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FILM BOILING FROM SPHERES – A COMPARISON OF THEORY AND DATA AT STANDARD AND REDUCED GRAVITY

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16. Abstract

Experimental film boiling heat transfer data for spheres emersed in liquid nitrogen are compared to analytic results. The analysis properly follows the data trends with sphere size, acceleration levels (approx 0.001 to 1 = a/g), and pressure (1, 3, and 5 atm); however, the predicted heat flux level is low.

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FILM BOILING FROM SPHERES - A COMPARISON OF THEORY AND DATA AT STANDARD AND REDUCED GRAVITY

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SUMMARY

Experimental data from spheres, film boiling in liquid nitrogen at standard and reduced gravity, are compared herein to analysis. The data and analytic results are presented in the form of heat flux as a function of temperature difference. The data were found to be Bond number $Bo = \left[(\rho_l - \rho)gR^2/\sigma\right]$ dependent where ρ_l is the liquid density and σ the surface tension. The analysis properly predicts the data trends with variations in sphere size (R) and acceleration (g). Trends with pressure level variations to 5 atmospheres were also predicted. However, the predicted heat flux level was generally about 20 percent lower than the experimental data.

For preliminary calculations a simplified form of Nusselt number Nu as a function of modified Rayleigh number Ra*

$$Nu = 0.14(Ra^*)^{1/3}$$

could be used with good rapport.

INTRODUCTION

Frederking and Clark (ref. 1) developed an integral theory for film boiling from cylinders and spheres; they found, however, that empirical modifications were necessary to fit existing data. For spheres they recommended the following rather simple form:

$$Nu = 0.14(Ra^*)^{1/3} \tag{1}$$

where

$$Ra^* = Gr \cdot Pr \cdot S = \frac{\rho(\rho_l - \rho)gd^3}{\mu^2} \cdot \frac{c_p\mu}{k} \cdot \frac{\lambda^*}{c_p \Delta T} \tag{2}$$

is usually called the modified Rayleigh number. It must be pointed out that the heat flux predicted by equation (1) does not depend on the sphere diameter.

Hendricks and Baumeister (ref. 2) modeled film boiling from spheres in terms of the vapor escaping into a spherical vapor dome which surmounted the sphere (see fig. 1).

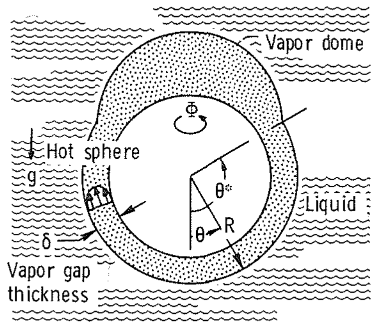


Figure 1. - Idealized model of film boiling from a sphere.

They solved the governing equations and, subject to a set of constraints, maximized the heat transfer for the given configuration. From the analysis, Bond number

$$Bo = \frac{(\rho_l - \rho)gR^2}{\sigma}; \quad Bo_d = 4\ Bo \tag{3}$$

appeared as a significant parameter relating the geometry and the interface configuration. The expression they recommended involves a rather complicated dependence on Bond number:

$$Nu = 2 + \frac{1}{4}\left[\frac{-2Ra^* G(Bo)}{3}\right]^{1/4} + \left[0.177\left(Ra^*\sqrt{Bo_d}\right)^{1/4} + \csc\theta^*\right](1 + \cos\theta^*) \tag{4}$$

The parameter θ^* and the function G(Bo) are both dependent on Bond number (ref. 2).

At large Bond numbers, equation (4) reduces to

$$Nu = 0.35\left(Ra^*\sqrt{Bo_d}\right)^{1/4} \tag{5}$$

For small Bond numbers, equation (4) becomes

$$Nu = 3 + \left(Ra^*\sqrt{Bo_d}\right)^{1/4}\left(\frac{0.71}{Bo_d^{1/8}} + 0.177\right) \tag{6}$$

Equation (5) is similar to equation (1) in that the predicted heat flux does not depend on sphere diameter. However, at low Bond numbers the predicted heat flux is dependent on sphere diameter; consequently, equations (1) and (6) are considerably different.

A small Bond number is associated with small spheres and/or low acceleration. (Low density differences are usually coupled with a rapid decrease in surface tension which increases Bond number.)

In reference 3 the effect of sphere size on film boiling heat transfer was investigated. The data of reference 3 were in good agreement with the theory (eq. (4)). Another test of the analysis was available, that is, that of low acceleration; unfortunately these data (ref. 4) were overlooked by the author (see also ref. 5). Thus, the purpose of this report is to test the analysis of reference 2 at low accelerations and at the same time to compare equations (1) and (4).

In all cases presented herein the fluid is liquid nitrogen.

SYMBOLS

a/g	g-level
Bo	Bond number, $(\rho_l - \rho)gR^2/\sigma$
c_p	specific heat, J/g-K
d	sphere diameter, cm
g	acceleration of gravity, cm/sec^2
h	heat transfer coefficient, W/cm^2-K
k	thermal conductivity, J/cm-sec-K
Nu	Nusselt number, hd/k
P	pressure, MN/m^2
q	heat flux, W/cm^2
R	sphere radius, cm
Ra*	modified Rayleigh number, $\rho(\rho_l - \rho)gd^3\lambda^*/\mu k(T_s - T_{sat})$

T	temperature, K
t	time, sec
δ	vapor gap thickness, cm
θ	angular coordinate, radians
θ^*	submergence angle, radians
λ^*	modified latent heat of vaporization, $\lambda\left[1 + \frac{c_p(T_s - T_{sat})}{2\lambda}\right]$, J/g
μ	dynamic viscosity, g/cm-sec
ρ	density
σ	surface tension, dyne/cm
Φ	angular coordinate, radians

Subscripts:

c	critical
l	liquid
s	sphere surface
sat	saturation

RESULTS AND DISCUSSION

Figure 2 represents the predicted heat flux, q, as a function of temperature difference, $\Delta T = T_s - T_{sat}$, using equations (1) and (4) (refs. 1 and 2, respectively) for various acceleration levels, a/g, at a pressure of 1 atmosphere. At $a/g = 1$, equations (1) and (4) agree on the average; however, the theory of reference 2 (eq. (4)) indicates a significant deviation as sphere diameter is halved from 2.54 to 0.635 centimeter. At $a/g = 0.03$ the variation with sphere diameter is more acute as Bond number has been reduced by nearly a factor of 6. The $a/g = 0.003$ and 0.001 predicted heat fluxes for the 2.54-centimeter-diameter sphere are included for comparison.

In order to assess the effect of pressure on film boiling from spheres, the calculations for heat flux were carried out at 3 and 5 atmospheres (see fig. 3). Note the significant increase (about 30 percent) in predicted flux by both equations (1) and (4) as the pressure is changed from 1 to 3 atmospheres. Further increases in pressure result in increases in predicted heat flux until in the near critical regime where the entire analyses of both references 1 and 2 become questionable. The theoretical prediction of heat

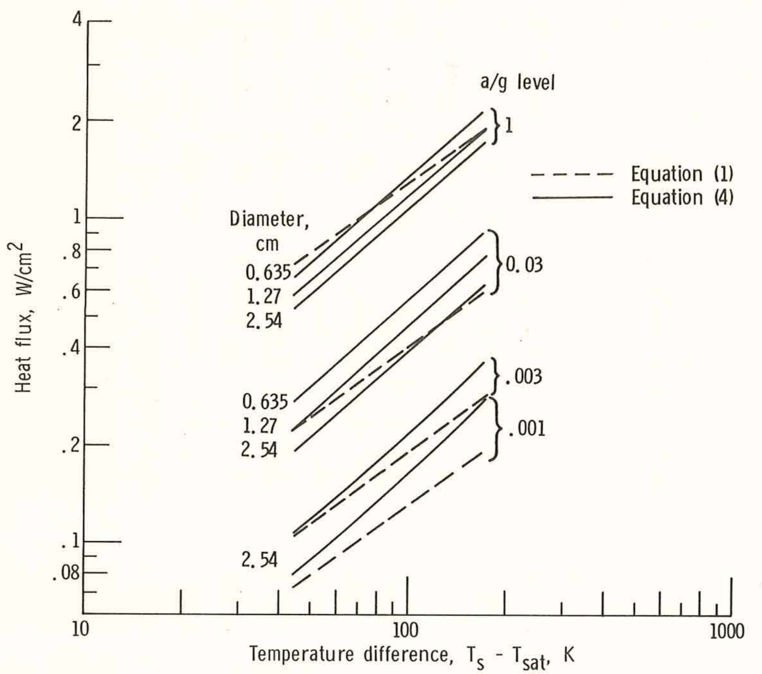
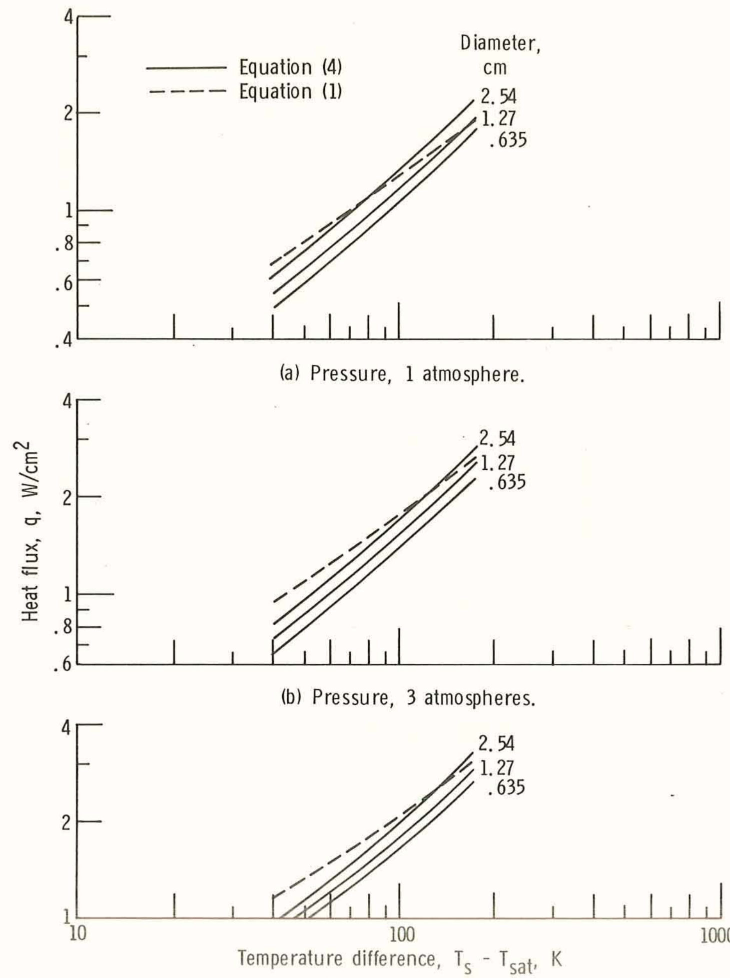


Figure 2. - Film boiling from spheres. Predicted heat flux comparisons for various a/g levels and diameters; pressure, 1 atmosphere.



(a) Pressure, 1 atmosphere.

(b) Pressure, 3 atmospheres.

(c) Pressure, 5 atmospheres.

Figure 3. - Film boiling from spheres. Predicted heat flux comparisons for various diameters and pressures (atm x 0.101325 = MN/m^2).

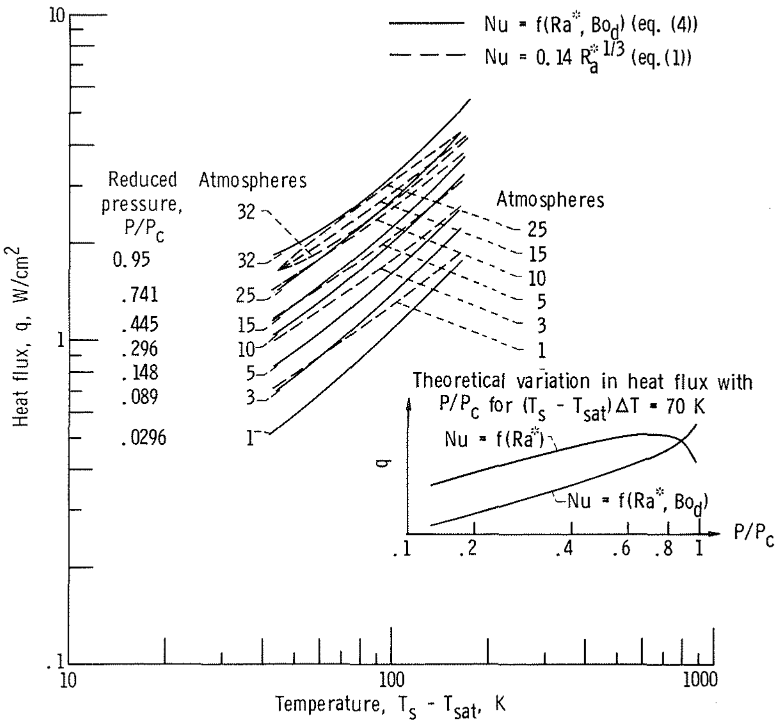


Figure 4. - Film boiling from a sphere. Theoretical predictions of heat flux with elevated pressures.

flux with pressure is illustrated in figure 4. The insert in figure 4 indicates the variation of heat flux with reduced pressure (P/P_c) for a fixed temperature difference of 70 K. Equation (1) predicts a broad maximum and a decrease in heat flux for $P/P_c > 0.75$; however, equation (4) exhibits no optimum and increases as $P/P_c \rightarrow 1$. It is evident that data are needed in this regime.

In figure 5, the data of reference 4 are compared to the heat flux predicted by equation (4) for $a/g = 1$ and pressures of 1, 3, and 5 atmospheres. At 1 atmosphere, the data separation agrees well with theory for three sphere diameters, 2.54, 1.27, and 0.635 centimeter. This of course indicates that the data are diameter (Bond number) dependent. However, the heat flux level is about 20 percent lower than the data. Note that equation (1) predicts the heat flux for the large sphere, 2.54 centimeters, very well for both level and trend, but that equation (1) does not predict the separation with diameter. The level will be discussed later in this section. At pressure levels of 3 and 5 atmospheres the data again exhibit a Bond number dependency, and trends agree well with the predicted heat flux. But, as indicated before, the heat flux levels are below the data. These data indicate that while equation (1) predicts an average value of heat flux, equation (4) properly predicts the data separation with diameter, which is directly related to Bond number.

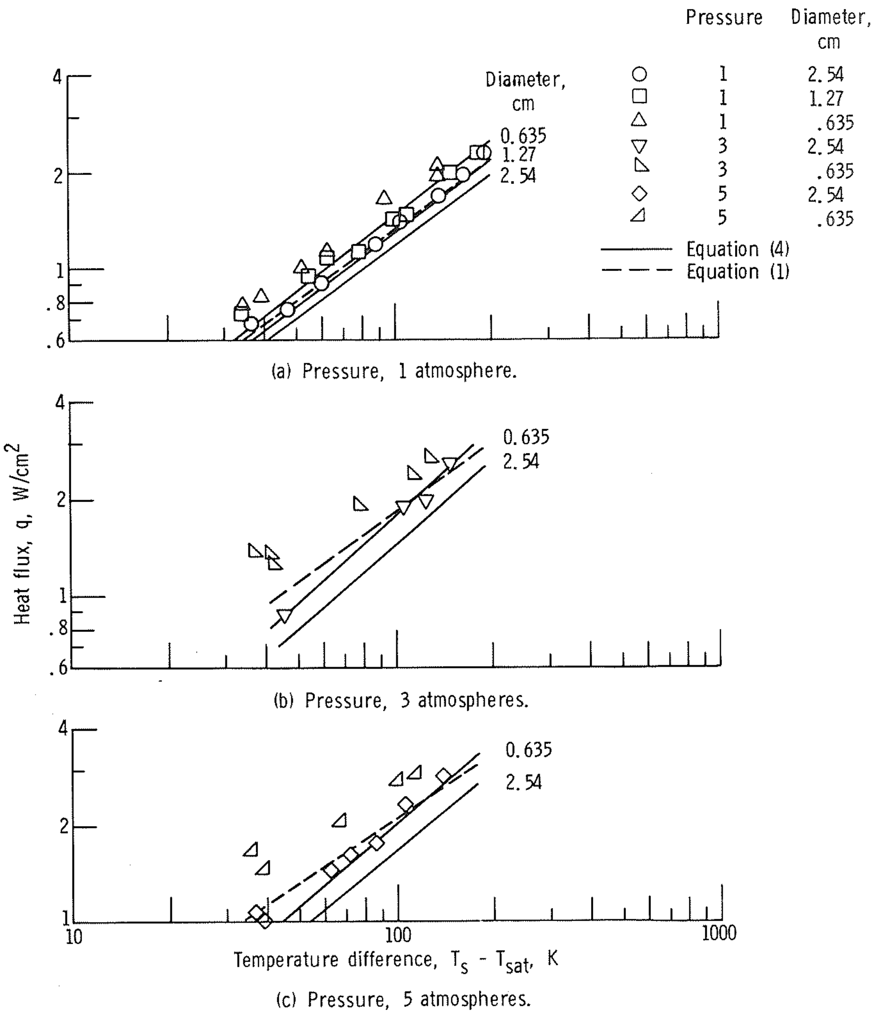


Figure 5. - Film boiling from spheres. Comparison of heat flux predicted by equations (1) and (4) with data of reference 4 for variations in pressure and sphere diameter; a/g level = 1.

At $a/g = 0.33$ and 0.2, the data are more closely predicted by equation (1) than equation (4), as shown in figure 6; however, at $a/g = 0.6$ the trend is more properly predicted by equation (4). This would tend to indicate that the trend with acceleration as predicted by equation (4) is doubtful.

However, comparing the data at a/g values of 0.01 to 0.03 for the 2.54- and 1.27-centimeter-diameter spheres indicates that both the trend and level are correct and in good agreement with the data (see fig. 7). On the other hand, with the experimental a/g level varied between 0.01 and 0.03, evaluation is difficult. It would appear that the data are still 20 percent higher than the heat flux predicted by equation (4).

The same trends are noted for the $a/g = 0.001$ to 0.003 data. Here the deviations between data and theory become more pronounced with the data still about 20 percent above the heat flux predicted from equation (4). But the agreement is much better in

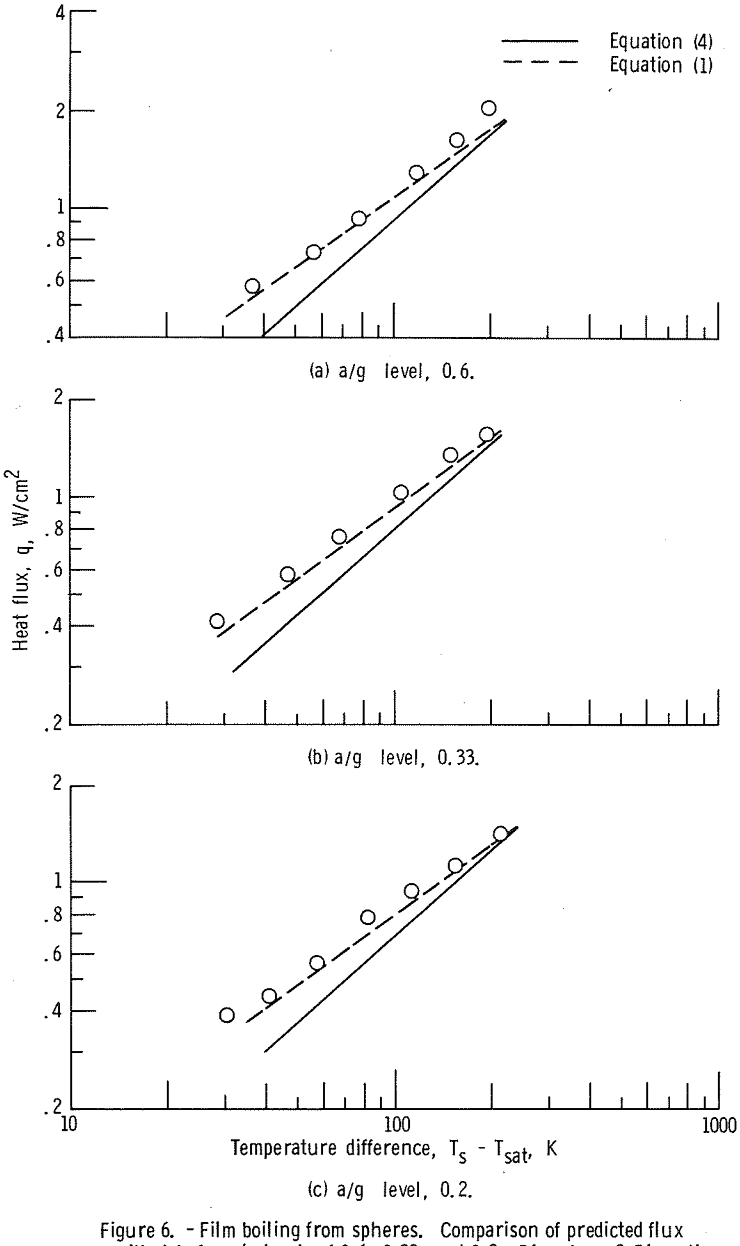
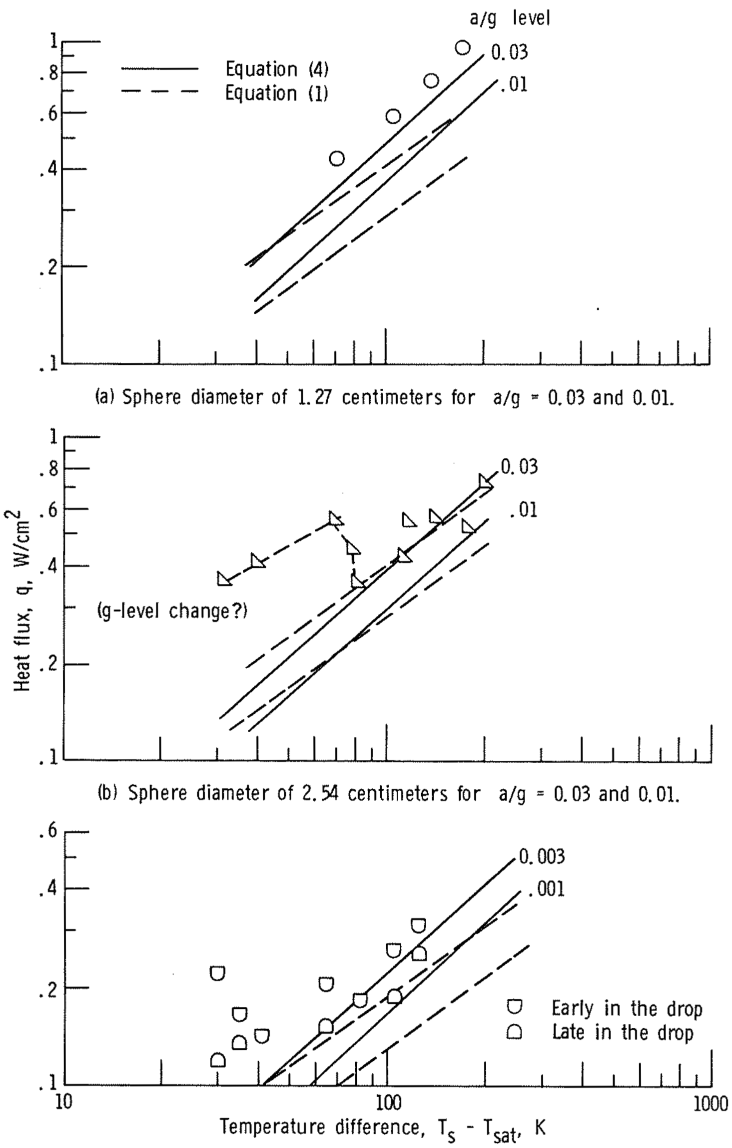


Figure 6. - Film boiling from spheres. Comparison of predicted flux with data for a/g levels of 0.6, 0.33, and 0.2. Diameter = 2.54 centimeters; pressure = 1 atmosphere.



(a) Sphere diameter of 1.27 centimeters for a/g = 0.03 and 0.01.

(b) Sphere diameter of 2.54 centimeters for a/g = 0.03 and 0.01.

(c) Sphere diameter of 2.54 centimeters for a/g = 0.003 and 0.001.

Figure 7. - Film boiling from spheres. Comparison of predicted heat flux (eqs. (1) and (4)) with data for reduced a/g levels and sphere diameter. Pressure, 1 atmosphere.

both level and trends than predicted by equation (1).

A number of the 2.54-centimeter-diameter-sphere data points are questionable indicating a g-level shift or transition out of film boiling for $\Delta T < 100$ K. A similar shift is to be noted at the 0.001 to 0.003 a/g level for the 2.54-centimeter-diameter sphere perhaps indicating a change in the heat transfer mechanism with an increased sensitivity to g-level variation.

A shift in the mechanism at the lower ΔT values is indicated by the data of reference 6 as discussed by reference 2 (see fig. 8). Nucleate boiling occurred on the sphere support stem which in turn significantly altered the heat transfer rates at the lower ΔT levels. More experimental work needs to be done in this area.

While there exists no evidence to indicate that the data of reference 1 suffer from the same type of problem, the 1/3-power variation, which also fits the uncorrected data of reference 6, seems to indicate that the data may be high. In comparison to other data (see refs. 2 and 3), the data of reference 1 are from 15 to 25 percent higher. This tends to indicate that if the data were reduced by 20 percent or equation (4) were augmented by 20 percent, agreement between theory and data would be good in both level and trend.

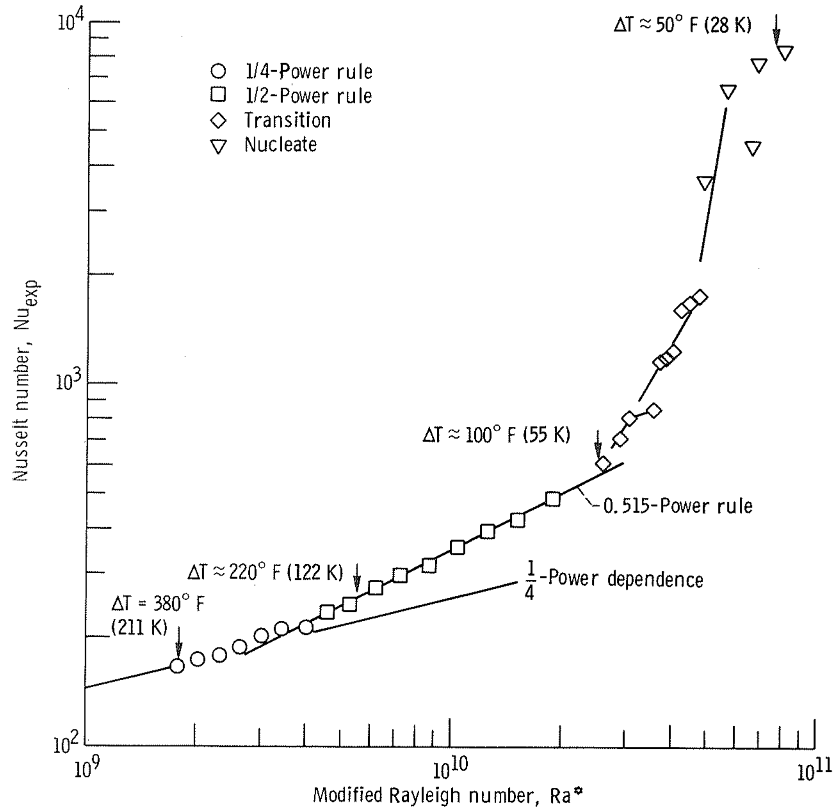


Figure 8. - Variation in Nusselt number with modified Rayleigh number for transient cooldown of 1-inch- (2.54-cm-) diameter sphere in liquid nitrogen (ref. 6).

As a final note, since laminar film condensation has been viewed as the inverse of the film boiling process (refs. 2, 7, and 8), it would seem that the analyses and data presented herein could be used to predict laminar film condensation at reduced gravity (probably not true for liquid metals). However, at very low accelerations one would expect steady state condensation to be dominated by diffusion and conduction.

CONCLUSIONS

The analysis of reference 2, equation (4) herein, appears to be in good agreement with the trends in the standard and reduced gravity data of reference 4, although the predicted heat flux level is about 20 percent low. The analysis, which is Bond number dependent, agrees well with the data trends for variations in sphere size and gravity level (major parameters of the Bond number). The data trends with pressure are properly predicted. However, the model will probably fail in the region near the thermodynamic critical point.

At $a/g = 1$ and $a/g = 0.01$ to 0.03, the data trends which clearly separate with sphere diameter are represented quite well by the theory. At lower a/g levels (0.001 to 0.003) the agreement is good; however, at temperature differences less than 100 K, there does appear to be some change in mechanism. As discussed herein these data are about 20 percent higher than the heat flux level predicted by equation (4). However, these data are 15 to 25 percent higher than other sphere data at $a/g = 1$, which may be connected to a mechanism change. This shift requires further investigation.

It appears that for preliminary calculations, equation (1) will give a good first-order estimate of the heat transfer coefficient, except perhaps at very low gravity or at pressures approaching the critical pressure.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 17, 1971,
129-01.

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