

II. Peak Nucleate Boiling Fluxes and a Test of Peak Flux Correlations

Peak nucleate boiling fluxes (P.N.B.F.'s) for nitrogen, oxygen, argon, methane, and carbon tetrafluoride on a flat, horizontal platinum plated copper disk were measured up to $P_r > 0.95$. The P.N.B.F. correlation in the form proposed by Chang and Snyder and various other investigators is superior, for these liquids, to those of Addoms, Noyes, Borishanskiy, and Moissis and Berenson. The P.N.B.F. on a given surface is found to be reproducible to within a few percent, but exposure of that surface to other test liquids or even to the laboratory atmosphere can produce changes of $\pm 15\%$.

The importance of the peak nucleate boiling flux (P.N.B.F.) in power dissipating systems with high boiling liquids for cooling is widely recognized; it is likewise an important design criterion for low temperature systems. It is improbable that a low temperature system will be physically destroyed if the P.N.B.F. is exceeded at constant power, but the operation of many systems demands that the temperature of some critical component not exceed some upper limit.

Many correlations (32, 41a, b, 51 to 60) have been proposed for predicting the P.N.B.F. of any fluid from only the thermophysical properties of that fluid. They enjoy considerable success for high boiling liquids, and data in the literature indicate comparable success in predicting the P.N.B.F. for liquefied gases.

However, experiment (6, 60, 61) shows the P.N.B.F. is a function of geometry and of orientation of the heated surface. Data of the literature (6, 62) indicate that the P.N.B.F. varies for a given fluid on surfaces of different chemical and physical properties.

It is uncertain whether the scatter in P.N.B.F. data is an inherent property of the process, as suggested by Zuber and Tribus (54), or whether it stems from a dependence upon the physical and chemical identity of the various surfaces.

Previously, we found (2) agreement with the correlation of Kutateladze (51) for P.N.B.F.'s for nitrogen and oxygen on horizontal flat platinum ribbon of 2 mm. width for $P_r < 0.6$. As P_r approached 1.0, the experimental values fell below the predicted by as much as two orders of magnitude, and it was postulated that this might be due to the small dimensions of the ribbon.

Reported values for P.N.B.F. at very low accelerations (63 to 66) indicate that there may be a finite P.N.B.F. under zero g , in contradiction to all correlations which predict a value of zero there.

Brentari, Giarratano, and Smith (49) collected the P.N.B.F. data extant in 1963 for oxygen, nitrogen, hydrogen, and helium. Their plots show much scatter, but the

data were obtained on a wide variety of solids of various dimensions, shapes, and orientations. We present here some of the P.N.B.F. data (1) for nitrogen, oxygen, argon, methane, and carbon tetrafluoride obtained in studies reported in Part I. The data were all measured on a flat circular face-up disk and thus correspond to the geometry assumed in most theoretical studies. Data were taken from 1 atm. or less to $P_r > 0.95$ under conditions such that the constancy of the boiling characteristics of the surface could be checked. Because of the departure of previous results from predicted P.N.B.F. values for $P_r > 0.6$, that region was explored with some care. We compare these data with various correlations to establish their relative success and range of validity for these simple liquids.

APPARATUS AND EXPERIMENTAL PROCEDURE

The apparatus, preparative procedures, experimental fluids and the sources of thermophysical data for them, and experimental procedures were described in Part I. The general procedure was to approach the P.N.B.F. from the nucleate regime by step-by-step increments of power of $\sim 3\%$ when quite near the P.N.B.F.

To check whether the previous low values of P.N.B.F. (for $P_r > 0.6$) were due to the small dimensions of the heater, we fabricated two nylon masks which could be clamped over the test surface. One provided a 6.35 mm. circular, and the second a 2×18.5 mm. rectangular aperture.

P.N.B.F. CORRELATIONS TESTED

We arbitrarily chose the following correlations for P.N.B.F. for testing:

Addoms (50);

$$\left(\frac{\text{P.N.B.F.}}{\lambda \rho_v} \right) = K_A \left[g \left(\frac{k}{\rho C} \right)_l \right]^{1/3} \phi \left(\frac{\rho_l - \rho_v}{\rho_v} \right) \quad (1)$$

where, at low pressures

$$K_A \approx 2.4 \quad (2)$$

$$\phi \left(\frac{\rho_l - \rho_v}{\rho_v} \right) \approx \left(\frac{\rho_l - \rho_v}{\rho_v} \right)^{1/2} \quad (3)$$

Noyes (58);

$$\left(\frac{\text{P.N.B.F.}}{\lambda \rho_v} \right) = 0.144 \left(\frac{\rho_l - \rho_v}{\rho_v} \right)^{1/2} \left(\frac{g \sigma}{\rho_l} \right)^{1/4} \left(\frac{C \mu}{k} \right)_l^{-0.245} \quad (4)$$

Kutateladze (51);

$$\left(\frac{\text{P.N.B.F.}}{\lambda \rho_v} \right) = 0.16 \left(\frac{\sigma g (\rho_l - \rho_v)}{\rho_v^2} \right)^{1/4} \quad (5)$$

Following Kutateladze's proposal of Equation (5) in 1951, several investigators have derived correlations which can be expressed as

$$\left(\frac{\text{P.N.B.F.}}{\lambda \rho_v} \right) = K \left(\frac{\sigma g (\rho_l - \rho_v)}{\rho_v^2} \right)^{1/4} \quad (6)$$

where K is some function of the fluid properties, as listed in Equations (7) to (10).

Borishanskiy (53);

$$K = 0.13 + 4 \left[\frac{\sigma \rho_l}{\mu^2} \left(\frac{\sigma}{g (\rho_l - \rho_v)} \right)^{1/2} \right]^{-0.4} \quad (7)$$

Zuber, and Zuber and Tribus (54a, b);

$$\frac{3}{\sqrt{2\pi}} \left(\frac{\pi}{24} \right) \left(\frac{\rho_l}{\rho_l + \rho_v} \right)^{1/2} \cong K \cong \frac{\pi}{24} \left(\frac{\rho_l}{\rho_l + \rho_v} \right)^{1/2} \quad (8)$$

Chang and Snyder, (55) and Kutateladze (41b)

$$K = 0.145 \left(\frac{\rho_l + \rho_v}{\rho_l} \right)^{1/2} \quad (9)$$

Zuber, Tribus, and Westwater (56);

$$0.157 \left(\frac{(16 - \pi) \rho_l}{(16 - \pi) \rho_l + \pi \rho_v} \right) \left(\frac{\rho_l + \rho_v}{\rho_l} \right)^{1/2} \cong K \\ \cong 0.12 \left(\frac{(16 - \pi) \rho_l}{(16 - \pi) \rho_l + \pi \rho_v} \right) \left(\frac{\rho_l + \rho_v}{\rho_l} \right)^{1/2} \quad (10)$$

Moissis and Berenson (59);

$$K = \frac{0.18 (1 + \rho_v/\rho_l)^{1/2}}{(1 + 2(\rho_v/\rho_l)^{1/2} + \rho_v/\rho_l)} \quad (11)$$

The limits arise in Equations (8) and (10) because of an assumed spectrum of unstable wavelengths leading to the critical condition. Zuber and Tribus (54b) therefore conclude that there is an inherent uncertainty in P.N.B.F. values of $\pm 14\%$.

EXPERIMENTAL RESULTS AND DISCUSSION

P.N.B.F. values and corresponding ΔT 's for selected nitrogen, oxygen, argon, methane, and carbon tetrafluoride runs are indicated on the Q/A vs. ΔT curves shown in Figures 6 to 12 of Part I. The entire collection of P.N.B.F. and ΔT data are listed in Appendix B of Kosky (1).

Reproducibility of P.N.B.F. When Slowly Approached

Run 68 was conducted with nitrogen at 1.96 atm. to check the inherent uncertainty in the P.N.B.F. The results are summarized in Table 1 in which the first column shows the maximum heat flux for which the test surface temperature was stable indefinitely. The second column shows the flux after the next power increment, which drove the test surface into film boiling. The P.N.B.F. lies between these limits.

The average scatter for the last nine points is $\pm 1.1\%$ which is to be compared with the $\pm 14\%$ prediction of Zuber and Tribus (54b).

This reproducibility of the P.N.B.F. on a surface during a given run does not represent the reproducibility from run to run following exposure of the surface to the laboratory atmosphere or to another test liquid. In other runs, following other surface preparative treatments, the P.N.B.F. for nitrogen at 1.96 atm. ranged from 20 to 29.7 w./sq.cm., averaging ~ 24.8 w./sq.cm. for thirteen separate runs.

TABLE 1. REPRODUCIBILITY OF THE P.N.B.F. FOR NITROGEN ON HORIZONTAL PLATINUM AT 1.96 ATM.

Precritical	Postcritical
(28.29) w./sq.cm.	(29.02) w./sq.cm. (exploratory)
28.71	29.04
28.53	29.02
28.67	29.02
28.71	29.02
28.71	29.15
28.80	28.99
28.75	29.02
28.72	29.06
28.77	28.84

Dependence of P.N.B.F. Upon Heated Surface Dimensions

P.N.B.F. data for nitrogen with the Nylon masks are summarized in Table 2.

Normalization of the P.N.B.F.'s with the 2 atm. values is necessary to exclude errors in the surface area actually wet by liquid with the masks in place, and variation in surface character between runs.

The last three columns of Table 2 show no measurable effect, in this apparatus, of heater dimension on the P.N.B.F. of nitrogen; therefore, the earlier measurements (2) at high pressures were almost certainly in error.

TABLE 2. TEST OF P.N.B.F. DEPENDENCE ON MINIMUM HEATED SURFACE DIMENSION FOR NITROGEN ON HORIZONTAL PLATINUM

Bath temp., °K.	Pressure, atm.	(P.N.B.F.) _P / (P.N.B.F.) _{2 atm.}		
		19 mm. circ. disk	6.35 mm. circ. mask	2 × 18.5 mm. rect. mask
82.8	2.0	1.00	1.00	1.00
123.4	29.4	0.51	0.46	0.48
125.4	32.4	0.15	0.14	0.16

Dependence of P.N.B.F. Upon Reduced Pressure of the Boiling Fluid

Apart from a numerical constant, the correlations of Kutateladze, Zuber et al., Chang and Snyder, and Moissis and Berenson differ only in the term involving the vapor-liquid density ratio [K of Equation (6)], which is significant only at high pressures.

To test the various relative liquid-vapor density terms we plotted the ratio of the measured to the predicted P.N.B.F. vs. ρ_v/ρ_l for all fluids. To compensate for changes in surface character between runs and for error in the numerical constant, the numerical constant for each correlation for each fluid was adjusted to fit the 1 atm. (nominal) P.N.B.F. The resulting plots for nitrogen, argon, and methane are shown here as Figures 1, 2, and 3. They are representative of all fluids. (Only data subsequent to the change in surface character are plotted in Figure 2.)

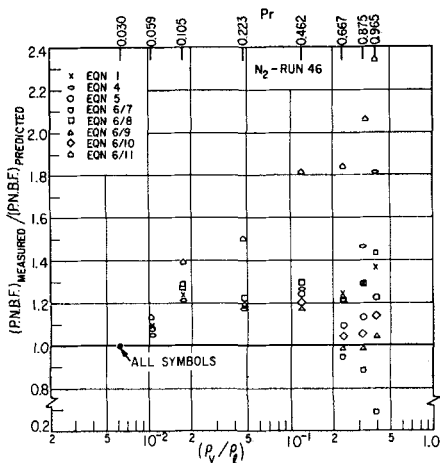


Fig. 1. Ratio of experimental P.N.B.F. for nitrogen on horizontal Pt to P.N.B.F. predicted by various correlations vs. vapor-liquid density ratio. (Constants of all correlations have been fitted to the 1 atm. data.)

Little weight should be given points at the very highest pressures in Figures 1, 2, and 3. The P.N.B.F. $\rightarrow 0$ as $P_r \rightarrow 1.0$ to increase experimental uncertainty, and increasing uncertainty in property data aggravates the situation. The highest points are within $\sim 0.2^\circ\text{K}$. of T_c . Underestimation of the bulk liquid temperature here by 0.2 deg. will double the predicted P.N.B.F. At these low fluxes, the absence of significant stirring action could lead to large variations in bulk liquid temperature and temperature errors. This may be the explanation of the low P.N.B.F. data obtained previously (2) at high pressure.

The methane plot of Figure 3 is the least reliable. The initial and check 1 atm. P.N.B.F. differed by 10% and were averaged for normalizing purposes.

The plots clearly indicate the Moissis-Berenson correlation [Equation (6/11)] seriously underpredicts the P.N.B.F. at any pressure greater than 4 atm., that Equation (6/9) is the best for these fluids, and that the original Zuber-Tribus correlation [Equation (6/8)] is inferior to Equations (5), (6/9), and (6/10). The Addoms, Noyes, and Borishanskiy correlations which require (often unavailable or inaccurate) transport property data are less successful than Equation (6/9) which does not require these data. Literature data (66, 67) indicate the gravitational dependence of the P.N.B.F. to be $g^{1/4}$ rather than the $g^{1/3}$ of Addoms.

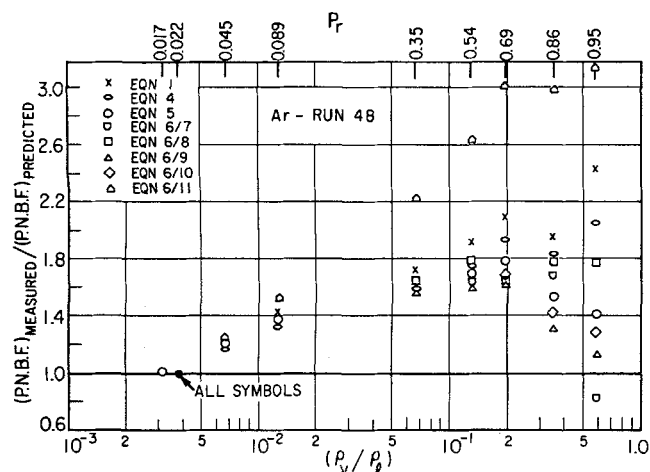


Fig. 2. Ratio of experimental P.N.B.F. for argon on horizontal Pt to P.N.B.F. predicted by various correlations vs. vapor-liquid density ratio. (Constants of all correlations have been fitted to the 1 atm. data.)

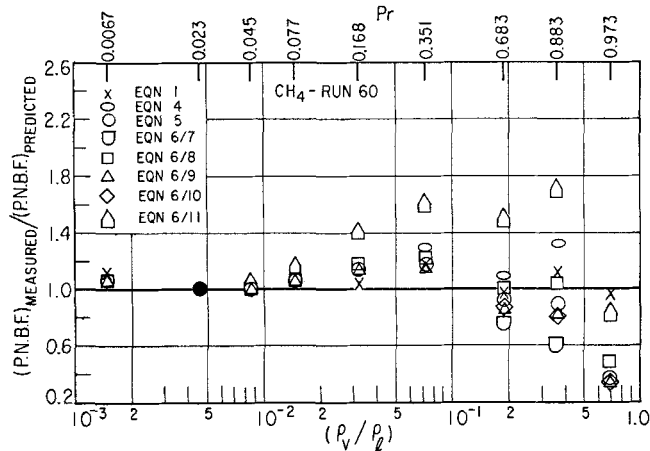


Fig. 3. Ratio of experimental P.N.B.F. for methane on horizontal Pt to P.N.B.F. predicted by various correlations vs. vapor-liquid density ratio. (Constants of all correlations have been fitted to the 1 atm. data.)

Dependence of P.N.B.F. Upon Surface Properties

Nitrogen and oxygen data from the various runs in this study indicate a dependence of the P.N.B.F. upon the specific character and nature of the heated surface by shifts of $\pm 15\%$ from run to run with the same liquid. That this is a property of the surface is indicated by the argon data of Run 48 plotted in Figure 4. The boiling character of the surface changed abruptly during an excursion into film boiling during measurements at the 8.4 atm. isobar, even though it experienced no treatment other than warming to the vicinity of 200°K . during that excursion. [Similar discontinuities have been observed previously (66) in the boiling character of oxygen on Pt.] The prior and subsequent P.N.B.F.'s when normalized by the prior 1 atm. data form two curves, displaced from but within the accuracy of the measurements, parallel to one another.

Figure 5 plots the ΔT at P.N.B.F. vs. bulk liquid-vapor surface tension for these argon data. The two curves probably reflect some change in the liquid-solid and solid-vapor interfacial tensions.

Figure 6 is a plot of the P.N.B.F. values taken in this laboratory for oxygen, nitrogen, argon, methane, carbon tetrafluoride, and helium (61) on face-up horizontal platinum surfaces in accordance with

$$\frac{Q/A}{\lambda \rho_v} = 0.15 \left(\sigma g \frac{(\rho_l - \rho_v)}{\rho_v^2} \right)^{1/4} \left(\frac{\rho_l + \rho_v}{\rho_l} \right)^{1/2} \quad (12)$$

We omitted the values at the two highest pressures from reference 2. The cluster of points at the lower left correspond to $P_r > (0.85 \text{ to } 0.98)$ for various fluids, and they should be given little weight in selecting the correct form for the correlation.

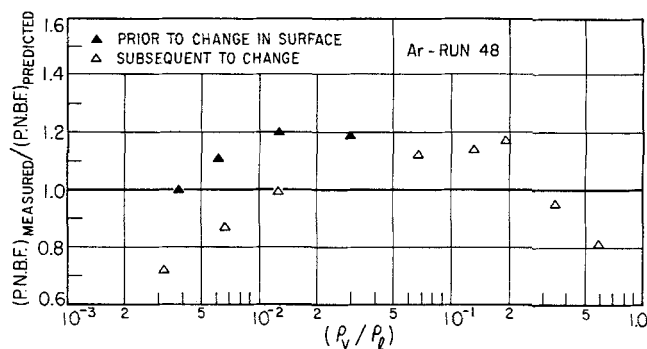


Fig. 4. Normalized ratio of measured P.N.B.F. to P.N.B.F. predicted by Equations (6/9) vs. vapor-liquid density ratio for argon before and after change in surface character.

Until a correlation which accounts for the effects of surface character upon P.N.B.F. is available, Equation (12) or Equation (5) can be used with equal confidence over the entire liquid range for $P_r > 0.95$ for the cryogenic liquids on solids of high thermal conductivity in the earth's gravitational field. Adjustment of the numerical constant will be needed for other geometries, or for other orientations of a flat surface.

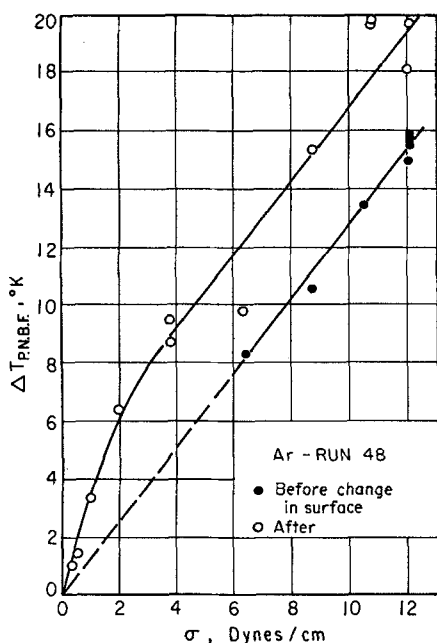


Fig. 5. ΔT at P.N.B.F. vs. vapor-liquid surface tension for argon.

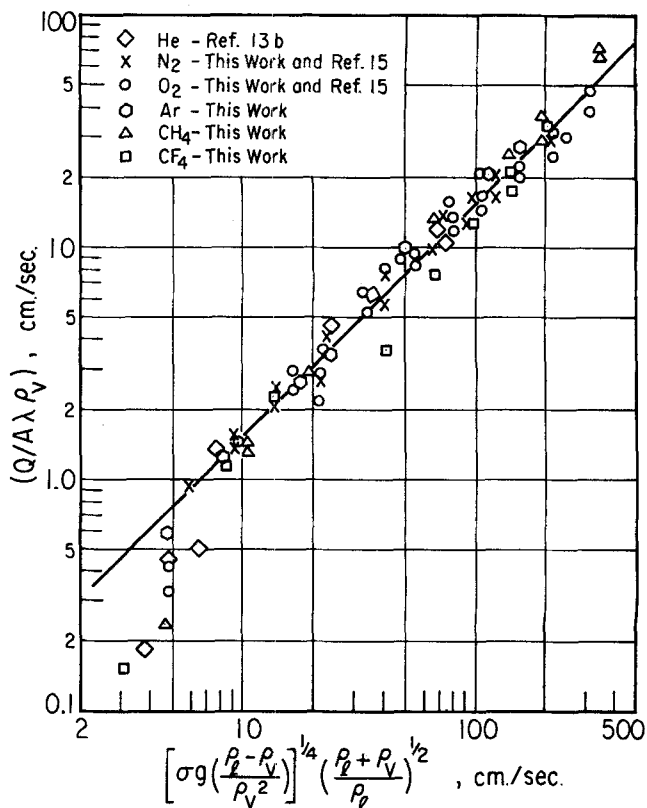


Fig. 6. Collected P.N.B.F. data for cryogenic liquids on horizontal flat platinum compared with Equations (6/9).

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III. Nucleate Boiling Data and Peak Nucleate Boiling Fluxes for Nitrogen-Oxygen Mixtures

Nucleate boiling curves and peak nucleate boiling fluxes (P.N.B.F.'s) have been measured for oxygen-nitrogen mixtures of 3.25, 8.35, and 68.5 mole % oxygen and for carbon dioxide free air on a flat horizontal platinum surface from 1 atm. to $P_r \sim 0.95$.

The nucleate boiling correlations of Kutateladze and of Borishanskiy-Minchenko, which were successful for the pure components, fail for the mixtures at elevated pressures. Of the correlations tested, that of McNelly is most nearly successful for both pure components and for their mixtures at all pressures.

The Chang-Snyder form of the Kutateladze correlation for the P.N.B.F. is successful for mixtures up to $P_r = 0.75$, beyond which it overpredicts the P.N.B.F. No anomalies in P.N.B.F. at 1 atm. similar to those reported for binary aqueous systems were observed.

The dramatic differences between the boiling heat transfer properties of pure fluids and of their mixtures are well known. Van Wijk et al. (68) found pronounced maxima, and occasionally double maxima, in the peak nucleate boiling flux (P.N.B.F.) vs. composition curves for the water-alcohol and water-ketone systems. Less than 0.1% of 1-octanol in water enhanced the P.N.B.F. \sim twofold. Westwater and co-workers (30, 31) found that as little as 10^{-4} mole % of certain solutes produced dramatic shifts in the boiling curves and P.N.B.F.'s of isopropanol.

Sterling and Tichacek (69) and Huber and Hoehne (70) found that the nucleate boiling heat transfer coefficient h was lower for intermediate compositions than the coefficient for either pure fluid for a wide variety of binary organic systems.

We are unaware of the existence of boiling data for cryogenic mixtures other than the 1 atm results of Giaque et al. (29) for 50% oxygen in nitrogen and the 1 atm. data (6) for the complete composition range of oxygen in