. The calibration procedure required subjecting the fluid to a range of magnetic body forces whose line of action would effectively reduce the weight of the liquid. At each field setting the change in weight of the fluid was recorded. The end point of this calibration was reached when the fluid became weightless.

The acceleration forces experienced by the fluid were obtained from the weight measurements by the following relation:

$$a = \frac{F}{W} g_e \quad (1)$$

where F is the weight measured under the vector summation of both the magnetic body force and Earth gravity, W is the weight of the fluid in Earth gravity, and g_e is the acceleration due to Earth gravity. Results of the calibration are shown in figure 3. The effective gravity felt by the fluid a/g_e is plotted against the field B_0 in kilogauss measured in the center of the magnet. A linear relation exists between field settings of 2 and 10 kilogauss. Below 2 kilogauss the apparent nonlinearity may be due to high percentages of the magnetic particles remaining unoriented in the magnetic field. At 10 kilogauss the fluid is weightless within the accuracy of the instrumentation. The weight measurements are accurate to 0.5 percent and the magnetic field measurements to 2 percent. Figure 3 was then used to describe the gravity state of the magnetic colloid during the heat-transfer tests that follow.

POOL-BOILING HEAT-TRANSFER TESTS

Apparatus and Instrumentation

The pool-boiling heat-transfer apparatus used for this study is described schematically in figure 4. The assembly consisted essentially of a container for the magnetic colloid and an instrumented heat-transfer surface submerged in the fluid. Heat loss from the assembly was minimized by using a vacuum Dewar as the fluid container. The Dewar was sized to fit the 4-inch (10.16-cm) opening of the magnet and to contain the equivalent amount of fluid that was used in the calibration. A reflux-type, water-cooled condenser was vented through the Dewar to prevent vapor loss from occurring during the boiling process.

The heat-transfer surface was a 1/16-inch-wide (0.159 cm) by 1-inch-long (2.54 cm) Chromel ribbon bonded flush to the surface of a phenolic resin block by a high-temperature epoxy resin. Three copper-constantan thermocouples, made from 36-gage wire, were silver-soldered to the side of the Chromel strip facing

the phenolic resin block. The wires were drawn through holes drilled in the block and brought out of the pool through the aluminum support tube. The millivolt output of the thermocouple was fed to an instrument capable of measuring temperature to $1/2^\circ \text{ F}$ (0.28° C) accuracy.

The power leads were connected to copper electrodes on the heater block and also drawn out of the pool through the support tube. Power to resistance-heat the Chromel strip was controlled by a 60-cycle, 120-volt Variac that was stepped down through a coil to supply approximately 2 volts and 25 amperes. Direct measurements of voltage and current were made on 0.1-percent-accurate instruments.

The support tube was positioned so that the heat-transfer surface would be in the center of the Dewar and oriented perpendicular to Earth gravity. Components of the apparatus were made of nonmagnetic materials to prevent possible distortion of the magnetic field.

Experimental Procedure and Data

The pool-boiling apparatus was filled with 6.10 cubic inches (100 cu cm) of test fluid, which was a sufficient volume to cover the heater but not to submerge the vent tube of the condenser. The apparatus was then placed in the predetermined position of the magnet used for the calibration runs. An auxiliary heater placed through the vent tube was used to bring the fluid up to the saturated condition. When the temperature of the fluid was at 205° F (96° C), the saturation temperature of the fluid, the auxiliary heater was removed. The fluid was then subjected to a desired body force loading by setting the required magnetic field at a value dictated by the calibration curve in figure 3.

A data run consisted of recording the heater temperature at discrete power settings from zero heat flux up to the critical heat flux, which is here defined as the heat flux above which the temperature of the heater increased rapidly and indicated a transition to film boiling. At each power setting sufficient time was allowed for steady-state conditions to prevail before recording the data. Convective-heat-transfer and nucleate-boiling data were obtained in this manner over a range of simulated gravitational acceleration between zero and Earth gravity.

The data are presented in figure 5 as a plot of heat flux q in Btu per hour per square foot and watts per square centimeter against $T_h - T_s$, which is the difference between heater temperature and saturation temperature of the fluid. Each curve includes the free-convection heat-transfer and boiling data obtained for a specific gravity load. Before and after each data run, with no power being supplied to the heater strip, the thermocouples on the heater strip indicated that saturation conditions existed in the bulk of the fluid. Since instrumentation was not provided to measure bulk temperature continuously, it was necessary to assume that saturation conditions existed in the bulk of the fluid during the data run.

The shapes of the individual curves are typical in that they show a rapid

increase in temperature for small increases in heat flux in the convective regime and a small increase in temperature for large increases in heat flux in the boiling regime. The rapid increase in temperature in the upper portion of the boiling curves depicts the change in the characteristics of the boiling process at the upper limit of nucleate boiling. Gravitational effects in portions of the boiling curves are apparent.

Discussion of Gravitational Effects

Differences in the curves in figure 5 represent gravitational effects on the pool-boiling system used for this study. An examination of the data, with the 1-g curve as a control point, reveals the magnitude and direction of these effects. Two distinct changes in the boiling curves can be observed. The first, in the region of low heat flux, is related to boiling incipience and is shown by a shift of the curves to the left. The second effect, in the region of high heat flux, is the reduction in the magnitude of the critical heat flux at reduced gravities. The following discussion will include an evaluation of both of these effects.

Boiling incipience. - The continuous nature of the curves (fig. 5) connecting the convective and boiling heat-transfer data makes it difficult to specify a position on these curves that could be identified as the incipient boiling point. Therefore, in order to enable an evaluation of the data, a technique formerly employed by other investigators was used to define an incipient boiling point. If the boiling and convective portions of the curves were to be extended as straight lines, their position of intersection could be called an incipient boiling point. The relative positions of these points would then show changes in boiling incipience.

Applying this technique to the data in figure 5 as illustrated by the dashed lines shows that a reduction in gravity on the fluid shifts the incipient boiling point to lower heater temperatures. Between 1 g and 0 g the change in heater temperature is about 5° F (2.78° C). This reduction in temperature represents lower values of superheating in the thermal layer near the heater.

The initiation of boiling at lower values of superheating can be explained by the sensitivity of the thermal layer to the gravity force. The thickness of the thermal layer is an inverse function of the gravity force; therefore, a reduction in gravity should increase the height of this layer and result in a medium more suitable for bubble ebullition. Hsu (ref. 18) describes the importance of the thermal-layer thickness in the activation of bubble sites. A thicker thermal layer can permit rapid initial bubble growth and shorter waiting periods between bubble departure and initiation. Boiling can, therefore, start at lower values of superheating and is reflected in the shift of the nucleate-boiling curves in figure 5 below a heat flux of approximately 80 000 Btu per hour per square foot (25.25 W/sq cm). Above this value of heat flux the data merge into a common curve because the vigorous nature of the boiling process in this region produces turbulence effects that become prominent. Above a heat flux of 140 000 Btu per hour per square foot (44.15 W/sq cm) the spread of the data is caused by the effect of gravity on the upper limit of nucleate boiling.

The shift in boiling incipience due to the gravitational body force has been reported by Graham and Hendricks (ref. 6) with data obtained in centrifuge experiments. The data showed that multigravity acceleration delayed boiling incipience to higher values of surface superheating. This effect was attributed to a thinning of the thermal layer with increased gravity forces. Thus, the trends noted in the incipience conditions are consistent for both multigravity and partial-gravity data.

Critical heat flux. - The relation between the acceleration and the critical heat flux on the pool-boiling system can be obtained from figure 5. The relative positions of the end points of the curves show that the critical heat flux decreases as the gravity field is reduced. This trend has been experimentally reported by Usiskin and Siegel (ref. 10), Sherley (ref. 13), Clark and Merte (ref. 12), and Clodfelter (ref. 14), who used drop towers to obtain their data. Semitheoretical analyses, which predict a 1/4-power relation to the gravity forces, are readily available, as reported, for example, by Borishanskii (ref. 19), Zuber (ref. 20), and Chang and Snyder (ref. 21).

The critical-heat-flux data were replotted in figure 6 along with the published data and the semitheoretical 1/4-power relation. The ratio of the critical heat flux at reduced gravity to that at standard Earth gravity $(q/q_e)_{cr}$ was plotted against the effective-gravity ratio a/g_e . The present data fall above the reference 10 drop-tower data, and both sets of data are higher than those for the 1/4-power relation. The reference 13 drop-tower data fall above the reference 10 data. A data point obtained from reference 12, also by drop-tower techniques, falls close to the semitheoretical curve. Reference 14 drop-tower data fall considerably below the curve. The spread in the value of the critical-heat-flux ratio at nearly zero gravity ranges from 0.176 to 0.850. The data from two of the more recent works (refs. 15 and 22) also fall in this range.

The significance of attempting to evaluate these data in terms of their relative values, as presented in figure 6, is open to question because the nature of the plot presupposes a simple functional relation between the parameters involved. Justification for presenting data in this manner is that fluid properties are gravity independent and can be divided out in the nondimensionalizing technique used. The functional relation of the form (function of properties) $(a/g_e)^{1/4}$ was derived by postulating a physical model based on observance at Earth gravity. At low gravity, however, buoyancy is greatly diminished; consequently, forces of surface tension, pressure, inertia, and forces induced by the presence of previously departed bubbles (vapor accumulation) become much more dominating and may change the vapor removal mechanism. Hence, a simple functional relation may not be valid for all fluids. The five sets of experimental data under consideration were obtained with four different heat-transfer fluids. Therefore, in view of the preceding discussion, it is suggested that data comparisons, as presented in figure 6, be made with reservations.

The divergence in the experimental data could also be attributed to differences in the experiments themselves. Geometry effects relative to the size of the pool and the heat-transfer surface could be quite significant. For instance, the proximity of the wall to the heat-transfer surface could influence

the heat-transfer characteristics of the surface. Free-convection cell-like effects could be present or absent at specific heat loads. The pool can be sized so that the critical heat flux at Earth gravity would subject the system to wall effects, while the relatively lower heat flux at nearly zero gravity might or might not be sensitive to these effects. The use of the nondimensional parameter q/q_e , as plotted in figure 6, would then reflect these differences.

The nature of the methods used to establish the reduced-gravity fields makes proper control of the experiments quite difficult. The nearly zero-gravity drop-tower data were obtained between 0.01 and 0.04 g's, depending on the amount of drag that the apparatus was subjected to during the free falling period. Variations in the amount of subcooling present in the heat-transfer fluid could be quite significant. The amount of testing time available in relation to the establishment of steady-state heat-transfer conditions could be an important factor in spreading the data. The towers used for these tests maintained nearly zero gravity fields for fractions of a second up to a maximum value of 1.8 seconds. It is suggested that these short periods of time do not permit the establishment of steady-state heat transfer. Adelberg and Forster (ref. 23) and others have also questioned the steady-state nature of drop-tower data.

Time requirements for the establishment of steady-state conditions could be related to the sensitivity of the thermal-layer thickness to the gravity field. In drop-tower techniques the thermal layer is first established in Earth gravity. During the drop, this layer must be attempting to adapt to the reduced-gravity field. This type of transient effect could certainly influence the data.

The driving forces that are associated with a Taylor-Helmholtz type of instability that occurs when both the liquid and the vapor phase of a fluid fight for possession of a heat-transfer surface could also require a finite time to adapt to a new gravity field. The critical heat flux may, therefore, be a function of time within certain limitations.

Theoretical approaches to determine the relation between the critical heat flux and the acceleration force have resulted in the $1/4$ -power relation presented in figure 6 as a dashed line. It is suggested that this relation not be considered an absolute standard because of its semitheoretical nature. The possibility exists that all pertinent parameters were not considered in the evaluation of the exponent or that the model used to develop the criteria might be wrong. The prediction of zero critical heat flux at zero gravity has not been substantiated by any type of experimental data.

The present data obtained by the magnetic body force technique are unique because of their freedom from transient effects. The nature of the gravity simulation allows tests to be run essentially independent of time. Although the technique eliminates one of the shortcomings inherent in drop-tower techniques, it produces others that are difficult to evaluate. In the Experimental Apparatus section of this report a description of the magnetic-colloid system showed that the vapor phase of the liquid cannot be significantly influenced by magnetic fields. Consequently, the vapor phase is always subject to Earth gravity.

This effect should be evaluated before the absolute values of the present data are accepted as valid.

Furthermore, the solid particles suspended in the fluid could possibly act as nucleation sites in the thermal layer near the heater. The thicker thermal layer present at low gravity might contain additional nucleation sites to influence the heater surface. It is also possible that vaporization of the fluid at the heater surface might cause an increased concentration of magnetic particles in the thermal layer. This would result in higher critical heat fluxes caused by local convective currents that are induced by a nonuniform magnetic gradient.

In addition, although calculations have established the uniformity of the magnetic gradient used for this study, it is still possible that a variation of the gradient, undetected by the calculations, might induce convective gradients and pressure forces on the bubbles.

Finally, a magnetic field induced by an ac current of approximately 10 amperes flowing through the heater might be sufficient to distort the magnetic field produced by the solenoid magnet and also result in convective gradients and pressure forces.

The present data (fig. 6) show that the critical heat flux at nearly zero g is still 85 percent of the critical heat flux available under Earth-gravity conditions. This percentage represents the amount of heat transfer that could be attributed to the gravity-independent forces of the boiling process. The remaining 15 percent is the gravity effect on the nucleate-boiling system caused by the elimination of the gravity-dependent forces. The differences in these percentages should be considered unique for the pool-boiling system used for this study until their generality is established by further tests.

SUMMARY OF RESULTS

A novel gravity simulation technique was described that uses magnetic body forces to cancel out the influence of Earth gravity on a low-viscosity, stable magnetic colloid. The weight of the fluid was reduced in a magnetic gradient oriented parallel but opposite to the Earth-gravity vector. Proper control of the magnitude of the gradient subjected the fluid to effective accelerations between nearly zero and Earth gravity. The lack of time dependency in the gravity simulation makes this technique a useful tool for examining gravitational effects on fluids for extended periods of time.

An experimental study was then made to determine the effect of the buoyancy force on a colloidal pool-boiling system consisting of 6.8 weight percent magnetic iron oxide in normal heptane. Steady-state, saturated nucleate pool-boiling heat-transfer data were obtained over a range of body force loadings between nearly zero and Earth gravity. Measurable changes in the boiling curves were observed in the critical-heat-flux region and the boiling incipience region.

In the high-heat-flux region, the data showed a decrease in the critical heat flux as the gravity field was reduced. At nearly zero gravity, the heat flux representing the upper limit of nucleate boiling dropped to 85 percent of the value of the critical heat flux available under Earth-gravity conditions. The 15-percent drop was attributed to the elimination of the buoyancy force on the heat-transfer mechanisms involved.

The reduced-gravity fields also affected the relative positions of the low-heat-flux portions of the data curves. The incipient boiling point shifted to lower temperatures as the gravity field was reduced. A drop in heater temperature of 5° F (2.8° C) was observed between Earth gravity and nearly zero gravity. Explanations for this phenomenon were made in terms of the thermal-layer thickness and its sensitivity to the gravity field. The thermal-layer thickness varies inversely as a function of the g field, and it is believed that the thicker thermal layer at low gravity can provide a medium more favorable for bubble ebullition.

Critical-heat-flux comparisons were made with data that included the present and reference data. At nearly zero gravity (0.01 to 0.04 g) a spread in the data of 68 percent was observed. The differences were, in part, attributed to possible transient, geometry, and fluid property effects. Experimental procedure and control could also be an important factor in assessing the differences in the data. Small differences in subcooling could result in significant differences in the data.

The present data, although unique because of their steady-state nature, could still possibly be subject to some of the shortcomings of the drop-tower data in the references, such as the effect of apparatus geometry. In addition, possible problems created by the nature of the magnetic body force gravity simulation technique itself could influence the heat-transfer data.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 3, 1965.

REFERENCES

1. Merte, Herman, Jr.; and Clark, J. A.: Pool Boiling in an Accelerating System. *J. Heat Transfer*, vol. 83, no. 3, Aug. 1961, pp. 233-242.
2. Costello, C. P.; and Adams, J. M.: The Interrelation of Geometry, Orientation, and Acceleration in the Peak Heat Flux Problem. *A.I.Ch.E. J.*, vol. 9, no. 5, Sept. 1963, pp. 663-671.
3. Costello, Charles P.; and Tuthill, William E.: Effects of Acceleration of Nucleate Pool Boiling. *Chem. Eng. Progr.*, vol. 57, Symp. Ser. no. 32, 1961, pp. 189-196.
4. Slember, Richard J.: An Investigation of Pool Boiling Under Variable Fluid Body Force Conditions. Ph. D. Thesis, Univ. of Pittsburgh, 1961.

5. Costello, C. P.; and Adams, J. M.: Burnout Heat Fluxes in Pool Boiling at High Accelerations. International Developments in Heat Transfer. Proceedings of the International Heat Transfer Conference, Boulder, Colo., and Westminster, Eng., 1961-1962. Pt. 2, 1961. ASME, 1963, pp. 255-261.
6. Graham, Robert W.; and Hendricks, Robert C.: A Study on the Effect of Multi-g Accelerations on Nucleate-Boiling Ebullition. NASA TN D-1196, 1963.
7. Choi, Harry Y.: Electrohydrodynamic Boiling Heat Transfer. Ph. D. Thesis, Massachusetts Institute of Technology, 1962.
8. Durfee, Robert L.; and Markels, Michael, Jr.: Effects of Electrical Fields on Boiling Heat Transfer. Rep. NYO-2404-1, Atlantic Research Nuclear Corp., 1964.
9. Siegel, R.; and Usiskin, C. M.: A Photographic Study of Boiling in the Absence of Gravity. Paper No. 59-AV-37, ASME, Mar. 1959.
10. Usiskin, C. M.; and Siegel, R.: An Experimental Study of Boiling in Reduced and Zero Gravity Fields. Paper No. 60-HT-10, ASME, Aug. 1960.
11. Steinle, Hans F.: An Experimental Study of the Transition From Nucleate to Film Boiling Under Zero-Gravity Conditions. Proceedings of the 1960 Heat Transfer and Fluid Mechanics Institute, D. M. Mason, W. C. Reynolds, and W. G. Vincenti, eds., Stanford Univ. Press, 1960, pp. 208-219.
12. Clark, John A.; and Merte, Herman, Jr.: Nucleate, Transition, and Film Boiling Heat Transfer at Zero Gravity. Physical and Biological Phenomena in a Weightless State. Vol. 14 of Advances in the Astronautical Sciences, ed. by Elliot T. Benedikt and Robert W. Halliburton, Western Periodicals Co., 1963, pp. 177-195.
13. Sherley, J. E.: Nucleate Boiling Heat-Transfer Data for Liquid Hydrogen at Standard and Zero Gravity. Advances in Cryogenic Engineering. Vol. 8, K. D. Timmerhaus, ed., Plenum Press, 1963, pp. 495-500.
14. Clodfelter, Robert G.: Low-Gravity Pool-Boiling Heat Transfer. Rep. APL-TDR-64-19, Aero Propulsion Lab., Research and Technology Div., Air Force Systems Command, (DDC No. AD 437803) Mar. 1964.
15. Lyon, D. N.; Jones, M. C.; Ritter, G. L.; Chiladakis, C. I.; and Kosky, P. G.: Peak Nucleate Boiling Fluxes for Liquid Oxygen on a Flat Horizontal Platinum Surface at Buoyancies Corresponding to Accelerations Between -0.03 and $1 g_E$. A.I.Ch.E. J., vol. 11, no. 5, Sept. 1965, pp. 773-780.
16. Brown, Gerald V.; Flax, Lawrence; Itean, Eugene C.; and Laurence, James C.: Axial and Radial Magnetic Fields of Thick, Finite-Length Solenoids. NASA TR R-170, 1963.

17. Bean, C. P.: Hysteresis Loops of Mixtures of Ferromagnetic Micropowders. J. Appl. Phys., vol. 26, no. 11, Nov. 1955, pp. 1381-1383.
18. Hsu, Y. Y.: On the Size Range of Active Nucleation Cavities on a Heating Surface. J. Heat Transfer (ASME Trans.), ser. C, vol. 84, no. 3, Aug. 1962, pp. 207-216.
19. Borishanskii, V. M.: An Equation Generalizing Experimental Data on the Cessation of Bubble Boiling in a Large Volume of Liquid. Zh. Tekhn. Fiz., vol. 26, no. 2, Feb. 1956, pp. 452-456.
20. Zuber, Novak: On the Stability of Boiling Heat Transfer. Trans. ASME, vol. 80, no. 3, Apr. 1958, pp. 711-721.
21. Chang, Yan-Po; and Snyder, Nathan W.: Heat Transfer in Saturated Boiling. Chem. Eng. Progr. Symp. Ser., vol. 56, no. 30, 1960, pp. 25-38.
22. Siegel, Robert; and Howell, John R.: Critical Heat Flux For Saturated Pool Boiling From Horizontal and Vertical Wires in Reduced Gravity. NASA TN D-3123, 1965.
23. Adelberg, Marvin; and Forster, H. Kurt: The Effect of Gravity Upon Nucleate Boiling Heat Transfer. Weightlessness - Physical Phenomena and Biological Effects, Elliot T. Benedikt, ed., Plenum Press, 1961, pp. 97-101.

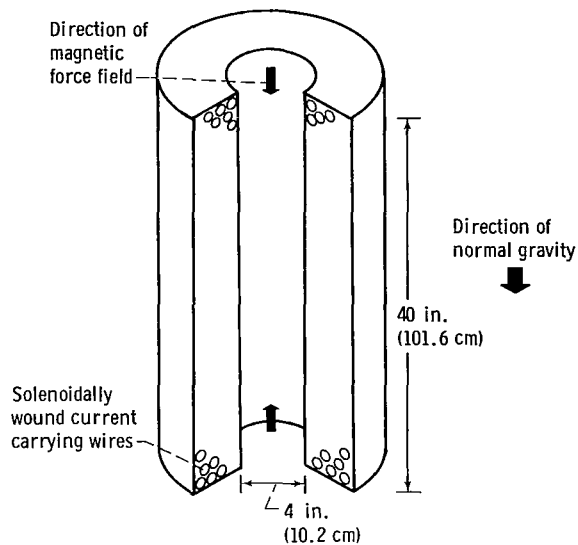


Figure 1. - Sectional view of electromagnet showing directions of magnetic force field.

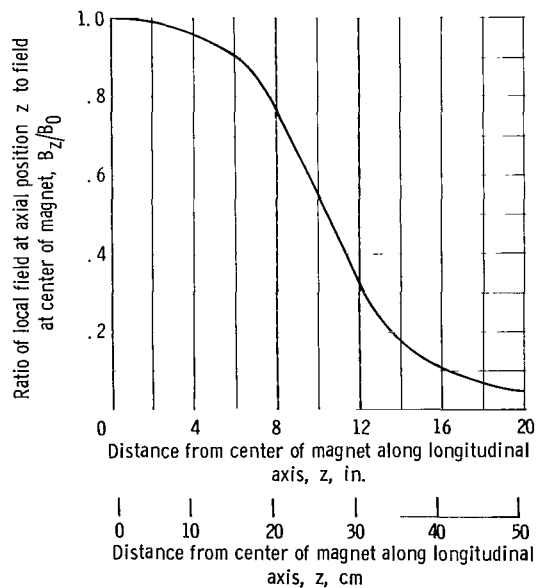


Figure 2. - Calculated distribution of axial component of magnetic field.

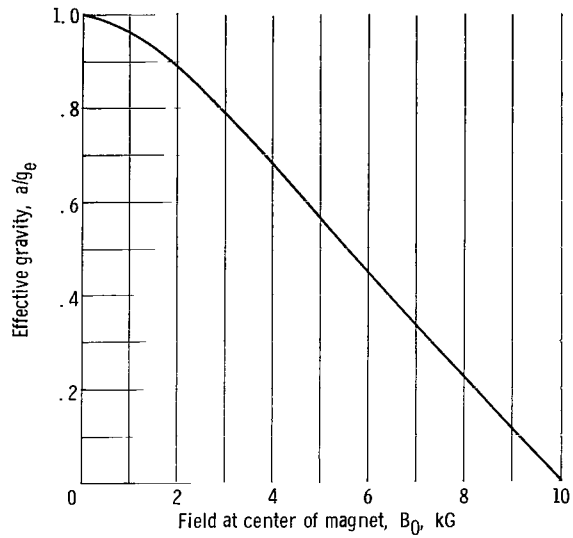


Figure 3. - Effective gravity calibration for magnetic iron oxide - normal heptane colloid at longitudinal distances from center of magnet of 8 to 12 inches (20.32 to 30.48 cm).

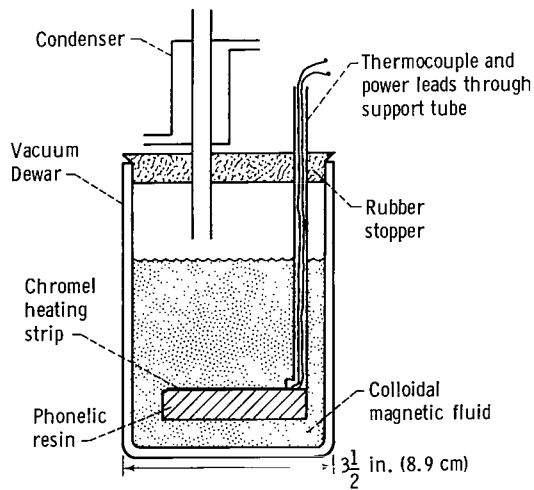


Figure 4. - Pool-boiling heat-transfer apparatus.

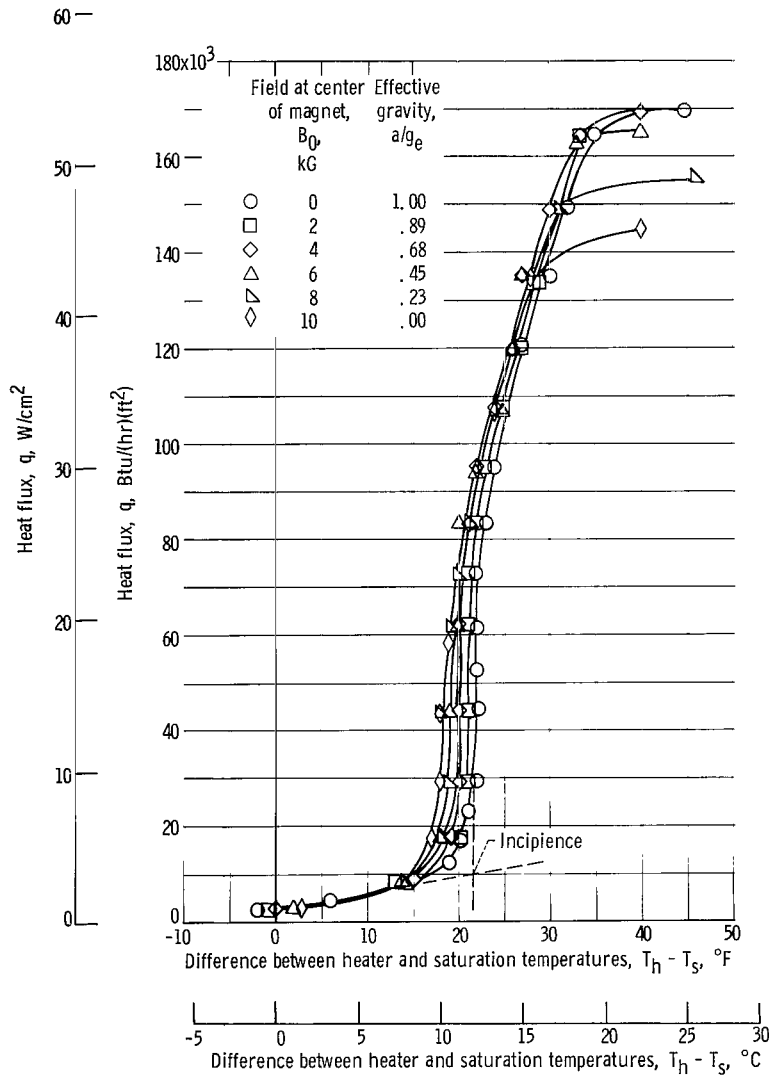


Figure 5. - Gravitational effects on pool-boiling heat transfer in magnetic iron oxide - normal heptane colloid. Saturation temperature, 205° F (96° C).

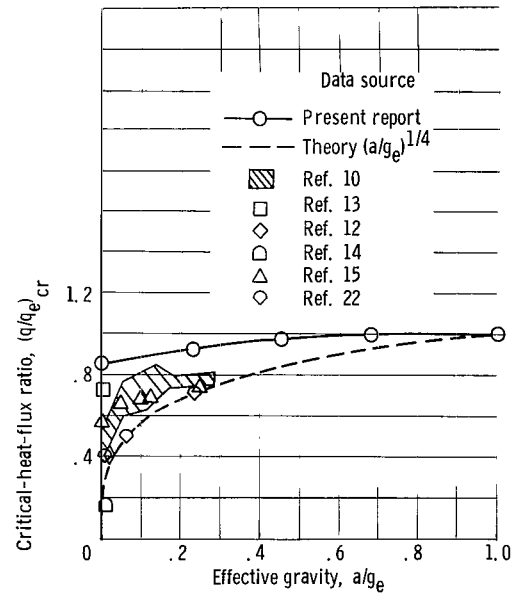


Figure 6. - Gravitational effects on critical heat flux during pool boiling of magnetic iron oxide - normal heptane colloid.

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