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Experimental Study of Free Convection Heat Transfer over a Vertical Tube

Anilkumar R. Shere[1] and S.N. Singh[2]

[1]*Master of Technology Indian School of Mines Dhanbad*
[2]*Indian School of Mines Dhanbad*
E-mail: [1]anilkumarshere505@mece.ism.ac.in, [2]snsingh631@yahoo.com

Abstract— *An experimental investigation of free convection heat transfer on four different geometries of rectangular duct (inside which vertical tube is fixed) at three different heat fluxes input **216**,**511** and **918W/m²** is presented. The four different geometries of rectangular duct are: (a) fully open from top and bottom of duct. (b) Partially closed from top and bottom of duct. (c) Having a circular hole of 6cm dia. at the middle of top and bottom plates of duct. (d) Fully closed from top and bottom of duct forming a cavity.*

The main objective of the present work leads to show the influence of heat flux input on nusselt number in different geometries, to show the variations of heat flux input on the temperature profile along the tube in different cases, to show the effects of heat transfer coefficient on heat flux input in different geometries so as to find out the case in which cooling effect (heat transfer rate) is being efficient.

A systematic experimental database for the local steady state free convection heat transfer behavior is obtained. As lower the temperature variation along the tube, more heat transfer will takes place. At each value of heat flux input it has been found that more heat transfer takes place in fully open from top and bottom case, as the temperature variation along the tube found to be lesser and effective as compared with the temperature variations in other remaining cases.

Keywords*: Different geometries, Heat flux input, vertical tube, free convection, Heat transfer.*

1. INTRODUCTION

Natural Convection is a mechanism in which fluid motion generated by density differences in the fluid occurring due to temperature gradients. Natural convection over a vertical tube of various arrangements has drawn research attentions for many practical applications in the design of heat transfer devices such as nuclear reactor cooling systems, transformer cores, electronic circuit board enclosures, heat exchangers, turbine blades, vertical tube of HVAC systems, wasted nuclear rods in repositories, refrigerating coils, hot radiators, and dry storage casks of spent nuclear fuels as the means of passive heat removal system. Considerable experimental and theoretical studies have been conducted on free convection heat transfer for geometries including vertical, horizontal and inclined flat plates; horizontal and vertical cylinders; and spheres over wide range of Rayleigh numbers [1-4]. However insufficient attention has been paid to vertical tubes with different geometries of rectangular duct.

The present work investigated the influence of the heat flux inputs on free convection heat transfer among different geometrical arrangements of rectangular duct (inside vertical tube is fixed). The test section is a vertical cylindrical pipe dissipating heat from the internal surface. As a result of the heat transfer to air from internal surface of pipe, the temperature of the air increases. The resulting density non-uniformity causes the air around the tube to rise.

2. THEORETICAL BACKGROUND

Bejan [1] reported that when the boundary layer δ_T is much smaller than a cylinder diameter, the heat transfer phenomena on vertical cylinder can be treated as those of vertical plates. Sparrow and Gregg [5] provided the first approximate solution for laminar flow of air over vertical cylinder heated with a prescribed surface temperature. Aziz and Na [6] had done the research to solve the laminar free convection from an isothermal, thin vertical cylinder. Laminar natural convection along the outer surface a vertical cylinder is compared with a vertical flat plate numerically by Fujii and Uehara [7]. Sad Jarah and Campo [8] have studied the natural convection heat transfer in vertical cylinders at constant heat flux experimentally. L.J. Crane [9] studied the natural convection over the vertical cylinder at very large Prandtl number and discussed how, high Prandtl number affect free convection through vertical cylinder. Y.A. Cengel [10] discussed the natural convection phenomenon in case of vertical cylinder and governing equations to determine heat transfer coefficient. Elenbass [11] carried out extensive analytical and experimental work on natural convection flow in cross sectional geometries as the equilateral triangle, square; rectangle, circle and infinite parallel plates and his results are often compared with analytical results for those channels. Bum Jin Chung [12] free convection experiments inside a vertical cylindrical cavity were performed for Rayleigh number for four different geometrical arrangements. Lieberman and Gebhart [13] experimentally investigated the heat transfer from heated wires with uniform flux. Heat transfer from vertical array of horizontal elliptic cylinders was studied by Yousefi and Ashjaee [14]. J. Wojthowaketm [15] studied experimentally the laminar free convective average heat transfer in air from isothermal vertical slender cylinder having circular cross section using a transient technique. Hari P. Rani [16] studied numerically unsteady natural convection of air and the effect of variable viscosity over an isothermal vertical cylinder and concludes that as the viscosity increases, the temperature and skin friction coefficient increases, while velocity near the wall and nusselt number decreases.

3. EXPERIMENTAL SETUP AND PROCEDURE

3.1 Experimental setup

Heat transfer experiment is carried out for four different geometries of Rectangular duct at three different values of heat fluxes input over vertical tube. Experiments are carried for three different values of constant wall heat flux **q = 216**, **511** and **918W/m^2**. The experimental set up consist of Brass tube of length(L) 510mm and outside diameter(D) 38mm with **air** as a working fluid. The Rectangular duct size consists of 200*200*750mm inside which vertical tube is fixed centrally. When a hot body is kept in a still atmosphere, heat is transferred to the surrounding fluid by natural convection. The fluid layer in contact with the hot body gets heated, rises up due to the decrease in its density and the cold surrounding fluid rushes in to take its place. The process is continuous and heat transfer takes place due to the relative motion of hot and cold particles.

The duct forms an enclosure which serves the purpose of undisturbed surrounding. One side of the duct is made up of Perspex for visualization. An electrical heating element is kept in the vertical tube which internally heats the tube surface. The heat is lost from the tube to the surrounding air by natural convection. The tube surface is polished to minimize the radiation loss.

The temperatures of the vertical tube are measured by seven iron constantan type thermocouples which are fixed on the tube by drilling holes along the tube wall and ambient temperature is measured by the eighth thermocouple. The heat input to the heater is measured by an ammeter and voltmeter; and is varied by a dimmer stat. The complete experiment is conducted with minimum disturbance from air movement so that free convection heat transfer prevails.

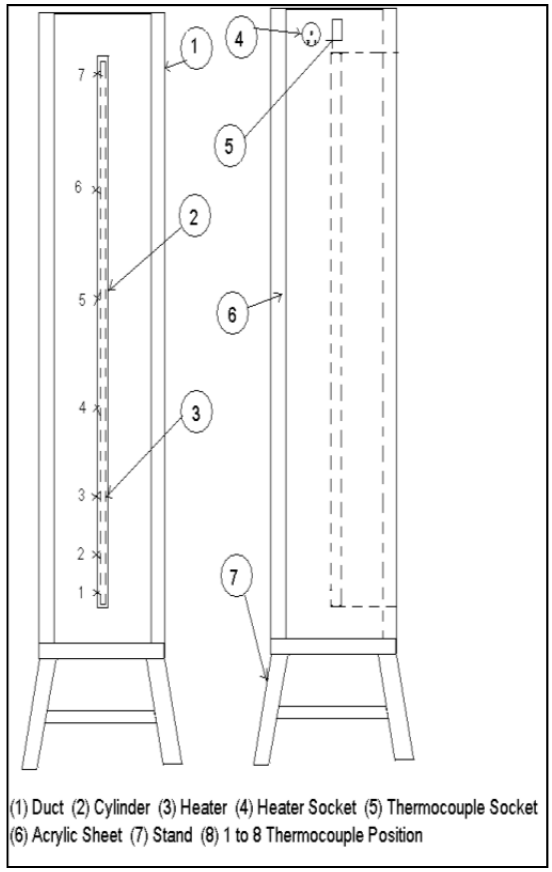

Fig. 1: Schematic diagram of free convection apparatus

3.2 Experimental procedure

The aim of the experiment is to measure the temperatures along the length of the tube and estimate the Grash of number; Rayleigh number and Nusselt number for four different geometrical configurations of the rectangular duct (inside which vertical tube is fitted) for three different heat flux input. The heater is adjusted for the desired power input with the help of dimmer stat. the experiment is allowed to turn on for at least 4 hours before the steady state condition is achieved. When steady state conditions are reached, seven temperature readings along the tube height and ambient temperature and power input to the heater are recorded by the data acquisition system. The experiments are repeated for three heat flux inputs for four geometrical arrangements of rectangular duct. The experiments are repeated for different ambient temperatures to test the repeatability of the results.

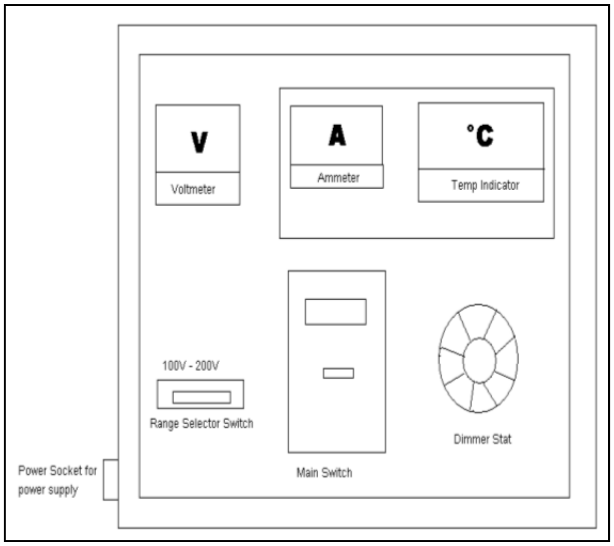

Fig. 2: Control panel for free convection apparatus

4. DATA REDUCTION

It is well known that when the cylinder diameter is much larger than the thermal boundary layer δ_T that develops along the heated wall, the free convection flow on vertical cylinder is same with that of the vertical plate. In this case, Nusselt number can be calculated with the correlations developed by natural plates. The general criterion when vertical cylinder may be treated as a vertical flat plate is

$\frac{D}{L} \geq \frac{35}{Gr^{\frac{1}{4}}}$ Where D is the diameter of the cylinder, L is height of the vertical flat plate and Gr is Grashof number.

For every experimental condition, variable power is supplied to maintain different heat flux to the set up. The temperatures are measured at seven locations along the tube and the ambient temperature.

The heat input to the tube assembly = V*I …. (i)

Where V is the voltage applied

I is the current applied

The net heat transfer from the tubes by natural convection is given as:

$Q_{conv} = hA(T_f - T_\infty)$ …. (ii)

Where h is the heat transfer coefficient – W/m^2K.

The average temperature along the tube is calculated. The bulk mean temperature or film temperature (T_f) is calculated as the average of ambient temperature and temperature along tube length. All the properties of air are calculated at the film temperature (T_f).

The local heat transfer is calculated as:

$$h_x = \frac{Q_{conv}}{(T_i - T_\infty)} \quad \text{…. (iii)}$$

Where T_i is the local surface temperature on the tube and T_∞ is the ambient air temperature.

The local Nusselt number is calculated as:

$$Nu_x = \frac{h_x x}{k} \quad \text{…. (iv)}$$

Where x is the distance measures from lower end of the tube to the thermocouple position along the tube.

The local Grashof and local Rayleigh number are calculated as:

$$Gr_x = \frac{\beta g x^3 (T_i - T_\infty)}{\nu^2} \quad \text{…. (v)}$$

Where $\beta = \frac{1}{T_f}$ is thermal expansion coefficient

ν = kinematic viscosity of air.

$Ra_x = Gr_x * Pr_x$ …. (vi)

For vertical tube losing heat by natural convection, the following empirical correlations have been used:

$$Nu = \frac{h_{th} L}{k} = 0.59(Gr.\Pr)^{0.25} \text{ For } 10^4 \leq Gr.Pr \leq 10^9$$

..(vii)

$$Nu = \frac{h_{th} L}{k} = 0.59(Gr.\Pr)^{0.33} \text{ For } 10^9 \leq Gr.Pr \leq 10^{12}$$

…….(viii)

5. RESULTS AND DISCUSSION

The experiment is conducted with variable heat flux for different geometrical arrangements of duct. The temperature is measured along the length for all the experiments. In these experiments hot air will flow from the bottom of the tube to the top of the tube due to the free convection heat transfer from the tube to the atmosphere.

Typical variation of local wall temperatures along the tube for various heat fluxes are shown in Fig. 3. It increases along the height of tube, which is in accordance with the theoretical predictions done by various investigators but it slightly decreases towards the end, which may be due to the heat rejection from the end of the tube. This can be attributed to the turbulence of the thermal boundary layer with the increase of vertical distance and also because the flow is closer to the critical Rayleigh number. Fig. also shows that temperature difference increases as the heat fluxes input increases.

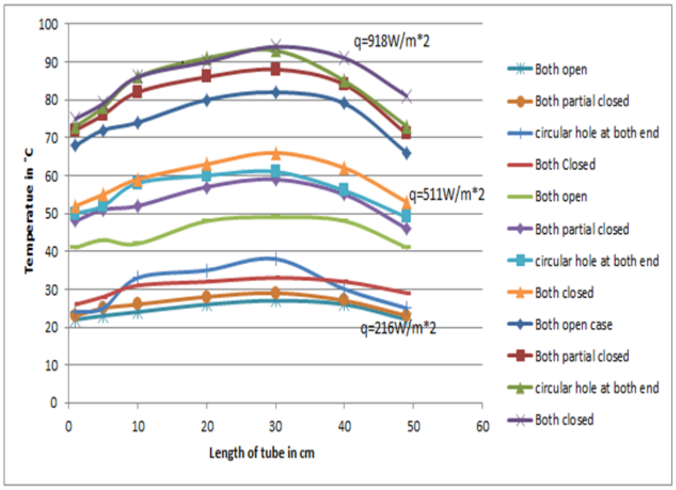

Fig. 3: Temperature variation along the tube at different heat flux input.

Variation of Nusselt number along the tube length is shown in Fig. 4. From the Fig. it shows that the local Nusselt number increases along the tube length but decreases as the heat fluxes input increases. This attributes the increase of boundary layer effect on the heat transfer. Along the length of tube, at same heat flux input to the four cases it is found that the Nusselt number is quite same however as the value of heat fluxes increases, the Nusselt number decreases very minutely.

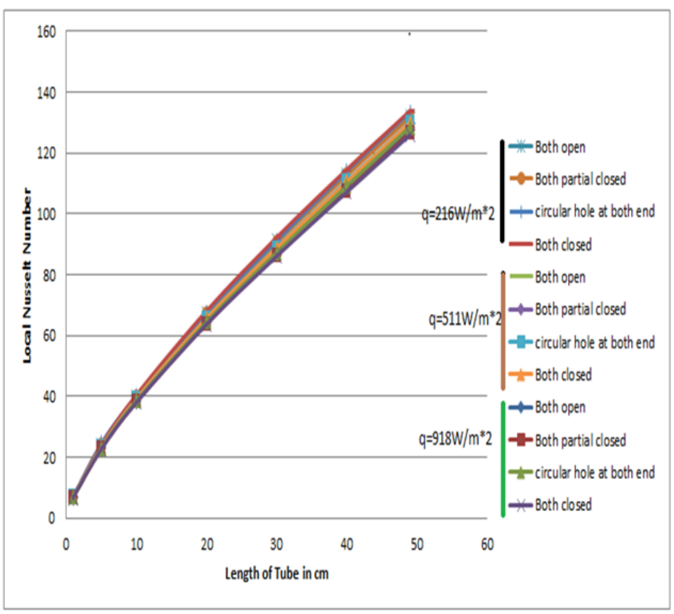

Fig. 4: Variation of local nusselt number for different heat flux input

The temperature variation along the tube with Rayleigh number for different heat flux input is shown in Fig. 5. The variation of temperature along the tube for different heat flux indicates that the temperature difference increases as the heat flux increases but observing at particular heat flux the temperature difference increases up to the maximum value and then starts decreasing towards the end while the Rayleigh number is increasing linearly.

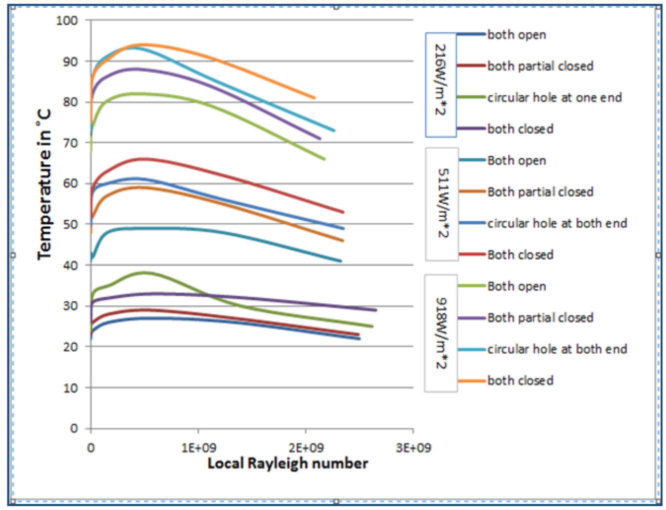

Fig. 5: Temperature variation with Rayleigh number for different heat flux input

The temperature variation with Nusselt number for different heat flux input is shown in Fig. 6. Along the length of tube; when heat flux remains constant, Nusselt number increases along the tube length for four different cases but at particular point of tube length, Nusselt number found to be quite same. As heat flux increases for different cases, Nusselt number decreases at particular point of tube length but increases along the tube length and the temperature variation also increases.

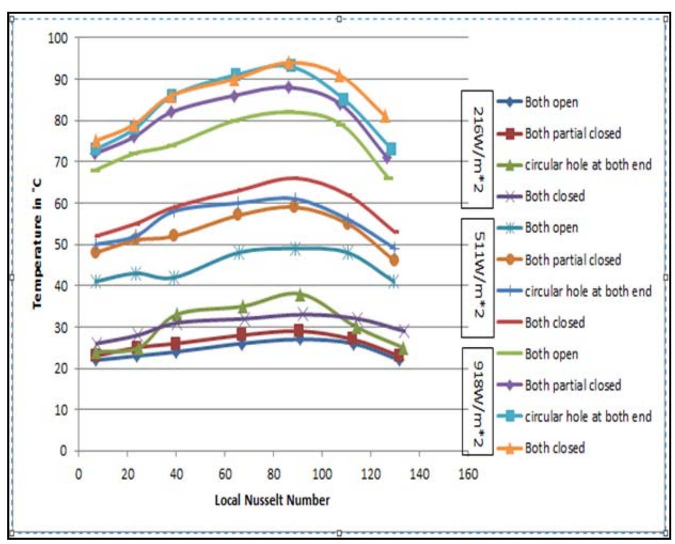

Fig. 6: Temperature variation with Nusselt number for different heat flux input

The relation between Rayleigh number and Nusselt number were shown in Fig. 7. The local Nusselt number increases with the increase of Rayleigh number along the tube and as the heat fluxes increases, the Nusselt number decreases in much slighter way as Rayleigh number is also decreasing at particular length of tube. Similarly at same heat input, the Nusselt number found to be quite similar in every case however as the value of heat flux increases, Nusselt number decreases for four different cases.

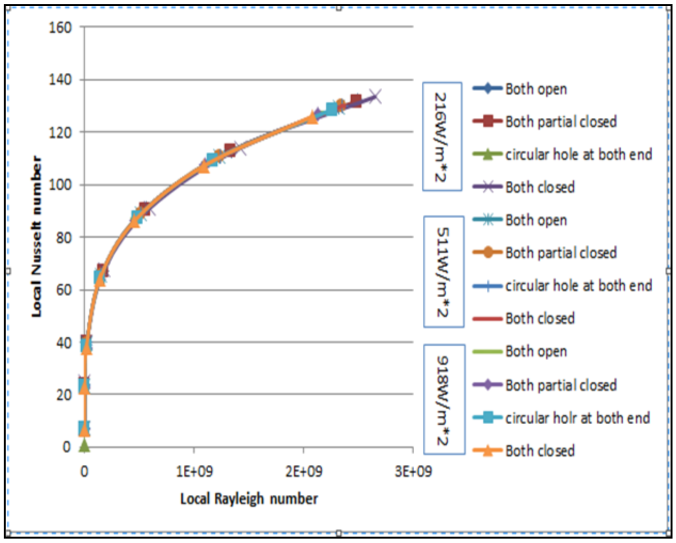

Fig. 7: Variation of Rayleigh number with Nusselt number for different heat flux input

6. CONCLUSION

The natural convection heat transfer over a vertical tube has been studied experimentally for four different geometrical configurations of rectangular duct (inside which vertical tube is fitted) at three different heat flux inputs. The influence of heat flux input on Nusselt number, the variations of heat flux input on the temperature profile along the tube, the effects of heat transfer coefficient on heat flux input on the characteristics of natural convection heat transfer are examined in detail.

It was observed that the temperatures along the tube increases up to a certain height and then decreases at the end due to the turbulence generation for all cases. The average heat transfer rate from the internal surfaces of a heated vertical tube increases when geometrical configuration of duct is open from both sides. The heat transfer rate reduces when duct is closed from both sides. As lower the temperature variation along the tube, more heat transfer will takes place. At each value of heat flux input it has been found that more heat transfer takes place in fully open from top and bottom case, as the temperature variation along the tube found to be lesser and effective as compared with the temperature variations in other remaining cases.

Nomenclature

q_{in} Heat input to heater [W/m^2]

L Length of tube [m]

D Diameter of tube [m]

V voltage applied [V]

I current applied [A]

Q_{conv} Convective heat transfer [W]

h Heat transfer coefficient [W/m^{2}K]

T_f mean film temperature [K]

T_∞ Ambient temperature [K]

T_i Local surface temperature [K]

k Thermal conductivity of air [W/mK]

g Acceleration due to gravity [m/sec^2]

h_x Local heat transfer coefficient [W/m^{2}K]

Gr_x Local Grashof number

Nu_x Local Nusselt number

Pr_x Local Prandtl number

Ra_x Local Rayleigh number

β Volume expansion coefficient [K^{-1}]

ν Kinematic viscosity [m^2/sec]

δ_T Thermal boundary layer thickness [m]

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