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# FILM BOILING OF FREON 113, NORMAL PENTANE, CYCLOPENTANE AND BENZENE FROM CYLINDRICAL SURFACES AT MODERATE PRESSURES

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**Abstract**—An investigation of film boiling heat transfer in saturated pools of liquid Freon 113, normal pentane, cyclopentane and benzene was conducted. The fluids were boiled from copper, cylindrical heat-transfer surfaces 0.0762 m (3 in) long, and 0.01397, 0.01905 and 0.0254 m (0.55, 0.75 and 1.0 in) in diameter. The data covers a moderate range of pressures up to 1.67 $(10)^6$ N/m$^2$ (242.5 psia). The experimental data are compared with existing film boiling correlations. The existing film boiling correlations were found to be inadequate in predicting heat-transfer coefficients for the conditions of this investigation.

## NOMENCLATURE

- $C_p$, heat capacity [J/g K (Btu/lb °F)]
- $D$, diameter [m (ft)];
- $F'$, $K_v^3 \rho_v(\rho_l - \rho_v) g \lambda / \Delta T \mu_v$ [J$^4$/m$^7$ s$^4$K (Btu$^4$/ft$^7$h$^4$ °F)];
- $F$, $K_v^3 \rho_v(\rho_l - \rho_v) g \lambda' / \Delta T \mu_v$ [J$^4$/m$^7$ s$^4$K (Btu$^4$/ft$^7$h$^4$ °F)];
- $g$, acceleration due to gravity [m/s$^2$ (ft/s$^2$)];
- $g_c$, gravitational constant [g m/dyne s$^2$, (lb ft/lb$_f$ s$^2$)];
- $h$, heat-transfer coefficient [J/s m$^2$ K (Btu/h ft$^2$ °F)];
- $K$, thermal conductivity [J/s m K (Btu/h ft °F)];
- $L$, Laplace length $[g\sigma/\rho_v(\rho_l - \rho_v)]^{1/2}$, [m (ft)];
- $T$, temperature [K (°R)];
- $\Delta T$, temperature difference $T_{sur} - T_{sat}$, [K (°R)].

Greek symbols

- $\sigma$, surface tension [g/m (lb/ft)];
- $\lambda_c$, critical wave length $2\pi L$ [m (ft)];
- $\mu$, viscosity [g/m s (lb/ft h)];
- $\rho$, density [g/m$^3$ (lb/ft$^3$)];
- $\lambda$, latent heat of vaporization [J/g (Btu/lb)];
- $\lambda'$, latent heat of vaporization plus average sensible heat content of vapor [J/g (Btu/lb)].

Subscripts

- $c$, refers to the critical point;
- $l$, refers to the liquid;
- $r$, refers to reduced property, $(T/T_c$, etc.);
- sat, refers to saturation conditions;
- sur, refers to heat-transfer surface;
- $v$, refers to vapor.

## INTRODUCTION

INVESTIGATION of film boiling of cryogens carried out by the authors [1–5] indicate that the commonly accepted film boiling correlations which appear in the literature will not adequately correlate experimental film boiling data. This investigation was initiated to obtain data for several organic compounds over a range of pressure and heat-transfer element diameter. The data obtained were used to test the adequacy of several film boiling correlations which appear in the literature.

There are several excellent reviews of the film boiling literature [6–10]. Therefore, the reader who is unfamiliar with the area is referred to these reviews for background material. The correlations for film boiling from cylinders which are commonly used for correlations will, however, be briefly covered.

The first film boiling correlation to gain acceptance was presented by Bromley [11]. He suggested an analysis for film boiling similar to the analysis used by Nusselt [12] for condensation. Bromley's resulting equation is given by equation (1).

$$h = 0.62\,(F'/D)^{1/4} \tag{1}$$

where $F'$ is defined by

$$F' = \left[\frac{K_v^3 \rho_v(\rho_l - \rho_v)\lambda g}{\Delta T \mu_v}\right]. \tag{2}$$

In a later paper [13] Bromley suggested that equation (2) could be improved by using a heat of vaporization corrected for sensible heat effects ($\lambda'$) instead of the latent heat of vaporization, $\lambda$. The expression suggested for $\lambda'$ is given by equation (3).

$$\lambda' = [1 + (0.34\,C_p \Delta T/\lambda]^2. \tag{3}$$

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Breen and Westwater [14] developed equation (4) which is based on hydrodynamics and Taylor instability

$$h = \left[0.59 + 0.069\frac{\lambda_c}{D}\right]\left(\frac{F}{\lambda_c}\right)^{1/4} \tag{4}$$

where

$$F = \left[\frac{K_v^3 \rho_v(\rho_l - \rho_v)\lambda' g}{\mu_v \Delta T}\right]$$

$$\lambda_c = 2\pi L \tag{5}$$

$$L = \frac{g\sigma}{\rho_l - \rho_v}.$$

Sciance [15, 16] suggested that film boiling data could be correlated by equation (6) which is a modification of Berenson's [17] flat plate correlation

$$\frac{hL}{K_v} = 0.346\left[\frac{L\rho_v(\rho_l - \rho_v)\lambda' g}{\mu_v \Delta T K_v T_r^2}\right]^{0.267} \tag{6}$$

Baumeister and co-workers [18–20] postulated a model which consisted of a thin tubular vapor film between the heat-transfer surface and the boiling liquid. Analysis of this model yielded equation (7)

$$h = C\left[\frac{F}{L}\right]^{1/4}\left[1 + \frac{9}{(6)^{1/2}}\frac{L}{D} + \frac{8}{3(6)^{1/2}}\left(\frac{L}{D}\right)^3\right]^{1/4}. \tag{7}$$

The constant $C$ was found to be 0.346; however, the constant was increased to 0.46 for nitrogen film boiling.

Pomerantz [21] in a study of the effect of gravity on film boiling suggested the following film boiling correlation

$$h = 0.62\left(\frac{D}{\lambda_c}\right)^{0.172}\left(\frac{F}{D}\right)^{1/4}. \tag{8}$$

In addition to the above equations, the equation of Chang [22] (equation 9) and the equation of Berenson [17] (equation 10) which were derived for flat plate geometry are sometimes used to correlate cylindrical film boiling data

$$h = 0.234\left[\frac{F'}{L}\right]^{1/3} \tag{9}$$

$$h = 0.234\left[\frac{F'}{L}\right]^{1/4}. \tag{10}$$

## EXPERIMENTAL EQUIPMENT

The experimental equipment used in this investigation can be described in terms of five subsystems: (A) heat-transfer elements; (B) boiling vessel; (C) pressure measurement and control; (D) power supply; (E) temperature measurement.

### (A) *Heat-transfer elements*

The heat-transfer elements shown in Fig. 1 consisted of copper cylinders heated by passing direct current through tungsten wire cemented inside the copper cylinders.

The heat-transfer surfaces were machined from copper tubing to outside diameters of 0.0254, 0.01905, and 0.01397 m (1.00, 0.75, and 0.55 in), a length of 0.0762 m (3.00 in) and a wall thickness of 0.00254 m (0.1 in). Four thermocouple wells were drilled axially into the walls of the cylinders to a depth of 0.0254 m (1.0 in) with a diameter of 0.00142 m (0.056 in). Two of the four thermocouple wells were located at one end of the cylinder and 180° apart. The remaining two thermocouple wells were located at the opposite end of the cylinder, 180° apart, and rotated by 90° from the other two thermocouple wells. All wells containing the thermocouples were filled with silver solder having a melting point of 658 K (725°F).

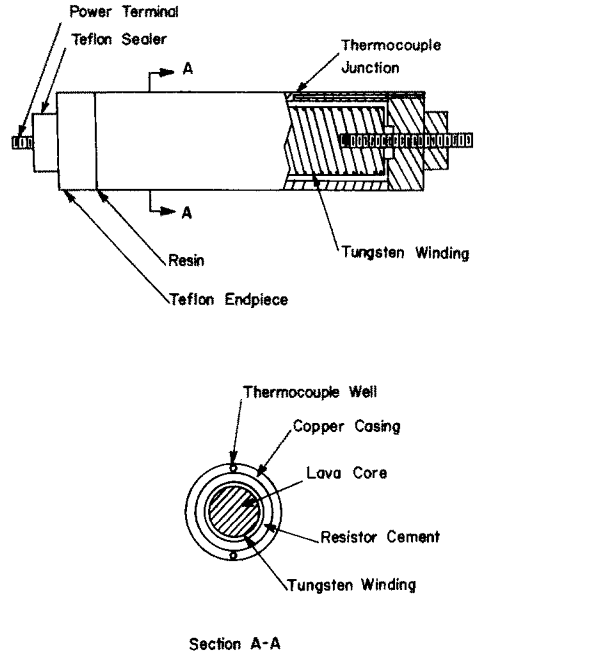

FIG. 1. Heat-transfer element.

The heat losses from the heat-transfer elements ends were estimated to be less than 7% for the 0.0254 m (1.00 in) diameter surface which is the element with the greatest losses.

### (B) *Boiling vessel*

The boiling vessel was a 0.0038 m$^3$ (1 gal) 304 stainless steel autoclave, 0.127 m (5 in) I.D., 0.3048 m (12 in) deep. The autoclave was sealed with a 304 stainless steel cap and plug with a Teflon O-ring. The sealing plug was fitted with five, 0.00635 m (1/4 in) coned fittings for a fill line, level indicator, pressure tap, and inlet-outlet ports for a condensing coil. The sealing plug also had three 0.01905 m (3/4 in) fittings to allow thermocouple and power leads to be introduced to the system.

The boiling vessel was wrapped with an asbestos tape heating element for auxiliary heating of the autoclave.

### (C) *Pressure measurement and control*

The pressure in the autoclave was controlled by regulating the flow of cooling oil through 6.1 m

(20 ft) of stainless steel cooling coil contained inside the autoclave.

The pressure in the autoclave was measured with a Bourdon tube pressure gauge which had a 0.0406 m (16 in) dial, a range from 0 to 1.38 $(10)^7$ N/m$^2$ (0–2000 psi) in 6.89 $(10)^3$ N/m$^2$ (1 psi) increments and was accurate to more than 0.1% of full scale. The system pressure was read to the nearest 3.44 $(10)^3$ N/m$^2$ (0.5 psi). During tests there were fluctuations in the system pressure of $\pm 1.72$ $(10)^3$ N/m$^2$ ($\pm 0.25$ psi) as measured from the d/p cell output by means of a 2.07 $(10)^4 - 1.03$ $(10)^5$ N/m$^2$ (3–15 psi) pressure gauge. The system pressure fluctuations of $\pm 1.72$ $(10)^3$ N/m$^2$ ($\pm 0.25$ psi) correspond to temperature fluctuations of the boiling fluid of $\pm 0.280$ K (0.05°F).

(D) *Power supply*

The power was supplied by a 60 V, 40 A, DC power supply and was measured with a DC ammeter which could be read to $\pm 0.1$ amp and a digital DC voltmeter which could be read to $\pm 0.01$ V. The accuracy of this voltmeter was 0.1% of the 100 V full scale. All power leads from the power supply to the autoclave were 10 gauge copper wire.

(E) *Temperature measurement*

Asbestos-coated, 24 gauge, copper-constantan thermocouple wires from the heat transfer element were connected to the Teflon coated thermocouple leads, leading through the autoclave cap to a thermocopule switch. The temperatures were read in millivolts using a digital DC millivoltmeter. In addition, a strip chart recorder was used in order to establish steady-state conditions of the system during operation. The temperatures during tests were read to within $\pm 0.004$ mV or $\pm 0.08$ K ($\pm 0.15$°F).

At the minimum values of voltage (9 V) and current (12 A), the maximum error in the experimentally determined heat flux was approximately 1%. In view of the accuracy of temperature measurements and pressure control of the system and taking into consideration the heat losses of 7% for a 2.54 cm (1 in) dia heater, a conservative estimate of the total error in the heat flux introduced by experimental limitations was 8%.

## EXPERIMENTAL PROCEDURES

The cylindrical heat-transfer element was horizontally suspended from the autoclave plug by the entering power leads. The level of the heater in the autoclave was adjusted to allow a 0.076 m (3 in) liquid level above the heater surface. A 0.0016 m (1/16 in) stainless steel tube was positioned through the autoclave cap to indicate when the vessel was filled to the proper level.

At the start of a run the voltmeters and power source were turned on and allowed to stabilize. The oil reservoir was pressurized to 4.14 $(10)^5$ N/m$^2$ (60 psia) with compressed air and the cooling water to the oil cooling tank was turned on.

After the metering systems had stabilized, the power to the heat-transfer element was turned on. The power was supplied in step increases of 1 V every 5 min. When the heat-transfer surface attained a temperature of approximately 533.3 K (500°F), the fluid to be tested was forced through the fill line with compressed air. As the fluid reached the level of the heater surface, additional power was supplied to the element to maintain the surface temperature at 533.3 K (500°F). When the level of the liquid was shown by the level indicator to be 0.0762 m (3 in) above the heater surface, the fill line and level indicator ports were capped. This procedure of pouring the liquid on the heated surface was adopted to avoid the necessity of going through the critical heat flux. The possibility of destruction of the heating element was decreased by avoiding the critical heat flux. After filling, the auxiliary power to the autoclave was turned on to bring the fluid in the boiling vessel to the desired saturation temperature and pressure. In general, the saturation pressure of the system was first set at a reduced pressure of 0.04. The temperatures of the heater surface were monitored with the strip chart recorder until there was no change in temperature with time. Temperatures on the circumference of the heater surface were then recorded along with the saturation temperature of the fluid, and the voltage and amperage supplied to the heat-transfer element. The next temperature level was attained after an approximate 0.5 V increase or decrease in the voltage to the heater. Every test consisted of a sequence of increasing voltage, followed by a sequence of decreasing voltage with occasional reverse steps.

The next step in the procedure was to increase the system pressure to a higher value by closing the cooling coil valves to the autoclave and increasing the delivery pressure from the nitrogen cylinder to the high pressure side of the d/p cell. Normally the pressure was increased by an amount to increase the reduced pressure of the system by 0.02. For a more complete description of the experimental equipment and procedures the reader is referred to [23].

## RESULTS AND DISCUSSION

The calculated results for the film boiling of Freon 113, *n*-pentane, cyclopentane, and benzene are presented in tabular form in [23]. The heat flux from the heater surface was determined by the electrical power input to the heat-transfer element and divided by the surface area of the copper surface. The surface temperatures around the circumference of the heater surface were arithmetically averaged to obtain the average surface temperature. The temperature gradient along the circumference was less than 4.44 K (8°F) for all tests. The saturation temperature of the fluid was recorded for each data point. The temperature difference, $T_{sur} - T_{sat}$, was calculated by subtracting the saturation temperature from the average surface temperature, and the heat-transfer coefficient was determined by dividing the heat flux by the temperature difference. Examples of the calculated

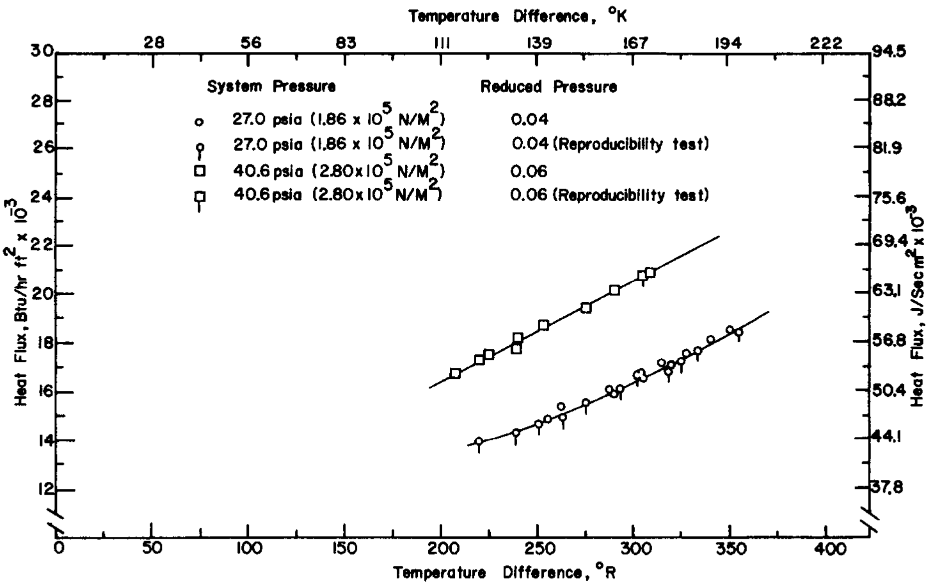


FIG. 2. Film boiling results for cyclopentane, 0.019 m surface diameter.

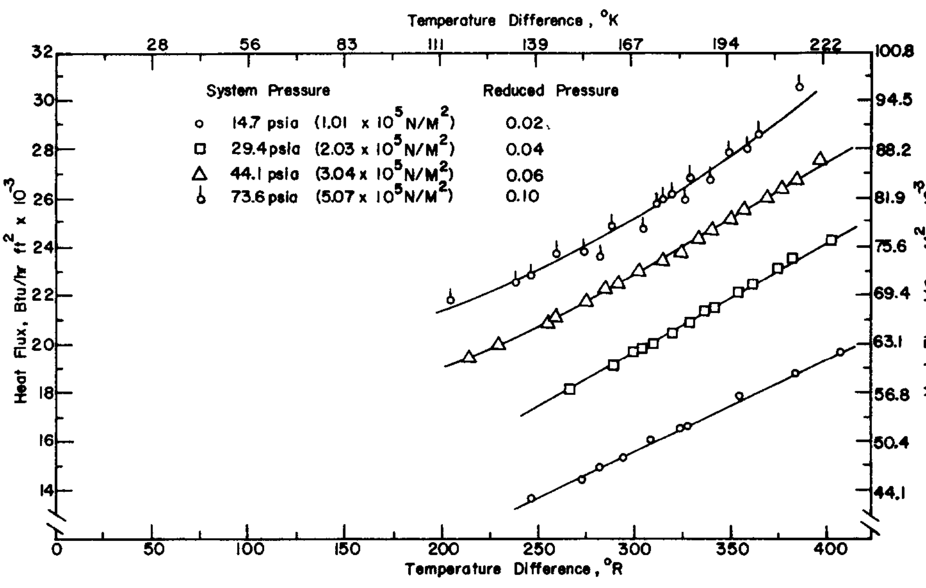


FIG. 3. Film boiling results for benzene, 0.0254 m surface diameter.

results are also presented in graphical form in Fig. 2 and 3.

Tests showing the reproducibility of the data are shown in Figs. 2 and 3 for cyclopentane and benzene, respectively. The scatter in the data shown in Fig. 2 for the cyclopentane boiling from a 0.0019 m (0.75 in) diameter heater is less than 3%. The benzene reproducibility shown in Fig. 3 was within 6%. The increased scatter for the benzene was caused by the increased difficulty in maintaining a stable film. At any particular temperature difference, system pressure, and surface diameter, the required heat flux increased in the following order: Freon 113, *n*-pentane, cyclopentane, and benzene. In general, the trend of the boiling behavior is an increase of the heat flux with an increase in the latent heat of vaporization.

Figures 4 and 5 show the heat input per m of heater surface as a function of heater diameter. The figures represent the data for Freon 113, however, similar trends were shown by the other data of the investigation. Figures 4 and 5 were presented in this manner instead of plotting heat flux or heat-transfer coefficient against diameter since both the flux and coefficient contain the diameter and this could tend to mask the trends of the data. Freon 113 at a pressure of 1.37 $(10)^5$ N/m$^2$ (19.8 psia) becomes more linear for heat per m as a function of diameter as the temperature difference increases (see Fig. 4). Figure 5 indicates that the diameter effect becomes linear at lower temperature differences when the pressure is increased.

As the diameter approaches zero, the heat required to maintain film boiling should approach zero.

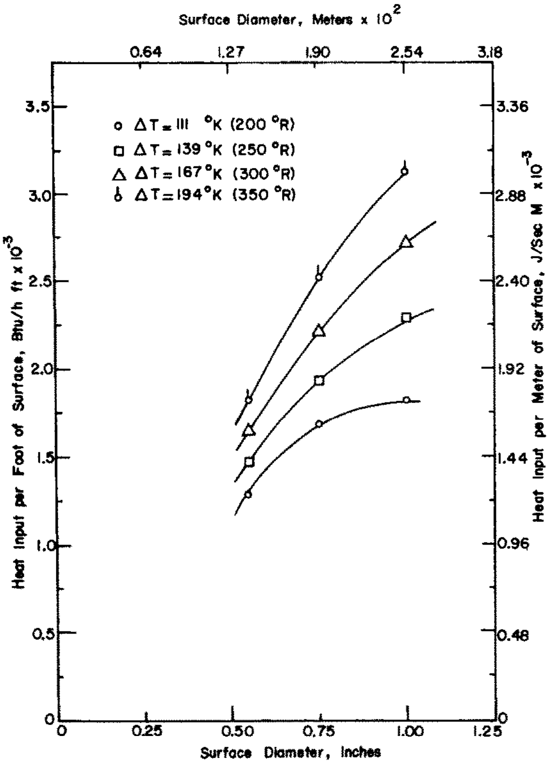


FIG. 4. Film boiling as a function of surface diameter for Freon 113 at 1.37 $(10)^5$ N/m$^2$.

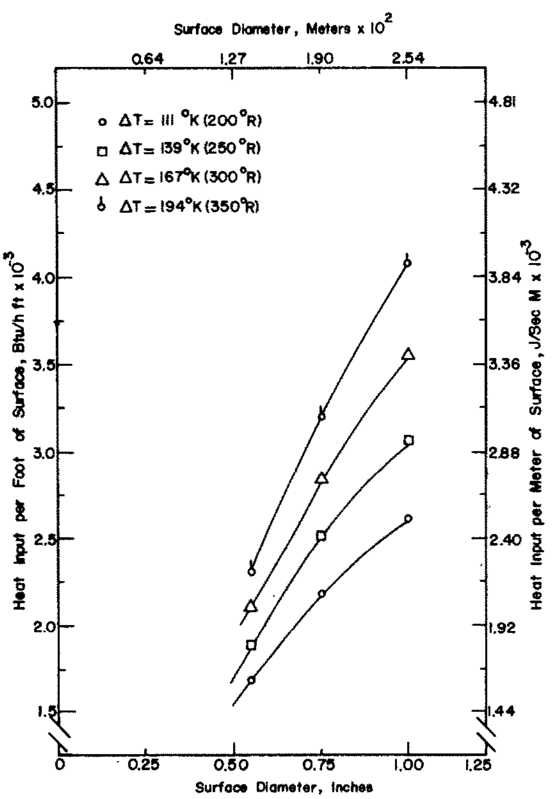


FIG. 5. Film boiling as a function of surface diameter for Freon 113 at 3.42 $(10)^5$ N/m$^2$.

However, the extrapolation to a value of zero was not attempted since a stable film may not be attainable at temperature differences shown in Figs. 4 and 5 for smaller diameters. An example of the relationship between the diameter and temperature difference required for stable film boiling was observed when boiling benzene. Only data for a 0.0254 m (1.00 in) surface could be obtained. No stable film boiling was observed for benzene from surfaces of 0.019 and 0.014 m (0.75 and 0.55 in) dia with surface temperatures of 505.5 K (450°F). More

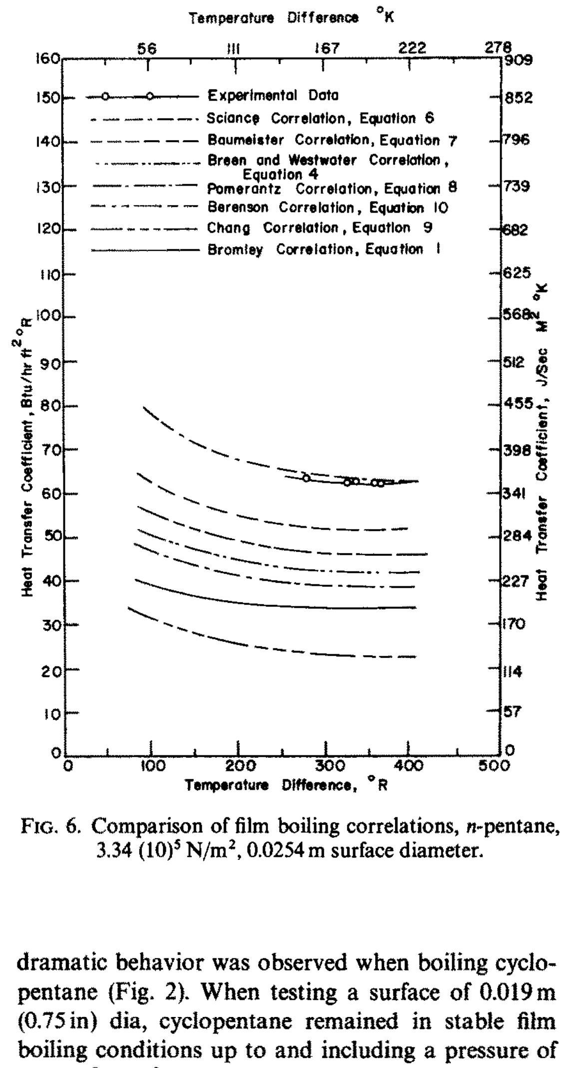


FIG. 6. Comparison of film boiling correlations, *n*-pentane, 3.34 $(10)^5$ N/m$^2$, 0.0254 m surface diameter.

dramatic behavior was observed when boiling cyclopentane (Fig. 2). When testing a surface of 0.019 m (0.75 in) dia, cyclopentane remained in stable film boiling conditions up to and including a pressure of 2.8 $(10)^5$ N/m$^2$ (40.6 psia). Increasing the pressure to 3.37 $(10)^5$ N/m$^2$ (54.1 psia) and holding the surface temperature at 533.3 K (500°F) resulted in the loss of stable film boiling conditions and the slippage into nucleate boiling. Stable film boiling of cyclopentane from a 0.014 m (0.55 in) surface could not be attained for surface temperatures of 505.5 K (450°F). Consequently, a surface's apparent stable boiling is a strong function of the type of fluid, system pressure, surface temperature, and surface diameter.

A comparison of the experimental data with the existing correlations are presented in Figs. 6–8. The

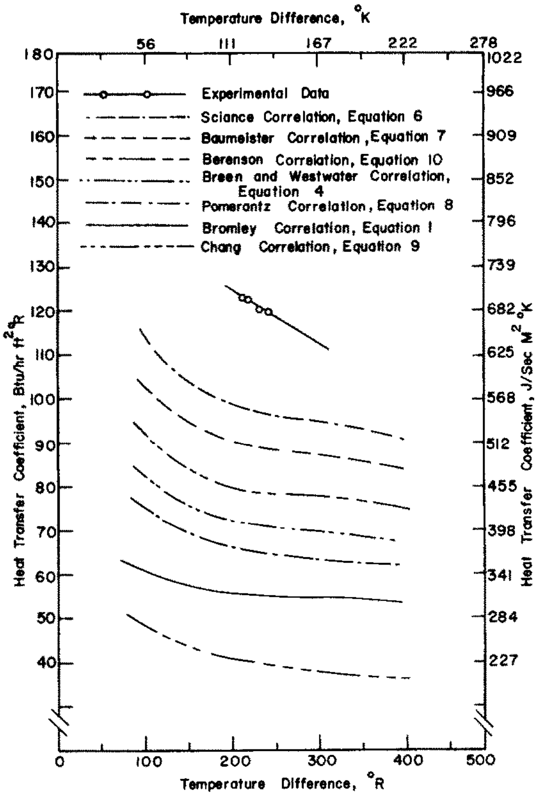


FIG. 7. Comparison of film boiling correlations, *n*-pentane, $1.67\,(10)^6$ N/m², 0.0254 m surface diameter.

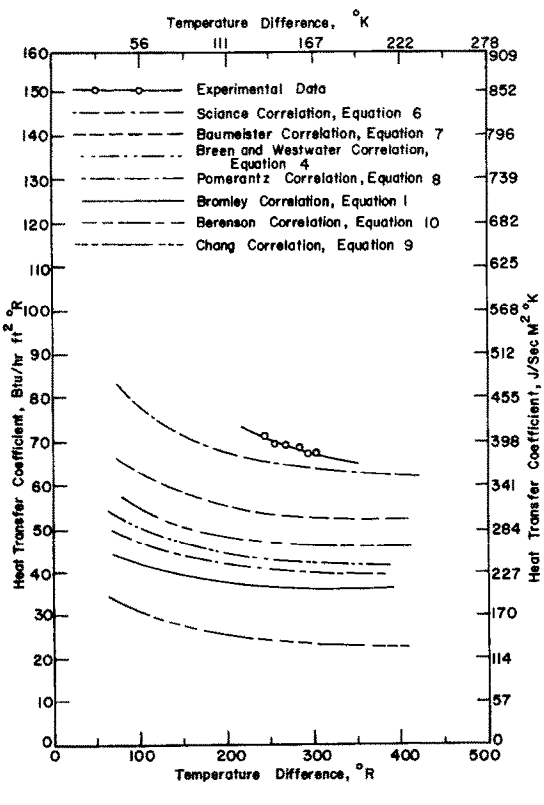


FIG. 8. Comparison of film boiling correlations, *n*-pentane, $3.34\,(10)^5$ N/m², 0.019 m surface diameter.

graphs represent the heat-transfer coefficient as a function of temperature difference.

Figure 6 shows that the Sciance correlation (equation 6) for *n*-pentane from 0.0254 m (1.00 in) dia surface and at $3.34\,(10)^5$ N/m² (48.5 psia) predicts values within a few percent of the experimental values. The other correlations presented in Fig. 6 agree with the experimental values to a lesser extent to a maximum of approximately 60% for the Chang correlation. As shown in Fig. 7, there is a lack of response of the correlations to an increase in pressure to $1.67\,(10)^6$ N/m² (242.5 psia). The Sciance correlation is

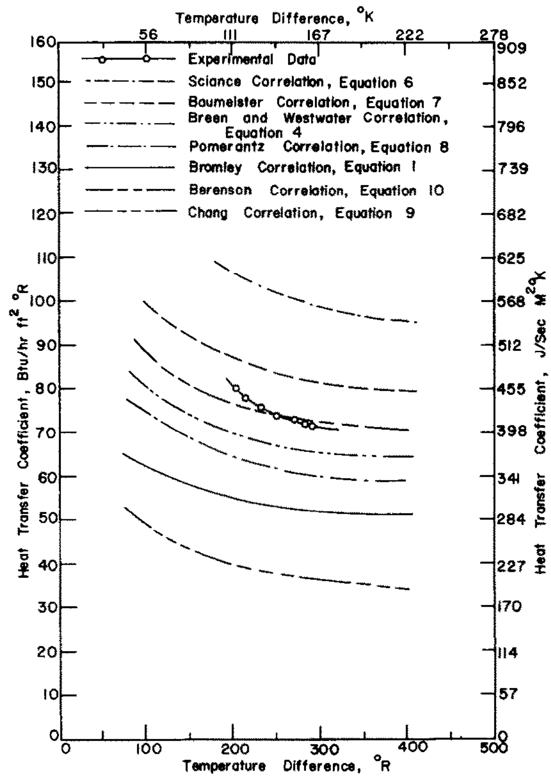


FIG. 9. Comparison of film boiling correlations, cyclopentane, $4.66\,(10)^5$ N/m², 0.0254 m surface diameter.

approximately 20% lower than the experimental values and the Chang correlation is approximately 70% lower than the experimental values at $1.67\,(10)^6$ N/m² (242.5 psia).

Figures 8–13 present similar comparisons of the experimental values with existing correlations. The correlations show insufficient response to changing pressures, fluids, and diameters. With the wide variations in the ability of the correlations to accurately predict experimental values, no correlation tested can be recommended with an acceptable (±20%) degree of reliability.

Many of the correlations which were tested were developed in a manner similar to the development of the correlation of Bromley [11]. An energy balance within the vapor flow surrounding the heat-transfer

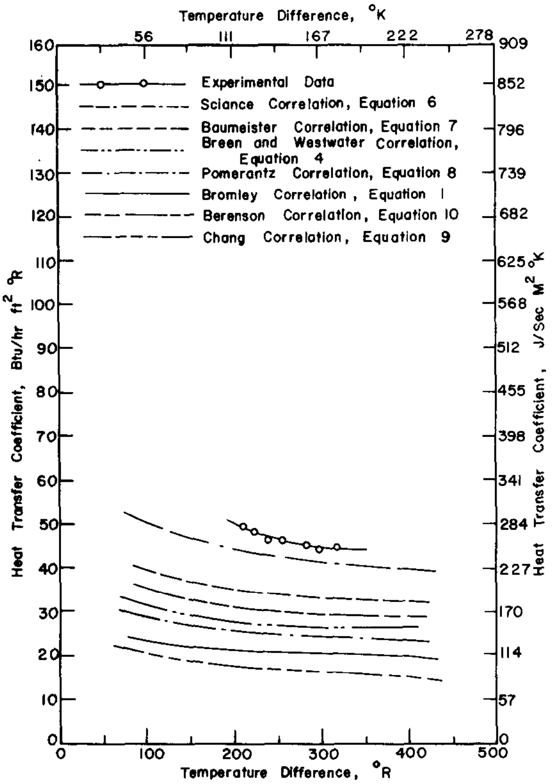


FIG. 10. Comparison of film boiling correlations, Freon 113, 3.41 $(10)^5$ N/m², 0.0254 m surface diameter.

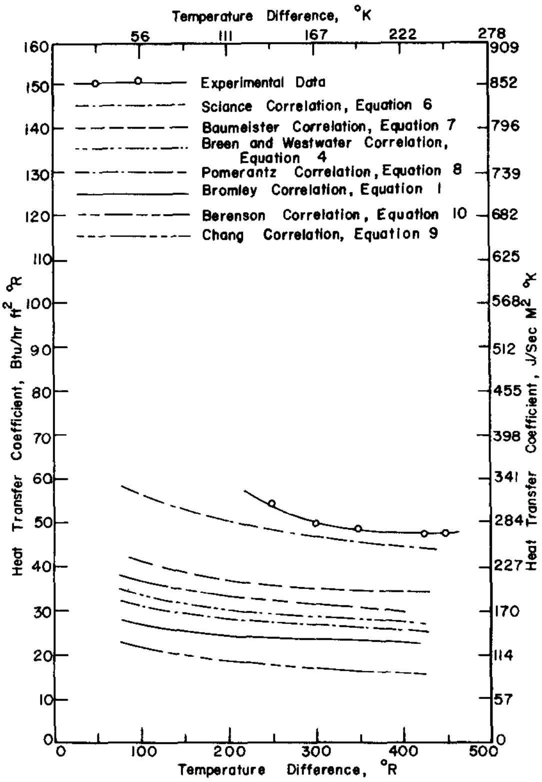


FIG. 12. Comparison of film boiling correlations, benzene, 1.01 $(10)^5$ N/m², 0.0254 m surface diameter.

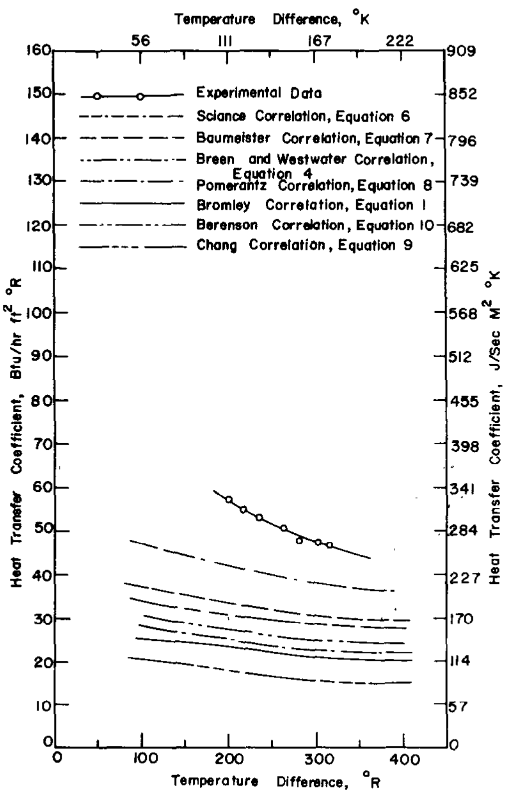


FIG. 11. Comparison of film boiling correlations, Freon 113, 3.41 $(10)^5$ N/m², 0.014 m surface diameter.

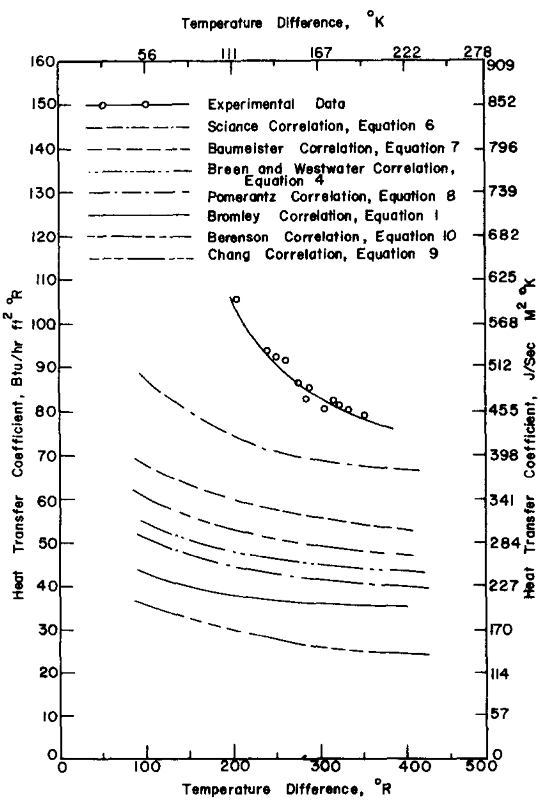


FIG. 13. Comparison of film boiling correlations, benzene, 5.09 $(10)^5$ N/m², 0.0254 m surface diameter.

element was the starting point for the Bromley development. The $F'$ factor in the Bromley (equation 2) is included in many of the other correlations. For example, Chang [22] obtains the same fluid property group, $F'$, but raised it to the 1/3 power instead of the 1/4 power. When considering just the fluid property dependent part of $F'$, comparisons of $F'$ with the experimental data at constant temperature and diameter were made for $n$-pentane at $1.013(10)^5$ N/m$^2$, $3.34(10)^5$ N/m$^2$; $1.67(10)^6$ N/m$^2$ (14.7 psia, 49.6 psia and 242.5 psi). At vapor film temperatures below 422 K (300°F) the $F'$ factor increased with an increase in the system pressure for $n$-pentane. However, at vapor film temperatures above 450 K (350°F) for pressure increases from $1.013(10)^5$ to $3.34(10)^5$ N/m$^2$ (14.7 to 48.5 psia) and from $3.34(10)^5$ to $1.67(10)^6$ N/m$^2$ (48.5–242.5 psia), the $F'$ factors as a function of the film temperature decreased with an increase in the system pressure which is the wrong trend since the heat flux increases with an increase in the system pressure. Also, $F'$ deviated by a factor of two from the experimental data when the system fluid was changed from Freon 113 to $n$-pentane. It is apparent that the grouping of physical properties as defined by $F'$ does not respond correctly to changes in system pressure or fluid properties.

## CONCLUSIONS

In general, the film boiling heat flux as a function of temperature difference, $T_{sur} - T_{sat}$, increases as the temperature difference and system pressure increase at the moderate temperature differences and pressures of this investigation.

The heat flux required to maintain stable film boiling increases as the latent heat of vaporization for the boiling fluid increases as found for Freon 113, $n$-pentane, cyclopentane, and benzene, respectively.

The correlations tested do not adequately ($\pm 20\%$) predict the film boiling behavior of Freon 113, $n$-pentane, cyclopentane, and benzene at moderate temperature differences and pressures, and at surface diameters of 0.01397, 0.01905 and 0.0254 m (0.55, 0.75 and 1.00 in). The difference between the correlations and experimental data are 3–40% for the Sciance correlation (equation 6) and up to a factor of three for the Chang correlation (equation 9).

In view of the results obtained in this investigation and in previous investigations [1–5] with cryogens, it is suggested that the existing theories concerning film boiling be revised.

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## EBULLITION EN FILM DU FREON 113, DU PENTANE NORMAL, DU CYCLOPENTANE ET DU BENZENE A PRESSION MODEREE

**Résumé**—On étudie l'ébullition en film dans des réservoirs de liquides saturants tels que le Freon 113, le pentane normal, le cyclopentane et le benzène. Les surfaces chaudes sont des cylindres de cuivre de 0,0762 m de longueur et de diamètre égaux à 0,01397, 0,01905 et 0,0254 m. Les mesures correspondent à un domaine modéré de pression allant jusqu'à 1,67 ($10^6$) Pa. Les résultats expérimentaux sont comparés à des formules connues pour l'ébullition en film. Ces formules ne sont pas adaptées aux conditions de la présente étude pour prévoir les coefficients de transfert thermique.

## FILMSIEDEN VON FREON 113, NORMAL-PENTAN, ZYKLOPENTAN UND BENZOL AN ZYLINDRISCHEN OBERFLÄCHEN BEI MÄSSIGEN DRÜCKEN

**Zusammenfassung**—Der Wärmeübergang beim Filmsieden in gesättigter Flüssigkeit von Freon 113, Normal-Pentan, Zyklopentan und Benzol wurde untersucht. Die Flüssigkeiten wurden verdampft an kupfernen zylindrischen Wärmeübertragungsflächen, 0,0762 m land und 0,01397, 0,01905 und 0,0254 m im Durchmesser. Die Meßwerte erstrecken sich über einen mäßigen Bereich von Drücken bis zu $1{,}67 \cdot 10^6\ N/m^2$. Die experimentellen Ergebnisse wurden mit vorhandenen Filmsiedekorrelationen verglichen. Es zeigte sich, daß die vorhandenen Filmsiedekorrelationen zur Berechning von Wärmeübertragungskoeffizienten bei den gegebenen Bedingungen unzureichend sind.

## ПЛЕНОЧНОЕ КИПЕНИЕ ФРЕОНА 113, Н-ПЕНТАНА, ЦИКЛОПЕНТАНА И БЕНЗОЛА НА ЦИЛИНДРИЧЕСКИХ ПОВЕРХНОСТЯХ ПРИ УМЕРЕННОМ ДАВЛЕНИИ

**Аннотация** — Проведено исследование переноса тепла при пленочном кипении в большом объеме насыщенных жидких фреона 113, н-пентана, циклопентана и бензола. Жидкости кипят на медных цилиндрических поверхностях длиной 0,0762 м и диаметром 0,01397, 0,01905 и 0,0254 м в диапазоне давлений до 1,67 $(10)^6$ н/м$^2$. Полученные экспериментальные данные сравниваются с известными корреляциями для пленочного кипения. Найдено, что эти соотношения не дают точных значений коэффициентов теплообмена для исследуемых условий.