NASA TECHNICAL MEMORANDUM

NASA TM X-52264

NASA TM X-52264

FACILITY FORM 602

N67-16044
(ACCESSION NUMBER)

(THRU)

14
(PAGES)

1
(CODE)

TMX-52264
(NASA CR OR TMX OR AD NUMBER)

33
(CATEGORY)

AN EXPERIMENTAL INVESTIGATION OF BOILING IN NORMAL AND ZERO GRAVITY

GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) 3.00

Microfiche (MF) .65

ff 653 July 65

by Thomas H. Cochran, John C. Aydelott
and Charles M. Spuckler
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at 1967 Annual Meeting of the Institute of Environmental Sciences Washington, D.C., April 10-12, 1967

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1967

AN EXPERIMENTAL INVESTIGATION OF BOILING IN NORMAL AND ZERO GRAVITY

by Thomas H. Cochran, John C. Aydelott and Charles M. Spuckler

Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at

1967 Annual Meeting of the Institute of Environmental Sciences
Washington, D.C., April 10-12, 1967

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

AN EXPERIMENTAL INVESTIGATION OF BOILING IN NORMAL AND ZERO GRAVITY

By: Thomas H. Cochran, John C. Aydelott and Charles M. Spuckler

THOMAS H. COCHRAN

Joined NASA-Lewis in 1962 and is a project leader performing research in studying the effect of a zero gravity environment on heat transfer processes. He graduated from Rensselaer Polytechnic Institute in 1962 with a BSME and is pursuing graduate work at Case Institute of Technology.

JOHN C. AYDELOTT

Performs technical supervision of projects studying heat transfer processes. Having been at NASA-Lewis since 1962, he has degrees from Cornell University of a BME in 1961 and a MS in 1967.

CHARLES M. SPUCKLER

Is an assistant project leader studying heat transfer processes. He graduated from Cleveland State University in 1966 with a BME degree.

SUMMARY

The effects of gravity on boiling from a flat horizontal surface is investigated in the heat flux range defined as the discrete bubble region for various subcoolings, fluid properties and heat transfer rates. The zero gravity data were obtained by allowing the experimental package to free fall in a 100 foot drop tower, which permitted the attainment of less than 10^{-5} times earth gravity. Data taken from high speed motion pictures indicated that boiling was independent of gravity at high subcooling and that the transition from the discrete bubble region occurred at a lower heat flux in zero gravity than in normal gravity. Application of an analysis to the data indicated that a newly defined pressure force was of major importance in bringing about bubble separation.

Introduction

In the last decade the scientific community has been confronted with a whole new class of problems because of the desire of man to travel in the low gravity environment of space. Tanks containing cryogenic liquids used as rocket propellants, and in life support systems, will be subjected to energy input from solar radiation and other sources. For a sealed tank this energy input will cause the tank pressure to increase and as a result the liquid bulk may become subcooled (Ref. 1). Consequently, one of the areas of interest for reduced gravity research has been heat transfer and, in particular, the subcooled nucleate boiling process.

The pioneering work in this field was carried out by Dr. Robert Siegel and co-workers (Refs. 2 to 6) at the Lewis Research Center. These investigators, using a $12\frac{1}{2}$ foot drop tower which made available approximately 1 second of reduced gravity time, photographed the gravitational effect on water boiling at saturation conditions. This work revealed the importance of bubble dynamics on heat transfer processes in low gravity environments.

The purpose of this paper is to present a summary of the results of an extension of this initial effort to study the effect of zero gravity on boiling for various subcoolings, fluid properties, and heat transfer rates (Refs. 7 and 8). Analysis of the photographic data included a statistical study of the maximum radii and lifetimes of the generated bubbles and calculation of the forces acting during the growth and collapse of the bubbles on the generating surface. From these results, interpretations regarding the dynamics of bubbles and effects on the boiling processes are made and discussed.

SYMBOLS

D	diameter, ft
F	Force, lb-force
F_B	buoyancy force, lb-force
F_{D_r}	drag force, lb-force
F_{D_y}	dynamic force, lb-force
F_P	pressure force, lb-force
F_S	total surface tension force, lb-force
F_{S_y}	surface tension force, lb-force
g	acceleration due to gravity, ft/sec^2
g_c	gravitational constant, (lb-mass/lb-force)(ft/sec^2)
g_o	standard acceleration of gravity on earth, ft/sec^2
R	radius measured from bubble center of mass, ft
R_T	radius of curvature of top surface, ft
t	time, sec
V	bubble total volume, ft^3
V_b	bubble volume directly over base, ft^3
Y	distance above heater surface to bubble center of mass, ft
μ	dynamic viscosity (lb-force)(sec)/ft^2
v	velocity, ft/sec

X-52264

ρ density, lb-mass/ft^3

σ surface tension, lb-force/ft

τ dimensionless time

φ contact angle

Subscripts:

b base

l liquid

max maximum

S heater surface

Sat saturated conditions

v vapor

ANALYSIS

Bubble Model

In order to calculate the volume and center of mass of the generated vapor mass, a bubble model is assumed. The only restrictions placed on the model are that it is symmetric with respect to the y-axis, as shown in figure 1, and that the surface of the bubble directly over the base is a spherical segment. Simple geometric formulas cannot be used to calculate bubble total volume because of the general nature of the model. Consequently, volume is determined by an integrative method in which a bubble is divided into segments, the volumes of which can be approximated if they are assumed to be circular disks. The sums of the volumes of the disks produce the total volume. The volume directly over the bubble base is obtained by assuming that the volume is a right circular cylinder with a segment of a sphere as a cap.

The center of mass of a bubble used to describe its motion is determined from the location of the plane parallel to the heater surface which divides the bubble in half with respect to its total volume.

BUBBLE FORCES

General. - An analytical investigation of the dynamics of a bubble on a heated surface results in the identification of buoyancy, surface tension, pressure, drag, and dynamic forces. The force associated with the vapor weight is neglected because the experimental conditions are such that it is very small. However, for all fluids near the critical thermodynamic state and for some fluids that do not have a large difference between liquid and vapor density, such as hydrogen, this force is large enough to be included.

Buoyancy force. - Buoyancy on an object submerged in a liquid is caused by the difference between the external hydrostatic pressure force on its top surface and the external hydrostatic pressure force on its bottom surface. Therefore, for a bubble attached to a heated surface, the volume of the bubble directly over the base does not generate a buoyant force because of the lack of liquid beneath the base; therefore, the buoyancy force, as derived in reference 7, is

$$F_B = (V - V_b)\rho_l \frac{g}{g_c} \tag{1}$$

and it acts in a direction opposite to the acceleration due to gravity.

Surface tension force. - A surface tension force is generated at the boundary of a liquid and some other substance, such as a vapor or a solid. Therefore, such a force exists at the base of a bubble attached to the heater surface at the boundary of the liquid, vapor, and solid surface. The direction of this force is perpendicular to the boundary and in the plane of the liquid-vapor interface. Surface tension is defined as the ratio of the surface force to the length along which the force acts, which, for an attached bubble, is

$$\sigma_S = \frac{F_S}{\pi D_b} \tag{2}$$

The horizontal component of the force is cancelled out around the circumference of the bubble base and only the vertical component remains, such that

$$F_{S_y} = \sigma_S \pi D_b \sin\varphi \tag{3}$$

The contact angle, φ, is the angle at the base between the liquid-vapor interface and the heater surface, as shown in figure 1. This force retards the movement of a bubble from the surface.

Pressure force. - The net force due to the uniform pressure on a bubble surface is zero for a bubble surrounded by liquid. For a bubble attached to a surface, however, the net internal pressure force on the spherical surface area directly over the base is unbalanced. Because the pressure is greater inside the bubble than outside, the force acts to remove the bubble from the surface. The detailed derivation of this force in reference 7, yields

$$F_P = \frac{1}{2}\ \frac{\pi D_b^2}{R_T}\ \sigma_{sat} \tag{4}$$

Drag force. - Viscous effects on a bubble are concerned with the motion of the liquid which surrounds the bubble; therefore, a knowledge of the liquid flow fields is necessary. In reference 7 it was observed that during the growth of a bubble the liquid flow is similar to a source type. Comparison of the viscous and liquid inertia terms in the equation of motion, as presented in reference 8, indicate that for this flow condition the viscous terms may be neglected.

During collapse of a bubble there was evidence of flow around the liquid vapor interface. Consequently, the viscous effects may be represented in the form of a drag force,

$$F_{D_r} = 12\mu_l \pi R_{max} \frac{dY}{dt}$$

as derived in reference 7.

Dynamic force. - The last force to be considered is termed the dynamic force F_{D_y}. This force is associated with effects on the bubble caused by the dynamics of the bubble and the liquid flow field surrounding the bubble. The nature of this dynamic force has not been clearly defined so that direct formulation is speculative. Therefore, in this work, the force is obtained by applying Newton's second law of motion to the generated vapor masses, or

$$F = \frac{d}{dt}\left(M_v \nu\right) \qquad (9)$$

If it is assumed that the positive force direction is that of increasing y, as shown in figure 1, the left side of equation (9) may be expanded in terms of the identified forces:

$$F_B + F_P - F_{S_y} - F_{Dr} + F_{D_y} = \frac{d}{dt}\left(M_v \nu\right) \qquad (10)$$

If, at any instant, a bubble is considered to be a rigid body whose motion is described by the movement of its center of mass, the inertia side of the equation may be expanded in terms of measurable quantities such that

$$F_B + F_P - F_{S_y} - F_{Dr} + F_{D_y} = \frac{\rho_v}{g_c}\left(\frac{dV}{dt}\frac{dY}{dt} + V\frac{d^2Y}{dt^2}\right) + \frac{V}{g_c}\frac{dY}{dt}\frac{d\rho_v}{dt} \qquad (11)$$

When the bubble is observable on the surface, the absolute pressure changes within the bubble are small, so that the change of vapor density with time may be considered negligible. Therefore, when the last term on the right in equation (11) is dropped and the equation is solved for the dynamic force,

$$F_{Dy} = \frac{\rho_v}{g_c}\left(\frac{dV}{dt}\frac{dY}{dt} + V\frac{d^2Y}{dt^2}\right) + F_{Dr} + F_{S_y} - F_B - F_P \qquad (12)$$

APPARATUS, EXPERIMENTAL PROCEDURE,

AND DATA REDUCTION

The zero gravity data was obtained in a drop tower (fig. 2) by allowing the experiment package to undergo an 85-foot unguided free-fall. A gravity level of less than 10^{-5} g_o (termed zero gravity in this work) resulted by having the package fall in a protective air drag shield. Deceleration occurred after 2.25 seconds when wooden spikes mounted to the drag shield, imbeded in a box of sand. The experiment package contained a boiling apparatus, camera and lighting equipment, power supplies and associated controls. Within the boiling apparatus were a strip heater (a chromel strip with an effective heating length of 0.50 in.), a secondary heater which was used to control the temperature of the bulk of the liquid, a thermistor to monitor the bulk temperature, and a temperature sensing device on the underside of the primary heater. The 16 mm motion picture camera provided a filming rate of approximately 6500 pictures per second.

Prior to a data run, the glassware was cleaned and the primary heater was polished and rinsed with Ethanol. The test liquid was deaerated by boiling prior to its insertion in the boiling apparatus. After filling the boiler and raising the package to the top of the drop tower, the test liquid was heated to its approximate saturation temperature with the secondary heater. Power to this heater was removed and the strip heater was turned on and set at a power level that initiated boiling. Because the heat input by the strip heater was not sufficient to maintain saturation conditions, the bulk cooled to the selected subcooling. The power level to the strip heater was then increased to the desired level and the package dropped. Motion pictures were taken during the last 1.25 seconds of zero gravity time. Normal gravity testing was the same as just described with the addition of monitoring the temperature sensing device mounted beneath the strip heater.

The bubbles recorded on the 100 foot rolls of film were viewed, measured, and counted on a motion analyzer that magnified the image eight times. A statistical analysis involved the recording of bubble lifetime and maximum radius for as many as fifteen bubbles at each test condition. Because of the large volume of work required, a computer was used to perform the calculations for the force analysis.

For a more detailed description of the above described equipment and procedures, see references 7 and 8.

RESULTS AND DISCUSSION

Bubble Characteristics

The primary purpose of the work of the authors has been to determine the effect of gravity on boiling under conditions in which the formation and departure of individual bubbles on a heated surface dominated the heat transfer mechanism. Therefore, one of the characteristics studied statistically was the maximum radii bubbles attained while they were attached to the surface. This was investigated for a range of subcoolings and heat transfer rates and for various fluid properties.

For water at high subcooling, little difference was evident between the normal and zero gravity results as shown in figure 3(a). However, for low subcooling there was a trend to larger bubbles in zero gravity than in normal gravity. In fact, for the lowest subcooling in zero gravity, it appeared that a transition out of the discrete bubble region was taking place because of the considerable amount of coalesence that occurred.

The effects of a reduction in surface tension were investigated by testing a liquid (an ethanol-water solution) with a surface tension approximately 30 percent that of water. The density and viscosity of this solution were approximately the same as that for water. The results along with those for water are shown in figure 3(b). Considering the data at approximately 44 000 Btu/hr-ft^2, it is evident that, unlike water, there was little difference between the normal and zero gravity data at all the subcoolings tested.

Lastly, the effect of heat transfer rate for the ethanol-water solution is also indicated in figure 3(b). No effect of gravity as a function of heat transfer rate is evident. However, it should be noted that no data is presented for the higher heat transfer rates at low subcooling in zero gravity. The predominance of coalesence due to (1) the relatively high population density and (2) the fact the bubbles lingered in the vicinity of the surface after separation suggests that a transition out of the discrete bubble region was occurring.

Another characteristic which was investigated statistically was bubble lifetime, or the time a bubble remained attached to the surface. The results of the effect of gravity as a function of subcooling, surface tension and heat transfer rate on bubble lifetime were similar to the findings of the maximum radii study, as shown in figure 4.

The statistical data suggests that gravity independent boiling occurred for high subcooling with all the test liquids and for low subcooling at the lower heat transfer rates with the ethanol-water solution. However, before positive conclusions can be drawn, a detailed study of the forces acting on the bubbles is necessary in order to determine the importance of gravity on the dynamics of the bubbles.

Discussion of Forces

Effect of subcooling. - Force histories (plots of force against time) for water are presented for high and low subcooling in normal and zero gravity in figure 5. At low subcooling, the relatively large role of the buoyant force in normal gravity necessitated the increase of the dynamic force in zero gravity as compared to normal gravity to effect bubble separation. Hence, this condition is gravity dependent. In contrast, at high subcooling, the unimportance of the buoyant force in normal gravity accounts for the similar normal and zero gravity histories. Therefore, from this force data and the statistical results it may be concluded that boiling is independent of gravity at high subcooling.

Effect of viscosity. - In addition to testing a liquid with a surface tension lower than water, one was selected which had a viscosity approximately ten times that of water, i.e., 60 percent sugar-water solution. The surface tension and density of this solution was approximately the same as that for water. The statistical data for this liquid was not presented earlier because the ultimate conclusions regarding its gravity dependence at the different subcoolings were the same as for water. However, dynamic effects caused by the difference in viscosity are apparent from the force histories. For water, the drag force was so small that it was not even plotted, as shown in figure 6. Also in this figure, the sucrose force histories indicate that, although in normal gravity the drag was small in relation to the buoyancy and dynamic forces, in zero gravity near separation, the drag force had a value comparable to the other forces and must have been a major factor in determining the resultant motion of the bubble.

Effect of surface tension. - The statistical analysis indicated that, for the ethanol-water solution, similar bubble characteristics were obtained in normal and zero gravity at comparable subcoolings. At high subcooling this is readily exlained by the small role of the buoyancy force in normal gravity. However, investigation of figure 7 reveals that at low subcooling there is a great difference between the normal and zero gravity histories. Apparently, at low subcooling, a change or changes took place in zero gravity, in addition to the effective absence of gravity, to enable the bubbles to separate from the surface with approximately the same average maximum radius and lifetime as was observed for normal gravity.

A difference that was evident between the water and ethanol-water bubbles was that bubbles generated in the latter were more spherical. A measure of the distortion of the bubbles from spherical may be obtained from the absolute magnitude of the ratio of the pressure force to the surface tension force. For a perfect sphere, the value of this quantity is unity. The ratio also reflects the relative importance of the pressure force as a removal agent. A plot of this distortion parameter versus dimensionless time (the ratio of real time to bubble lifetime) in figure 8 indicates the more spherical nature of the ethanol-water bubbles as compared to those generated in water. It is also apparent that at low subcooling, the ethanol-water bubbles in zero gravity were more spherical than bubbles generated in the same liquid in normal gravity. Therefore, the pressure force dominated bubble dynamics for this liquid at high subcooling in both gravity levels and low subcooling in zero gravity as shown in figure 7.

SUMMARY OF RESULTS

An experimental study of the effects of gravity on boiling from a flat horizontal surface and in the heat flux range defined as the discrete bubble region for various subcoolings, fluid properties, and heat transfer rates yielded the following results:

1. Boiling was independent of gravity at high subcooling.

2. The drag on a bubble generated in a liquid of high viscosity in relation to water and in a zero gravity environment was of importance near separation.

3. A reduction in surface tension from that of water resulted in the average maximum radii and lifetime characteristics of bubbles being similar in normal and zero gravity.

4. The average maximum radii and lifetime characteristics of bubbles generated in a liquid with reduced surface tension compared to water showed no dependence on heat transfer rate in either normal or zero gravity.

5. For low subcooling, the transition from the discrete bubble region occurred at a lower heat flux in zero gravity than in normal gravity.

Addtional findings concerning boiling in general are:

1. The newly defined pressure force was of significance in determining the motion of a generated bubble.

2. Viscous effects on a bubble were negligible during its growth.

REFERENCES

1. Aydelott, John C.: Self Pressurization or Liquid Hydrogen Tankage. M.S. Thesis, Cornell University. To be published.

2. Siegel, R.; and Usiskin, C.: A Photographic Study of Boiling in the Absence of Gravity. J. Heat Trans., vol. 81, no. 3, Aug. 1959, pp. 230-236.

3. Usiskin, C. M.; and Siegel, R.: An Experimental Study of Boiling in Reduced and Zero Gravity Fields. J. Heat Trans., vol. 83, no. 3, Aug. 1961, pp. 243-253.

4. Siegel, R.; and Keshock, E. G.: Effects of Reduced Gravity on Nucleate Boiling Bubble Dynamics in Saturated Water. AIChe J., vol. 10, no. 4, July 1964, pp. 509-517.

5. Keshock, Edward G.; and Siegel, Robert: Forces Acting on Bubbles in Nucleate Boil-Under Normal and Reduced Gravity Conditions. NASA TN D-2299, 1964.

6. Siegel, Robert; and Keshock, Edward G.: Nucleate and Film Boiling in Reduced Gravity From Horizontal and Vertical Wires. NASA TR R-216, 1965.

7. Cochran, Thomas H.; and Aydelott, John C.: Effects of Subcooling and Gravity Level on Boiling in the Discrete Bubble Region. NASA TN D-3449, 1966.

8. Cochran, Thomas H.; and Aydelott, John C.: Study of Fluid Properties and Gravity Level on Boiling in the Discrete Bubble Region. Proposed NASA Technical Note.

E-3765

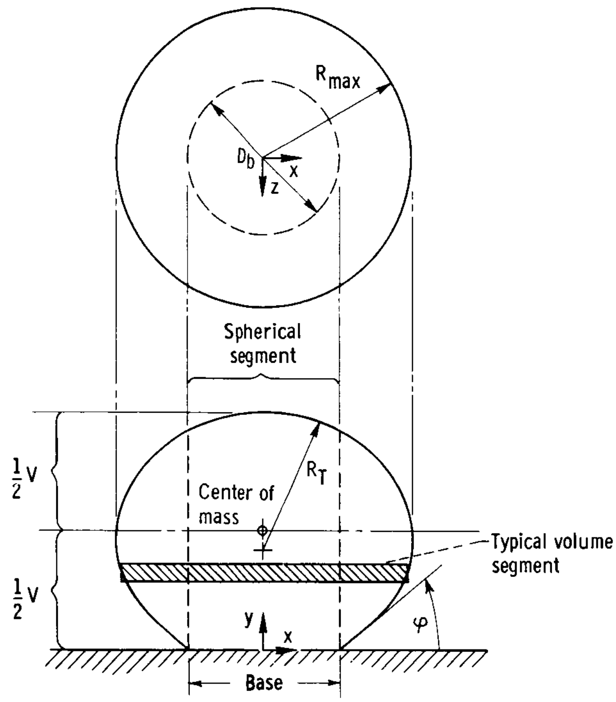
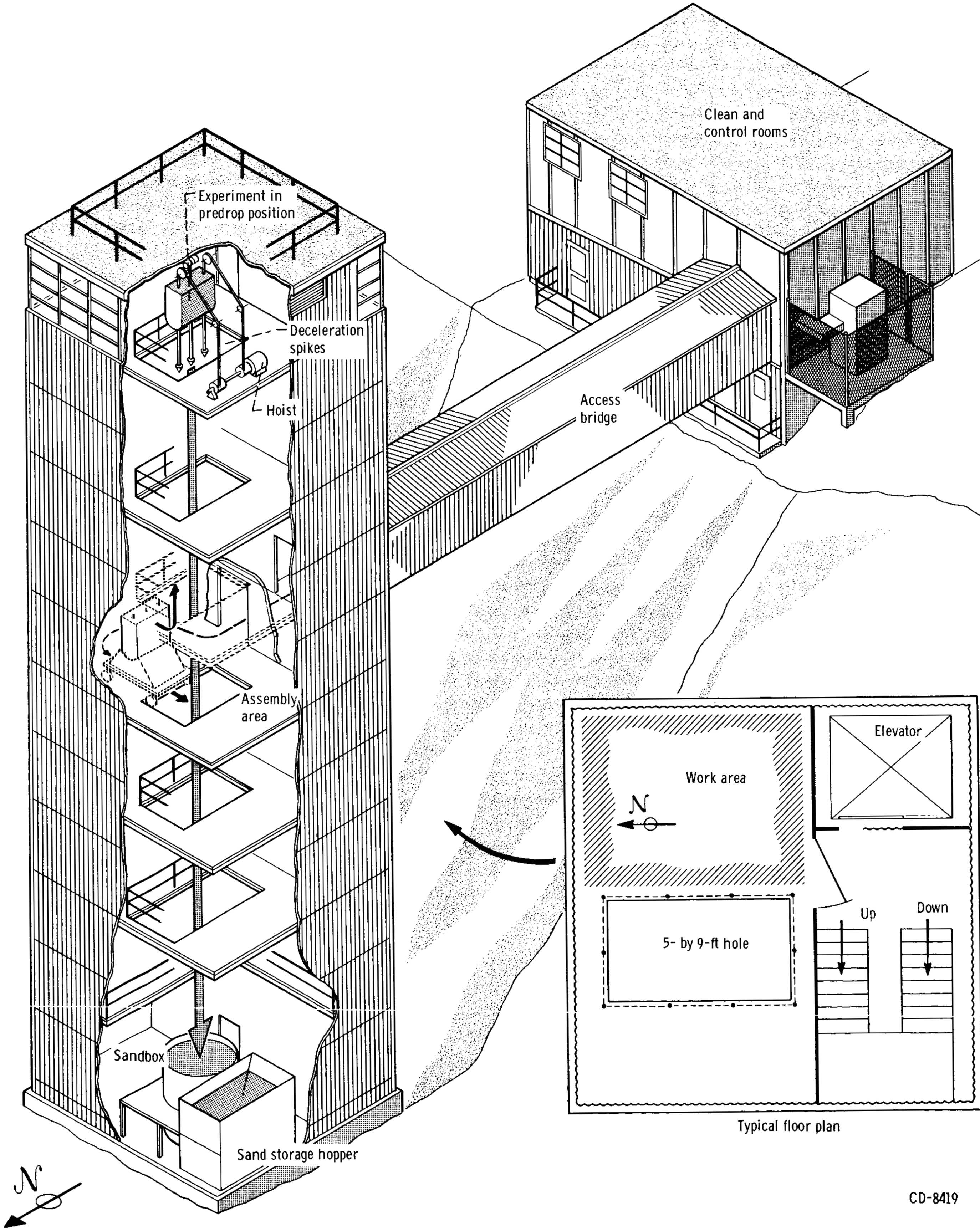


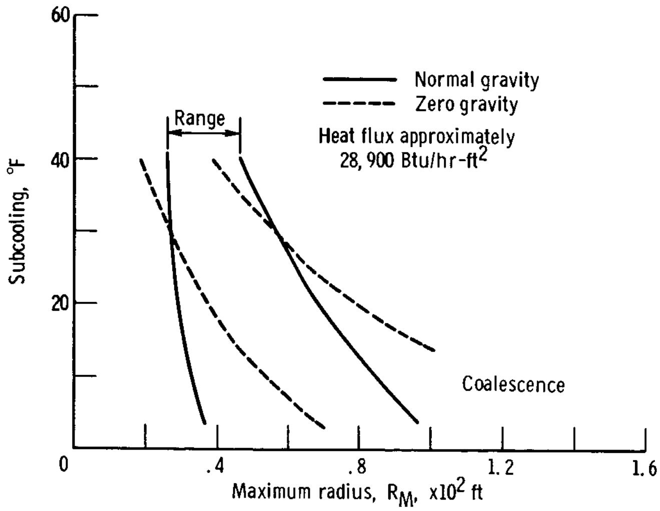
Figure 1. - Bubble model.

E-3765



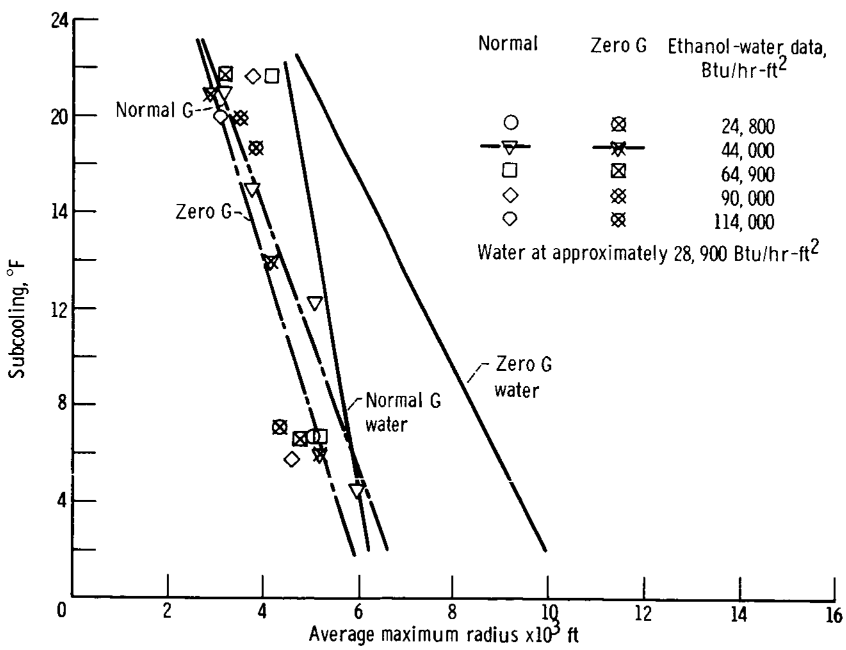
CD-8419

Figure 2. - 100-Foot drop tower.



(a) Subcooling.

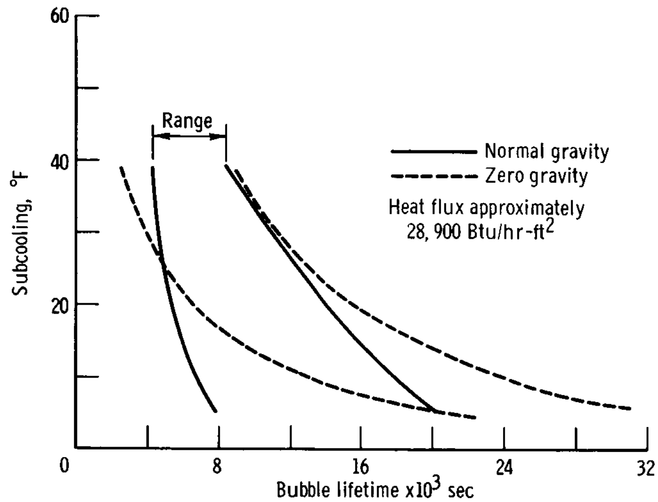
Figure 3. - Effects of gravity as a function of subcooling, surface tension and heat transfer rate on bubble maximum radius.



(b) Surface tension and heat transfer rate.

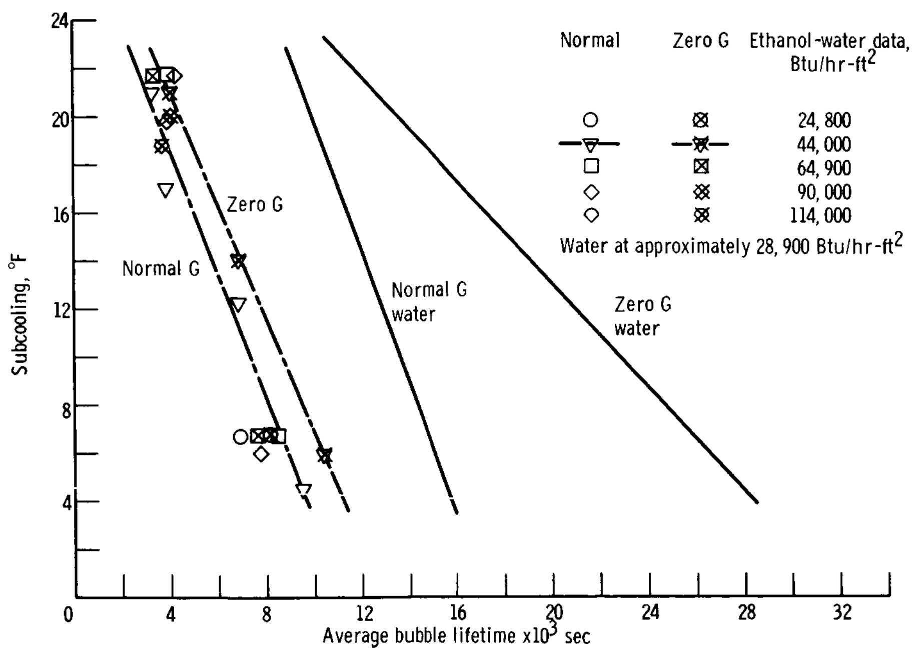
Figure 3. - Concluded.

E-3765



(a) Subcooling.

Figure 4. - Effects of gravity as a function of subcooling, surface tension, and heat transfer rate on bubble lifetime.



(b) Surface tension and heat transfer rate.

Figure 4. - Concluded.

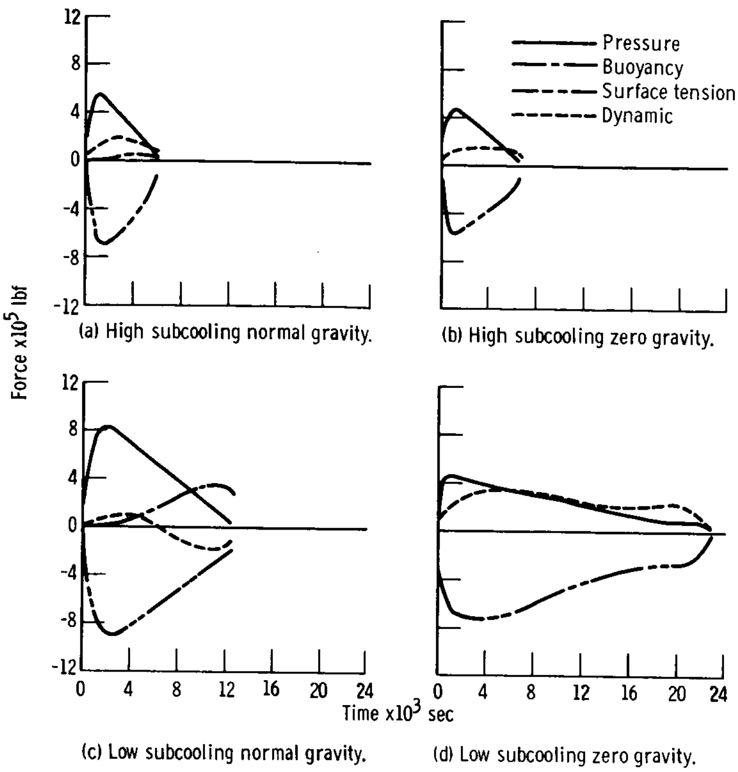


Figure 5. - Dynamics of water bubbles at high and low subcooling in normal and zero gravity.

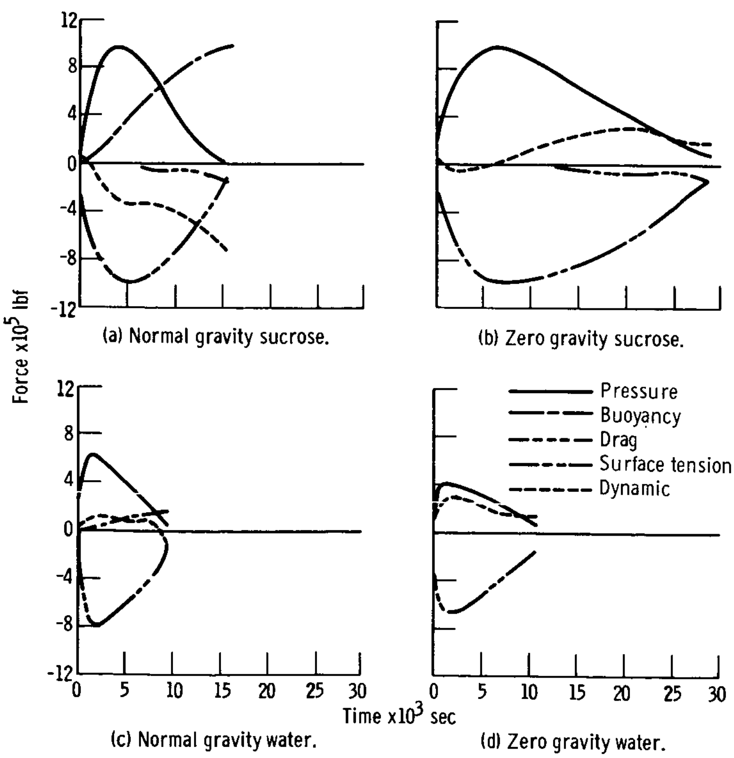
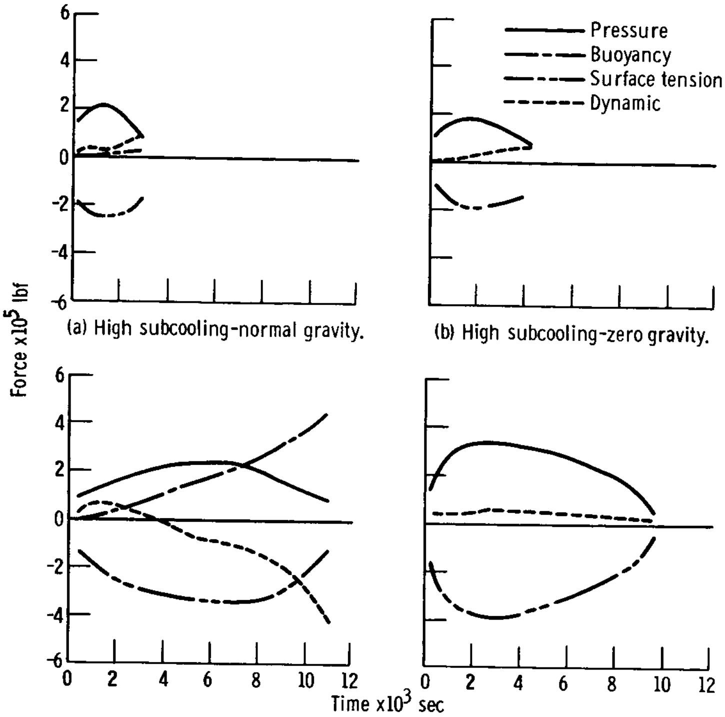


Figure 6. - Dynamics of a sucrose bubble and a water bubble at approximately the same subcooling in normal and zero gravity.

E-3765



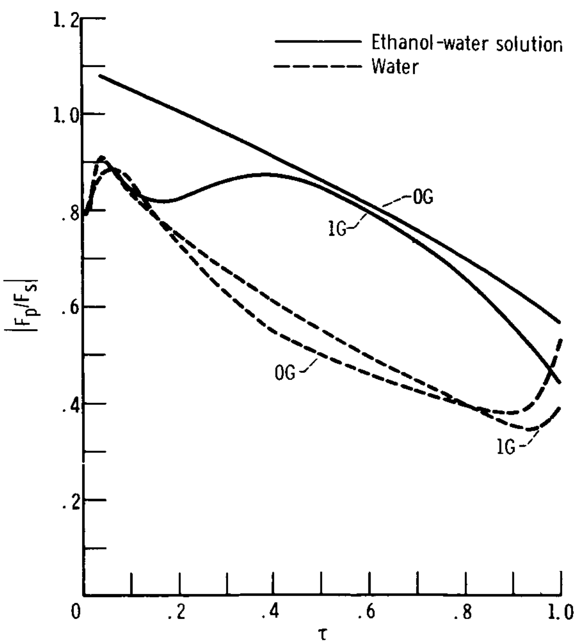
(a) High subcooling-normal gravity.

(b) High subcooling-zero gravity.

(c) Low subcooling-normal gravity.

(d) Low subcooling-zero gravity.

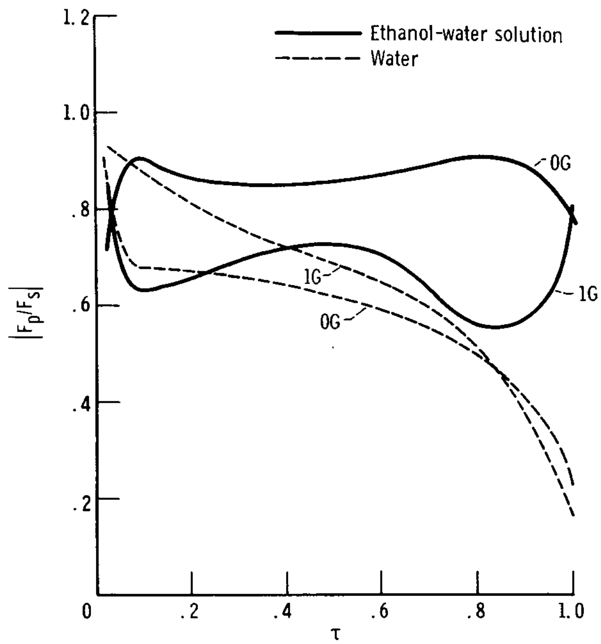
Figure 7. - Dynamics of bubbles in an ethanol-water solution at low and high subcooling in normal and zero gravity.



(a) High subcooling.

Figure 8. - Distortion of bubbles from spherical at high and low subcooling.

E-3765



(b) Low subcooling.

Figure 8. - Concluded.