Natural Convection Heat Transfer from an Inclined Isothermal Cylinder

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Abstract : Experimental investigation of natural convection heat transfer from an inclined isothermal cylinder to ambient fluid at different pressures was carried out. It is revealed that although the pressure variation always has a favorable effect on heat transfer, the effect diminishes continuously with the rise in ambient pressure. In particular the value of the heat transfer coefficient is found to be extremely sensitive in the vacuum region. The heat transfer coefficient and the inclination of the cylinder with the vertical are related linearly and the highest value of the heat transfer coefficient occurs when the cylinder is horizontal. From the experimental results a correlation is developed for Nusselt number in terms of Rayleigh number and inclination in the form of $Nu = C(Ra_L)^m$.

Keywords : *Natural Convection , Inclined Cylinder, Inert Gas, Isothermal Cylinder.*

INTRODUCTION

Inclined cylinders have extensive application in many industrial plants. Inclined pipes and tubes carrying steam, hot or cold chemicals etc. are common examples of heat transfer from or to the inclined cylindrical surfaces.

Literature shows that many investigations [2 -9] have been carried out on natural convection heat transfer from the outside surface of vertical or horizontal tubes in both constant wall temperature and constant heat flux conditions at atmospheric pressure. The data on natural convection from inclined cylinders are, however, very limited. Furthermore, very few investigations have been carried out on heat transfer behavior in fluids other than air and at pressures higher or lower than atmospheric pressure. The present work [1] is undertaken to generate some data under those less addressed situations.

THE SET-UP AND THE EXPERIMENTS

Figures 1 and 2 show the schematic diagrams of the experimental set up and the test cylinder. The apparatus used in the investigation was a 'Radiation and Convection Heat Transfer Equipment', manufactured by Plint and Partners Ltd., England. It consists of an almost spherical steel vessel, within which the test

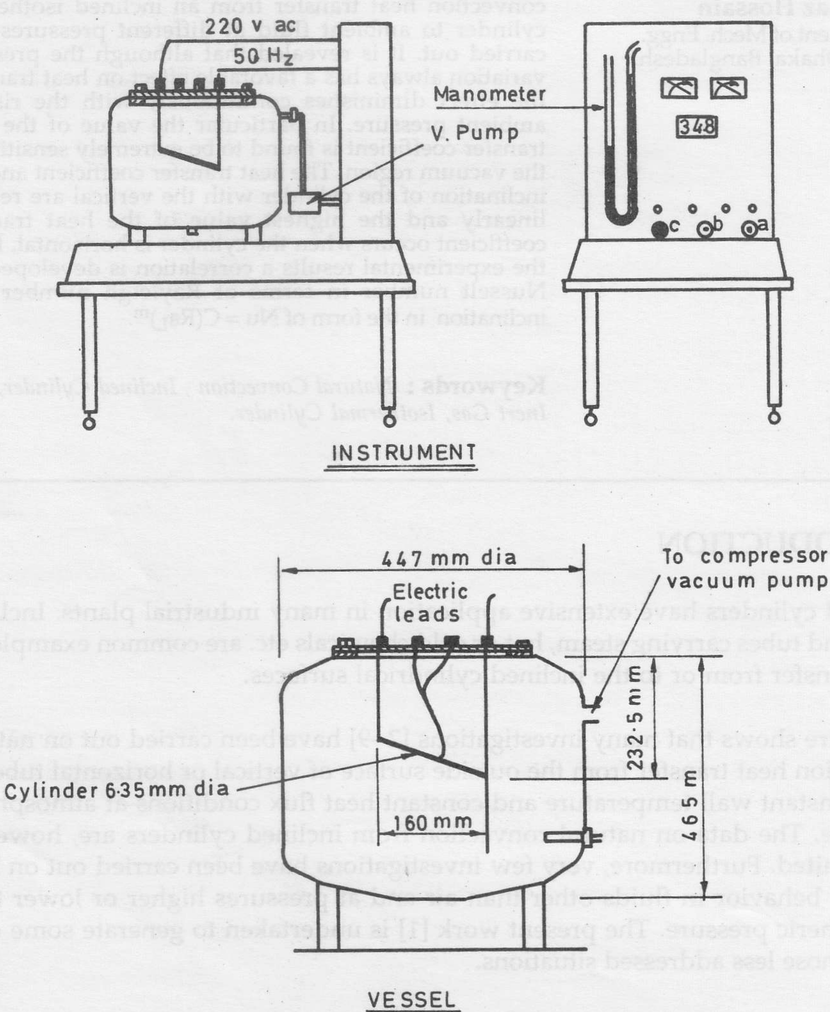

Fig. 1 Schematic diagram of the experimental set-up.

cylinder was suspended. It was equipped with a voltmeter, an ammeter, a vacuum pump, a high pressure connection line, a mercury manometer for measuring vessel pressure and thermocouples to measure the temperature of the spherical vessel. The temperature of the heated cylinder was measured by another thermocouple attached to the mid point of the cylinder and connected to a digital thermometer of the set-up.

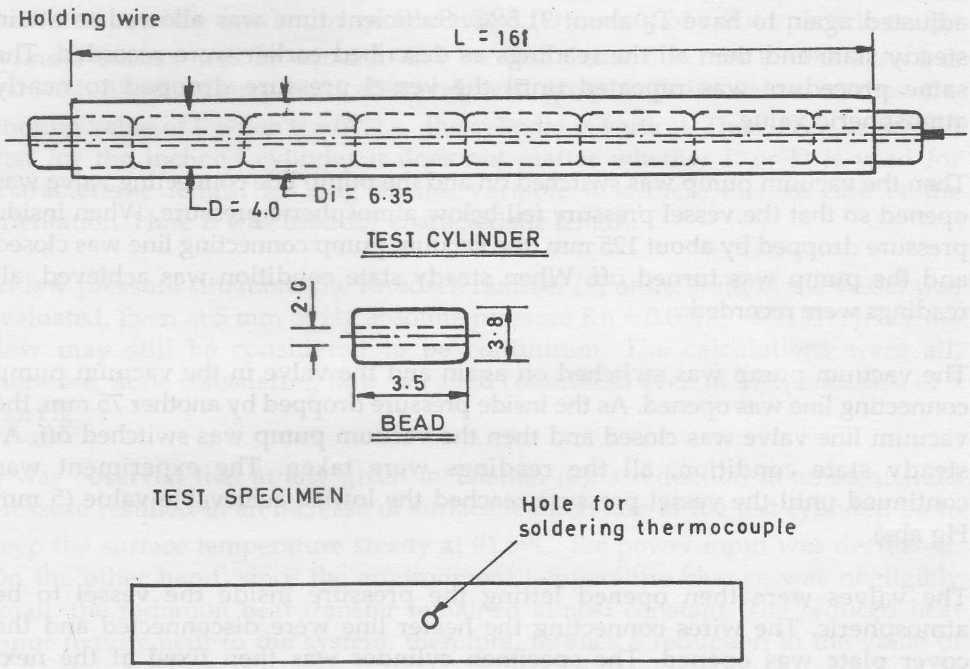

Fig. 2 The test cylinder detail.

The test cylinder was made of copper with matt black surface and could be suspended from the top cover of the vessel at a predetermined inclination with the help of holding wires. The specimen was 161 mm long, 6.35 mm in outside diameter and 4.00 mm in inside diameter. The test cylinder was heated internally by electrical means.

To carry out experiments with air as the ambient fluid, the compressor delivery line was connected to the high pressure connection line and the compressor was switched on. The gas disconnecting valve was closed when the Hg manometer showed a gage pressure of about 900 mm. The compressor was switched off and the heater switch was turned on. Voltmeter and ammeter readings were adjusted to get the test-cylinder temperature (T_e) approximately 91.5^{o}C. When the cylinder surface temperature remained steady for about half an hour, the voltmeter and ammeter readings, the vessel temperature, the test cylinder temperature and manometer readings were recorded.

To set the experiment at a different ambient pressure, some amount of the air was let out by opening the gas release valve until the pressure dropped by about 175 mm when the gas release valve was closed. The voltmeter and ammeter were adjusted again to have T_e about 91.5°C. Sufficient time was allowed to attain steady state and then all the readings as described earlier were recorded. The same procedure was repeated until the vessel pressure dropped to nearly atmospheric value.

Then the vacuum pump was switched on and the pump line connecting valve was opened so that the vessel pressure fell below atmospheric pressure. When inside pressure dropped by about 125 mm, the vacuum pump connecting line was closed and the pump was turned off. When steady state condition was achieved, all readings were recorded.

The vacuum pump was switched on again and the valve in the vacuum pump connecting line was opened. As the inside pressure dropped by another 75 mm, the vacuum line valve was closed and then the vacuum pump was switched off. At steady state condition, all the readings were taken. The experiment was continued until the vessel pressure reached the lowest achievable value (5 mm Hg abs).

The valves were then opened letting the pressure inside the vessel to be atmospheric. The wires connecting the heater line were disconnected and the cover plate was opened. The specimen cylinder was then fixed at the next inclination and the same procedure were followed to get the set of readings at other inclinations of the test cylinder.

The experimental data with argon were recorded by taking similar steps as that with air. However to reduce the dilution of argon by air, the vessel was emptied and refilled with argon twice, before recording any data.

RESULTS AND DISCUSSION

All fluid properties were evaluated at film temperature (T_f). The investigations were carried out within the Rayleigh number (Ra_L) range of 10^3 - 3.5×10^7 and hence the convection flow was in the laminar range. The fluids used were either air or argon.

While calculating Gr and Nu, for horizontal and vertical cylinders, usually the diameter and the length of the cylinder respectively are used for the characteristic length. This is justified from the viewpoint that a fluid particle travels a maximum distance equivalent to the length of the vertical cylinder or equivalent to the diameter of the horizontal cylinder before it leaves the cylinder surface. In the present case orientation of the cylinder is expressed by a variable θ, the inclination angle. When θ is 90^o i.e. the cylinder is horizontal, the corresponding maximum vertical travel (D cosecθ) of a fluid particle on the cylinder surface will be equal to D (because Cosec $\theta = 1$ for $\theta = 90^o$). As θ is reduced, the maximum vertical travel will grow and its value reaches the limiting value of L when $\theta = 0^o$, i.e. the cylinder is vertical. Thus it can be argued that for the inclined cylinder it does not matter whether L or D is used for characteristic length as long as the variable θ is there to take care of the orientation. Here L was used for characteristic length.

At low pressure situations the Knudsen number [9] of the fluid in the vessel was evaluated. Even at 5 mm of Hg absolute pressure $Kn = 0.00165 << 0.01$. Hence the flow may still be considered to be continuum. The calculations were all, therefore, done considering flow through continuum even at high vacuums of 5 mm Hg.

It was observed that at any given inclination (θ), a reduction in ambient fluid pressure resulted in an increase of surface temperature of the test cylinder. So to keep the surface temperature steady at 91.5^oC, the power input was decreased. On the other hand, since the environment temperature change was negligibly small, the radiation heat transfer remained almost constant. The reduced heat input requirement to the system, therefore, implies a reduction in the value of convection heat transfer.

Figure 3 shows the comparison of heat transfer coefficient in the environment of air and argon for an inclination of 45^o of the cylinder. From this graph it is observed that the heat transfer co-efficient for air is higher than that for argon at the set inclination and ambient pressure. Air has a higher value of specific heat and heat capacity than argon. Higher value of heat capacity helps air to hold and carry more heat with it which ultimately leads to a higher value of convection heat transfer. In quantitative terms, the value of the heat transfer coefficient for air at any pressure is about 40% higher than the corresponding value for argon. The result confirms the argument given because the heat capacity of air is about 40% higher than that of argon. Similar nature of the graph was found for all the other inclinations.

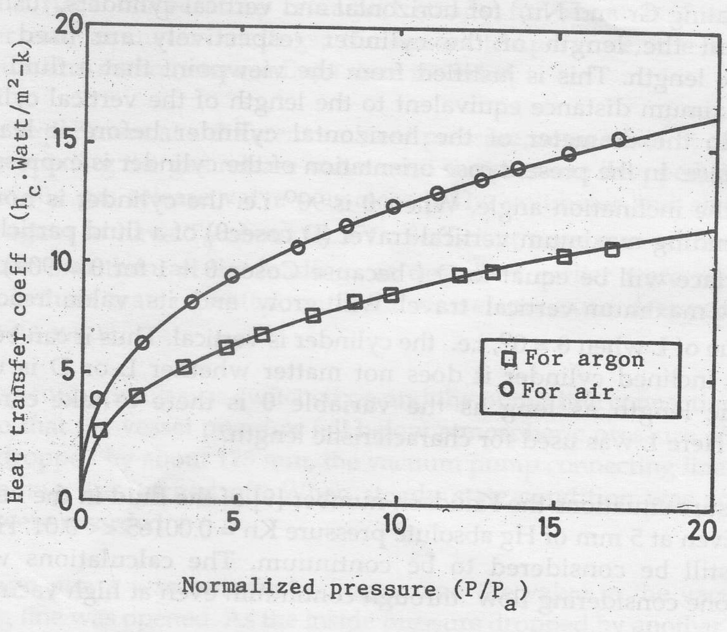

Fig. 3 Comparison of heat transfer coefficient in air /argon at an inclination of 45° with vertical.

Figure 4 shows the plot of average heat transfer coefficient (h) against pressure in air for different inclinations (θ). There are five curves in this plot and they correspond to the inclinations of 0, 30, 45, 60 and 90 degree with the vertical. It is quite clear from the graph that with the increase in the inclination, the heat transfer coefficient increases consistently. It also reveals that the heat transfer coefficient at a given inclination increases with pressure with a decreasing gradient. Thus at low pressures the rate of change of heat transfer coefficient is more than that at high pressures. It may be noted that the heat transfer action is very sensitive to ambient pressure in the vacuum region. Figure 5 is the plot of heat transfer coefficients obtained for the tests with argon. The nature of the curves in this plot is similar to those in figure 4 and the heat transfer coefficient varies with the pressure and inclination exactly in the same way as they do in figure 4 for air.

Figure 6 shows the variation of heat transfer coefficient (h) with the inclination (θ) of the test cylinders in air. It is seen that with the increase of inclination with vertical, the heat transfer rate increases. The highest value of the heat transfer coefficient occurs when the test cylinder is horizontal. Figure 7 shows the plot of h vs. θ for argon data. This plot shows the same nature as that

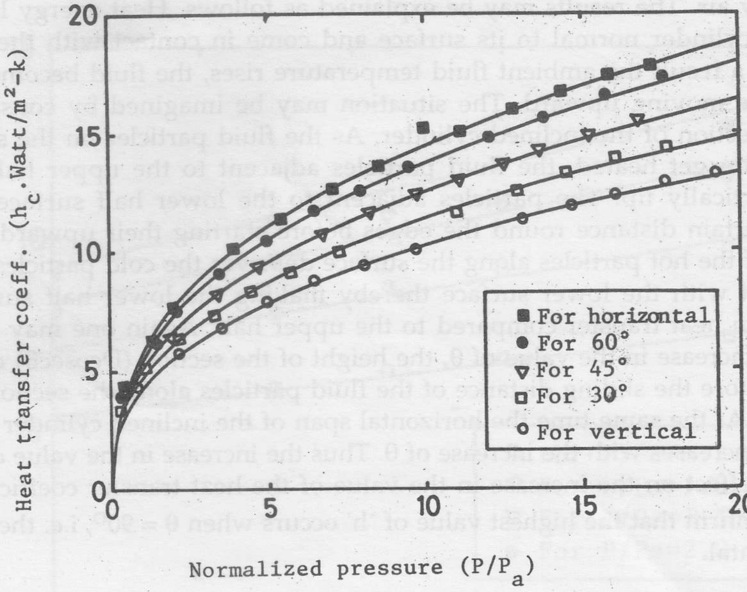

Fig. 4 Heat transfer coefficient against normalized pressure for different inclinations of the cylinder in air.

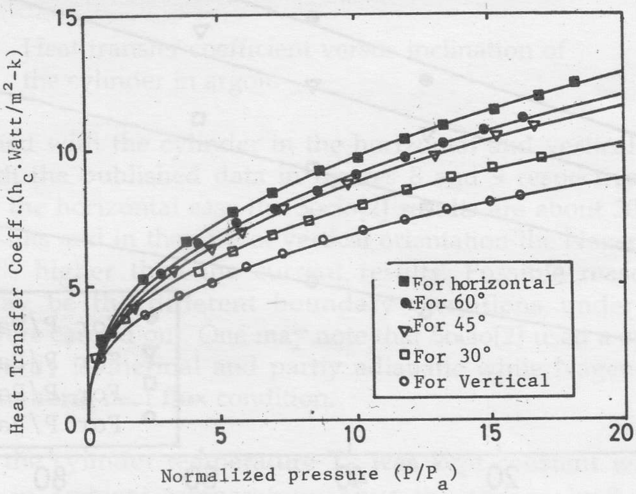

Fig. 5 Heat transfer coefficient against normalized pressure for different inclinations of the cylinder in argon.

shown by air. The results may be explained as follows. Heat energy leaves the inclined cylinder normal to its surface and come in contact with the ambient fluid. As a result the ambient fluid temperature rises, the fluid becomes lighter and starts moving upward. The situation may be imagined by considering a vertical section of the inclined cylinder. As the fluid particles on the surface of this section get heated, the fluid particles adjacent to the upper half surface move vertically up. The particles adjacent to the lower half surface have to slide a certain distance round the edges before starting their upward journey. Sliding of the hot particles along the surface deprives the cold particles to come in contact with the lower surface thereby making the lower half surface less efficient in heat transfer compared to the upper half. Again one may note that with the increase in the value of θ, the height of the section (Dcosecθ) decreases and therefore the sliding distance of the fluid particles along the section surface decrease. At the same time the horizontal span of the inclined cylinder (limiting value L) increases with the increase of θ. Thus the increase in the value of θ has a two-fold effect on the increase in the value of the heat transfer coefficient. The results confirm that the highest value of `h' occurs when θ = 90°, i.e. the cylinder is horizontal.

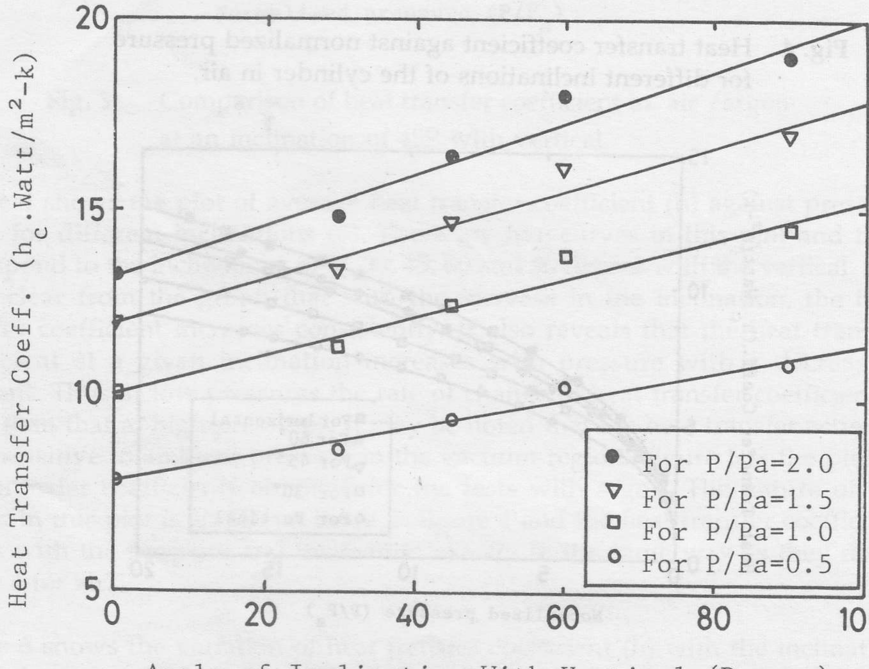

Fig. 6 Heat transfer coefficient versus inclination of the cylinder in air.

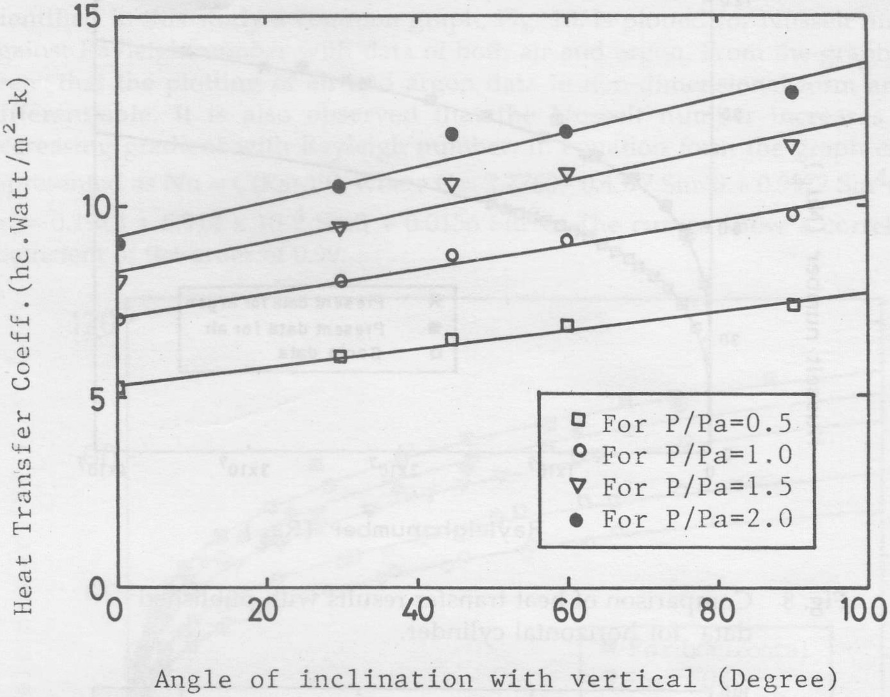

Fig. 7 Heat transfer coefficient versus inclination of the cylinder in argon.

Results obtained with the cylinder in the horizontal and vertical positions are compared with the published data in figures 8 and 9 respectively. It may be noted that for the horizontal case the Socio[2] results are about 30% lower than the current results and in the case of vertical orientation the Nagendra[5] results are about 20% higher than the current results. Possible reasons for these deviations may be the different boundary conditions under which their experiments were carried out. One may note that Socio[2] used a cylinder whose surface was partly isothermal and partly adiabatic while Nagendra[7] used a cylinder with uniform heat flux condition.

In this study the cylinder temperature T_e was kept constant with negligibly small change in ambient temperature. Thus the change in β and ΔT were insignificant. Grashof number and hence Rayleigh number, therefore, became almost proportional to the density i.e. pressure, since the volume in this case was constant and Prandtl number was almost unchanged. So the change in ambient fluid pressure will be reflected in the value of the Rayleigh number.

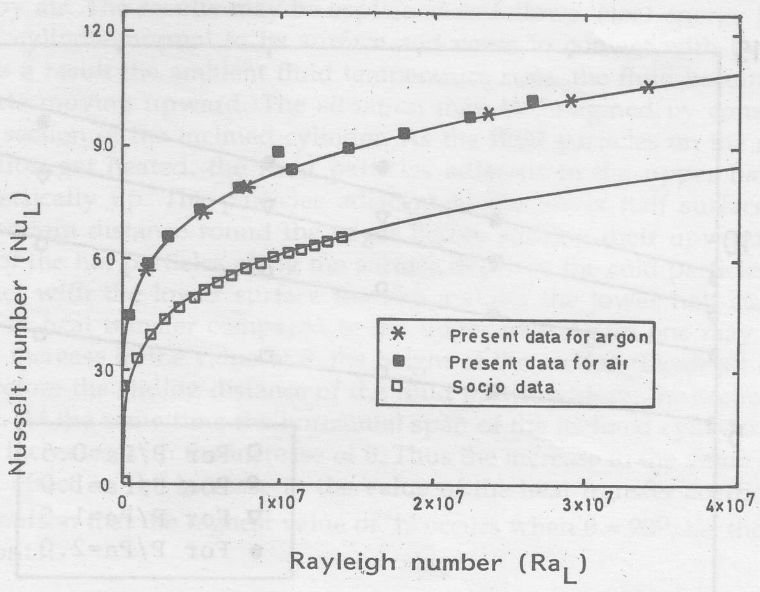

Fig. 8 Comparison of heat transfer results with published data for horizontal cylinder.

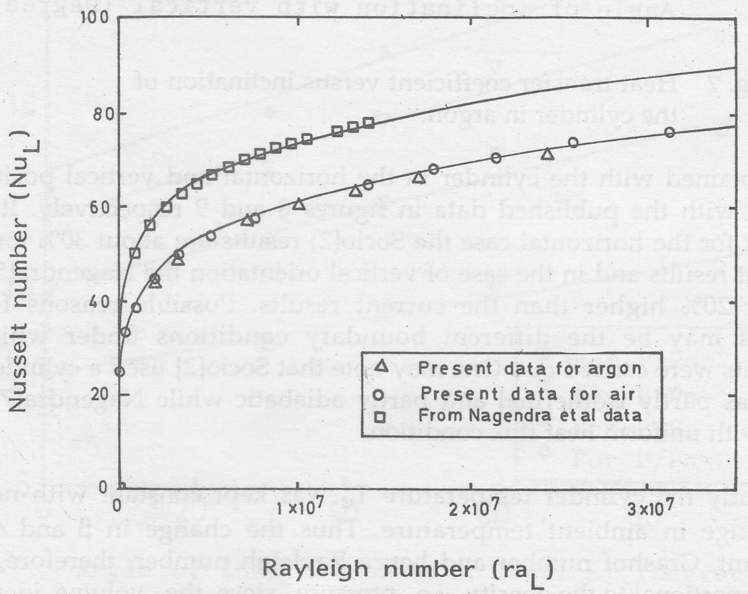

Fig. 9 Comparison of heat transfer results with published data for vertical cylinder.

Hence in order to correlate the heat transfer coefficient with the variables identified in this study a common graph, Fig. 10, is plotted for Nusselt number against Rayleigh number with data of both air and argon. From the graph it is seen that the plotting of air and argon data in non-dimensional form are not differentiable. It is also observed that the Nusselt number increases with decreasing gradient with Rayleigh number. In equation form the graph can be represented as $Nu = C(Ra_L)^m$, where $C = 2.7760 - 0.4377 \sin^3\theta + 0.9972 \sin^4\theta$ and $m = 0.1913 + 5.914 \times 10^{-4} \sin\theta + 0.0156 \sin^2\theta$. The curves show a correlation coefficient of the order of 0.99.

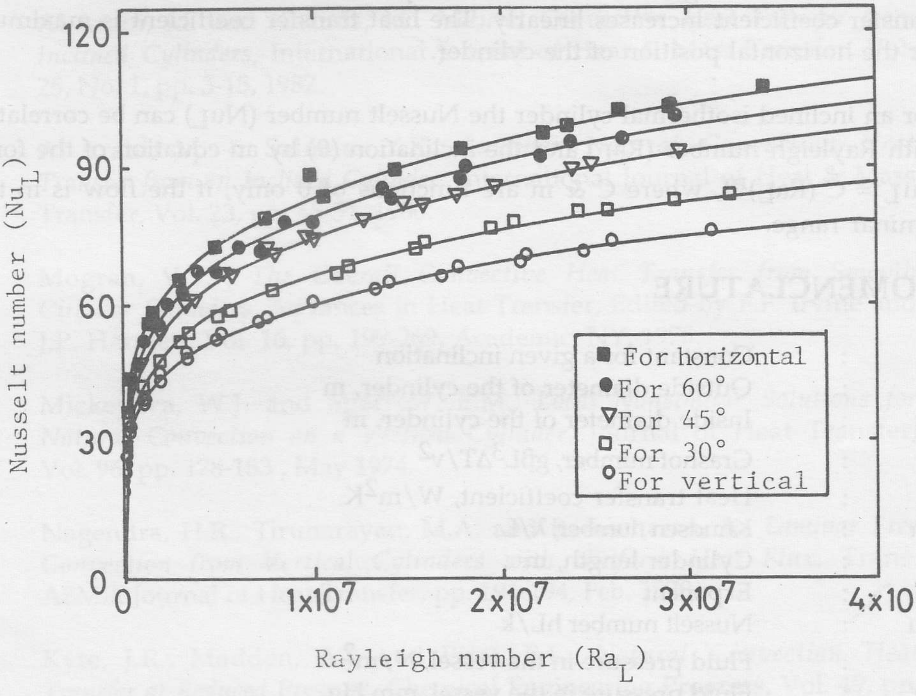

Fig. 10 Nusselt number variation with Rayleigh number for both air and argon.

CONCLUSIONS

The conclusions from the present investigations are as follows :

Air acts as a better medium for natural convection heat transfer compared to argon.

The factors of `ambient fluid pressure' and `inclination of the cylinder with vertical' are of considerable importance in the evaluation of the natural convection heat transfer coefficient (h) for heat transfer from an inclined cylinder. With the increase of ambient pressure the heat transfer coefficient increases with decreasing gradient. This makes the heat transfer situation very sensitive in the low pressure region. Specially near vacuum a small change in pressure would cause a large variation in the value of the heat transfer coefficient.

With the increasing inclination of the cylinder with the vertical the heat transfer coefficient increases linearly. The heat transfer coefficient is maximum for the horizontal position of the cylinder.

For an inclined isothermal cylinder the Nusselt number (Nu_L) can be correlated with Rayleigh number (Ra_L) and the inclination (θ) by an equation of the form $Nu_L = C\,(Ra_L)^m$, where C & m are functions of θ only, if the flow is in the laminar range.

NOMENCLATURE

C	:	Constant for a given inclination
D	:	Outside diameter of the cylinder, m
D_i	:	Inside diameter of the cylinder, m
Gr	:	Grashof number, $g\beta L^3\Delta T/\nu^2$
h	:	Heat transfer coefficient, W/m^2K
Kn	:	Knudsen number, λ/L
L	:	Cylinder length, m
m	:	Exponent
Nu	:	Nusselt number hL/k
P	:	Fluid pressure in the vessel, N/m^2
P_o	:	Fluid pressure in the vessel, mm Hg.
P_a	:	Atmospheric pressure, N/m^2
Pr	:	Prandtl number, $\mu C_p/k$
Ra_L	:	Rayleigh number, Gr x Pr
T_e	:	Temperature of the cylinder, K
T_v	:	Vessel temperature, K
T_f	:	Film temperature, $(T_e + T_v)/2$, K
β	:	Coefficient of thermal expansion, K^{-1}
λ	:	Mean free path (10) of the surrounding fluid, $159 \times 10^{-9}\, T_f/P_o$, m
θ	:	Inclination of cylinder axis with vertical, degree
ΔT	:	Temperature difference, $T_e - T_v$, K

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