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An Overview of Natural Convection Heat Transfer from Horizontal Cylinders

Nazia Kouser Choudhary[1] and N.K. Singh[2]

[1]*M.Tech Scholar, Department of Mechanical Engg. NIT Kurukshetra, Kurukshetra, India*
[2]*Department of Mechanical Engg. NIT Kurukshetra, Kurukshetra, India*
E-mail: [1]kalasnazu5@gmail.com, [2]kant.nirmal@gmail.com

Abstract—*This paper incorporates the overview and understanding related to natural convection heat transfer from horizontal cylinder. A number of national and international publications were referred from available resources to give a comprehensive understanding to the researchers and the readers about natural convection heat transfer. The paper is organized as introduction, literature review, governing equations, conclusion and the references at the end.*

Nomenclature

Gr, Grashoff number;
Ra, Rayleigh Number
Nu, Nusselt number;
Pr, Prandtl number;
β, coefficient of thermal expansion
Ө, angle of inclination of cylinder.
λ *, mixed convection parameter*
Ri , Richardson number

Keywords: *Natural convection, Heat transfer, Cylinder.*

1. INTRODUCTION

The understanding of natural convection heat transfer in liquid metals is important because they act as effective coolant due to their high thermal conductivity. Many technical applications of natural convection heat transfer over horizontal cylinders are found in case of heat exchangers, boilers, air cooling system. In case of nuclear reactors where liquid metal is used as coolant, the phenomenon of natural convection may get established when there is loss of power to the coolant pump as the forced flow of the liquid metal is suddenly lost. To the author knowledge, no specific review paper up to date was found in the literature which deals with the natural convection in cylinders. Therefore, this comprehensive paper is prepared carefully to collect and describe about most published papers in the natural convection flows in cylinders and gives both researchers and readers in this field a review to prepare and improved published papers.

2. LITERATURE REVIEW

Hatton et al. [1], in 1970, investigated the combined forced and natural convection with less speed air flow over horizontal cylinders immersed in Newtonian fluids .Fand and Keswani [2], in 1973, experimentally studied the heat transfer rate in the natural and forced convection heat transfer from horizontal cylinders to water in the cross-flow configuration. As per Richardson number value (Ri), they identified four heat transfer regimes. They concluded that when ($Ri \leq 1$), buoyancy effect was less significant in the flow while, for ($Ri \geq 1$), it became more significant. Sparrow and Lee [3], in 1976, considered the problem of mixed convection boundary layer flow about a horizontal cylinder. They obtained a similarity solution for the aiding flow by expanding velocity and temperature profiles using power-law type expressions of the distance from the lowest point of the cylinder. The local Nusselt number distribution was obtained in the region upstream of the point of separation. Merkin [4], in 1977, studied the combined convection boundary layer on a horizontal circular cylinder in a stream flowing vertically upwards in heated as well as cooled cylinder. It was observed that the cylinder heating delayed, if the cylinder was warm enough then suppressed it completely and the cylinder cooling led the separation point and for a sufficiently cold cylinder there would not be a boundary layer on the cylinders. Nguyen et al. [5], in 1983, studied the combined free and forced convection of water between horizontal concentric cylinders. Lee et al. [6], in 1985, utilize Navies-strokes and energy equation to simulate numerically by utilization of finite element method the laminar natural as well as forced convection flow and heat transfer from an isothermal horizontal cylinder.

Kaviany [7], in 1986, studied numerically the laminar steady combined convection in a horizontal annulus which is subjected to a constant heat flux on the inner cylinder and an adiabatic outer cylinder. Numerical results were presented for Rayleigh numbers varying from 10^5 to 10^9 and Prandtl number varying as (Pr = 0.7, 7 and 70). The profiles of axial velocity and the inner surface temperature were presented and discussed. P. Wang et.al [8], in 1990, investigated unsteady Laminar natural convection flow from a heated horizontal cylinder under diverse surface boundary conditions using spline fractional step method. They found that immediately after the start of heating ($t' = 0$). The fluid bordering the cylinder surface is motionless. Ahmad and Qureshi [9], in 1992, studied numerically the laminar mixed convection of air from a uniform heat flux horizontal cylinder in a cross flow by using the finite difference method. The results were presented for a wide range of Grashof and Reynolds numbers.

Ahmad and Qureshi [10], in 1993, studied the effect on forced convection of air from horizontal cylinder in a cross flow by using the finite difference method. Results were for the large range of Grashof and Reynolds number. Marcel and Regis [11], in 1975, numerically investigated the mixed convection heat transfer from vertically separated horizontal cylinders within confining adiabatic wall. The outcome was that when the distance between the parallel plates ($L/D \geq 1.5$), then with the increase in the cylinder spacing, the overall heat transfer coefficient increases. Koichi Hata et al. [12], in 1999, did an experimental study on natural convection heat transfer from a horizontal cylinder. The experimental setup consists of horizontal test cylinder having diameter 7.6 and 10.7 mm. The material of test cylinders was inconel-600 and nickel-sheathed. Natural convection heat transfer were measured for the heat flux ranging from 8×10^3 to 2.64×10^6 W/m^2 , for Rayleigh numbers ranging from 41 to 25650, and for the bulk liquid temperature of 673, 773 and 873 K. From the results, it can be concluded that with the rise in bulk temperature, Nusselt number rises slightly. But, with the rise in diameter, there is more increase in heat transfer coefficient. Also the surface temperature varies from bottom to top along periphery. The temperature is minimum at bottom and maximum at top which indicates more cooling at bottom and lesser cooling at top. This is due to flow separation over cylinder which result in low velocities at top.

Bassam and Abu-Hijleh [13], in 1999, numerically brings the solution of laminar mixed convection from an isothermal cylinder and calculate the Nusselt number at various values of Reynolds number, Grashof number and incoming free stream angle of attack. The correlations were presented for a specific range of Reynolds number, buoyancy parameter and angle of attack. Hanani et al. [14], in 2002, studied theoretically and modeled the natural convection, they utilize the idea of intersection of asymptotes to show the existence of maximum of optimum spacing for maximum rate of heat transfer. They concluded that there exist a distance between the confining wall for which Nusslet numbers were maximum and by increasing the number of cylinders or their spacing, or, decreasing the Rayleigh number the optimal spacing will increase. Nazar et al. [15], in 2003, numerically studied laminar mixed convection boundary layer flow of a micropolar fluid past a horizontal circular cylinder with constant temperature of the wall. Solutions for the flow and heat transfer characteristics were evaluated for various parameters as the mixed convection parameter, the vortex viscosity parameter and the Prandtl number (Pr =1 and 6.8) and was found that their model is useful for industrial problem with polymeric liquid processing. Teamah et al. [16], in 2005, studied numerically the mixed convection flow and heat transfer between two horizontal concentric cylinders as the outer cylinder was rotating. They observed the flow transitions from no cells to one cell and from one cell to two cells with different Prandtl number, radius ratio and rotational Reynolds number. Mohammed and Salman [17], in the year 2007, performed an experimental investigation for combined convection heat transfer for thermally developing flow in a horizontal circular cylinder. They presented a number of values of surface temperature related to the horizontal circular cylinder.

Olivier Reymond et al. [18], 2008, investigates Natural convection heat transfer from a single horizontal cylinder and a pair of vertically aligned horizontal cylinders, presents heat transfer distributions around the circumference of the cylinders for Rayleigh numbers of 2×10^6, 4×10^6 and 6×10^6 and a range of cylinder spacing of 1.5, 2 and 3 diameters. In the presence of second cylinder lower cylinder is unaffected. When both cylinders are heated then plume rising from the heated lower cylinder interacts with the upper cylinder and affects the surface heat transfer distribution. The distribution of the mean Nusselt number around the circumference of a single cylinder is maximum at the bottom of the cylinder (Θ = 0) and to decrease towards the top (Θ = 180) as the boundary layer develops. The root-means-square Nusselt number distributions indicate the unsteadiness in the flow around the cylinder, which influences the overall heat transfer.

Anwar et al. [19], in 2008, numerically studied the steady mixed convection boundary layer flow of a viscoelastic fluid over a horizontal circular cylinder in a stream flowing vertically upwards for heated as well as for the cooled cylinders and was found that the cylinder heating delayed separation and suppressed the separation completely if the cylinder was warm enough, there would not be a boundary layer for a cold cylinder. S.ozgur Atayılmaz and İsmail Teke. [20], in 2009, experimentally and numerically studied natural convection heat transfer over a horizontal cylinder in different environmental temperatures. The temperature variation was between 10°C–40°C and 20°C–60°C respectively for environmental and cylinder surface. The experiment was carried out on two cylinders having diameters of 4.8 mm–9.45 mm and constant heat was applied. A correlation for the average Nusselt number over the cylinder was proposed in the range of $7.4\times10^1 < Ra < 3.4\times10^3$ .The results obtained were with increasing Rayleigh numbers, Nusselt numbers increases. Ahmad et al. [21], in 2009, numerically studied using an implicit finite-difference scheme the steady laminar mixed convection boundary layer flow past an isothermal horizontal circular cylinder placed in a viscous and incompressible fluid of temperature-dependent viscosity. The solutions were obtained for various values of the Prandtl number (Pr), the mixed convection parameter (λ) and the viscosity/temperature parameter (θr). The obtained results showed that the flow and heat transfer characteristics were significantly influenced by these parameters.

Srinivas et al. [22], in2009, studied mixed convection heat transfer through the effect of aiding buoyancy from an isothermally heated horizontal cylinder immersed in incompressible power-law fluids in the steady flow regime. The results were taken keeping imposed flow and buoyancy induced motion in simultaneous direction. The calculation of the buoyancy effect was stronger in shear-thinnig fluid at low Reynolds numbers than in shear-thickening at high Reynolds number. Salleh et al. [23], in 2010, assumed that the steady mixed convection boundary layer flow over a horizontal circular cylinder, generated by Newtonian heating in which the heat transfer from the surface was proportional to the local surface temperature. The solutions were obtained for the skin friction coefficient, local wall temperature also the velocity and temperature profiles with the mixed convection parameter and the Prandtl number.

Kang and Iaccarino [24], in 2010, calculated the turbulent Prandtl number around a heated cylinder in a channel with heating beneath for mixed convection. They observed that the turbulent Prandtl number near by the cylinder illustrated a large variation, which implied that the assumption of a single value in the entire flow domain was invalid for their considered problem. Rohni et al. [25], in 2012, studied numerically the laminar steady mixed convection boundary layer flow over a horizontal circular cylinder with constant wall heat flux, immersed in a viscous and incompressible fluid of temperature-dependent viscosity by using an implicit finite-difference scheme. The effects of temperature-dependent viscosity parameter on the flow and heat transfer characteristics were examined for various values of Prandtl number (Pr) and the mixed convection parameter (λ). It was found that for both assisting and opposing flows, as the viscosity parameter increased, the local skin friction coefficient increased while the wall temperature decreased for air, but for water, the local skin friction coefficient decreased then slightly increased while the wall temperature decreased.

3. GOVERNING EQUATIONS

The governing equation used natural convection heat transfer problem for the solution.

3.1 Continuity equation

For time dependent 3-D equation is

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u}{\partial x}+\frac{\partial \rho v}{\partial y}+\frac{\partial \rho w}{\partial z}=0$$

3.2 Momentum equation

Momentum equations are based on newton's second law which states that the rate of change of momentum equals the sum of forces on the fluid particle. The time dependent and 3-D momentum equation in X- direction is

$$\frac{\partial(\rho u)}{\partial t}+u\frac{\partial(\rho u)}{\partial x}+v\frac{\partial(\rho u)}{\partial y}+w\frac{\partial(\rho u)}{\partial z}=-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}[\lambda\Delta * V+2\mu\frac{\partial u}{\partial y}]+\frac{\partial}{\partial y}[\mu(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y})]+\frac{\partial}{\partial z}[\mu(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x})]+\rho f_x$$

In Y – axis:-

$$\frac{\partial(\rho v)}{\partial t}+u\frac{\partial(\rho v)}{\partial x}+v\frac{\partial(\rho v)}{\partial y}+w\frac{\partial(\rho v)}{\partial z}=-\frac{\partial p}{\partial y}+\frac{\partial}{\partial y}[\lambda\Delta * V+2\mu\frac{\partial v}{\partial y}]+\frac{\partial}{\partial x}[\mu(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y})]+\frac{\partial}{\partial z}[\mu(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y})]+\rho f_y$$

In Z – axis:-

$$\frac{\partial(\rho w)}{\partial t}+u\frac{\partial(\rho w)}{\partial x}+v\frac{\partial(\rho w)}{\partial y}+w\frac{\partial(\rho w)}{\partial z}=-\frac{\partial p}{\partial z}+\frac{\partial}{\partial z}[\lambda\Delta * V+2\mu\frac{\partial w}{\partial y}]+\frac{\partial}{\partial y}[\mu(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y})]+\frac{\partial}{\partial x}[\mu(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x})]+\rho f_z$$

3.3 Energy equation for fluids

$$\rho c_p\,(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z})=\mathrm{k}\,(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2})$$

3.4 Equations and dimensionless number used in natural convection problem

$q=h*A*\Delta T$ Newton's law of cooling

$$Nu=\frac{hd}{k},\ \Pr=\frac{\mu c_p}{k},\ Gr=\frac{l^3 g\beta\Delta t}{\nu^2},\ \beta=\frac{1}{\nu}(\frac{\partial\nu}{\partial t})_p$$

Criterion for laminar or turbulent flow in natural convection

$Gr*\Pr<10^9$ flow is laminar.

$Gr*\Pr>10^9$ …… flow is turbulent.

4. CONCLUSION

The work presented in this paper gives a thorough overview and brief fundamentals of convection. The reviewed paper have been collected, studied and explained carefully. For study the physics of natural convection heat transfer in laminar flows enough data is available but from the reviewed papers, it has been concluded that there is a need of more experimental, numerical and analytical work for the study the physics of natural convection in case of turbulent flows.

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