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HEAT TRANSFER THROUGH VERTICAL CYLINDER IN STATIONARY FLUID

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Natural convection heat transfer has been experimentally investigated for high Raleigh number by placing the cylindrical heating element in stationary water. The uniform heat flux has been applied to large L/D ratio in this experiment. The thermal behavior of this heating element has been found in good agreement with the existing information. The temperature distribution along the surface of heating element with respect to the time was recorded. The experimental result showed that the surface temperature of the water in narrow annular space heat sink increases more than that in wide annular space heat sink with respect to time. The heat transfer coefficient, Nusselt number and Raleigh number have been presented for experimental data and the corresponding relation is developed.

Keywords: Natural convection, Temp. distribution, Heat transfer coefficient, Nusselt number, Raleigh number

1. Introduction

Heat Transfer is the major operation in industries. The natural convection is observed as a result of motion of the fluid due to density changes by heating or cooling process. Natural convection heat transfer from vertical cylinders is relevant to engineering applications such as vertical tubes of HVAC system, launch pad of space shuttle, in restrictive heating of electronic components, heat loss from process piping, steam heated coils and electric immersion heater in process vessels, heat removal from spent nuclear fuel bundles and cooling of nuclear reactor core after loss of coolant accident and wasted nuclear rods stores in repositories etc.

Literature data concerning natural convective heat transfer from vertical cylinders are widespread [1]. Several factors can affect significantly as the experimental conditions usually are different and not always precisely documented. Also there is an inaccuracy in experimental data as the disturbances of temperature and velocity can be affected by bulk fluid movement or by fluid circulation in undesired position. The heated fluid is very sensitive to slight movement in bulk fluid. The deflection in verticality also increases the convective heat transfer from the upper part of hot cylinder.

The natural convection heat transfer through vertical cylinders in various configurations has been studied [2] studied steady state natural convection in vertical annulus enclosed from both ends while Chughtai and Inayat studied the annulus open from both ends. For large values of L/D the curvature effects can not be ignored [1]. The natural convection heat transfer from vertical slender cylinder was investigated numerically and experimentally by many researchers. The correlations suggested by them do not comprise the dimensionless height of cylinder L/D showing that these equations are used in narrow range of curvature parameters. The steady state natural convection from a single cylinder with constant heat flux was studied numerically [3-5] in which limited experiments were performed. The computational investigations for natural convection over vertical cylinders was done [6] with COSINAC code using single channel mode to achieve the goal of assembly of cylinders for which axial temperature distribution was experimentally required yet. In the present study, steady state natural convection is studied experimentally with L/D ratio of 44.88 with outer dia of 0.5 in SS tube.

In this natural convection problem, a cylindrical electrical heating source of constant heat flux is placed in stationary water tank. In order to measure the surface temperatures, thermocouples are installed at different axial locations on cylinder. The experiments performed at different power levels. Thermocouples reading are recorded on personnel computer by means of Data Acquisition

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System. For uniform heat flux, experiments are carried out to measure the surface temperature variation with the flow of fluid due to density difference. The surface to ambient fluid temperature difference obtained and dimensional correlations will be developed. Natural convection phenomenon is characterized by a dimensionless combination of internal, buoyancy & viscous forces, known as Grashof number. Raleigh number is another dimensionless group which is studied with variation of Nusselt number to characterize natural convection.

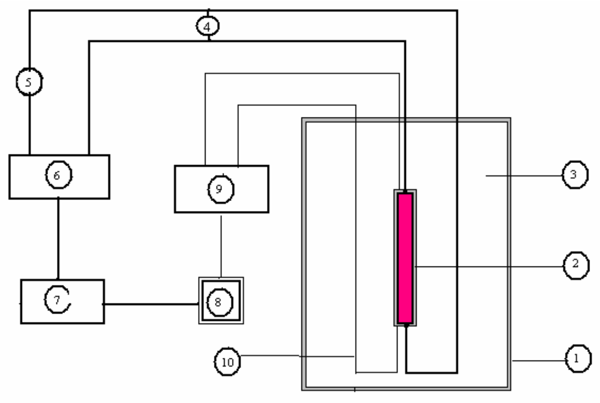

Figure 1. Schematic diagram of experimental setup.

2. Experimental

The experimental setup consists of a S.S. cylinder, variable voltage power supply (variac), data acquisition system and instrumentations for temperature, voltage and current. A schematic view of the setup is illustrated in Figure 1. The cylinder is S.S. tube of 12.7mm outer diameter, 24 BWG, the active heated length is 570mm of total length of 609mm. The both ends of the cylinder are brass coupled to ensured sealing of power and thermocouple wires against water. Twelve T-type (copper constantan 1.5mm outer diameter) thermocouples are embedded into the cylinder internally at six axial positions with two thermocouples at diametrically opposite position to remove the perturbations in reading[7]. The thermocouples are fiber glass insulated to resist the temperature effects. A tubular heater of same length of cylinder is installed at the center of S.S. cylinder. The gap between the heater and the cylinder wall is filled with Magnesium Oxide (MgO). All the thermocouples are calibrated in ice and at different temperatures using constant temperature bath.

The cylinder was immersed vertically in 800 liter stationary demineralized water tank of 4ft height and 2.5ft diameter. The cylinder was internally heated by passing current through heater by adjusting voltage. The vertical cylinder surrounding by a quiescent bulk fluid (water) at constant temperature T_b is heated such that the unit surface heat flux is constant. The experiments to determine the heat transfer characteristics of cylinder were conducted using demineralized water to avoid scaling on the surface of the cylinder. Constant power was supplied to the cylindrical heater by adjusting voltage at same level by variable voltage regulator (variac). The temperature changes at the surface of the cylinder measured by thermocouples were recorded after each second on PC by data acquisition system. The bulk water temperature at different depths was found constant throughout the experiment due to the large volume of water. The surface temperatures were seemed to be at steady state after 10-15 minutes but the data was recorded for more than two hour. The verticality of the cylinder was set very precisely. Due to high thermal conductivity of MgO the electric power supplied to the heater was almost obtained thermal power at the surface of cylinder. The experiments were performed at different power levels and corresponding data of surface & bulk temperatures with above procedure were recorded.

The major independent parameter of the experiments is Grashof number. The experiment was performed for more than two hour to reach steady state. When the steady state was established, the average readings of thermocouples, input power was recorded to study the steady state natural convection heat transfer subjected to constant heat flux boundary conditions were analyzed.

All the water properties are calculated at mean film temperature (average of surface and bulk temperature), by Yunus [8].

$$T_f = \frac{T_s + T_b}{2}$$

The local Nusselt number

$$Nu_L = \frac{h_x L}{k}$$

Where

$$h_x = \frac{Q}{A_s \Delta T_x}$$

The average values of Nusselt number can be calculated as

$$\overline{Nu_L} = \frac{\overline{h_L} L}{k}$$

Where

$$\overline{h_L} = \frac{1}{L} \int_{x=0}^{x=L} h_x dx$$

The average values of surface temperature, bulk temperature and mean film temperature can be evaluated as:

$$\overline{T_S} = \frac{1}{L} \int_{x=0}^{x=L} T_S dx$$

$$\overline{T_b} = \frac{1}{L} \int_{x=0}^{x=L} T_b dx$$

$$\overline{T_f} = \frac{\overline{T_S} + \overline{T_b}}{2}$$

The Grashof and the Raleigh numbers can be calculated as

$$\overline{Gr_L} = \frac{g \beta L^3 (\overline{T_S} - \overline{T_b})}{\nu^2}$$

$$\overline{Ra_L} = \overline{Gr_L}.\mathrm{Pr}$$

All the physical properties (C_p,ρ,β,μ and k) of water were evaluated at average film temperature.

3. Results and Discussion

The heating cylinder was vertically immersed in demineralized water tank. The water tank diameter was too large (about 750 dia of S.S. cylinder), so the bulk temperature at different locations was constant throughout the experiment. The condition, "constant temperature of the fluid at large distances from heating source" was satisfied. Thermal power applied to the heater, installed at the center of the cylinder is calculated same at the surface of the cylinder. So the uniform heat flux is observed at the surface of the cylinder. The temperature was recorded by thermocouples by taking the average value of two diametrically installed T-type thermocouples which leads to minimize the error caused by perturbation of the temperature distribution around the thermocouples measuring junction. The experiments were performed for seven different uniform heat fluxes ranges from 835 watt per meter square to 4422 watt per meter square with L/D of 44.88.

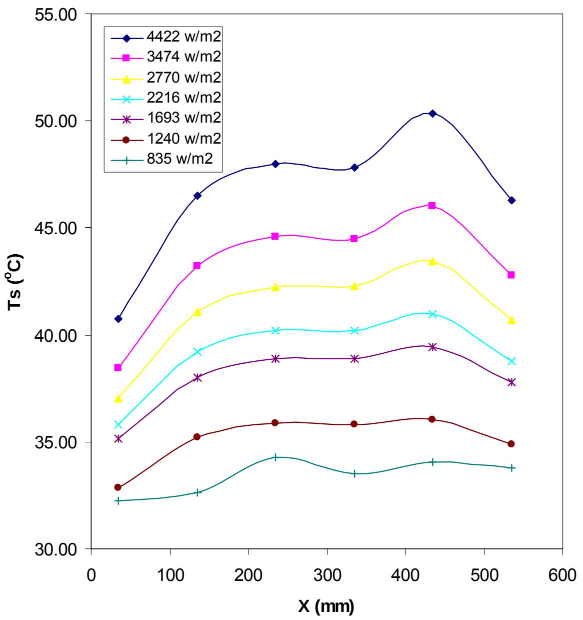

Figure 2. Surface temperature distribution along axial distance at different uniform heat fluxes.

The temperature variations along the vertical cylinder at different axial distances from lower side are shown in Figure 2. The surface temperature distributions or different uniform heat fluxes are illustrated. The rise in the temperature can be observed along the axial distances as uniform heat flux has been applied. Due to the high local heat transfer coefficients at the lower side the surface temperature rapidly raises in this portion and then gradually after that as the local heat transfer coefficient decreases as shown in Figure 3. Generally heat flux is the main variable which may effect the variation in surface temperature along the cylinder. Figure 2 shows that the value of the surface temperature gradually increases with length until a limit beyond which it begins to decrease. At the lower part of the cylinder, the boundary layer thickness is zero at the start of heated length along the cylinder. Then the boundary layer gradually increases which results in heat transfer decreases locally and the surface temperature begin to rise along the axial length of cylinder. It should be straight after that due to uniform heat flux but it can never approach due to the following reason due to which the temperature decreases. The water temperature rises as it is heated along the cylinder and its physical properties gradually changes with rise in temperature. The increase in thermal conductivity provide less resistance to the heat flow and the decrease in viscosity gives less resistance to water flow which causes the radial flow of hot water to the bulk. So the local heat transfer begins to increase. For the uniform heat flux in this portion the temperature decrease is observed. The Ts—X curve shows the variation of the surface temperature along the cylinder for different heat fluxes. Figure 2 reveals that the surface temperature increase to reach the maximum value then it decreases which can be attributed to the development of thermal boundary layer faster due to buoyancy effects.

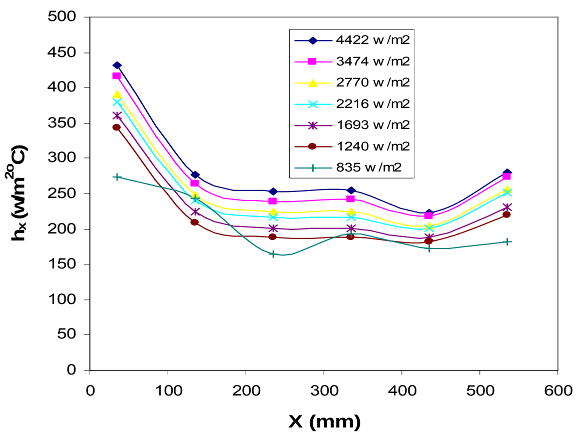

Figure 3. Local Heat Transfer Coefficient along axial distance at different uniform heat fluxes.

The natural convection from uniformly heated cylinder surface of length (L) exposed directly to the water. The surface temperature variation is used to calculate the local heat transfer coefficient at different axial length of cylinder. The physical properties of the water were calculated at average film temperature. The local dimensionless constants (Nusselt, Grashof and Raleigh number) are calculated to find out the correlation for natural convection heat transfer. The local Nusselt number at different heat fluxes is plotted with the dimensionless length of the vertical cylinder in Figure 4. The figure shows the gradual increase in Nusselt number along the length.

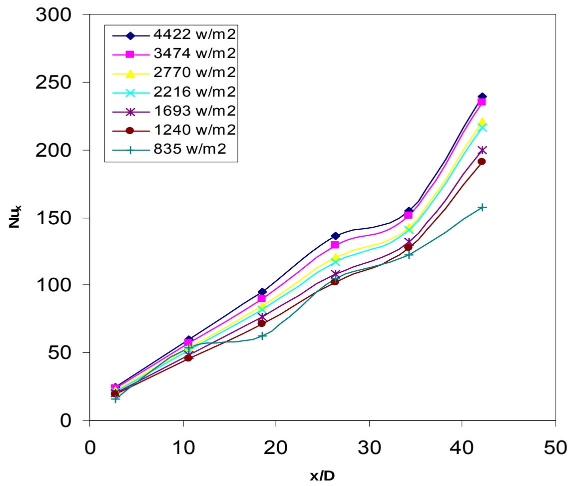

Figure 4. Local Nusselt number along dimensionless length x/D at different uniform heat fluxes.

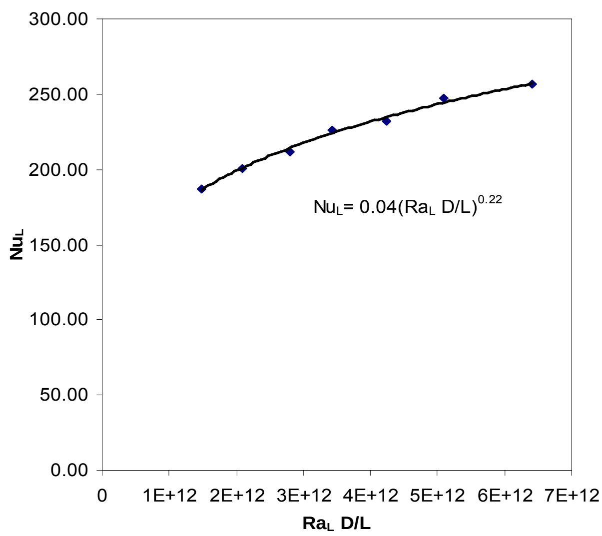

Figure 5. Correlation between average Nusselt number and Raleigh number with geometric configuration.

The general correlation obtained by dimensional analysis for convection heat transfer in literature is empirically correlated in this study. In this case of heat transfer from the surface of vertical cylinder one can expect that there are combine effects of length and diameter. For similarity with the flat surfaces of infinite diameter, the characteristic linear dimensions in Nusselt and Grashof numbers may be taken as cylinder length (L). The Nusselt and Raleigh numbers are based on length.

$Nu_L = f(Gr_L\ Pr)^n$

Figure 5 shows the average correlation obtained from the present study for Ra_L range $6.6x10^{13}$ to $2.88x10^{14}$.

$Nu_L = 0.04(Ra_L\ D/L)^{0.22}$

4. Conclusion

The steady state natural convection heat transfer of uniformly heated vertical cylinder has been investigated for high Grashof numbers. The local and average parameters are presented. The empirical correlation for average Nusselt number and the product of average Raleigh number & D/L is obtained. The experimental results shows an addition to the previous work as most of the results are reported for Ra_L below the range of 10^{13}.

Nomenclature

L	overall heated length of cylinder, m
x	local length of cylinder, m
D	diameter of cylinder, m
Q	rate of heat transfer, watt
q	heat flux, w/m^2
g	gravitational acceleration, m/sec^2
Ts	surface temperature, ^oC
Tb	bulk temperature of water, ^oC
k	thermal conductivity, w/m^oC
Cp	specific heat capacity of water, J/kg^oC
β	thermal expansion coefficient, $1/^oK$
ρ	density of water, kg/m^3
μ	dynamic viscosity of water, kg/m-s
ν	kinematic viscosity of water, m^2/s
h	local heat transfer coefficient, $w/m^2\ ^oC$
Nu	Nusselt number
Pr	Prandtle number
Gr	Grashof number
Ra	Raleigh number
$_x$	in suffix shows the local value
$_L$	in suffix shows the average value

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