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DETERIORATION OF HEAT TRANSFER TO SUPERCRITICAL* HELIUM AT 2·5 ATMOSPHERES

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Abstract—Heat transfer has been investigated for supercritical helium at 2·5 atm flowing inside a vertical tube with inlet bulk fluid temperatures less than the transposed critical temperature. Results indicate that for high heat flux conditions, the heat-transfer coefficient passes through a maximum and then deteriorates as the fluid temperature approaches the transposed critical temperature. This is contrary to the predictions of a correlation developed in an earlier study of supercritical helium heat transfer under low heat flux conditions, which only predicts enhancement in heat transfer as the transposed critical temperature is approached.

The experimental data are presented and conditions under which heat-transfer deterioration was observed are discussed. The probable limitations to the validity of the above mentioned heat-transfer coefficient correlation, developed for a different range of experimental data, are also discussed.

NOMENCLATURE

D, inside tube diameter [cm];
C_p, specific heat at constant pressure [J/g-K];
i_{IN}, enthalpy at $T_{B\,\mathrm{INLET}}$, P [J/g];
i_{TC}, enthalpy at T_{TC}, P [J/g];
G, mass velocity [g/s-cm²];
h, heat-transfer coefficient [W/cm²-K];
k, thermal conductivity [W/cm-K];
z, length along test section [cm];
P, pressure [atm];
$\dot{m}$, mass flow rate [g/s];
Q, total heat added to fluid [W];
q, heat flux [W/cm²];
T_B, bulk fluid temperature [K];
$T_{B\,\mathrm{INLET}}$, fluid temperature at test section inlet [K];
$T_{B\,\mathrm{OUTLET}}$, fluid temperature at test section outlet [K];
T_{TC}, transposed critical temperature [K];
T_W, inside wall temperature [K].

Greek symbols

Φ, $\dfrac{4zq}{D[(i_{TC}-i_{IN})G]}$;
μ, viscosity [g/cm-s].

1. INTRODUCTION

IN A PREVIOUS study of forced convection heat transfer to supercritical helium in a vertical tube [1] a correlation was developed from the experimental data to predict the heat transfer in this region. The correlation is:

$$\frac{hD^{0.2}}{G^{0.8}}\left(\frac{T_W}{T_B}\right)^{0.716} = 0.0259k^{0.6}C_p^{0.4}/\mu^{0.4} \qquad (1)$$

in which fluid properties μ, C_p and k have been collected together on the right hand side. Equation (1) predicts a maximum in the heat-transfer coefficient when the bulk fluid temperature is equal to the transposed critical temperature. For a given pressure, the transposed critical temperature is defined as the temperature at which C_p is a maximum. The prediction of equation (1) is consistent with the experimental observations of Johannes [2] and Ogata and Sato [3] in their investigations of supercritical helium heat transfer under low to moderate heat flux conditions. Similar enhancement in heat transfer to carbon dioxide as the bulk fluid approaches the transposed critical temperature has been observed by Tanaka *et al.* [4].

In [1] we noted that the peak in the properties parameter, $k^{0.6}C_p^{0.4}/\mu^{0.4}$, at the transposed critical temperature accounts for the enhanced heat transfer observed under the operating conditions of that study.

However, at high heat fluxes, a degradation, rather than enhancement, in heat transfer in the transposed critical region has been observed by many investigators, e.g. Ogata and Sato [3] for helium, Shiralkar and Griffith [5] for carbon dioxide, Shitsman [6] for water, and Powell [7] for oxygen.

As summarized by Shiralkar and Griffith, the conditions under which degradation occurred are:

1. The wall temperature must be above, and the bulk temperature below the transposed critical temperature.
2. The heat flux must be above a certain value, dependent on the flow rate and pressure.

Heat-transfer degradation seems therefore to be a function of the inhomogeneity of the fluid resulting from the temperature dependence of fluid properties. Equation (1) when $T_W \approx T_B$, is essentially a homogeneous heat-transfer model.

With the experimental apparatus described in [1] for supercritical helium it was not possible to attain both criteria noted above. Because of the inefficiency of the

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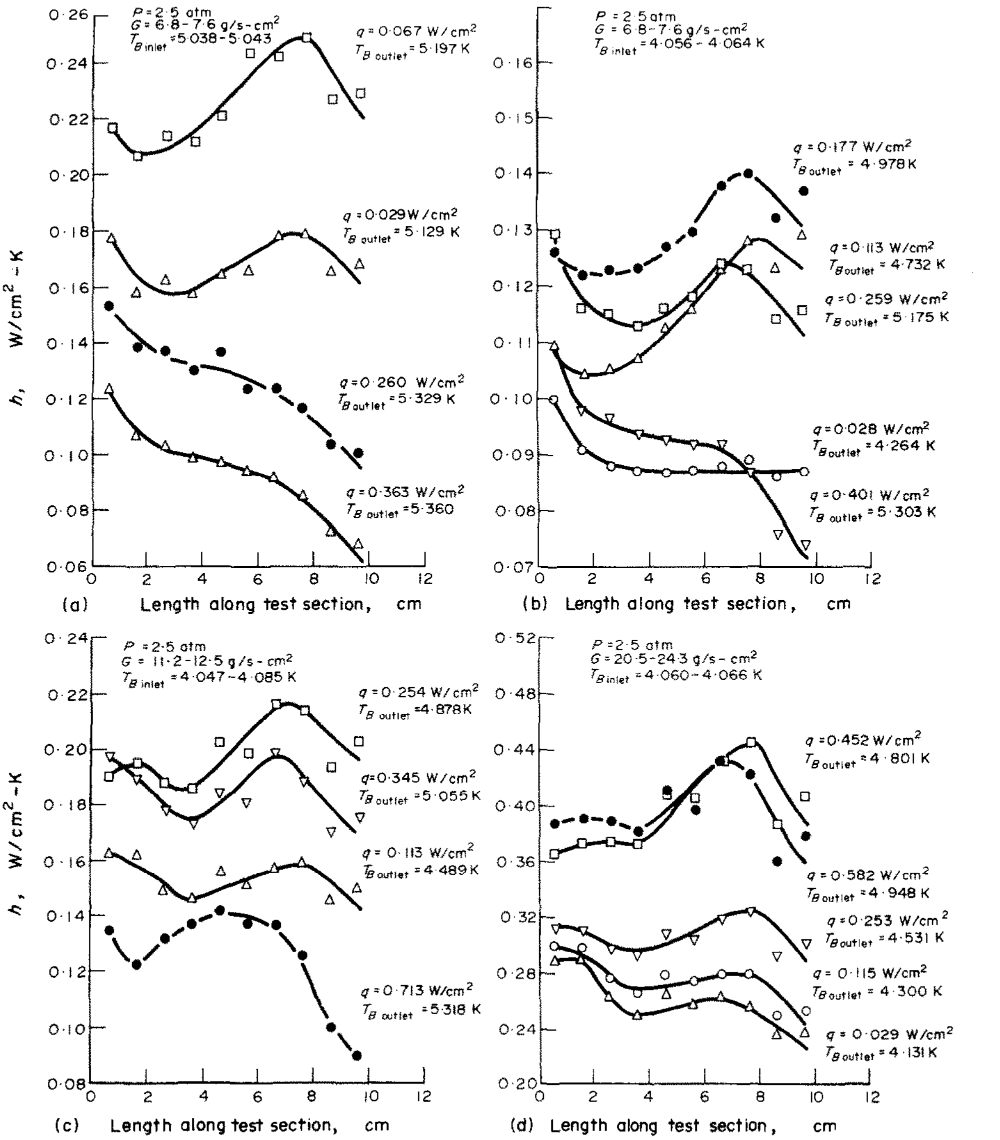

FIG. 1. Heat-transfer coefficient profiles at 2·5 atm.

heat exchanger, as the heat flux to the test section was increased there was a corresponding increase in the inlet bulk fluid temperature. Therefore high heat flux measurements were obtained only for high bulk temperatures (greater than T_{TC}).

Subsequent revision of the experimental apparatus, including the heat exchanger, for subcritical helium heat-transfer studies [8] has enabled us to obtain supercritical helium heat-transfer data under conditions described in the above two criteria. We chose, therefore, in the present study to attempt to verify the above criteria for the degradation of heat transfer to supercritical helium and to quantify them as far as possible. An operating pressure of 2·5 atm was selected as being one which could be comfortably controlled and which would at the same time be close enough to the critical pressure of 2·245 atm to give good definition to specifically supercritical effects.

In this paper we present the experimental data and discuss the conditions under which departures of supercritical helium heat transfer from equation (1) were observed. The probable limitations to the previously developed correlation, equation (1), are also discussed.

The ranges of experimental variables are as follows:
- Pressure: 2·5 atm (T_{TC} = 5·4 K)
- Mass velocity: 7, 12, 22 g/s-cm²
- Test section inlet temperature: 4·05, 5·04 K
- Heat flux: 0·008–0·713 W/cm²

Flow direction: vertically downward.

Reference [8] contains a complete description of the experimental apparatus.

2. EXPERIMENTAL RESULTS AND DISCUSSION

2.1. *Heat-transfer coefficients profiles*

The experimental results are shown first in the form of heat-transfer coefficient profiles, Fig. 1, for the uniformly heated 0·213 cm i.d. × 10-cm long stainless steel test section. The estimated systematic error in the measured heat-transfer coefficients varies from 55 per cent for the worst condition (high flowrate and low heat flux) to 8 per cent for the most favorable condition (low flowrate and high heat flux). However, the plot of Fig. 3 which compares the experimental heat-transfer coefficient with that predicted by equation (1) suggests the systematic error is much lower than the estimated upper bound of 55 per cent. The major source of error arises from the uncertainty in the outside wall temperature and thickness of the stainless steel test section.

For a constant property fluid having a fully developed turbulent velocity profile along the entire length of a uniformly heated tube, the typical variation of the heat-transfer coefficient h with position in the tube is one of rapid reduction from a high value at the entrance of the tube (the thermal entrance region) to a lower and essentially constant value at positions in the tube more than approximately twenty diameters from the beginning of the heated section. As can be seen in Fig. 1 for helium at 2·5 atm and conditions noted, the variation of h with position in the tube is generally in contrast with that expected for a fluid having negligible property variation. Although the usual entrance effects are exhibited in the profiles, the subsequent peaks (or in some instances further deterioration in heat-transfer coefficient) can be related to the rapidly changing properties in the tube (in the vicinity of the transposed critical temperature).

General trends can be noted by reference to Figs. 1(a)–(d). At low heat flux, e.g. 0·028 W/cm², Fig. 1(b), and bulk fluid temperature less than 4·264 K a heat-transfer coefficient profile typical of that expected for turbulent heat transfer to a constant property fluid is observed. An increase in the heat flux to 0·113 W/cm², and as a consequence, increase in the temperature rise of the bulk fluid, produces a substantial change in the shape of the h vs length curve. In addition to the overall increase in h, after the initial reduction of heat-transfer coefficient in the thermal entrance region it rises to a maximum value at 37 diameters from inlet, deteriorating again beyond. Further increase in heat flux produces a similar result until, eventually, a heat flux somewhere above 0·177 W/cm² is reached where the overall magnitude of the heat-transfer coefficient decreases. However, the characteristic shape remains the same (e.g. 0·259 W/cm² curve). Finally, at 0·401 W/cm² the overall heat-transfer coefficient is seen to be further reduced and the peak exhibited at the lower heat fluxes has disappeared, the profile generally exhibiting deterioration along the entire length of the test section.

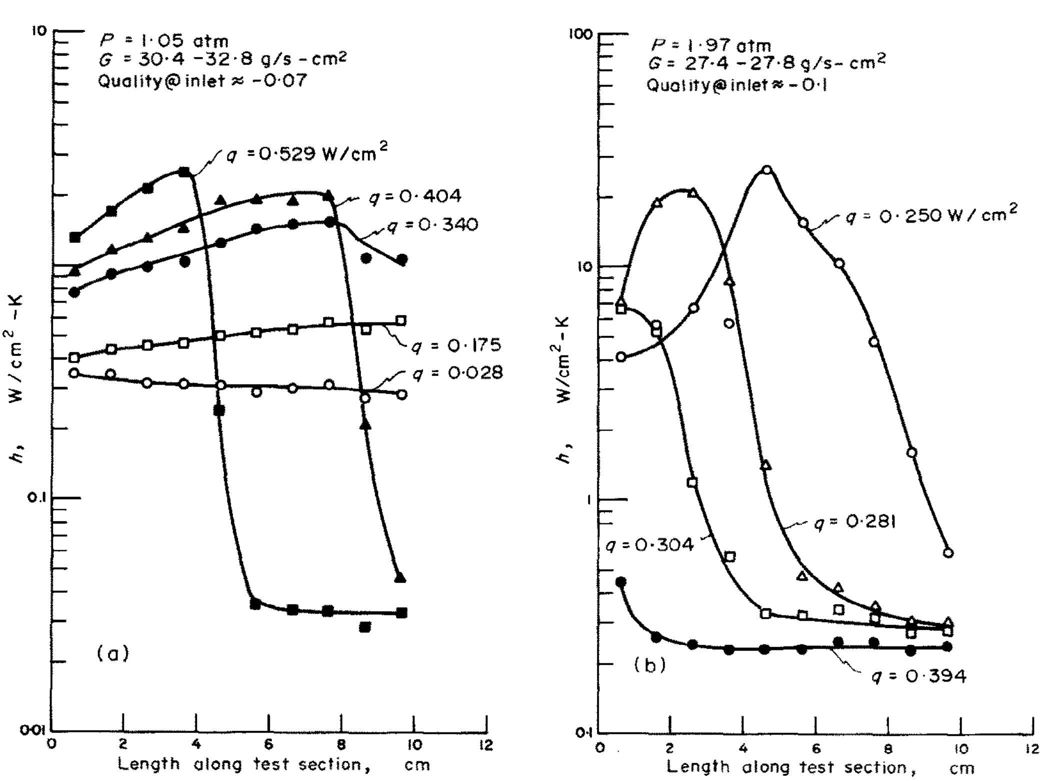

FIG. 2. Heat-transfer coefficient profiles at subcritical pressures (1·05 and 1·97 atm).

2.2. *Comparison of supercritical and subcritical helium heat-transfer coefficient profiles*

It has been suggested by Goldmann [9] that supercritical fluids exhibit "pseudo boiling" like characteristics under high heat fluxes and low bulk temperatures. Figures 2(a) and 2(b) show heat-transfer coefficient profiles for subcritical helium at 1·05 and 1·97 atm (taken from data of [8]); the transition from nucleate to film boiling at a critical heat flux is evidenced by the sharp reduction in the heat-transfer coefficient.

The critical heat flux phenomenon observed in the supercritical case bears some analogy, but we note two striking differences. In the first place the supercritical heat-transfer coefficients are almost two orders of magnitude lower than the subcritical coefficients before degradation or transition. Only at high mass velocities (e.g. $\sim$ [illegible] g/s-cm^2) are comparable supercritical heat-transfer coefficients obtained [1]. Secondly, the transition in the subcritical case is much sharper, i.e. a small change in heat flux gives rise to a more dramatic decline in the heat-transfer coefficient than is observed for supercritical helium. This evidence does not therefore specifically substantiate the pseudo boiling hypothesis, although qualitative similarities are undeniable.

2.3. *Correlation of experimental results*

We have examined the data for some indicator of heat-transfer coefficient degradation in order to provide a quantitative criterion for this phenomenon. While the criteria of Shiralkar and Griffith were generally found to be true when degradation took place, it was not possible for the present experimental conditions to relate the maximum in the heat-transfer coefficient with the bulk fluid temperature being at the transposed critical, as was found in [1]. Neither was this true for a film temperature (defined as the mean of wall and bulk fluid temperature) or wall temperature being at the transposed critical. Although there are many possibilities which we have not tried, we present in Fig. 3 a plot of the ratio of the observed heat-transfer coefficient to that calculated from equation (1) vs a dimensionless parameter Φ. Φ is defined as

$$\Phi = \frac{\text{heat per unit mass added to fluid up to a given point along the tube}}{\text{enthalpy at transposed critical}-\text{enthalpy at inlet}} = \frac{Q(z)/\dot{m}}{i_{TC}-i_{IN}} = \frac{4zq}{(i_{TC}-i_{IN})GD}$$

Φ is thus the fraction of the heat required to bring the fluid to T_{TC} which has been added up to point z. The data plotted are for two different inlet temperatures, 4 and 5 K, and for three different thermometer stations clear of the entrance region where $z/D = 22$, 31 and 45 respectively. This plot appears to bring the data together fairly well and adds confirmation to our interpretation of equation (1), developed in our earlier work. The data exhibit a clear deviation from the predicted heat transfer for $\Phi > 0{\cdot}3$ (relatively high heat flux conditions) and show somewhat of a crisis as Φ approaches 1·0. However, equation (1) is apparently a good representation of low heat flux data and according to Fig. 3 at least, should be valid for $\Phi \leqslant 0{\cdot}3$.

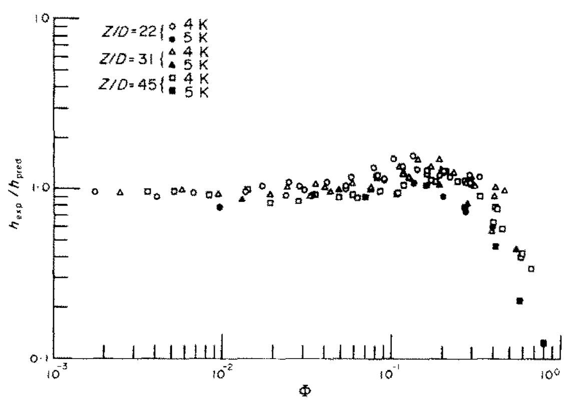

FIG. 3. Ratio of experimental to predicted heat-transfer coefficients (h_{exp}/h_{pred}) vs correlating parameter, Φ.

While it correlates the present data, the plot of Fig. 3 may not be universally applicable for all inlet conditions. For example, when inlet temperatures are very near the transposed critical, substantial values of Φ could be achieved even under low heat flux (i.e. homogeneous) conditions and significant deviation from equation (1) would not be expected. For the range of the present inlet conditions Table 1 contains the maximum heat fluxes above which departures of more than 20 per cent from equation (1) were observed (i.e. $\Phi > 0{\cdot}3$).

Table 1. Experimental values of q where $0{\cdot}8 < h_{exp}/h_{calc} < 1{\cdot}2$

G (g/s-cm^2)	$T_{B\,INLET}$ (K)	q (W/cm^2)
5·7–7·6	4·056–4·064	less than 0·177
6·8–7·6	5·038–5·043	less than 0·187
11·2–12·5	4·047–4·085	less than 0·345
20·5–24·3	4·047–4·085	less than 0·582

We were not able to run the apparatus with $\Phi > 1$ for reasons which are not entirely clear. Several things happened simultaneously as the fluid approached the transposed critical temperature, including the problem that the superconducting power leads to the test section went normal. It should be noted that similar experiences occurred in our subcritical experiments in film boiling once the heat flux exceeded about 1·1 W/cm^2 and this may simply be a limitation imposed by the transition temperature of the superconducting leads.

An unexpected feature of Fig. 3 is the region $0{\cdot}07 < \Phi < 0{\cdot}3$ which shows clear enhancement above the value of h given by equation (1). It should be remembered that equation (1) already accounts fairly well at higher pressures for enhancement due to the temperature dependence of the fluid properties as well as the non-linearity of the heat-transfer process indicated by the term $(T_W/T_B)^{0{\cdot}716}$.

In view of the apparent significance of the parameter Φ for the present study at 2·5 atm it is natural to inquire as to the values obtained in the experiments of [1] since the correlation developed there seems to represent the low heat flux limit. Table 2 lists the maximum values of Φ for the pressures investigated for those runs in which the fluid entered below the transposed critical temperature. A value of Φ for each thermometer is given.

Table 2. Values of Φ from [1]

Pressure (atm)	T_{INLET}/T_{TC}	Φ_1 ($z/D = 20$)	Φ_2 ($z/D = 40$)
3	0·88	0·048	0·096
4	0·88	0·37	0·74
5	0·97	0·64	1·28
7	0·86	0·37	0·74
8	0·69	0·077	0·15
9	0·91	0·104	0·208
10	0·76	0·160	0·320
14–15	0·44	0·96	1·92
19–20	0·97	0·40	0·80

Since substantial values of Φ were achieved in [1] at higher pressures one can only surmise that degradation of heat transfer was not significant and perhaps this is of concern only quite close to the critical pressure as is here the case. Further experiments along the lines of those reported here would be required to clarify this point. Judging from these observations at 2·5 atm, a safe range of application of equation (1) would be given by values of T_{INLET}/T_{TC} greater than those shown in Table 2 with corresponding values of Φ less than those shown in Table 2.

3. CONCLUSIONS

The experiments reported here for heat transfer to supercritical helium in forced flow at 2·5 atm lead to the following conclusions:

1. For supercritical helium, both enhancement and deterioration in heat transfer can occur as observed with other fluids. In general the criteria quoted from Shiralkar and Griffith for the existence of an impaired heat-transfer coefficient are verified. A good quantitative indicator of the particular behavior to be expected for the inlet conditions of this experiment at 2·5 atm is given by the value of the dimensionless parameter Φ defined in the text.

2. At 2·5 atm and conditions noted with heat fluxes below those given by $\Phi = \leqslant 0{\cdot}3$ equation (1) gives heat-transfer coefficients within ± 20 per cent of the experiments.

3. For $0{\cdot}3 < \Phi < 1{\cdot}0$ the experimental heat-transfer coefficient deteriorates to as low as 12 per cent of that given by equation (1), the value $\Phi = 1{\cdot}0$ appearing to be somewhat of a heat-transfer crisis.

4. There is a strong indication from earlier results that this type of behavior may not be observable at 4 atm and above. The estimated range of applicability of equation (1) is given by information contained in Table 2.

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