CORRELATION OF HEAT TRANSFER DATA FOR BUOYANCY-OPPOSED TURBULENT MIXED CONVECTION IN A VERTICAL TUBE

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ABSTRACT

In this study, different correlating parameters available in the literature for heat transfer data for buoyancy-opposed turbulent mixed convection are examined. For this purpose, the data obtained for water in a vertical tube were used. It was found that the present data are well-correlated in terms of parameter ($Gr^*/Re^{3.425}Pr^{0.8}$) and that a semi-emprical equation based on this parameter describes the present data very well.

INTRODUCTION

For conditions of turbulent flow in a vertical tube, the interaction between forced and free convection influences the effectiveness of heat transfer in a surprising manner. In the buoyancy-opposed case, i.e. for downward flow in a heated pipe, the effect is to enhance turbulence production and therefore to increase the heat transfer coefficient relative to the corresponding forced convection value. This is clearly illustrated in Figure 1 using results for water in a 100 mm bore tube obtained by the authors in recent experiments aimed at extending the earlier studies of Jackson and Fewster [1] and Rouai [2]. As pointed out by Hall and Jackson [3] the enhanced turbulence production and improved heat transfer stems from an increase of shear stress in the near-wall region of the boundary layer caused by the force due to buoyancy acting on the fluid of lower density in the thermal layer.

CORRELATION OF MIXED CONVECTION DATA

Using the idea of Hall and Jackson [3], Jackson and Hall [4] argued that the ratio of Nusselt number for mixed convection to that for forced convection could be correlated in terms of a buoyancy parameter involving a particular combination of Grashof, Reynolds and Prandtl number ($Gr^*/Re^{3.425}Pr^{0.8}$). Figure 2 shows the present data correlated in this manner and fitted by a semi-empirical equation:

$$\frac{Nu}{Nu_{fc}} = \left[1 + 1.15x10^5 \left(\frac{Gr^*}{Re^{3.425}\ Pr^{0.8}}\right)\left(\frac{Nu}{Nu_{fc}}\right)^{-2}\right]^{0.46} \qquad (1)$$

This equation is based on established relationships for friction and heat transfer in forced flow arrived at by likening the buoyancy-influenced pipe flow to one at a higher Reynolds number and free of buoyancy influences. For limiting conditions where such influences become completely dominant, this semi-empirical equation reduces to a form which follows very closely established behaviour for turbulent free convection (as described by the equation of Vliet and Liu [5]).

Figure 3 shows the present data in terms of the parameter ($\overline{Gr}$ / $Re^{2.7}$) used by Fewster [6] in his study of buoyancy-influenced heat transfer to supercritical pressure carbon dioxide. This parameter also stemmed from the model of Hall and Jackson and it is therefore not surprising, therefore, that the present data are again well-correlated. Also shown is the empirical equation used by Fewster to fit his data:

The form of equation (2) was deliberately chosen so that in the limit of strong buoyancy

$$\frac{Nu}{Nu_{fc}} = \left[1 + 2750\left(\frac{\overline{Gr}}{Re^{2.7}}\right)^{0.91}\right]^{1/3} \qquad (2)$$

influences it yielded a Nusselt number which was independent of Reynolds number.

A very similar buoyancy parameter ($Gr^*/Re^{3.636}Pr^{0.82}$) to that resulting from the theoretical model of Hall and Jackson is yielded by the entirely empirical approach of Alferov *et al.* [7]. They chose to characterise the extent of buoyancy influences in downward flow mixed convection using the ratio of the heat transfer coefficient for free convection to that for forced convection. Using established correlation equations for these conditions the present data are correlated on that basis in Figure 4. They are fitted by an equation:

$$\frac{Nu}{Nu_{fc}} = \left[1 + 1.2x10^6 \left(\frac{Gr^*}{Re^{3.636}\ Pr^{0.82}}\right)\right]^{0.22} \qquad (3)$$

This equation was obtained by simply combining the Nusselt numbers for forced and free convection in a non-linear manner which ensures that the limiting conditions of forced and free convection are satisfied.

From Figures 2 to 4 it is apparent that the present data are fitted extremely well by three equations of very different appearance. Each of the equations utilises essentially the

same buoyancy parameter and each equation is of a form that yields the correct limiting behaviour in the case of small and large buoyancy influences.

In Figures 5 and 6, the present data are presented in terms of two different correlating parameters (Gr/Re^2 and $GrNu/4Re^2$) used in earlier studies of buoyancy-opposed mixed convection by other authors (Swanson [8] and Petukhov and Strigin [9]). It is apparent that these parameters do not successfully correlate the present data and, furthermore, the equations proposed by Swanson [8]

$$\frac{Nu}{Nu_{fc}} = 1 + 0.9\left[\log_e\left(\frac{Gr}{Re^2}\right)\right]^{1.39} \qquad (4)$$

and Petukhov and Strigin [9]

$$\frac{Nu}{Nu_{fc}} = \left[1 - 0.5\left(\frac{Gr\,Nu}{4\,Re^2}\right)\right]^{1/3} \qquad (5)$$

do not describe the present results.

CONCLUSIONS

The correlation parameters proposed by Jackson and Hall, Fewster and obtained from the entirely emprical approach of Alferov *et al.* correlates the present buoyancy-opposed mixed convection data very well. An equation based on any of these parameters describe the present results satisfactorily. The parameters used by Swanson and Petukhov and Strigin do not successfully correlate the present data and the equations proposed by these authors fails to describe the data.

NOMENCLATURE

d : Pipe diameter [m]

Gr : Grashof number $[Gr = g d^3(\rho_b - \rho_w)\rho_b / \mu^2]$

Gr* : Modified Grashof number $[Gr^* = g d^4 \beta q_w / k\nu^2]$

$\overline{Gr}$: Grashof number based on density difference $[\overline{Gr} = g d^3(\rho_b - \bar{\rho})\rho_b / \mu^2]$

h : Heat transfer coefficient $[h = q_w / (T_w - T_b)]$

Nu : Nusselt number $[Nu = hd / k]$

Pr : Prandtl number

q : Heat flux [W/m^2]

Re : Reynolds number $[Re = U_m d / \nu]$

U : Velocity [m/s]

x : Axial distance [m]

Greek

b :Coefficien of volume expansion [K^{-1}]

r : Density [kg/m^3]

m : Dynamic viscosity [kg/ms]

n : Kinematic viscosity [m^2/s]

Subscript

b : Bulk

fc : Forced convection

m : Mean

w : Wall

REFERENCES

[1] Jackson, J.D. and Fewster, J. "Enhancement of turbulent heat transfer due to buoyancy for downward flow of water in vertical tubes". pp. 759-775, *Proceedings of ICMT Seminar on Heat Transfer and Turbulent Buoyant Convection,* Dubrovnik, Yugoslavia, 1976, (eds. Spalding, D.B. and Afgan, N.), Hemisphere Publishing Corporotion, Washington D.C., 1977.

[2] Rouai, N.M. "Influences of buoyancy and imposed flow transients on turbulent convective heat transfer in a tube". *Ph.D. Thesis,* University of Manchester, 1987.

[3] Hall, W.B. and Jackson, J.D. "Laminarization of a turbulent pipe flow by buoyancy forces", *ASME Paper* No. 69-HT-55, 1969.

[4] Jackson, J.D. and Hall, W.B. "Influences of buoyancy on heat transfer to fluids flowing in vertical tubes under turbulent conditions". *Turbulent Forced Convection in Channels and Bundles*, pp. 613-640. Vol. 2, Proceedings of Advanced Study Institute, Istanbul, Turkey, Hemisphere Publishing Corporotion, (eds. Kakac, S. and Spalding, D.B.), 1979.

[5] Vliet, G.C. and Liu, C.K. "An experimental study of turbulent natural convection boundary layer". Vol. 91, *Trans. ASME C, J. Heat Transfer,* 1969.

[6] Fewster, J. "Mixed forced and free convective heat transfer to supercritical pressure fluids flowing in vertical pipes". *Ph.D. Thesis*, Manchester University, 1976.

[7] Alferov, N.S., Balunov, V.F., Zhukowski, A.V., Rybin, R.A. and Fokin, B.S. "Features of heat transfer due to combined free and forced convection with turbulent flow". *Heat Transfer Soviet Research,* Vol. 5, pp. 57-59, 1973.

[8] Swanson, L.W. "Mixed turbulent convective heat transfer in vertical ducts". *Ph.D. Thesis*, University of California, Los Angeles, 1987.

[9] Petukhov, B.S. and Strigin, B.K. "Experimental investigation of heat transfer with viscous inertial-gravitational flow of a liquid in vertical tubes". *Teplofizika Vysokikh temperatur,* Vol. 6, No. 5, pp. 933-937, 1968.

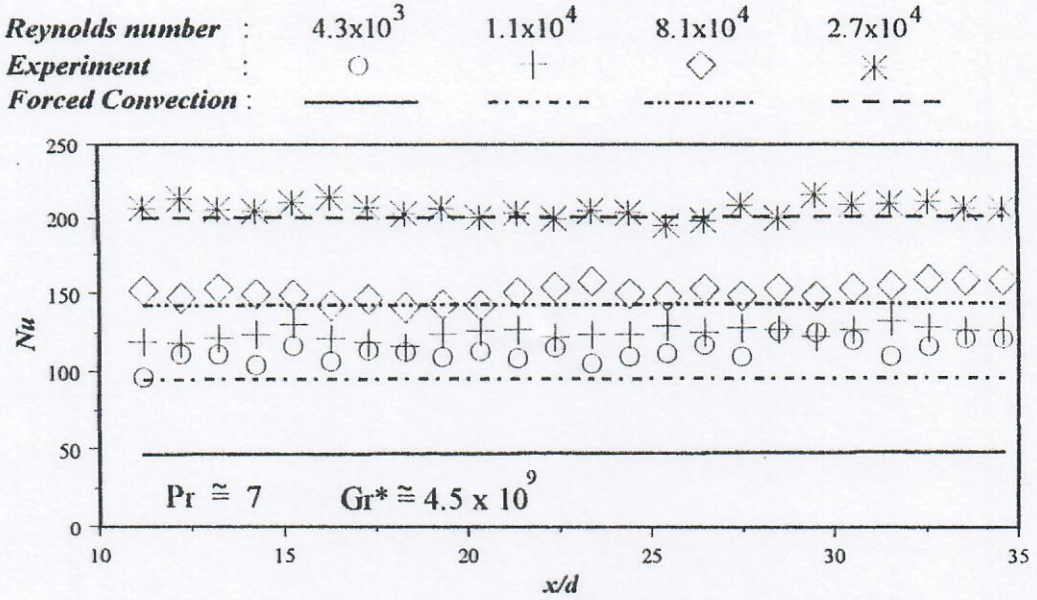


Figure 1. Variation of local heat transfer coefficient with nondimensional axial distance.

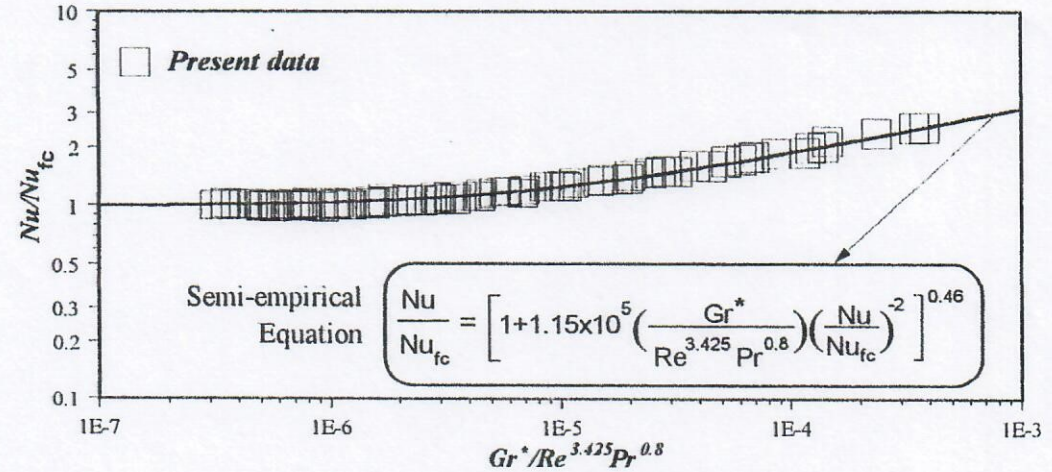


Figure 2. Correlation of mixed convection data using the parameter proposed by Jackson and Hall (1979).

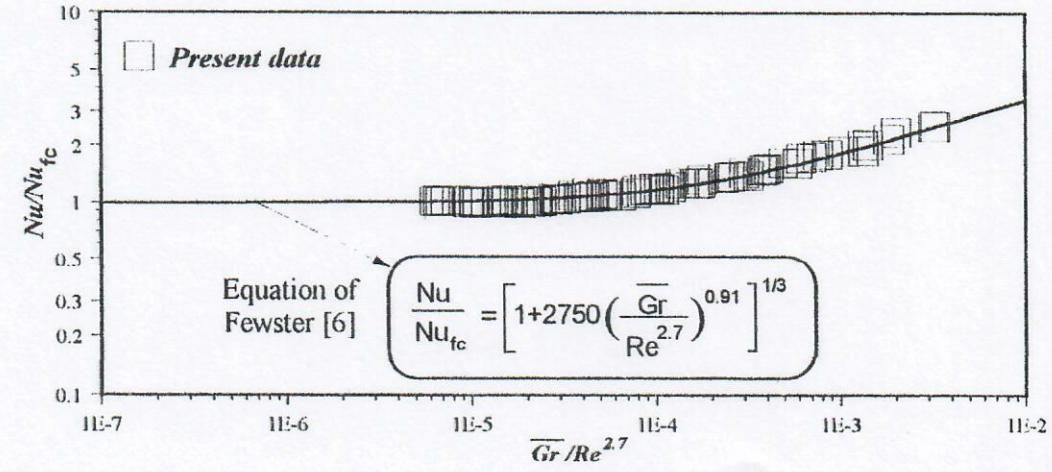


Figure 3. Correlation of mixed convection data using the parameter proposed by Fewster (1976).

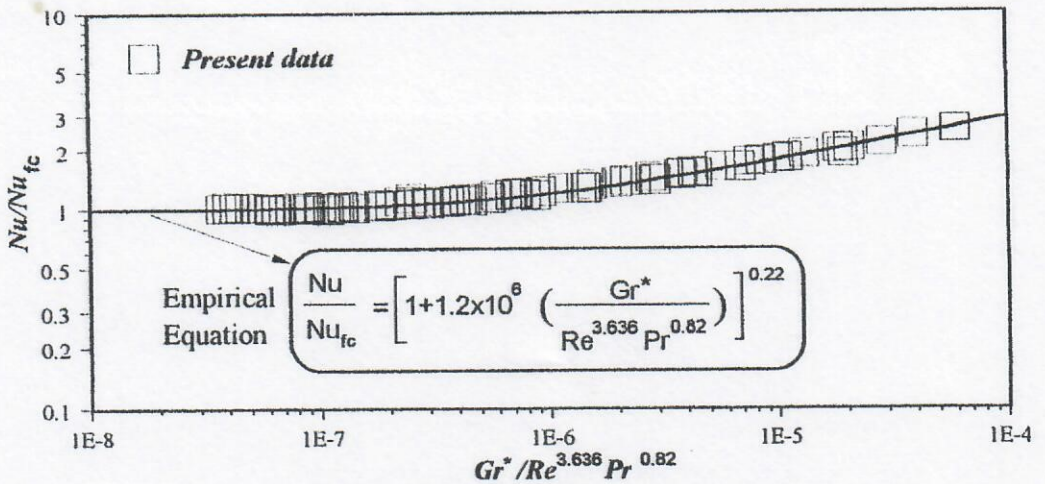


Figure 4. Correlation of mixed convection data using the approach of Alferov et al. (1973).

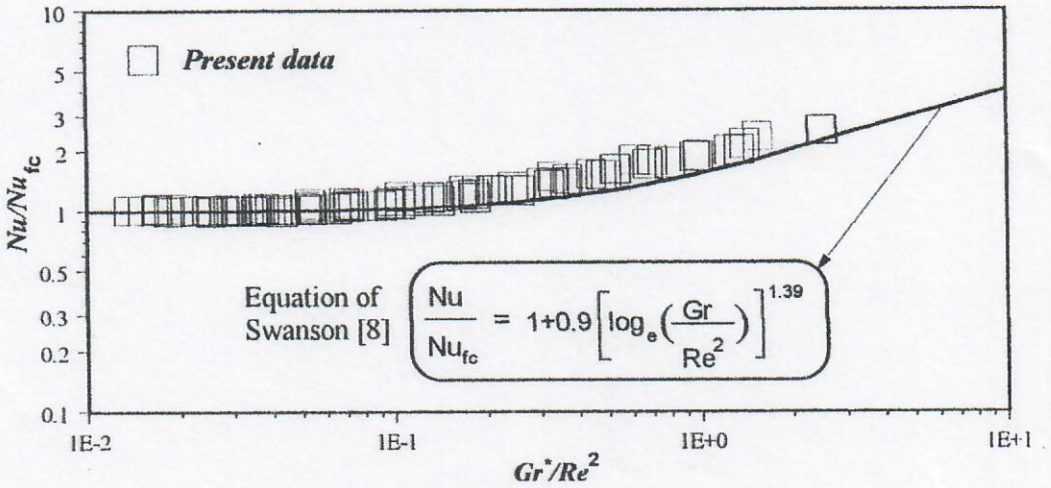


Figure 5. Correlation of mixed convection data using the parameter proposed by Swanson (1987).

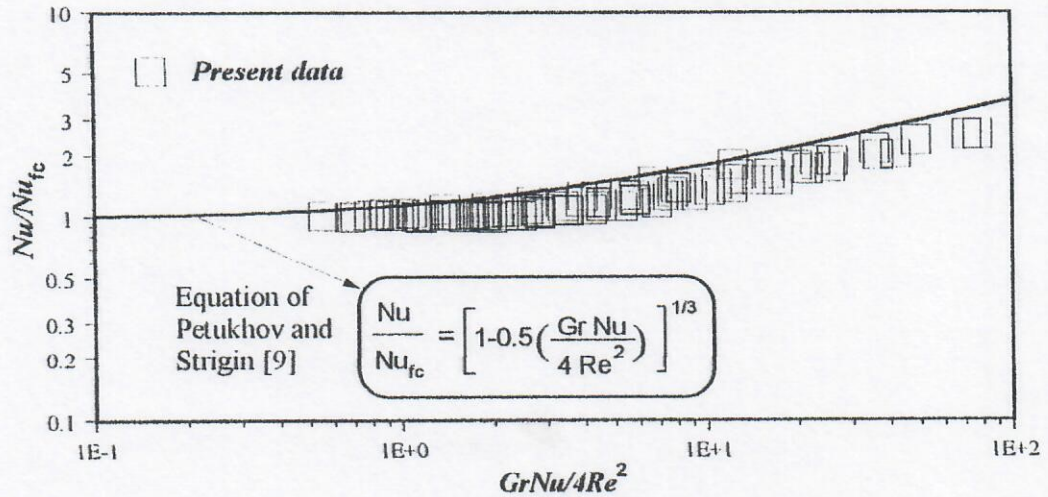


Figure 6. Correlation of mixed convection data using the parameter proposed by Petukhov and Strigin (1968).

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