Effect of Tube Diameter on Natural Convection Heat Transfer in Circular Vertical Pipe Flows

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Abstract: ***A numerical study of convective heat transfer from a uniformly heated vertical tube under constant wall heat flux has been investigated .The effect of different sections (restrictions) diameter placed at the exit of the tube on temperature; velocity and Nusselt number were examined. The restrictions were circular tubes having same length but different diameters. A set of governing equations i.e. continuity equation (mass conservation), momentum conservation, and energy conservation equations were non- dimensionalized and then solved using the Finite Difference Method. Discretized finite difference equations together with their boundary conditions were solved using the R-software and matlab Analysis of the effect of diameter on temperature, velocity profiles and Nusselt number for different diameters was done. The results obtained were presented graphically and discussed.***

Keywords: Tube diameter, convection heat transfer, vertical tube

1. Introduction

Convection involves the transfer of heat by the motion and mixing of "macroscopic" portions of a fluid. The term natural convection is used if this motion and mixing is caused by density variations resulting from temperature differences within the fluid. The term forced convection is used if this motion and mixing is caused by an outside force, such as a pump. The transfer of heat from a hot water radiator to a room is an example of heat transfer by natural convection.

Convective heat transfer is a term applied to the process involved when energy is transferred from a surface to a fluid flowing over it as a result of a difference in temperature of the surface and fluid. In convection then, there is a surface, a fluid flowing relative to the surface and a temperature difference between the surface and the fluid. Convective heat transfer between a moving fluid and the wall is defined by the relationship

$q_h = h_c (T_s - T_f)$

Where q_h - heat flux

h_c - convective heat transfer coefficient($w/m^2 K$)

T_s - Surface temperature (K)

T_f - fluid temperature (K)

It implies that convective heat transfer is dependent on the temperature gradient at the fluid-solid interface. The main concern is the rate of heat transfer between the surface and the fluid. Convective heat transfer can therefore be classified as either natural convection or forced convection.

Circular tubes are used in a wide range of piping networks such as in boilers, heat exchangers ,condensers, evaporators etc and as the fluid flows, heat is generated which has to be transferred to or from the fluid by convection processes Heat transfer coefficients are always considered when designing equipments specifically intended to transfer heat or not transfer heat. In the last decades efforts have been made to produce more efficient devices with an aim of improving heat transfer rate.

In determining convective heat transfer coefficient, all fluid properties i.e. mass density, specific heat capacity, dynamic viscosity, kinematic viscosity, and thermal conductivity which are dependent on temperature are usually determined at mean temperature, $T_m = \frac{1}{2} (T_{in} + T_{out})$,

Heat transfer coefficients are required in practically all heat transport calculations and are often determined using empirical correlations based on measurement of different geometry and flows. Natural convection is preferred to forced convection in applications where heating /cooling rates and loads are not large. Natural convection heat transfer has been the subject of extensive experimental and numerical investigation over the years. In investigating natural convection in tubes, walls of the tube may be at uniform wall temperatures (UWT) or at uniform heat flux (UHF).

Applications of this work have emerged in modern equipments and devices such as nuclear reactors, solar panels, cooling in buildings and electronic circuit boards. Even though forced convection is usually a main method of removing excessive heat in such applications, natural convection is always present. In other situations natural convection alone is preferable for carrying out the cooling since the process is spontaneous, simpler and requires no compressors, fans, blowers and pumps. Research interest in buoyancy driven convection has been motivated by its relevance in many applications including geophysical, chemical and nuclear engineering.

2. Literature Review

Khanorkar M.P and Thombre R.E [4] experimentally studied natural convection flow of water in vertical pipes of different diameters and lengths using CFD analysis. They found out that as the diameter increases, the outlet velocity decreases but the outlet temperature increases. It was also shown that as the length of the pipe was increased, both outlet velocity and temperature increased. They also found out that outlet velocity profile along diameter is parabolic because of fully developed flow at outlet boundary conditions.

Adam N *et al*, [1] observed that the equation for convective heat transfer requires a fluid temperature, T_f whose value largely depend on the geometry used in the problem.

Liao S.M and Zhao T.S. [7] experimentally investigated heat transfer from supercritical carbon dioxide flowing in horizontal mini/micro circular tubes cooled at constant temperature. They used stainless steel tubes of varying inside diameters (ranging from 0.50mm to 2.16mm) tested under pressures of carbon dioxide ranging from 74 to 120 bar and temperatures ranging from 20^0c to 110^oc.It was shown that although supercritical carbon dioxide was in forced motion through the horizontal tube at Re up to 10^5, the buoyancy effect was still significant. This was reflected by the fact that the Nu decreased with reduction in tube diameter. The influence of buoyancy effect becomes weaker as the tube diameter is decreased due to the fact that the buoyancy parameter Gr/Re_b^2 is proportional to the tube diameter.

Lunde D.M. [5] in his research on single- phase convective heat transfer in a pipe with curvature discussed the convective heat transfer for curved pipes (spiral, helical, and bent tubes) and observed that due to stream wise curvature, there was increased heat transfer in curved pipes. Totala N.P *et al* [10] experimentally studied Natural Convection phenomenon from vertical cylinder in terms of average heat transfer coefficient and they observed that as the length of the cylinder increases from bottom to the top, temperature also increases up to a length nearly half the length of cylinder and then decreases continously after attaining maximum temperature point. They also found out that the value of heat transfer coefficient is having maximum value at the beginning and decreases in an upward direction due to thickening of the boundary layer.

Kandlikar S.G [3] classified flow channels based on hydraulic diameter, D_h as conventional channels (Dh ≥ 3mm), mini channels (200μm ≤ D_h ≤ 3mm), micro channels (1μm ≤ D_h≤ 200μm) and this posses considerable challenges on the best hydraulic diameter to be used for a given function. He observed that laminar to turbulent transition flows at constant wall heat flux condition, depends on the tube diameter and recommended further research on this area. In spite of all these studies, effect of tube diameter on convective heat transfer on flow in circular tubes at low Nusset number has received little attention. Hence the main objective of this project is to study dependence of convective heat transfer on the flow diameter in the case of a vertical tube.

The study is based on the assumption that:

a) The fluid flow is two dimensional, laminar and is incompressible.
b) The fluid properties except density are independent of temperature

3. Geometry of the Problem

Natural convection of an incompressible fluid in a vertical tube was considered. The y-axis is assumed to be parallel to the tube and the x-axis perpendicular to it. Due to this assumption the governing equations will be functions of x and y only

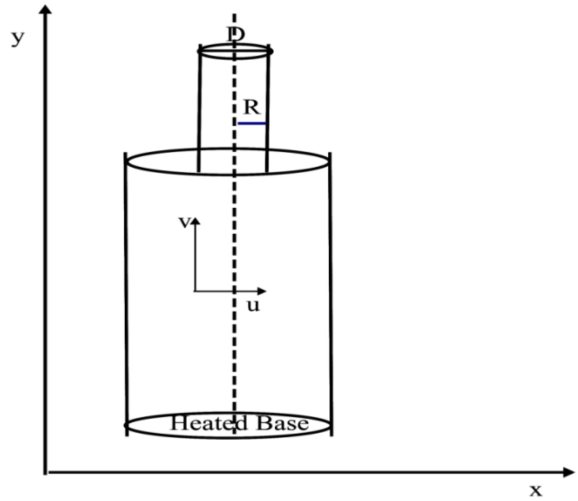

Figure 1: Geometry of the problem

4. Governing Equations

1 Continuity Equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

2 Momentum Conservation Equations

i) x- component

$$\rho\left[\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right]=-\frac{\partial p}{\partial x}+\mu\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right]+\rho g$$

(2a)

Similarly

ii. y-component

$$\rho\left[\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right]=-\frac{\partial p}{\partial x}+\mu\left[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right]+\rho g \quad (2b)$$

3 Energy Equations

$$\rho C_p\left[u\frac{\partial T}{\partial x}+v\frac{\partial v}{\partial y}\right]=\kappa\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\mu\left(\frac{\partial u}{\partial y}\right)^2$$

(3)

5. Non Dimensionalized Equations

Momentum equation

$$u'\frac{\partial v'}{\partial x'}+v\frac{\partial v'}{\partial y'}=Eu\frac{\partial p'}{\partial x'}+\frac{1}{\mathrm{Re}}\left[\frac{\partial^2 v'}{\partial x'^2}+\frac{\partial^2 v'}{\partial y'^2}\right]+\frac{1}{Fr} \quad (4)$$

Energy equation

$$\left[u\frac{\partial\theta}{\partial x}+v\frac{\partial\theta}{\partial y}\right]=\frac{\alpha}{L}\left[\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}\right]+(Ec)L\left(\frac{\partial u}{\partial y}\right)^2 \quad (5)$$

6. Discritization

The centered difference scheme is used to discritize the non dimensionalised governing equations. The centered difference method approximations is obtained using the Taylor's series expansion of $y(x+h)$ and $y(x-h)$ respectively.

$$y(x+h)=y(x)+hy'(x)+\frac{h^2}{2}y''(x)+\frac{h^3}{6}y'''(x)+.... \quad (6)$$

$$y(x-h)=y(x)-hy'(x)+\frac{h^2}{2}y''(x)-\frac{h^3}{6}y'''(x)+.... \quad (7)$$

Adding equations 6 and 7 we obtain

$$y''(x)=\frac{y(x-h)-2y(x)+y(x+h)}{h^2}$$

Subtracting (7) from (6) and ignoring higher orders we get

$$y'(x)=\frac{y(x+h)-y(x-h)}{2h} \quad (8)$$

Where, $x=ih$ i=0, 1, 2, 3…….

$y=jh$, j= 0, 1, 2, 3………..

This implies that

$$y''(x)=\frac{\partial^2 u}{\partial x^2}=\frac{\partial^2 u}{\partial y^2}=u''$$

$$y'(x)=\frac{\partial u}{\partial x}=\frac{\partial u}{\partial y}=u'$$

Thus $$\frac{\partial u}{\partial x}=u'=\frac{u_{i+1,j}-u_{i-1,j}}{2h} \quad (9)$$

$$\frac{\partial^2 u}{\partial x^2}=u''=\frac{u_{i-1,j}-2u_{i,j}+u_{i+1,j}}{h^2} \quad (10)$$

$$\frac{\partial u}{\partial y}=u'=\frac{u_{i,j+1}-u_{i,j-1}}{2k} \quad (11)$$

$$\frac{\partial^2 u}{\partial y^2}=u''=\frac{u_{i,j-1}-2u_{i,j}+u_{i,j+1}}{k^2} \quad (12)$$

$$\frac{\partial \theta}{\partial y}=u'=\frac{\theta_{i,j+1}-\theta_{i,j-1}}{2k}$$

7. Results and Discussion

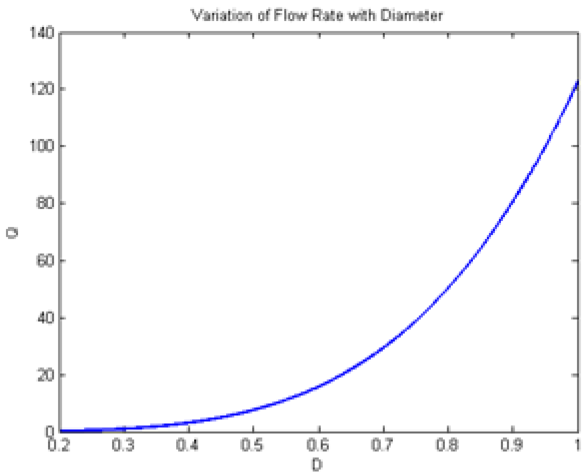

Figure 2: Variation of flow rate with diameter

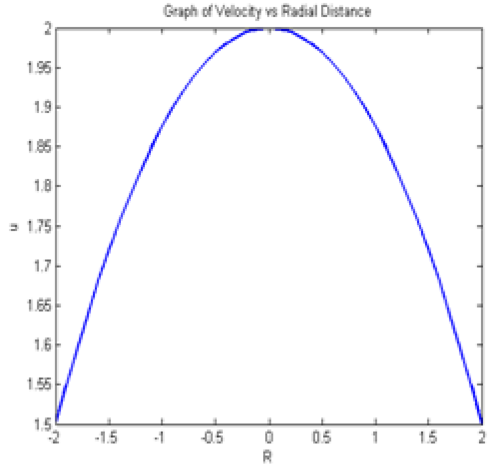

Figure 3: velocity –radial distance

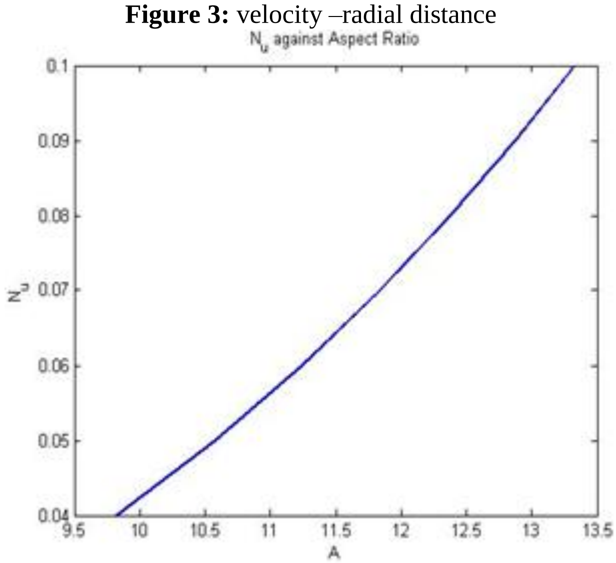

Figure 4: Variation of Nussetl number with diameter

8. Discussion of Results

From figure 2, as the diameter of the tube increases the flow rate also increases. This is because the flow rate is directly proportional to the cross sectional area i.e as the area increases the flow rate also increases because of the increase in mass flux. From figure 3, it is observed that the velocity profile is parabolic with maximum velocity at the center line and minimum at the tube wall. The particles of the fluid near the wall have low temperature because of the boundary layer condition and therefore their velocity is low. The velocity increases towards the centre of the tube attaining maximum value at the centre. Also as the diameter of tube increases, the velocity of the fluid in the tube decreases as shown in figure 5. This is because as the diameter increases the mass of the fluid flowing increases and thus the volume also increases .For an upward heated flow, the Nusselt number varies as diameter of the tube and this is attributed to the buoyancy effects. The length of the exit restriction L is kept constant while the diameter D was varied giving the aspect ratio A (D/L). For the upward heated (buoyancy-assisted) flow, the Nusselt numbers increases as the tube diameter increases.

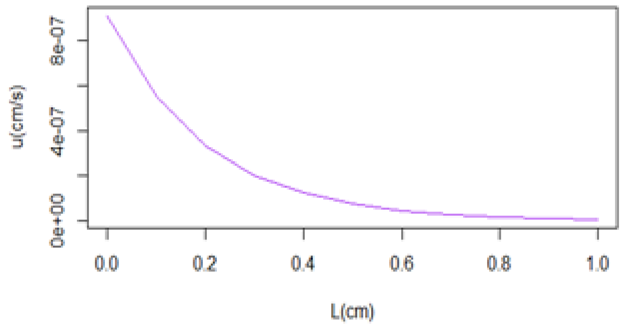

Figure 5: Variation of velocity, u with diameter L

9. Conclusion

The objective of this study was to investigate the effect of tube diameter on velocity and Nusselt number in an enclosure brought about by convective heat transfer. A two dimensional enclosure in the form of a vertical pipe was considered .The fluid flowing in the pipe being heated at the bottom of the tube. Natural laminar flow was therefore considered with Reynolds number 2000 and prandtl number 0.7. Effect of tube diameter of the restriction at the exit on flow field was analyzed for varying diameters. When the tube is narrow, it was found that the velocity is higher than when the tube is wider i.e the velocity decreases with increase in diameter.. It was also found out that the Nusselt number increased with increase in diameter of the restriction section.

10. Recommendations

a) An experimental approach to this problem is recommended in order to reduce the theoretical assumptions in this work.
b) Study on forced convection and its effect on flow field in a circular vertical pipe to be considered.
c) Study on natural convection heat transfer in more viscous fluids like glycerine to be conducted. .

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