Int. J. Heat Mass Transfer. Vol. 21, pp. 76–77. Pergamon Press 1978. Printed in Great Britain

PREDICTION OF HEAT TRANSFER TO SUPERCRITICAL HELIUM AT HIGH HEAT FLUXES USING NON-BULK VALUES OF *Pr* AND *Re*

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(*Received 20 December 1976 and in revised form 27 April 1977*)

NOMENCLATURE

- D, test section diameter;
- g, average mass flow rate per unit area $4\dot{m}/\pi D^2$;
- h, heat-transfer coefficient $q/(T_w - T_b)$;
- k, thermal conductivity;
- $\dot{m}$, total mass flow rate;
- Nu, Nusselt number hD/k;
- Pr, Prandtl number $C_p\eta/k$;
- q, heat flux;
- Re, Reynolds number gD/η;
- Re_{min}, lesser of Re_w and Re_b;
- T_w, wall temperature;
- T_b, bulk temperature;
- T_{pc}, pseudo-critical temperature;
- x, distance along test section from start of heater;
- η, viscosity.

Subscripts

- w, parameter evaluated at T_w;
- b, parameter evaluated at T_b.

Heat transfer to supercritical helium is important in connection with cooling superconducting devices of various kinds (generators, magnets, power cables etc.). Because of the low temperature of the helium (typically 5 K) high heat fluxes lead to large values of T_w/T_b and, for example, in the recovery of superconducting AC power cables from faults, heat transfer at T_w/T_b of up to 4 can be important. Unfortunately there is little data covering these conditions. There have been several studies of supercritical helium heat transfer [1, 3, 4] but these have been mostly concerned with lower heat fluxes; only the work of Giarratano and Jones [5] covers high heat flux, with T_w/T_b upto 2.5, but they used a pressure very close to critical (2.7 bar) and their results show gross effects associated with the very large near critical property variations. During a recent study [1, 2] we made some observations of high heat flux heat transfer at pressures more representative of those likely to be encountered in practical applications (~4 bar) and with T_w/T_b upto 3.8. Some of these data are shown in Fig. 1(a). The experimental techniques were covered in [1]. The data shown are for downflow in a 1.78-cm dia tube at $x/D = 40$. The heat-transfer coefficient is plotted against T_w/T_b as a convenient parameter and the results cover a series of measurements taken with increasing heat input. The series starts with T_w and T_b below T_{pc} and finishes with T_w and T_b above T_{pc}. The variation through the series of T_w, T_b, p and other parameters is shown in Fig. 1(b). The main features of the heat transfer variation are a maximum, which occurs soon after T_w reaches T_{pc}, followed by a steady decrease as T_w/T_b increases. The maximum is clearly associated with the maximum in C_p, and thus Pr, when $T \simeq T_{pc}$ and we now examine the success of a selection of heat-transfer correlations in predicting the maximum and the subsequent decrease in h.

We consider first three equations already used to correlate supercritical helium data:

$$Nu_b = 0.0218 Re_b^{0.8} Pr_b^{0.4} \tag{1}$$

$$Nu_b = 0.0259 Re_b^{0.8} Pr_b^{0.4} (T_w/T_b)^{-0.716} \tag{2}$$

$$Nu_b = 0.0213 Re_b^{0.8} \bar{P}r^{0.51} \tag{3}$$

where $\bar{P}r$ is a harmonic average defined by

$$\left[\frac{1}{T_w - T_b}\int_{T_b}^{T_w} 1/Pr(t)\,dT\right]^{-1}$$

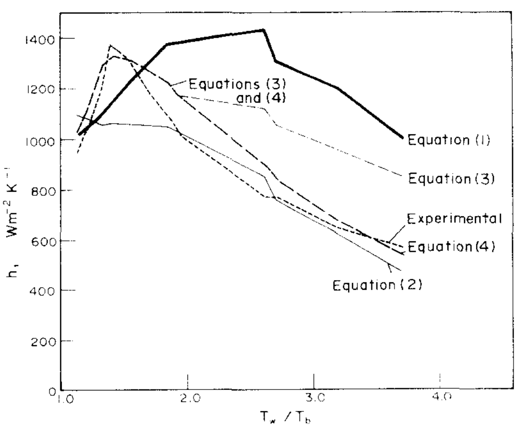

Fig. 1(a). Variation of the heat-transfer coefficient with T_w/T_b compared with the predictions of various correlations. The estimated experimental errors are $\pm 3\%$. The predictions of the equations are evaluated for each experimental point separately and are not continuous functions.

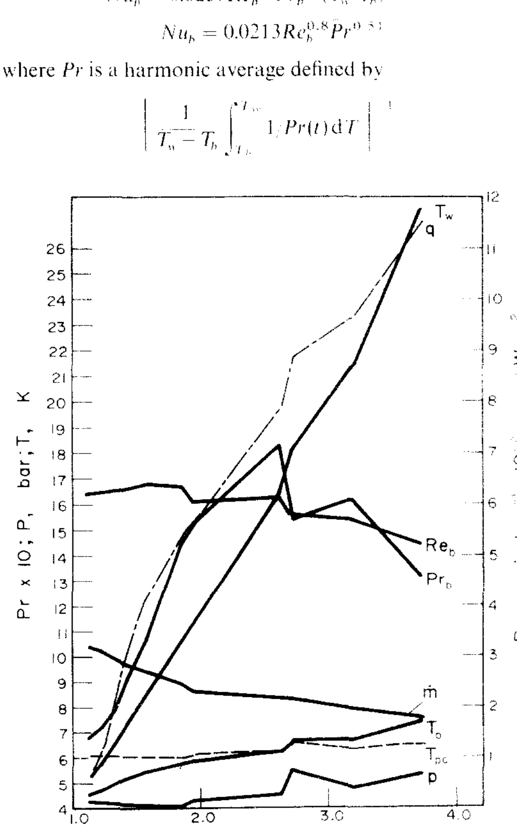

Fig. 1(b). Variation of T_w, T_b, Re, Pr etc. with T_w/T_b for the experimental data of Fig. 1(a).

In this paper a simplified method of evaluating $\overline{Pr}$ has been used which is described in [1]. Equations (1) and (3) were used by Brassington and Cairns [1] and equation (2) is the recommended equation of Giarratano *et al.* [3]. These equations were best fits to the original data of [1] and [3], the multiplying factors and the (T_w/T_b) and $\overline{Pr}$ exponents having been the adjustable parameters. With their original data, which had (T_w/T_b) up to ~ 1.4 in both cases, they achieved standard deviations of 11, 8 and 6% respectively.

The heat-transfer coefficients predicted by the above equations are plotted on Fig. 1. Equation (1) is clearly totally inadequate at high T_w/T_b. This is because it uses a bulk Prandtl number which has a maximum when $T_b \simeq T_{pc}$, whereas the experimental results show a maximum soon after T_w reaches T_{pc}. The (T_w/T_b) factor of equation (2) enables it to predict the heat transfer at high T_w/T_b very well but it fails to predict the enhancement at $T_w/T_b \simeq 1.4$. There are two other objections to equation (2), firstly the use of a T_w/T_b factor has no physical basis: temperatures do not appear in the basic equations describing the flow and heat transfer except as a temperature difference, and secondly, equation (2) predicts the same deterioration of h at high T_w/T_b at higher pressures where property variations and thus presumably heat-transfer variation would be much less. We thus consider that the success of equation (2) at high (T_w/T_b) is largely fortuitous. Equation (3) on the other hand has a more plausible theoretical backing, being based on a Prandtl number averaged over the range T_w to T_b, and it predicts the heat-transfer enhancement at $T_w/T_b \simeq 1.4$ very well. It is not surprising that this equation was so successful at correlating the heat-transfer data of [1]. However with the present data it does not predict sufficient reduction in h at high T_w/T_b.

The reason for this could be that for the high T_w/T_b data the viscosity at T_w is considerably higher than at T_b [$\eta(T)$ has a minimum at T_{pc}] and one would expect the wall viscosity to be more important to heat transfer than the bulk value because it controls the important viscous sub-layer thickness. Replacing Re_b by Re_w in equation (3) does in fact give excellent agreement with the experimental results at high T_w/T_b but then the predicted h at $T_w/T_b \simeq 1.4$ becomes much too high (because there $\eta_w \ll \eta_b$). We therefore propose the use of Re_{min}, defined as the lesser of Re_w and Re_b, to give:

$$Nu_b = 0.0213 Re_{min}^{0.8}\, \overline{Pr}^{0.51}. \qquad (4)$$

This use of a minimum value has a precedent in the successful use of Pr_{min} in the supercritical correlation of Miropolsky and Shitsman [6]. The predictions of equation (4) are plotted on Fig. 1 and they lie within 10% of the experimental values throughout the range of T_w/T_b. The data of Fig. 1 were taken at $x/D = 40$; the corresponding data for $x/D = 20$ are also represented by equation (4) to within 10%. This is hardly a test against independent data though and equation (4) requires further experimental checking over a wider range of pressures and temperatures. Equation (4) does have the advantage that it differs from equation (3) only at high heat flux, since it is only then that Re_w is appreciably lower than Re_b, and it is thus known to be a good representation of the low heat flux data.

The heat-transfer data of Fig. 1 may in some cases be of direct use since the conditions are typical of those encountered in superconducting devices (but note that for fixed Re, h scales with D^{-1}). In general though Fig. 1 should not be regarded as giving the variation of h with T_w/T_b. h is a function of p, T_w and T_b separately and T_w/T_b is used as the independent variable only for convenience.

Acknowledgements—This work was carried out at The Central Electricity Research Laboratories and is published by permission of the Central Electricity Generating Board.

REFERENCES

1. D. J. Brassington and D. N. H. Cairns, Measurements of forced convective heat transfer to supercritical helium, *Int. J. Heat Mass Transfer* **20**, 207–213 (1977).
2. D. N. H. Cairns and D. J. Brassington, A pumped supercritical helium flow loop for heat-transfer studies, *Cryogenics* **16**, 465–468 (1976).
3. P. J. Giarratano, V. D. Arp and R. V. Smith, Forced convection heat transfer to supercritical helium, *Cryogenics* **11**, 385 (1972).
4. H. Ogato and S. Sato, Forced convection heat transfer to supercritical helium, *Teion Kogaku* (*Cryogenic Engineering*) **7**, 20–28 (1972).
5. P. J. Giarratano and M. C. Jones, Deterioration of heat transfer to supercritical helium at 2.5 atmospheres, *Int. J. Heat Mass Transfer* **18**, 649–653 (1975).
6. Z. L. Miropolsky and M. E. Shitsman, Heat transfer to water and steam at variable specific heat (in near critical region), *Soviet Phys. JETP* **2**, 10 (1957).