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A Review of Natural Convection Heat Transfer from Inclined Cylinders

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Abstract—*This paper gives a comprehensive overview related to natural convection heat transfer from inclined cylinders. From the past decade to present time number of research paper on natural convection heat transfer from inclined cylinder are collected and described in this paper to give good background to the researcher about natural convection heat transfer from inclined cylinder. The reviewed includesexperimental, numerical and analytical work related with natural convection in inclined cylinders of various cross section.*

Nomenclature
Gr, Grashoff number;
Ra, Rayleigh Number
Nu, Nusselt number;
Pr, Prandtl number;
β, coefficient of thermal expansion
Ɵ, angle of inclination of cylinder.

Keywords: *Natural convection heat transfer, numerical, analytical work and experimental work.*

1. INTRODUCTION

Free convection is the process of heat transfer which occurs due to movement of the fluid particles by density changes associated with temperature difference in fluid. Natural convection from cylindrical surface given much attention in recent days due to its easy and cheap manufacturing capability and its practical utility in many applications. Its application is found generally in heat pipe, refrigeration system, solar energy, extended surfaces, thermal design of the buildings and power generation application. In the present scenario the electricity generation is costly and electricity generation method causes harmful effect on the environment. Other important reason for the study of natural convection is that if the system is cooled by forced convection and power failure occurs in such a situation natural convection phenomena becomes very important for the equipment safety. To the author knowledge, there is no specific review paper was found in the literature which deals which convection heat transfer from the inclined cylinders. Therefore this comprehensive paper is prepared to collect and describe about most of published papers in the natural convection heat transfer from the cylinder

2. LITERATURE REVIEW

There are number of investigation available in the area of inclined cylinders.

2.1 Experimental Work on inclined cylinders

Farber and Rennat [1], in 1957, did an experimental investigation for the inclined cylinder and angle of inclination were 0 to 90^0. The experiment was carried out on stainless steel tube 6ft long and 0.125in OD and the heat flux was given to cylinder through electric current to give constant heat flux to the cylinder. They concluded that the rate of heat transfer increases as the angle of inclination increased from vertical. Khamis [2], in 1975, did an experimental investigation for the inclined cylinder for angle of inclination 30^0 to 90^0 to horizontal.The experimental set up was consist of a brass tube of different length and diameters. The heat flux was given to cylinder through heated steam at constant temperature. The range for ($Gr_L \times Pr$) varied from 9.88×10^7 to 2.93×10^{10}.Oosthuizen [3] in 1976, did an experimental investigation for the inclined cylinder for angle of inclination 0 to 90^0 to horizontal. Experiment was conducted on the aluminium cylinder with varying length and diameters of cylinder. The rate of heat transfer measured the rate at which cylinder was cooled to 90^0C after being heated to 100^0C. An empirical equation was given for calculation of Nusselt number for inclined cylinder.

Al – Arabi and salman [4] in 1982, studied experimentally natural convection heat transfer from inclined cylinders with uniform surface temperature in laminar and turbulent flow region. They did experiment on cylinders of different length to diameter ratio. From results they concluded that the heat transfer rate depends upon both diameter and inclination angle of cylinder. The length of laminar flow region increased with increasing the angle of inclination from horizontal. They presented correlation equations that can be used to calculate local and average Nusselt number for inclined cylinders. Oosthuizen and Pual[5] in 1991, did the experimental study for short and inclined cylinders to the horizontal with the exposed end pointing downward. They examined that rate of heat transfer from cylinders with exposed ends is lower than the cylinders with insulated ends and the difference increase with decreasing the length to diameter ratio. Their results also indicate that the heat transfer rates exposed ends pointing downward for short cylinder are very close to those for short cylinders with exposed ends pointing upwards.

Kalendar and Oosthuizen [6] in 2010 experimentally studiedthe mean heat transfer rate values of the inclined square cylinders. The angle of inclination was varying from 0 to 180 degrees. The isothermal cylinder having one end is mounted on flat adiabatic plate and other end is exposed to the environment. The cylinder was maintained at constant temperature for experiment. The results were obtained using the transient lumped capacitance method. The experimental results were compared with the numerical results and show a good agreement.

Jeong – Hwan Heo, Bum – Jin Chung [7], in 2012 did an experimental investigation for the range of Rayleigh number 1.69×10^8 to 5.07×10^{10}. They varied the angle inclination of cylinder from 0 to 90 degrees. Copper electroplating system was employed in experimental set up to simulate heat transfer in a mass transfer system, based on the analogy between heat and mass transfer. For horizontal cylinder the mass transfer coefficients were maximum and gradually decreased with increase in angle of inclination. Results show the similar trend to the existing correlation of heat transfer for inclined cylinders. This study will be useful for deriving turbulent heat transfer correlations for inclined cylinders.Ali F. Hasobee, Yasin K. Salman [8]; in 2014, investigated natural convection heat transfer inside the inclined circular cylinders at constant heat flux condition for various angle of inclination. The effect of inclination was studied on the heat transfer through experiments. Empirical correlation were given for Nusselt number as a function of Rayleigh Number. They conclude from results that local and average Nusselt number increases with increase in heat flux and angle of inclination from 0 to 90 degrees to horizontal.

Kalender and Alhadhrami [9] in 2011, did experimentally study on convective heat transfer from a circular cylinder which is inclined to the vertical. The test chamber was constructed by using transparent acrylic plates. The heat transfer rate were determined by using the transient method. The results were found similar to the previously numerical simulation work done on the same configuration. It was concluded that Nusselt number for entire surface of cylinder based on the height of cylinder is dependent on Rayleigh number based on the height, heat transfer cofficient overall temperature difference, Prandtl number, angle of inclination to vertical. SamaneHamzekhani, Amir Akbari, [10] in 2014, did an experimental study on the free convection heat transfer from the outside surface of an inclined cylinder for water and glycerol at different heat flux condition. Form results it was concluded that average nusselt Number decrease with increase in inclination of cylinder to the horizontal at constant heat flux condition.

2.2 Numerical Work on inclined cylinders

Stefan Schneider and Johannes Straub [11] in 1992, numerically studied the laminar natural convection in a fluid filled cylinder with different end wall temperature and results were verified experimentally. The variation in natural convection heat transfer and convection motion was studied by changing the fluid inside cylinder, geometrical parameters, like Rayleigh number, Prandtl number, aspect ratio and inclination angle. From results it was concluded that maximum heat transfer and highest velocity are found at aspect ratio one and angle of inclination between 45 to 60 degree with exposed ends is lower than that from cylinders.Oosthuizen and Paul [12] in 1991studied natural convection heat transfer from an inclined cylinder pointing downward and ends were exposed in air. The cylinder were short and inclined to the horizontal. From results it was conclude that heat transfer rate from cylinders with insulated ends. The difference in heat transfer rate increases with decreasing length to diameter ratio. It was also found from results that heat transfer rate from short cylinders with exposed ends pointing downward are close to short cylinders pointing upward with exposed ends.

Oosthuizen [13] in 2007 numerically studied natural convection heat transfer from a vertical cylinder isothermal circular cylinder. The exposed horizontal upper surface is maintained at same temperature as the vertical cylindrical side wall of cylinder. The cylinder is mounted on a flat horizontal adiabatic base plate. From results it was concluded that the mean Nusselt number for a heated top horizontal surface is much lower than that for the heated vertical side surface. The curvature effect on the Nusselt number for the vertical cylinder side surface are negligible.Oosthuizen PH [14] in 2008, numerically studied natural convection heat transfer cylinder from a vertical cylinder having square cross section. The square cylinder was maintained at the constant temperature. The isothermal cylinder having one end is mounted on flat adiabatic plate and other end is exposed to the environment. From results it was concluded that the lower the value of Ra number and dimensionless width of the cylinder will increase the mean Nusselt number. The mean Nusselt number for the heated top horizontal surface is much lower than that for a vertical side surfaces. Empirical correlation was given for the mean Nusselt number to an accuracy of approximately 3%.Oosthuizen PH [15] in 2008 did numerical simulation for natural convection heat transfer from isothermal vertical upward pointing rectangular cylinder. The rectangular cylinder having one end is mounted on flat adiabatic plate and other end is exposed to environment. From results it was concluded that dimensionless width and dimensionless depth of the rectangular cylinders have a very less effect on the mean Nusselt number for the entire surface of the rectangular cross section cylinder. For low values of Ra number the mean

Nusselt number tends to increase with decreasing dimensionless width and depth. Rather than the lowest value of Rayleigh number the mean Nusselt number for horizontal top surface of the cylinder is much less than the values for the vertical side of cylinder.Kalendar and Oosthuizen [16] in 2009, numerically studied the natural convective heat transfer from an inclined isothermal square cylinder. The angle of inclination was varying from 0 to 180 degree. The simulation was done on the ANSYS Fluent software. From results it was concluded that the lower the value of Ra number and dimensionless width of the cylinder will increase the mean Nusselt number. At the higher values of Ra number the lowest mean Nusselt number occurs when cylinder is horizontal. The highest meanNusselt number occurs for angle of inclination 45 and 135 degrees.

Kalendar and OosthuizenVinoj Kurian, Mahesh N. Varma, A. kannan [17]; in 2009, did CFD simulation on natural convection the inclined cylinders for unity aspect ratio. The simulation is done for laminar flow inside the cylinders. Cylinders top and bottom surface were maintained at different temperature and curved surface was given adiabatic condition. Helium fluid was used inside the cylinder for simulation at fixed Prandtl number 0.71. Relaxing the convergence criterion caused false hysteresis in the conversed result for vertical cylinder. Fluid flow and temperature pattern were obtained from CFD simulation for inclination 0 to 180 degree. It was found from simulation that above the inclination of 90 degree the hydrodynamics of the flow changed from single vortex to double vortex pattern. Empirical correlation for maximum velocity and Nusselt Number were developed as function of Rayleigh number and angle of inclination.

Kalender and Oosthuizen [18] in 2009, they performed numerical simulation of the inclined isothermal cylinder having one end is mounted on flat adiabatic plate and other end is exposed to the environment. Simulation was done on ANSYS FLUENT software. From results it was concluded that Nusselt number for entire surface of cylinder based on the height of cylinder is dependent on Rayleigh number based on the height, heat transfer cofficient overall temperature difference, Prandtl number, angle of inclination to vertical.Kalendar AY, Oosthuizen PH [19] in 2009 numerically studied the natural convection heat transfer from an inclined square cylinder with a uniform surface heat flux. The simulation was done on the ANSYS Fluent software. The angle of inclination was varying from0 to 180 degrees. The square cylinder having one end is mounted on flat adiabatic plate and other end is exposed to environment. The mean Nusselt number for the cylinder increase with decreasing dimensionless width of cylinder. At the higher values of the heat flux Rayleigh number the lowest mean Nusselt number occurs when the cylinder is in horizontal position while the highest mean value of Nusselt number value occurs when cylinder is at inclination of 45 and 135 degree.

A.M.Vaidya, P.K.Vijayan [20] in 2010, they did simulation on the natural convection heat transfer from horizontal cylinder which is placed in liquid metal pool using PHOENICS CFD software. From simulation they concluded that with rise in bulk mean temperature of fluid, Nusselt number rises very slightly but with rise in diameter of cylinder the heat transfer more increases. A correlation was proposed to predict Nusselt Number On the basis of simulation.Mikhail A. Sheremet [21] in 2012 did numerical simulation for unsteady natural convection of inclined cylinders having finite wall thickness. Heat transfer occur through the ends of cylinders as well as curved surface of cylinder. The heat source was maintained at constant temperature condition. A detailed analysis of influence of the Rayleigh number, prandtl number, dimensionless time and angle of inclination of the tube was studied for unsteady natural convection heat transfer.

2.3Analytical work on inclined cylinders

Chand and Vir [22] in 1980, gave a unified approach for inclined cylinders for convective heat transfer in laminar region. Number of investigations were performed for long and short cylinders with various inclination angles. Their analysis of the experimental data confirms the validity of unified approach for the case of long cylinder.Neetu Rani, HemaSetia, [23], in 2014 developed an empirical correlation for the prediction of heat transfer coefficient for a inclined cylinder in case of free convection in terms of Nusselt number, Prandtl number and Grashof number. Correlation was checked using available experimental data on inclined cylinders. The proposed correlation predicts the available data within ±10% for Prandtl number in the range 0.68 to 0.72 and Grashof number in the range 1.4×10^4 to 1.2×10^{10}.

3. GOVERNING EQUATIONS

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

Continuity equation

The equation states that mass of fluid is conserved

The rate of increase of mass in fluid element = net rate of flow of mass into fluid element

For time dependent 3-D equation is

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

For 2-D, incompressible and steady flow equation is

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$$

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:-

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

Energy equation for fluids

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

Diffusion equation

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}=0$$

Equations and dimensionless number used in natural convection problem

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

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

The value of Gr and Pr are evaluated at mean film temperature.

Criterion for laminar or turbulent flow in natural convection

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

$Gr * \mathrm{Pr} > 10^9$ …… flow is turbulent.

4. CONCLUSION

The present work gives a comprehensive overview of number of research papers related with natural convection heat transfer from the inclined cylinders of various cross sections. The reviewed paper have been collected, explained for various cross section and angle of inclination of the cylinders. In turbulent flows the physics of natural convection heat transfer not yet completely studied. There must be more experimental, analytical and numerical researches to study the natural convection heat transfer from the inclined cylinders of different size, inclination and cross section to study the flow and thermal characteristics.

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