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FORCED CONVECTION HEAT TRANSFER TO FREON 12 NEAR THE CRITICAL STATE IN A VERTICAL ANNULUS

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Abstract—Experimental investigations of forced convection heat transfer to Freon 12 in a vertical annulus indicate a pseudo-boiling phenomenon when bulk temperatures are maintained within a few degrees of the critical temperature. An empirical correlation of the experimental data, as well as visual and photographic studies, indicate a film boiling type of process.

NOMENCLATURE

A,	area of heat-transfer surface [ft^2];
$f(p)$,	empirical pressure function defined by equation (2);
h,	average heat-transfer coefficient [Btu/h-ft^2-degF];
p,	test section pressure [psia];
p_c,	critical pressure [psia];
q,	heat-transfer rate [Btu/h];
T_B,	bulk temperature [°F];
T_c,	critical temperature [°F];
T_f,	film temperature, $(T_B + T_W)/2$ [°F];
T_W,	wall temperature [°F];
Nu,	Nusselt number, dimensionless;
Pr,	Prandtl number, dimensionless;
Re,	Reynolds number, dimensionless.

Subscripts

B,	evaluated at bulk conditions;
f,	evaluated at film conditions;
W,	evaluated at wall conditions.

INTRODUCTION

STUDIES of critical state heat transfer have yielded variable results. Free convection has been reported to increase by a factor of 10 [1], forced convection with oxygen, nitrogen, and hydrogen produced minimum heat-transfer coefficients near the critical temperature and at supercritical pressures [2], while forced convection studies with water, carbon dioxide, and Freon 12 indicated increased heat-transfer rates near the critical point [3–6, 16]. A pseudo-boiling phenomenon has been postulated to explain the increased heat transfer, this phenomenon being the result of the growth and collapse of bubbles or clusters of molecules in the supercritical region [7]. Flow visualization studies in free convection have served to verify this hypothesis [8], but the heat-transfer rates did not vary appreciably from those observed outside the critical region. Bonilla and Sigel [9] found that strong natural convection heat transfer could be obtained in the critical region using n-pentane, but that the data follow the same general correlation as for turbulent natural convection in the subcritical region.

Increased heat transfer near the critical state is generally attributed to the very large values of specific heat and volume coefficient of expansion which occur in this region. The theoretical analysis of Deissler [10] has considered the property variations of water in the critical region in an attempt to predict the heat-transfer behavior, but the results are not in good agreement with experiment. Conventional dimensionless groups have been employed for empirical correlations but there is considerable disagreement as to the proper method to use for evaluation of properties in the Nusselt, Reynolds, and Prandtl moduli. The rapid change of properties in the critical region accentuates the disagreement because of the substantial variations which

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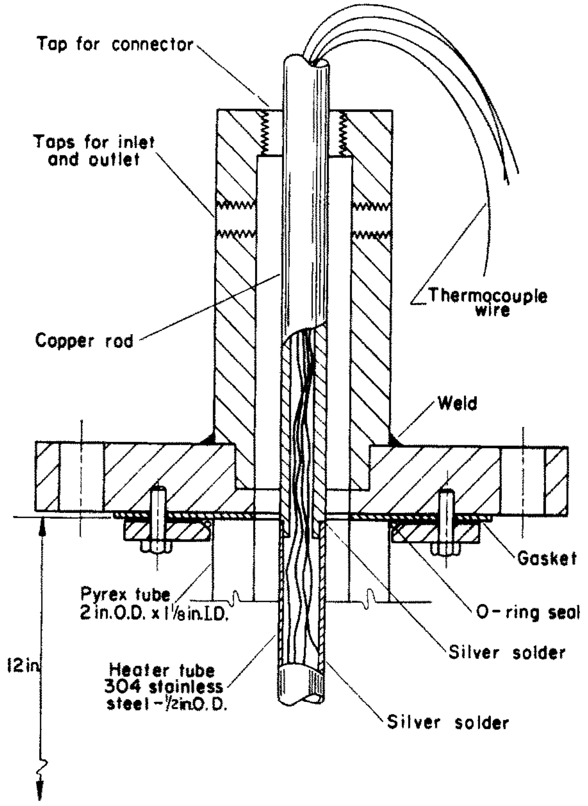


FIG. 1. Schematic of test section.

can occur over a rather narrow temperature or pressure range.

EXPERIMENTAL INVESTIGATION

The purpose of the present investigation was to obtain further detailed measurements near the critical state and make visual observations of the flow. For this purpose Freon 12 was selected as the working fluid because of its modest critical temperature and pressure ($T_c = 233{\cdot}6$°F, $p_c = 596{\cdot}9$ psia). A 12-in vertical annulus was constructed as shown in Fig. 1. An electrically heated 0·500-in O.D. stainless steel tube served as the inner surface of the annulus while a 2-in O.D. by $\frac{1}{8}$-in I.D. tempered Pyrex tube formed the outer surface. The heating element was instrumented with eight chromel–alumel thermocouples and alternating-current heating was employed.

A schematic of the overall system is shown in Fig. 2. A steam preheater was used to control the inlet temperature to the test section and a water-cooled condenser served to cool the Freon after leaving the test section. A calibrated venturi was used for the flow measurement while a small gear pump served to circulate the fluid. Stainless steel construction was employed in all sections of the heat-transfer loop at temperatures above ambient in order to insure that no chemical decomposition of the Freon would occur. Fluid bulk temperatures were measured with calibrated iron–constantan Megopak thermocouples inserted in mixing sections at entrance and exit to the test section. A Heise bourdon tube gage was employed for the test section pressure measurement and a calibrated Honeywell bellows gage was used to measure the differential pressure across the venturi.

The test section thermocouples were calibrated directly by comparison with the bulk

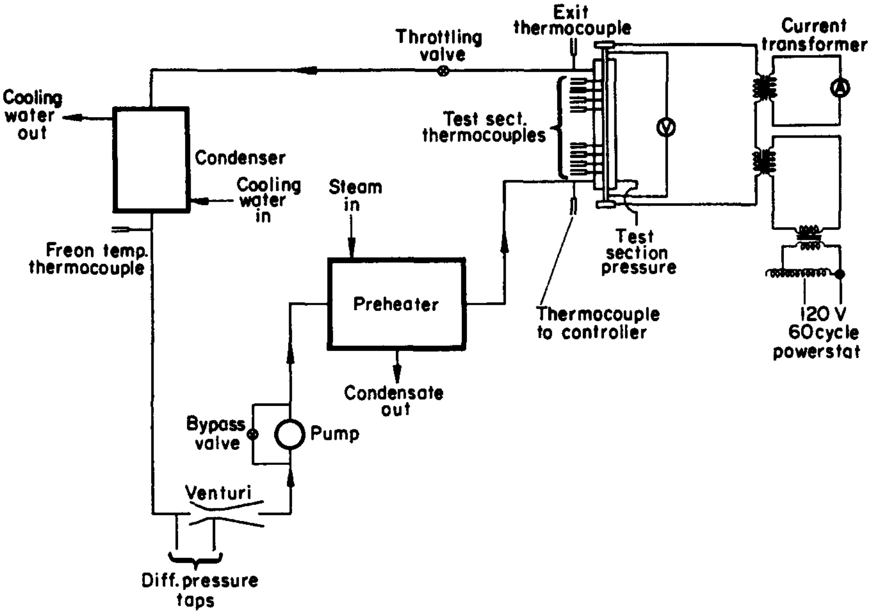


FIG. 2. Flow schematic for heat-transfer loop.

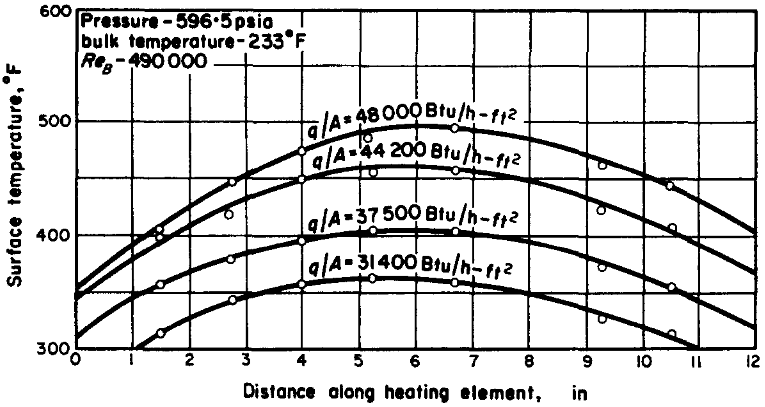


FIG. 3. Typical wall temperature profiles.

temperature thermocouples at various preheat temperatures but without heating of the test section. Test section voltage and current measurements were made with conventional electrical instruments having a calibrated accuracy of 0·2 per cent.

The Freon 12 was supplied by E. I. DuPont de Nemours and Company in the purity of their commercial product.

As a check on the purity and thermodynamic properties of the Freon 12, several preliminary runs were made with various degrees of preheating. The throttling valve at exit from the test section was adjusted until wisps of vapor were visible in the test section. In general, the observed pressures and temperatures agreed with the saturation property data of reference [11], within 2 psia. The critical state could be observed within one or two degrees Fahrenheit of the accepted value of 233·6°F. After the heat-transfer tests were conducted this procedure was repeated as a check against contamination or decomposition of the fluid. The check indicated no change in the fluid properties.

The thermodynamic properties of Freon 12 were obtained from reference [11]. Viscosities were calculated from the generalized correlation of reference [12]. Thermal conductivities were evaluated in a similar fashion using references [13] and [14]. These calculations are in agreement with those of Calcaterra [15]. The advantage of the use of the generalized property correlations is that consistent variations are obtained. More precise calculations must await experimental data on transport properties in the critical region.

RESULTS OF EXPERIMENTS

Experiments were conducted with the Freon bulk temperature below, above, and in the immediate vicinity of the critical temperature. Pressures ranged from 530 to 750 psia with the bulk temperature varying between 200 and 290°F. Heat flux varied from 1500 to 85000 Btu/h-ft^2 while the mass flow ranged from 2000 to 5000 lbm/h. An average heat-transfer coefficient was evaluated for each experimental run from the relation

$$\bar{h} = \frac{q}{A(T_{W\text{avg}} - T_{B\text{avg}})} \tag{1}$$

where q is the total heat transfer as determined from the voltage and current measurements and A is the area of the heated surface. The average outside wall temperature is obtained by integrating wall temperature profiles like those shown in Fig. 3. The outside wall temperatures were calculated from the measured inside temperatures by assuming uniform heat generation in the heater tube with an adiabatic inner surface. A constant heat flux was assumed so that the average bulk temperature was taken as the mean of the measured inlet and outlet bulk temperatures.

For those data with bulk temperatures either 10 degrees above or below the critical temperature it was possible to obtain sets of empirical correlations. Figure 4 shows the result when Nusselt and Prandtl numbers are evaluated at the wall temperature and Reynolds number at the mean film temperature defined by

$$T_f = \frac{T_B + T_W}{2}.$$

Two curves result, depending on whether the bulk temperature is subcritical or supercritical. A similar result is obtained when Reynolds number is evaluated at the bulk temperature as shown in Fig. 5. In this instance the two correlations

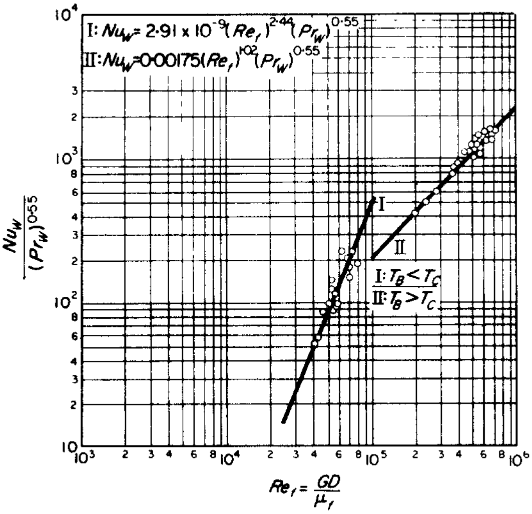


FIG. 4. Correlation of heat-transfer data with Reynolds number based on average film temperature.

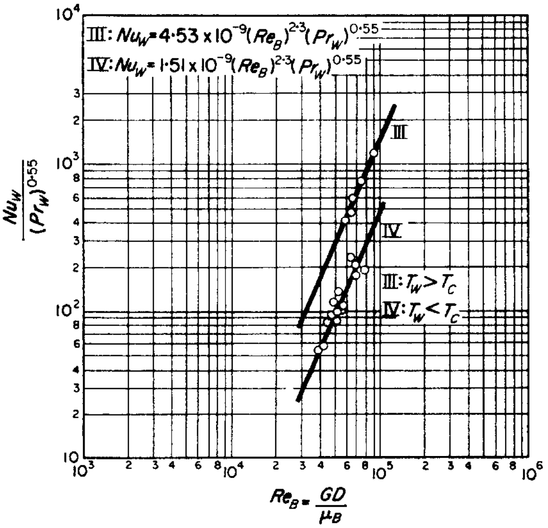


FIG. 5. Correlation of heat-transfer data with Reynolds number based on average bulk temperature.

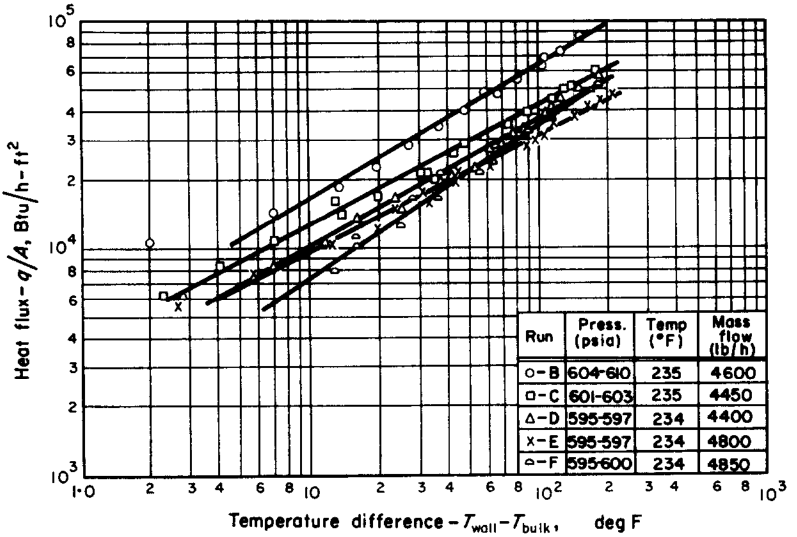


FIG. 6. Heat flux variation in vicinity of critical point.

depend on whether the wall temperature is subcritical or supercritical. Generally unsatisfactory results are obtained when all groups are evaluated at the bulk temperature. More specifically, the Dittus–Boelter type of relation as used in references [5] and [3] is inadequate for correlating the data. In all of the above correlations the hydraulic diameter is used in the Reynolds and Nusselt numbers.

When data points with bulk temperatures closer than ten degrees to the critical value are plotted on the above coordinates, considerable scatter results and no specific conclusions may be drawn. A strong contributing factor to this scatter is probably the uncertain property values in the critical region. It may be noted, for example, that experimental and calculated densities of reference [11] may differ by as much as 6 per cent in the critical region. It is possible that intense free convection currents may account for some of the scatter near the critical state, but this effect should be relatively small in view of the high Reynolds numbers.

A number of measurements were made with fluid bulk conditions as close to critical temperature and pressure as could be attained. This state is very difficult to maintain and pressure fluctuations of a few psi are almost impossible to eliminate. It was necessary to maintain a rather constant flow rate of about 4600 lbm/h in order to maintain critical conditions in the test section. Figure 6 shows the results of the tests in the immediate vicinity of the critical point. To account for the slight pressure variation between the runs a simple linear empirical function was determined to bring these data together as shown in Fig. 7. This function is

$$f(p) = 107{\cdot}5\,(p - 580{\cdot}7) \qquad (2)$$

The correlation for the heat flux in the critical region is

$$q/A = 1{\cdot}62\, f(p)\, (T_W - T_B)^{0{\cdot}54} \qquad (3)$$

The corresponding heat-transfer coefficients are shown in Fig. 8. A comparison of these data with the subcritical and supercritical correlations is shown in Fig. 9, indicating the incompatibility of the critical data with these correlations.

Photographs of the flow corresponding to the data of Fig. 6 indicate a boiling-like phenomenon as shown in Fig. 10. The intensity of the vapor trails increases considerably at wall temperatures in the supercritical range. When the fluid bulk conditions are more removed from the critical state the intensity is substantially reduced. For bulk temperatures twenty degrees above critical no vapor-trails are observed whatsoever.

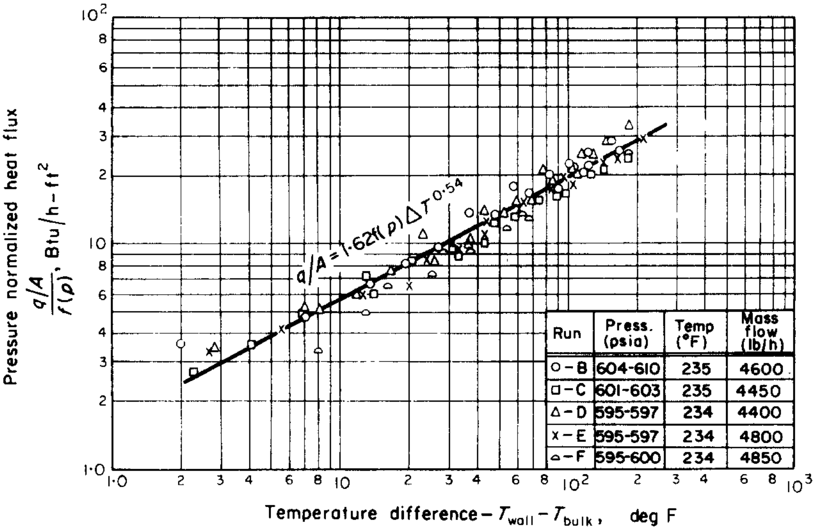


FIG. 7. Normalized heat flux data of Fig. 6.

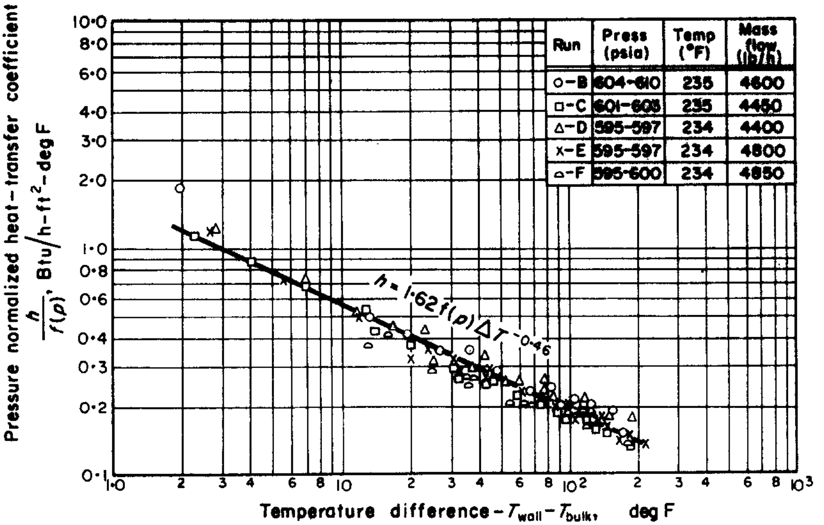
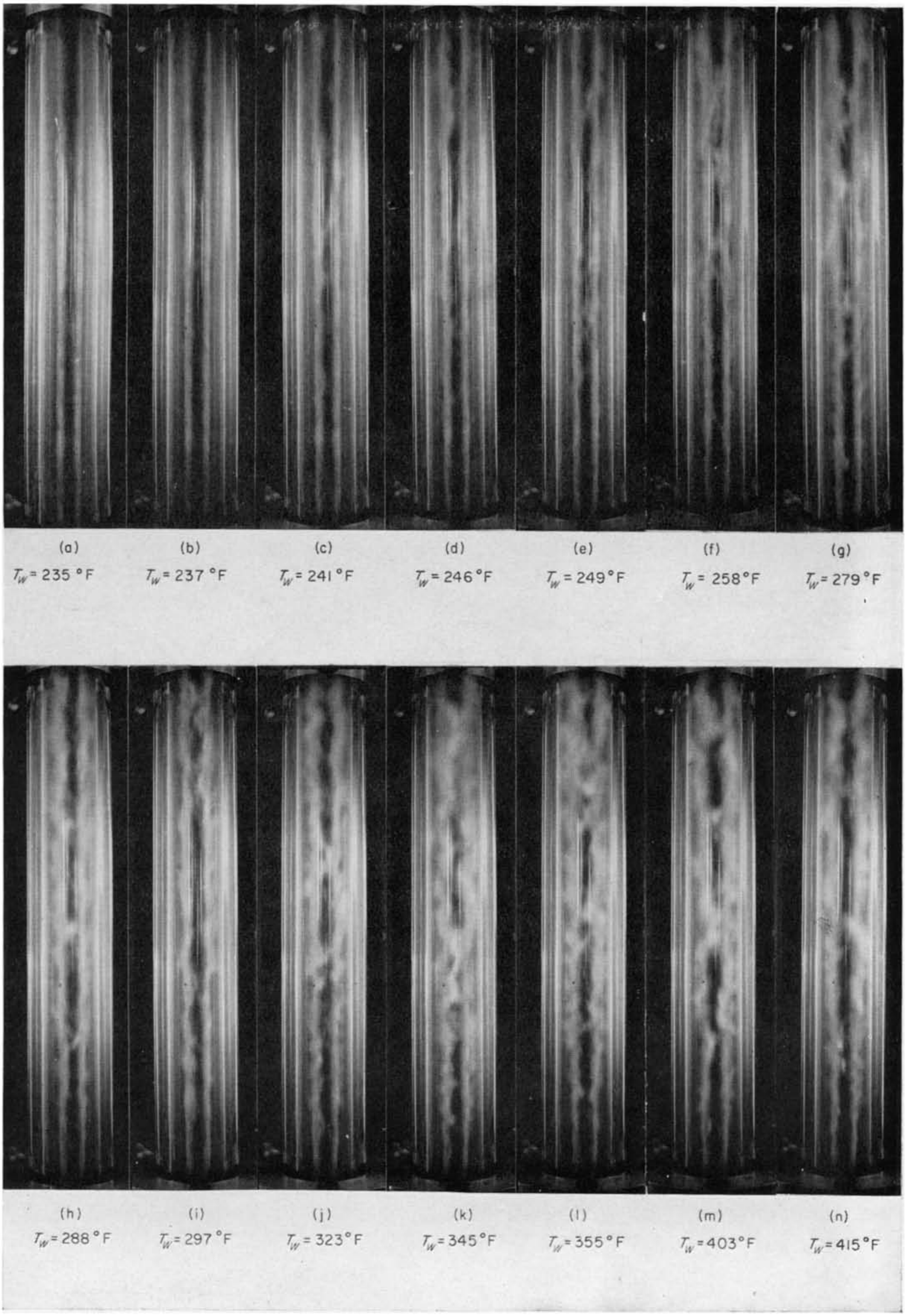


FIG. 8. Heat-transfer coefficients corresponding to data of Fig. 7.

It is not clear whether the vapor-trails observed in Fig. 10 are actually the result of a pseudo-boiling phenomenon at supercritical wall temperatures, or are evident because of the refraction of light resulting from the strong density gradients which occur in the critical region. This is a tenuous point however, because boiling results from strong density gradients and it seems reasonable to give the phenomenon a pseudo-boiling name even if it is not possible to maintain a distinguishable liquid and vapor interface at supercritical temperatures. Equation (3) suggests a film conductance type of mechanism so that the overall heat-transfer mechanism might be referred to as a film boiling process. The increase in heat-transfer coefficient as the critical state is approached, as indicated in Fig. 8, is probably the result of increases in thermal



(a) $T_w = 235$ °F

(b) $T_w = 237$ °F

(c) $T_w = 241$ °F

(d) $T_w = 246$ °F

(e) $T_w = 249$ °F

(f) $T_w = 258$ °F

(g) $T_w = 279$ °F

(h) $T_w = 288$ °F

(i) $T_w = 297$ °F

(j) $T_w = 323$ °F

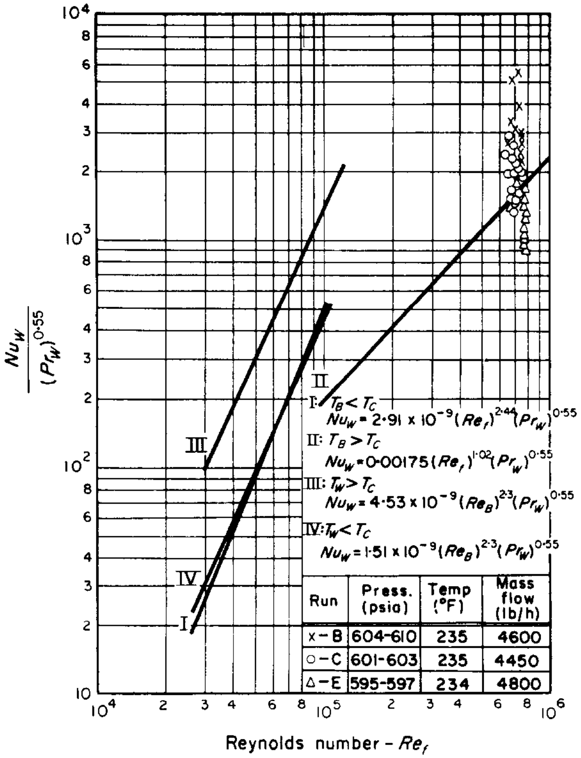
(k) $T_w = 345$ °F

(l) $T_w = 355$ °F

(m) $T_w = 403$ °F

(n) $T_w = 415$ °F

FIG. 10. Photographs of annulus flow near the critical state p = 596–599 psia, T_B = 233–235°F.



Run	Press. (psia)	Temp (°F)	Mass flow (lb/h)
x – B	604–610	235	4600
○ – C	601–603	235	4450
△ – E	595–597	234	4800

FIG. 9. Critical region data compared with subcritical and supercritical data.

conductivity, density, and specific heat for this region.

CONCLUSIONS

Different empirical correlations for heat transfer are obtained for subcritical and supercritical flow regions close to the critical point. The results of this investigation indicate these correlations to be:

$$Nu_W = 1.51 \times 10^{-9}\, Re_B^{2.3}\, Pr_W^{0.55} \qquad (4)$$

for $T_B < T_c,\ T_W < T_c,\ p > p_c$

$$Nu_W = 4.53 \times 10^{-9}\, Re_B^{2.3}\, Pr_W^{0.55} \qquad (5)$$

for $T_B < T_c,\ T_W > T_c,\ p > p_c$

$$Nu_W = 0.00175\, Re_f^{1.02}\, Pr_W^{0.55} \qquad (6)$$

for $T_B > T_c,\ T_W > T_c$

When bulk fluid conditions were maintained in the immediate vicinity of the critical point the above relations were inadequate to describe the experimental data and the heat-transfer coefficient was found to follow a variation of

$$h \sim (T_W - T_B)^{-0.46} \qquad (7)$$

for $T_B \approx T_c$ and $p \approx p_c$

Considerable uncertainty exists in the property data and the above relations should be accepted with caution. It does appear, however, from the form of equation (7) and also from the flow visualization studies that a film-boiling type of process occurs when the fluid bulk conditions are maintained very close to the critical state.

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Résumé—Les recherches expérimentales du transport de chaleur par convection forcée de Fréon 12 dans un tuyau annulaire vertical indique un phénomène de pseudo-ébullition lorsque les températures globales sont maintenues à quelques degrés de la température critique. Une corrélation empirique des données expérimentales, ainsi que les études visuelles et photographiques, indiquent un processus du type ébullition par film.

Zusammenfassung—Experimentelle Untersuchungen des Wärmeüberganges an Freon 12 bei Zwangskonevektion in einem senkrechten Ringspalt weisen ein "Pseudo-Siedephänomen" auf, wenn die Mischtemperatur des Mediums nahe der kritischen liegt. Eine empirische Beziehung für die Versuchsdaten deutet ebenso wie die visuelle oder photographische Beobachtung auf eine Art von Filmsieden hin.

Аннотация—Экспериментальные исследования переноса тепла к Фреону-12 при вынужденной конвекции указывают на явление псевдокипения в случае, когда объемные температуры поддерживаются в диапазоне нескольких градусов в области критической температуры. Эмпирическая корреляция экспериментальных данных, а также визуальное наблюдение и фотографирование свидетельствуют о пленочном характере процесса кипения.