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The correction to take account of variable property effects on turbulent forced convection to water in a pipe

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Abstract—An experimental study is reported of the effects of fluid property variation on turbulent heat transfer to water in a uniformly heated pipe. Data were obtained for bulk to wall viscosity ratios of up to 1.4 over a range of Reynolds numbers from 2.1×10^4 to 5.3×10^4. After establishing constant-property values of heat transfer coefficient, the effect of variable properties was determined. This was expressed in terms of bulk to wall viscosity ratio raised to a power n. It was found that n increased steadily from about 0.1 to about 0.18 over the Reynolds number range covered, the mean value being close to the widely quoted Sieder and Tate index of 0.14. © 1997 Published by Elsevier Science Ltd.

INTRODUCTION

Turbulent forced convection in pipes has received extensive study. For conditions such that wall to bulk temperature differences are small, experimental data for fully developed flow and heat transfer are found to correlated in terms of local Nusselt number, Reynolds number and Prandtl number without the need for special consideration of variable property effects. Simple, constant property empirical equations are available which provide an adequate basis for thermal design. In some practical situations, however, significant temperature differences do exist between the wall and the bulk fluid and the use of constant property relationships is inappropriate. For liquids, the properties density, specific heat and thermal conductivity vary only weakly with temperature, but viscosity varies strongly. The usual approach in the case of liquids is to employ a property ratio correction to the constant-property value of Nusselt number. Thus, the parameters Nu, Re and Pr in the correlation equation are evaluated at the local bulk temperature and a term is added involving the ratio of viscosities evaluated at the bulk and wall temperatures. Thus,

$$Nu = Nu_{c_p}(\mu_b/\mu_w)^n \tag{1}$$

Experimental investigations into the influence of variable properties on heat transfer to liquids have not been numerous. The earliest study reported was that of Sieder and Tate in 1936 [1]. Their viscosity ratio correction with $n = 0.14$, based on heating and cooling experiments with three different oils, is widely quoted even today.

The Sieder and Tate study was followed by a number of others, see Table 1.

Petukhov [9] suggested that the Sieder and Tate [1] value of 0.14 was too large and instead proposed 0.11. This conclusion was reached by considering the data of Yakovlev [3], Hufschimidth *et al.* [6] and Kreith and Summerfield [2].

Allen and Eckert [4] made some particularly careful measurements of heat transfer to water flowing in a tube with uniform wall heat flux. Although they did not present their results in a form which involved the index n, it is clear that if they had done so it would have depended on the Reynolds number (see later). Malina and Sparrow [5] made measurements for both water and oils using the same experimental equipment and also produced results which indicate a dependence of n on Reynolds number. Everett [7] also reported a dependency of n on Reynolds number.

The fact that the values of n reported in the literature differ significantly is not surprising. The determination of n is not a simple matter due to the fact that the influence of property variation on heat transfer to liquids is relatively small.

EXPERIMENTAL ARRANGEMENT

The working fluid used in the present investigation was water at atmospheric pressure. Water flowed from a header tank through a test section of length about

NOMENCLATURE

n	viscosity ratio correction index (eqn (1))
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number.

Greek symbol

μ	viscosity.

Subscripts

b	value evaluated at local bulk temperature
c_p	constant property
exp	experimental
PK	calculated from Petukhov–Kirillov equation
vp	variable property
w	value evaluated at local wall temperature.

Table 1. Experimental studies of convective heat transfer to liquids with variable properties

Reference	n
Sieder and Tate [1]	0.14
Kreith and Summerfield [2]	0.10
Yakovlev [3]	0.11
Allen and Eckert [4]	0.05–0.13 for $2 \times 10^4 < Re < 1.1 \times 10^5$
Malina and Sparrow [5]	0.05
Hufschimidth *et al.* [6]	0.11
Everett [7]	$(Re/87 \times 10^4)^{0.84}$ for $Re < 62{,}500$; 0.11 for $Re > 62{,}500$
Oskay and Kakaç [8]	0.262

7.15 m manufactured from stainless steel tube of bore 48.3 mm and wall thickness 1.29 mm. An unheated flow development section of length 3.7 m (approximately 76 diameters) was followed by a section of length 3.0 m (approximately 62 diameters) which was uniformly heated by resistive means. On leaving the test section, the water passed through a flow control valve and a turbine flow meter before draining into the bottom tank from which it was pumped steadily back to the header tank.

The distribution of temperature along the heated part of the test section wall was measured using 17 thermocouples attached to the outer surface of the tube at intervals of about 5 diameters. The temperature of the water was measured at inlet and also at outlet using thermocouple probes mounted within the flow. All the thermocouple emfs were supplied through two multi-channel scanners to a pair of digital voltmeters interfaced to a personal computer.

The electrical power input to the test section was calculated from a knowledge of the electrical current and voltage drop. These were also measured using the data acquisition system.

EXPERIMENTAL CONDITIONS

The water temperature at inlet to the test section was maintained steady at 18 ± 0.1°C. A detailed programme of experiments was conducted in which the flow rate and electrical power input were systematically varied.

At low Reynolds numbers, buoyancy influences became important. The threshold for onset of such influences was found experimentally to be 1.8×10^4 for the maximum heat flux used. In order to avoid any influence of buoyancy on heat transfer, Reynolds number was restricted to values above 2×10^4 in the experiments reported here.

Experiments were performed with six different flow rates ranging from 0.8 to 2.1 kg/s, giving a range of Reynolds numbers at the tube inlet from 2.1×10^4 to 5.3×10^4. For each flow rate five different values of electrical power input were applied. The wall heat flux varied from 8.8×10^3 to 2.6×10^4 W/m^2.

Further information concerning the experimental arrangement, procedures and data reduction can be found in Büyükalaca [10].

RESULTS AND DISCUSSION

Attention was initially focused on the region of fully developed heat transfer. Results for a particular flow rate at locations between 36 and 52 diameters from the start of heating were carefully extrapolated back to the zero heat flux condition ($\mu_b/\mu_w = 1$) to obtain constant property values of heat transfer coefficient. These were correlated in terms of Nusselt number and Reynolds number and fitted by an equation of the form proposed by Petukhov and Kirillov [11]. Thus the constant-property Nusselt number Nu_{c_p} was given by

$$Nu_{c_p} = C \times Nu_{PK} \tag{2}$$

in which factor C, which was close to unity, depended weakly on Reynolds number over the range considered.

Local values of Nusselt number for conditions of variable properties normalised using corresponding constant property values Nu_{c_p} are shown in Fig. 1 for several values of Reynolds number. By fitting the data as shown, the index n in eqn (1) was calculated for each case. The values of n obtained are presented in Fig. 2 for two separate test series. As can be seen, they increase from about 0.10 to about 0.18 over the range of Reynolds number considered. The maximum uncertainties in determining the heat transfer coefficient and the index n are estimated to be 6% and 9%, respectively, using an established technique [12].

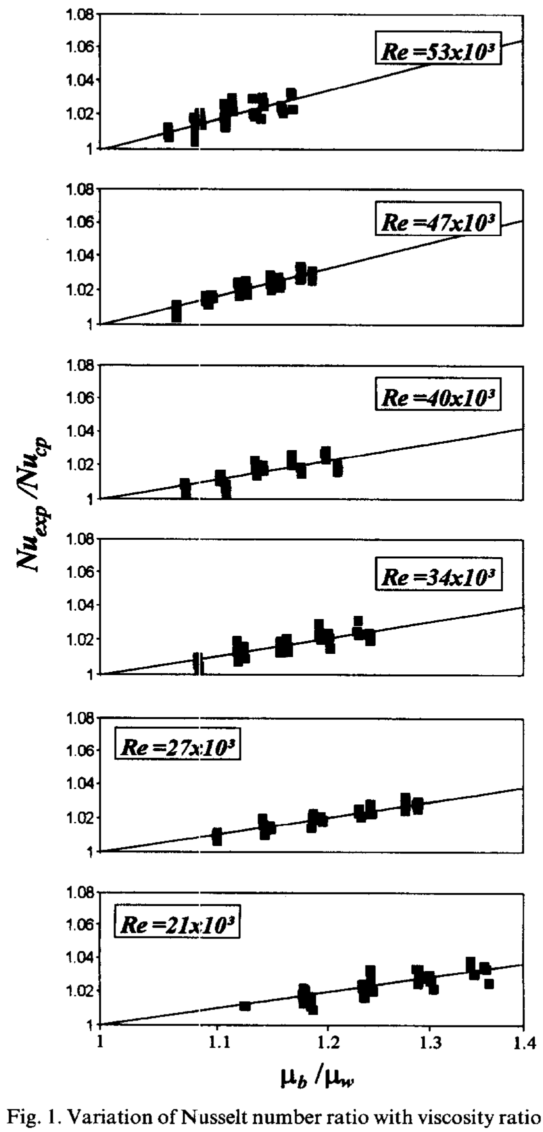

Fig. 1. Variation of Nusselt number ratio with viscosity ratio.

Calculations were also performed for measurements recorded for the remainder of the thermocouple positions using the procedure described earlier. It was found that there was no systematic variation of n with axial position for a fixed value of Reynolds number. These results confirmed the dependency of n on Reynolds number already found. A first order fit to all the data yielded;

$$n = 0.048 + 2.6 \times 10^{-6} \times Re \tag{3}$$

EVALUATION OF THE PRESENT RESULTS

Allen and Eckert and Malina and Sparrow presented their results in the form Nusselt number ratio versus wall-to-fluid bulk temperature difference. For the purpose of making comparisons with the results of present study their Nusselt number ratio values have been expressed as a function of μ_b/μ_w for each Reynolds number and values of n evaluated. They are shown in Fig. 3. There are clear differences between the values yielded by the study of Allen and Eckert and that of Malina and Sparrow.

Figure 4 shows a comparison between the data of Allen and Eckert, Malina and Sparrow, and the present results (eqn (3)). Also shown is the relationship between n and Reynolds number proposed by Everett. It can be seen that the present results lie well above the data of Allen and Eckert and Malina and Sparrow and the Everett curve. The Sieder and Tate result, $n = 0.14$, is close to the mean of the present values whereas the values $n = 0.11$ recommended by Petukhov and the value $n = 0.1$ proposed by Kreith and Summerfield lie below them. The value $n = 0.262$ reported by Oskay and Kakaç [8] lies well above those found in all other studies.

As can be seen, the recommendations which have stemmed from the various investigations differ considerably. This reflects the fact that establishing the variable property correction is difficult. Great care is needed in experimental work to achieve the required precision. The investigations reported to date in the literature have been spread over a long period of time and the reliability of the results from some of the early studies must certainly have been limited by the accuracy of the measurement systems available to the investigators.

It is of interest to speculate as to the explanation of the variable property effect. Clearly, raising the temperature of the liquid within the near-wall region reduces its viscosity. As a result, turbulent motion in that region should be less damped. However, any tendency for less constrained turbulent motion to enhance heat transfer would be offset by the local reduction in the Prandtl number in the near-wall region. Parallel arguments based on the idea of the universality of near-wall velocity distribution, combined with the assumption that wall shear stress is

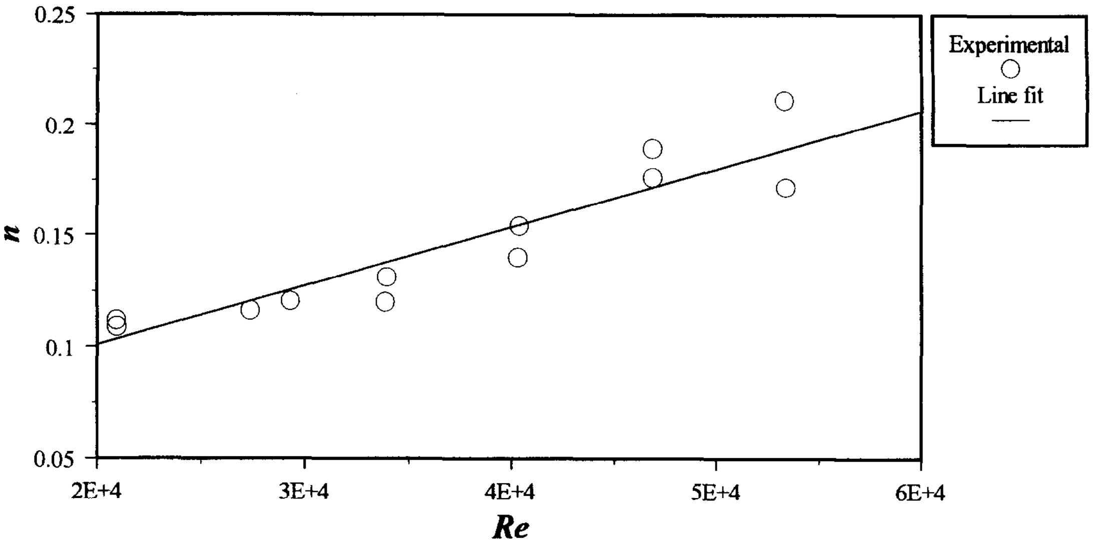

Fig. 2. Variation with Reynolds number of the viscosity ratio correction index n.

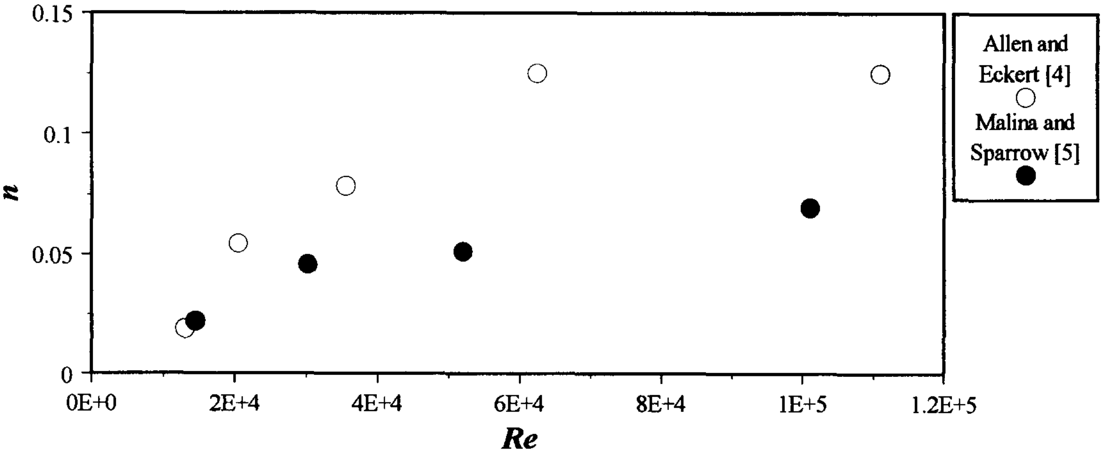

Fig. 3. Variation with Reynolds number of n values calculated from Allen and Eckert [4] and Malina and Sparrow [5].

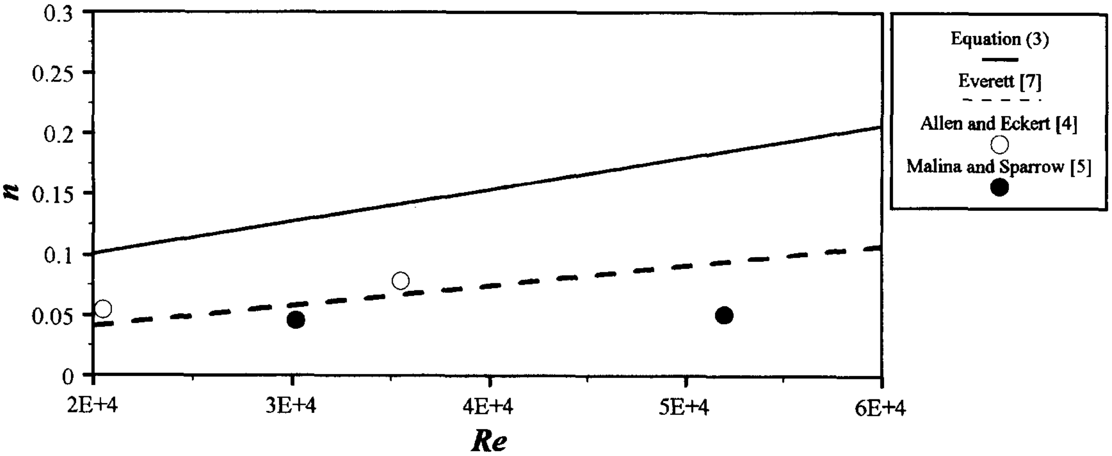

Fig. 4. Comparison between the present correlation, other data and the correlation of Everett [7].

unaffected, certainly lead to the conclusion that the viscous sub-layer will be thinner as a result of reduction of near-wall fluid viscosity. However, on considering the effect of this on heat transfer in terms of the effective thermal conductivity of the fluid in the near-wall region, it becomes clear that the ratio of the thermal layer thickness to that of the viscous sub-layer will be increased. This will offset the effect that the reduction of sub-layer thickness might have had. In practice, there will be some influence on shear stress of reducing the viscosity of fluid in the wall layer and consequently turbulence production will be affected. However, whether it will increase or decrease can not be resolved by simple argument. The fact that in practice non-uniformity of properties is found to enhance heat transfer certainly indicates that turbulent diffusion is improved.

CONCLUSION

The present study has shown that the index *n* in the correction for property variation on forced convection heat transfer to water increases with Reynolds number. The mean value obtained is quite close to the widely quoted Sieder and Tate value of 0.14.

REFERENCES

1. Sieder, E. N. and Tate, G. E., Heat transfer and pressure drop of liquids in tubes. *Ind. Eng. Chem.*, 1936, **28,** 1429–1935.
2. Kreith, F. and Summerfield, M., Heat transfer to water at high flux densities with and without surface boiling. *Trans. ASME*, 1949, **71,** 805–815.
3. Yakovlev, V. V., Local and average heat transfer to water below boiling point in turbulent flow along a tube subject to a high heat loading. *J. Nuclear Energy A/B*, 1961, **17,** 365–368. (Translated from *Atomnaya Energiya*, 1960, **8.**)
4. Allen, R. W. and Eckert, E. R. G., Friction and heat-transfer measurements to turbulent pipe flow of water ($Pr = 7$ and 8) at uniform wall heat flux. *Trans. ASME C, J. Heat Transfer*, 1964, **86,** 301–310.
5. Malina, J. A. and Sparrow, E. M., Variable property, constant property and entrance region heat transfer results for turbulent flow of water and oil in a circular tube. *Chem. Eng. Sci.*, 1964, **19,** 953–962.
6. Hufschimidth, W., Burck, E. and Riebold, W., Die bestimmung Ortlicher und Warmeubergangs-zahlen in rohren bei hohen Warmestromdichten. *Int. J. Heat Mass Transfer*, 1966, **9,** 539–565.
7. Everett, M., Forced convection heat transfer inside tubes-turbulent flow. *Chem. Engr.*, 1969, **231,** CE159.
8. Oskay, R. and Kakaç, S., Effect of viscosity variations on turbulent and laminar forced convection in pipes. *METU. J. Pure and Appl. Sci.*, 1973, **6,** 211–230.
9. Petukhov, B. S., Heat transfer and friction in turbulent pipe flow with variable physical properties. *Advances in Heat Transfer*, 1970, **6,** 504–564.
10. Büyükalaca, O., Studies of convective heat transfer to water in steady and unsteady pipe flow, Ph.D. thesis, University of Manchester, 1993.
11. Petukhov, B. S. and Kirillov, V. V., The problem of heat exchange in the turbulent flow of fluids in tubes. *Teploenergetika*, 1958, **4,** 63–68.
12. Moffat, R. J., Describing the experimental uncertainties in experimental results. *Experimental Thermal Fluid Science*, 1988, **1,** 3–17.