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ONSET OF STABLE FILM BOILING AND THE FOAM LIMIT

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THE ONSET of stable film boiling plays an important role in the transient behavior of water and organic cooled nuclear power reactors, and in the behavior of cryogenic devices and rocket nozzles. The prediction of surface temperature at the onset of stable film boiling has been attempted previously using a hydrodynamic model [1]. In this note we propose an alternative model consisting of two assumptions. First, the wall temperature at which stable film boiling begins is the foam limit, i.e. the maximum temperature to which the liquid can be superheated; and second, the foam limit can be computed satisfactorily from Van der Waals equation. Experimental data on the onset of stable film boiling are in fair agreement with wall temperatures predicted by this model.

In reduced co-ordinates, the Van der Waals equation is

$$p' = \frac{8T'}{3(v' - 1/3)} - \frac{3}{(v')^2}$$

$$p' = \frac{p}{p_c}, \qquad v' = \frac{v}{v_c}, \qquad T' = \frac{T}{T_c} \tag{1}$$

where p, v and T are the pressure, volume and temperature, respectively, the subscript c refers to critical, and the prime refers to reduced co-ordinates. The point of maximum superheat T_M' is found by setting

$$\left(\frac{\partial p'}{\partial v'}\right)_{T'} = 0$$

whence

$$\frac{8T_M'}{3(v_M' - 1/3)^2} = \frac{6}{(v_M')^3} \tag{2}$$

and substituting this condition in equation (1)

$$p_M' = \frac{1}{(v_M')^2} \left[\frac{2(3v_M' - 1)}{v_M'} - 3\right]. \tag{3}$$

Equations (2) and (3) can be combined to give T_M' as a function of p_M'. When $p_M' = 0$, $T_M' = 27/32$, a result which has been used recently to correlate experimental

data on extreme superheats of various liquids [2, 3, 4]. Thus, at pressures well below critical, $27/32\ T_c$ should be a good approximation to the foam limit and hence to the wall temperature at the onset of stable film boiling.

In comparing the calculated foam limit with experimental data, we assume that the onset of stable film boiling occurs at the minimum of the curves of heat flux versus temperature difference. Since the minimum heat flux point is not generally well defined experimentally, we have reproduced the data in the region of the minimum and indicated the position of the calculated foam limit. In Figs. 1, 2 and 3 we show data of q vs. $T_w - T_s$ (T_w
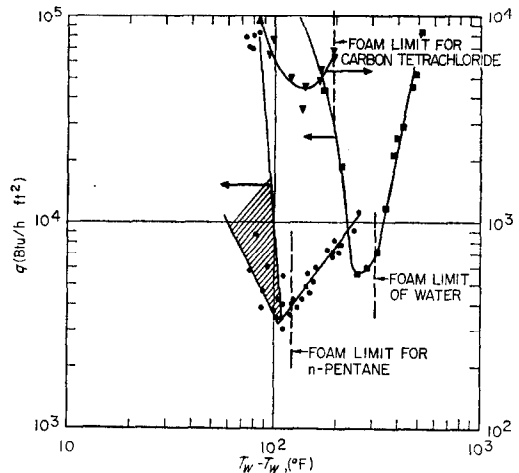

FIG. 1. The data for water were obtained from [9]. The experiment consisted of electrically heating a metallic ribbon submerged in water, under transient conditions. The water temperature was 203°F and the duration of the experiment was 50 ms. The data for pentane and carbon tetrachloride were obtained from Figs. 2 and 7 of reference [5]. In the case of pentane, Berenson performed experiments with surfaces of different roughness and cleanliness, using copper, nickel and inconel heating surfaces. From these experiments he concluded that stable film boiling is independent of surface material, cleanliness, and roughness, provided that the roughness height is less than the film thickness.

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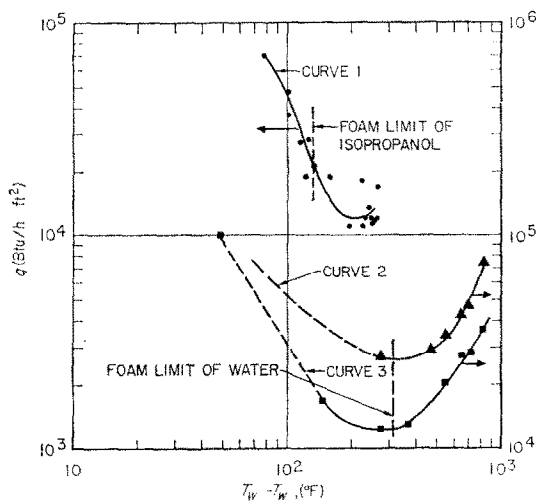† Department of Radiology, University of California, Los Angeles, California.

FIG. 2. The data for isopropanol (curve 1) were obtained from [7]. These authors quote q_{min} as occurring somewhere between a $T_w - T_c$ of 190–240°F. The foam limit is somewhat low by comparison. The data for water (curves 2 and 3) were obtained from [8]. The experiments were pool boiling measurements from a downward facing surface. The heating element consisted of a copper rod connected to a cylinder of refractory material. The data in curve 2 were obtained with a copper rod 25 mm in diameter and a refractory cylinder of 100 mm in diameter. In curve 3 the copper rod was 50 mm in diameter and the refractory cylinder 200 mm in diameter.
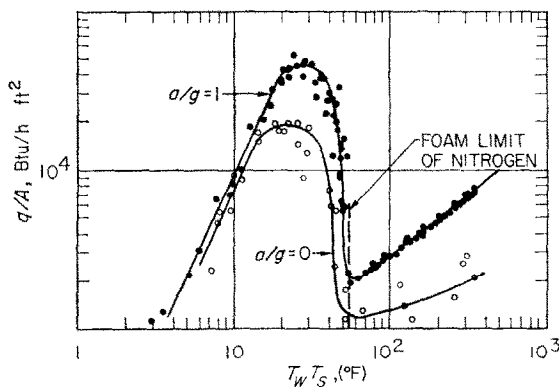

FIG. 3. Boiling heat transfer to liquid nitrogen at atmospheric pressure from a 1-inch diameter sphere in force fields of $a/g = 1$ and $a/g = 0$. The data were obtained from [10]. The data for $a/g = 0$ conditions were obtained under free fall conditions.

is the wall temperature and T_s is the saturation temperature) for water, pentane, carbon tetrachloride, isopropanol, and liquid nitrogen obtained from pool boiling experiments. The agreement can be considered good for water, pentane, and liquid nitrogen, and fair for carbon tetrachloride and isopropanol. In Fig. 4, data obtained by Borishanskii on the evaporation time of liquids in the spheroidal state is presented. The author shows that the maximum evaporation time corresponds to the onset of stable film boiling. As can be seen, the calculated foam limits fall very close to the maximum evaporation times.

The foam limit is an intrinsic property of a liquid. Therefore, associating the onset of stable film boiling with the foam limit is tantamount to making it independent of surface roughness or geometric consideration. The data in general also supports this notion.
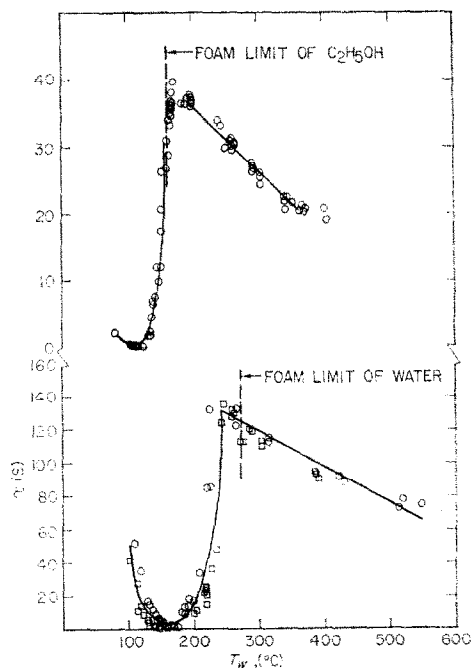

FIG. 4. The data were obtained from [6]. The experiments consisted of measuring the evaporation time of droplets of liquids deposited on heating surfaces. In the case of ethanol, the heating surface was a brass plate 8 mm thick. The initial volume of the droplets was 0·01362 cm³ and the initial ethanol temperature was 38°C. In the case of water, two experiments were performed. In the first test (○), the heating surface was a brass plate 2 mm thick, the initial volume of the droplets was 0·0465 cm³ and the initial temperature of the water was 20°C. In the second test (□), the heating surface was a brass plate 8 mm thick, with initial droplet volume of 0·0458 cm³, and an initial water temperature of 38°C.

REFERENCES

1. P. J. BERENSON, Transition boiling heat transfer from a horizontal surface. Report MIT-TR-17 (March 1, 1960).
2. L. T. BRIGGS, Superheating of water as a measure of negative pressure, *J. Appl. Phys.* **26**, 1001 (1955).
3. H. N. V. TEMPERLEY, The behaviour of water under hydrostatic tension, *Proc. Phys. Soc. Lond.*, **59**, 199 (1947)
4. P. SPIEGLER, J. HOPENFELD and A. NORMAN, Operating conditions of bubble chamber liquids, *Rev. Sci. Instrum.* **34**, 308 (1963).
5. P. J. BERENSON, Experiment on pool boiling heat transfer, *Int. J. Heat Mass Transfer*, **5**, 985 (1962).
6. V. M. BORISHANSKII, *Problems of Heat Transfer During a Change of State*, Ed. by S. S. Kutateladze. Report AEC-tr3405, p. 109 (1953).
7. T. DUNSKUS and J. W. WESTWATER, The effect of trace additives on heat transfer to boiling isopropanol. *Chem. Engng. Progr. Symp.*, published by *A.I.Ch.E.*, **57**, 173 (1961).
8. S. ISHIGARI, K. INOUE, Z. KIWAKI and T. INOIU, Boiling heat transfer from a flat surface facing downward. International Development in Heat Transfer, published by *ASME*, Part II (1961).
9. R. COLE, Investigation of transient pool boiling due to sudden large power surge. Report NACA-TN-3885 (1956).
10. H. MERTE and J. A. CLARK, *Advances in Cryogenic Engineering*, Vol. 7, p. 546. Ed. by K. D. Timmerhaus. Plenum Press, New York (1962).

COMMENTS ON HEAT TRANSFER BETWEEN SOLID PARTICLES AND A GAS IN A NON-UNIFORMLY AGGREGATED FLUIDIZED BED

S. S. ZABRODSKY, *Int. J. Heat Mass Transfer*, **6**, 23 (1963)

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MANY workers have investigated heat transfer from gas to particles in a fluidized bed and the best survey of this field is by Frantz [1]. The experimental technique of some investigators or their interpretation of data can be questioned but there is a residual core of results that indicate Nusselt numbers less than 2. Starting from this point, Dr. Zabrodsky argues that in a bed of particles the minimum Nusselt number should be appreciably greater than 2 but he goes on to show that, in spite of this, apparent values can approach zero if one assumes certain hydrodynamic conditions within the bed. In this note it is shown first that Dr. Zabrodsky's argument about minimum Nusselt numbers can be extended and generalized but does not accord with experimental facts and second, that the hydrodynamic conditions within a gas fluidized bed are different from those assumed and are not so amenable to generalized calculation as has been supposed.

If a hot sphere of diameter d is surrounded by a concentric spherical shell of diameter d_1 which acts as a heat sink and the intervening spherical annulus is filled with stagnant fluid, Zabrodsky shows that the Nusselt number is $2/(1 - d/d_1)$. It takes its familiar limiting value of 2 therefore only when the concentric sink is infinitely distant. In a bed of packed uniform spheres, the intervening fluid can be imagined to be re-disposed as spherical shells around each particle and in this way a value can be ascribed to d_1 in order to estimate a limiting Nusselt number, that is to say, the Nusselt number with stagnant fluid ($Re = 0$). Zabrodsky writes the volume of this equivalent spherical shell as $\pi d^2 \delta$ which should really be $(\pi/6)[(d + 2\delta)^3 - d^3]$ and for the case of cubic packing this leads to $Nu_{min} = 10 \cdot 3$ instead of the value $8 \cdot 6$ given in the paper. The value is, of course, different again if one considers any other packing geometry. Morris [2] has made an identical analysis for the case of mass transfer and the limiting Sherwood number.

Consider any arrangement of equal sized spheres dispersed more or less uniformly in a fluid and let the porosity or voidage be ϵ. The amount of fluid per sphere will be $(\pi d^3/6)[\epsilon/(1 - \epsilon)]$ and, following Zabrodsky's method, this can be expressed as an equivalent spherical shell of fluid so that,

$$(\pi d^3/6)[\epsilon/(1 - \epsilon)] = (\pi/6)[(d + 2\delta)^3 - d^3]$$

whence,

$$2\delta = \left[\left(\frac{1}{1 - \epsilon}\right)^{\frac{1}{3}} - 1\right] d \qquad (1)$$

and the minimum Nusselt number becomes,

$$Nu_{min} = 2/[1 - (1 - \epsilon)^{\frac{1}{3}}]. \qquad (2)$$