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Computation of Free Convective Nusselt Number from Horizontal Cylinders Using Semi-Empirical Relationships

B. S. Mbang[1], M. F. Haque[2]

Abubakar Tafawa Balewa, University, Bauchi, P.M.B. 0248, Bauchi

Abstract: ***Natural convective heat transfer from a horizontal cylinder in gases is theoretically studied. A test cylinder of length 20cm is used. A thin wire runs coaxially in the cylinders of varied diameter of 0.01 to 0.03mm and is maintained at a constant temperature of 54^{0}C by an electric current. The wire is exposed progressively to air, argon, carbondioxide, nitrogen and oxygen at atmospheric pressure and at 23^{0}C. On a logarithmic scale, the Nusselt number is plotted against the Raleigh number using five traditional correlations; Morgan, Kyte et al, Chu and Churchill, Kuehn and Goldstein, and Raithby and Holland. A new correlation relation is developed which agrees well with the basis: Kyte et al experimental.***

1. Introduction

Natural convection is a mechanism of heat transport, in which the fluid motion is not generated by an external source (like a pump, fan or suction device) but only by density difference in the fluid occurring due to temperature gradients. The driving force for natural convection is buoyancy, a result of difference in fluid density.

Natural convection heat transfer from a heated body to its surrounding enclosure is currently of interest to designers of microelectronic systems and cabinets. The rapid growth of wireless and cellular communications has led to a more widespread use of "outside plant" applications, products designed to withstand harsh, outdoor environments. The sensitive electronics contained in these products require a sealed enclosure to protect them from moisture and contaminant in their surroundings, and cannot rely on a supply of fresh, ambient air to dissipate the heat produced during typical operation.

Convective heat transfer is governed by the laws of fluid flow, the equation of continuity, and the equation for the heat flow in a moving fluid. An exact solution of these equations with particular boundary solutions is not feasible except in certain simple cases. However, important relationships may be obtained from these equations by means of the theory of similarity. Thus, for natural convection, the Nusselt number should be a function of the Grashof number and the Prandtl number, that is,

$$Nu = f\,(Gr, Pr) \qquad (1)$$

The form of $f(Gr, Pr)$ can be determined either strictly experimentally or by using theoretical analysis with some experimental information.

Heat transfer from horizontal cylinders has the most amount of literature out of all orientations. This is likely due to the symmetric, two – dimensional nature of horizontal cylinders. According to Morgan [1], who in 1975 published an all-encompassing review article on the natural convection from smooth, circular cylinders, there is a wide dispersion in experimental results due to axial heat conduction losses to the supporting structures of the horizontal cylinders, temperature measurement location, interference of the temperature and velocity fields by convective fluid movements, and the utilization of small containing chambers for the experiment.

2. Results and Discussion

Experimental/Theoretical Analysis

From the work of Sigurds Arajs and J.B Mclaughlin [2], figure 1 shows an experimental value of Nu as a function of $GrPr$. It is obvious from the figure that the corrected experimental data by Kyte et al [3] from equation (3) do not agree at all with the experimental plot. Infact, it is the plot of Kyte et al as proposed by equation (4) that actually agrees with the experimental data.

Figure 1 also shows the proposed empirical curve by Morgan [1]. Specifically, Morgan after a careful analysis of all published experimental data together with possible errors, proposed that

$$Nu = C(GrPr)^m \qquad (2)$$

The constants C=0.675 and m=0.058 where $10^{-10} < GrPr < 10^{-2}$. It is suggested that the proposed correlation has a maximum uncertainty of $\pm 5\%$. Morgan's curve with indicated $\pm 5\%$uncertainties lies slightly above the corrected values due to Kyte et al. The reason for this discrepancy is not clear at the present time. New and careful experimental studies using wires of aspect ratio in the neighbourhood of 10^5 should help to clarify this situation [2].

Figure 1 further presents some other proposed correlations. The curve due to Kyte et al [3] is a plot of

$$Nu = \left\{In\left[1 + \frac{7.09}{(GrPr)^{0.37}}\right]\right\}^{-1} \qquad (3)$$

The curve due to Kyte et al [4] as proposed in the work of S. K. S.Boetcher is plotted as Kyte et

al II;

$$Nu = \frac{2}{In\left[1+\frac{7.09}{(GrPr)^{0.37}}\right]} \qquad (4)$$

Churchill and Chu [5] have published the following semi-empirical correlation equation for heat

transfer by natural convection from horizontal cylinders.

$$Nu = 0.36 + 0.518\left\{\frac{GrPr}{\left[1+(0.559/Pr)^{9/16}\right]^{16/9}}\right\}^{0.25} \qquad (5)$$

Churchill and Chu state in their publication that this equation provides a goodfit of representative data for all $Pr\ and\ 10^{-6} \leq GrPr \leq 10^{9}$, except for the experimental data of Collis and Williams [6], which fall below equation (5) for $GrPr \leq 10^{-6}$. It is clear from figure (1) that the correlation represented by equation (5) does not agree with Kyte et al II.
Another correlation equation for horizontalcylinders is due to Raithby and Hollands [7].

$$Nu = \left\{\frac{2}{In\left[1+\pi 2^{3/4}/_{2.04A\ GrPr^{1/4}}\right]}\right\}^{3.337} + \left[0.72B\,(G_rP_r)^{1/3}\right]^{3.337} \qquad (6)$$

$Where\ A = \left(\frac{2}{3}\right)/\left[1+(0.49/Pr)^{9/16}\right]^{4/9}$ and
$B = 0.14\,Pr^{0.084}\ or\ 0.15$, whichever is smaller

This function, plotted in figure 1 predicts values for given $Gr\ and\ Pr$ data which are too small in comparison with the experimental data for $GrPr$ between $10^{-7}\ and\ 10^{-2}$. The correlation according to Raithby and Holland [7] actually takes the form (7) as documented in the work of Petr Svare and Vaclav Dvorak [8]

$$Nu^{3.337} = \left\{\frac{2}{In\left[1+\pi 2^{3/4}/_{2.04A\ GrPr^{1/4}}\right]}\right\}^{3.337} + \left[0.72B\,(G_rP_r)^{1/3}\right]^{3.337} \qquad (7)$$

$Where\ A = \left(\frac{2}{3}\right)/\left[1+(0.49/Pr)^{9/16}\right]^{4/9}$ and $B = 0.14\,Pr^{0.084}\ or\ 0.15$, whichever is smaller.

Conversely, the correlation equation for horizontal cylinders due to Kuehn and Goldstein [9] is,

$$\frac{2}{Nu} = ln\left[1 + \frac{2}{\left[\left\{0.518(GrPr)^{1/4}\left[1+(0.559/Pr)\right]^{3/5}\right\}^{-5/12}\right]^{15}}\right] \qquad (8)$$

This correlation as stated is valid for any Rayleigh and Prandtl number. It predicts together with (7) values for given $Gr\ and\ Pr$ data which are too large on comparison with the experimental data for $GrPr$ between 10^{-7} and 10^{-2}.
Figure 1 presents the correlation curve used by Lykoudis and Yu [10] in their theory of electro convectional heat transfer from horizontal cylinders.

$$Nu = 2\{In\,[1+(546/GrPr)]\}^{-1} \qquad (9)$$

This curve lays almost directly on that of Raithby and Holland and Kuehn and Goldstein and thus these two correlations overestimate the natural convectional heat loss from a horizontal cylinder.
Lastly, a new model correlation is proposed which takes the form;

$$N_u = \exp(0.125)\ /\ln\,(0.9872 + 4.5 * \mathrm{Pr} * \mathrm{GrPr}\hat{\ }0.275) \qquad (10)$$

Fig. 1: Experimental Nu=f(GrPr) in Comparison with various proposed correlations (Air)

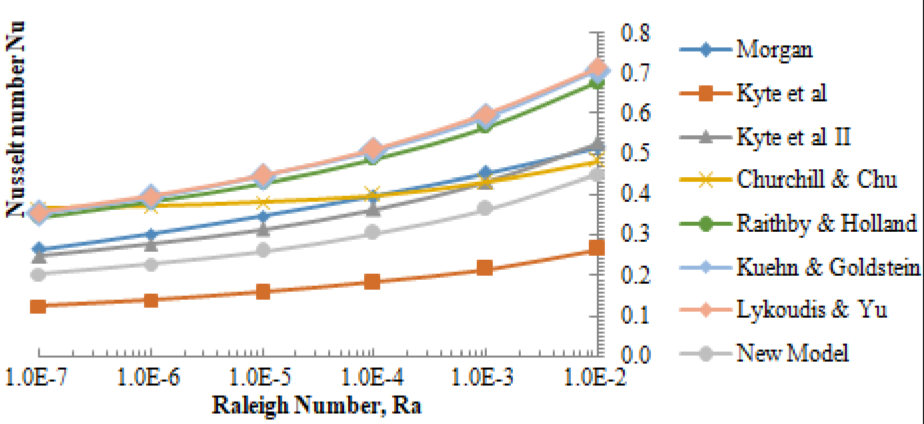


Fig. 2: Experimental Nu=f(GrPr) in Comparison with various proposed correlations (Argon)

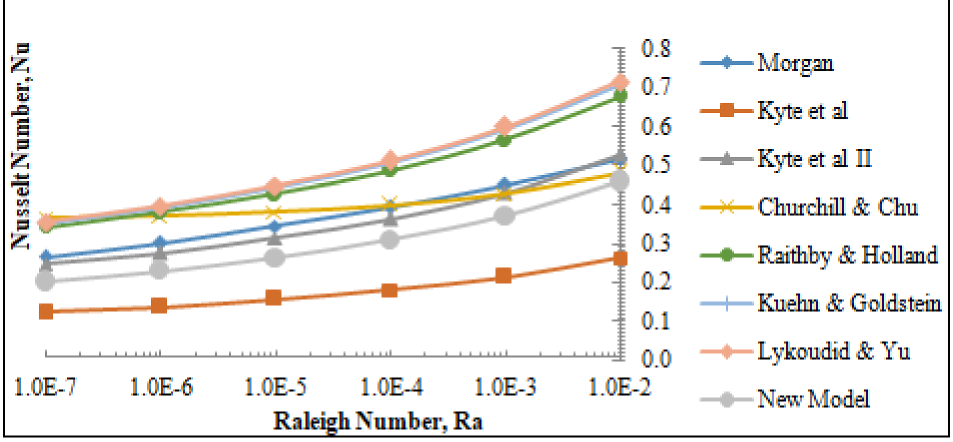


Fig. 3: Experimental Nu=f(GrPr) in Comparison with various proposed correlations (Carbondioxide)

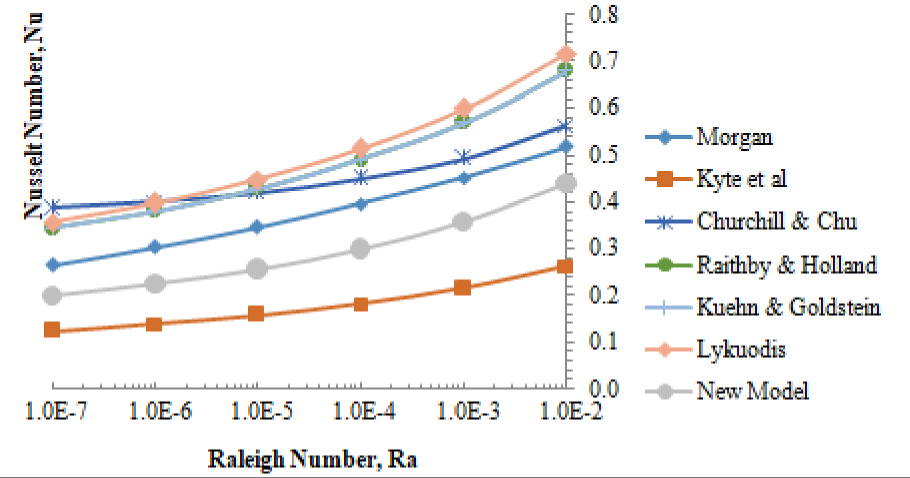


Fig. 4: Experimental Nu=f(GrPr) in Comparison with various proposed correlation (Nitrogen)

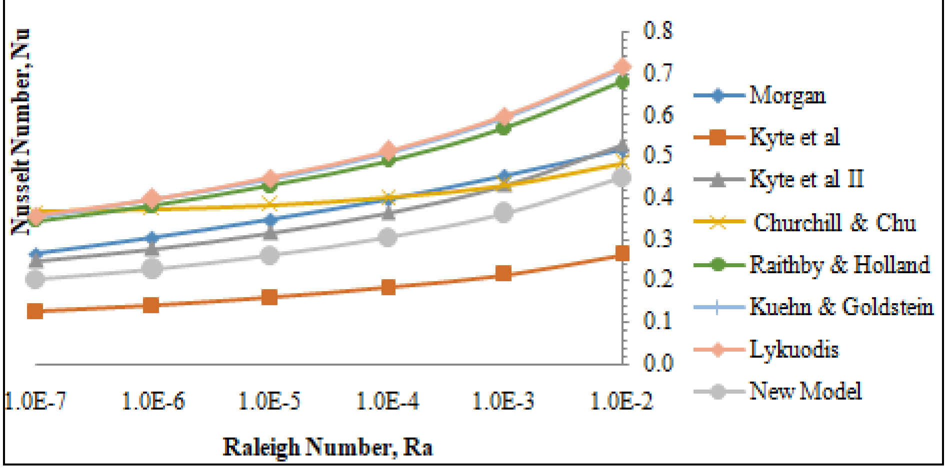
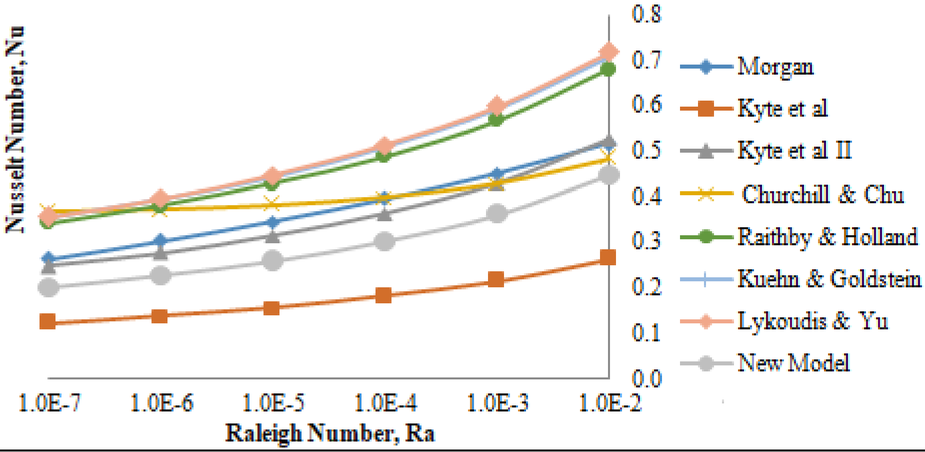


Fig. 5: Experimental Nu=f(GrPr) in Comparison with various proposed correlation (Oxygen)



3. Summary and Conclusion

The analysis has brought some observations to light. The proposed correlations, based on equation (1) do not sufficiently represent the experimental data for small Raleigh values. As observed on the graphs, the dispersion from the experimental result is much. The new model however fits close enough to the Kyte et al – experimental as proposed by Sigurds Arajs and J.B. McLaughlin [2].

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