NANO-FLUID FLOW PAST AN ELLIPTIC CYLINDER: STEADY STATE CHARACTERISTICS

Riaz Jafri[1], Syed Fahad Anwer[2], Nadeem Hasan[3]

Abstract

In the present work, two dimensional numerical simulation of mixed convective flow of water based nano-fluid (nano sized copper (Cu) particles suspended in water are used with Prandtl number (Pr) = 6.9) past an elliptic cylinder placed in vertically upward flow is performed. The nanoparticles are assumed to be uniform shape and size. In addition, we have assumed that nanoparticles are in thermal equilibrium state and flowing at the same velocity. The thermo-physical properties of the nano-fluids are assumed to be constant. The buoyancy-driven flow from the heated surface interacts with the uniform main flow. The governing equations are discretised on a collocated non-staggered body fitted grid by employing finite difference type of spatial discretisation. A semi-explicit, pressure correction scheme is employed which is fourth order accurate in space. The range of nanoparticle volume fractions (ϕ) considered is $0 \leq \phi \leq 20\%$. Numerical simulations are carried out at a representative Reynolds number (Re) of 100, while Richardson number (Ri) varied in the range from 0 to 1.2. The local Nusselt number over the surface of the cylinder increases with increasing ϕ at fixed Ri. At a fixed Ri, the time averaged local Nusselt number increases with the concentration of nano-fluid volume fraction (ϕ) upto 15%.

Keywords: elliptic cylinder, mixed convection, nano-fluid, Richardson number.

I. Introduction

The analysis of flow past cylinders of various cross sections such as circular, elliptic and rectangular represents an idealisation of several industrially important applications. The heat transfer characteristics, hydrodynamic forces and flow configurations are major criteria for the design of structures in many engineering applications, i.e., tubes in tubular and in pin-type heat exchangers which are used extensively in the cooling of electronic components and in food, polymer processing applications. In the development of energy-efficient heat transfer equipment, the thermal conductivity of the heat transfer fluid plays a vital role. However, traditional heat transfer fluids such as water, oil, and ethylene glycol mixtures are inherently poor heat transfer fluids. With increasing global competition industries have a strong need to use advanced heat transfer fluids with significantly higher thermal conductivities than are presently available.

Despite considerable previous research and development efforts on heat transfer enhancement major improvements in cooling capabilities have been constrained because of the low thermal conductivity of conventional heat transfer fluids. However, it is well known that at room temperature, metals in solid form have orders-of-magnitude higher thermal conductivities than those of fluids. For example, the thermal conductivity of copper at room temperature is about 700 times greater than that of water and about 3000 times greater than that of engine oil. The thermal conductivity of metallic liquids is much greater than that of nonmetallic liquids. Therefore, the thermal conductivities of fluids that contain suspended solid metallic particles could be expected to be significantly higher than those of conventional heat transfer fluids. Thus the nano-fluids are new class of heat transfer fluids and are engineered by suspending nanometer-sized particles in conventional heat transfer fluids. The average size of particles used in nano-fluids is below 50 nm. [1].

Valipour [2] performed numerical simulation to study the fluid flow and heat transfer around a square cylinder utilising AL_2O_3-H_2O nano-fluid over low Reynolds numbers. Here, the Reynolds number is varied within the range of 1 to 40 and the volume fraction of nanoparticles (ϕ) is varied within the range of $0 < \phi < 0.05$. Two-dimensional and steady mass continuity, momentum, and energy equations have been discretised using finite volume method. SIMPLE algorithm has been applied for solving the pressure linked equations. The effect of volume fraction of nanoparticles on fluid flow and heat transfer were investigated numerically. It was found that at a given Reynolds number, the Nusselt number, drag coefficient, re-circulation length, and pressure coefficient increases by increasing the volume fraction of nanoparticles.

Ganguly et al. [3] investigated numerically entropy generation due to laminar mixed convection of water-based nanofluid past a square cylinder in vertically upward flow. Streamline upwind Petrov–Galerkin (SUPG) based finite element method is used for numerical simulation. Nanosized copper (Cu) and alumina (Al2O3) particles suspended in water are used with Prandtl number (Pr) = 6.2. The range of nanoparticle volume fractions considered is 0 – 20%. Computations are carried out at a representative Reynolds number (Re) of 100 with Richardson number (Ri) range $-0.5 \leq Ri \leq 0.5$, both values inclusive. For both the nanofluids (Al_2O_3–water and Cu–water nanofluids), total entropy generation decreases with increasing nanoparticle volume fractions. It is found that for the present case of mixed convection flows with nanofluids, thermal irreversibility is much higher than that of frictional irreversibility. The Bejan number decreases with increasing nanoparticle volume fractions. Sarkar et al. [4] investigated numerically buoyancy driven mixed convective flow and heat transfer characteristics of water-based nanofluid past a circular cylinder in cross flow using a SUPG based finite element method. Nano sized copper particles suspended in water is used with Prandtl number (Pr) = 6.2, and the range of solid volume fractions ($0 \leq \phi \leq 25\%$) are considered. Computations are carried out for the range of Reynolds number ($80 \leq Re \leq 180$). Effect of aiding and opposing buoyancy is bought about by considering two representative Richardson numbers of 1 and -1. Increase in nanoparticle loading show symmetric vortex structure distributions and have minimal effect of negative buoyancy. Width of the flayers of thermal energy reduces with increasing nanoparticle volume fractions. Increase in solid volume fraction show reduction in thermal boundary layer thickness and increased thermal gradient at the cylinder surface. The local and average Nusselt numbers are found to increase with increasing Re and ϕ. The average Nusselt number at Ri = 1 and Ri = -1 are found to vary as $0.947Re^{0.550}(1 - \phi)^{1.6253}$ and $0.881Re^{0.559}(1 - \phi)^{1.7349}$ respectively. It is observed that the presence of nanoparticles imparts a counter balancing force to that of buoyancy force. This tries to minimise the effect of buoyancy force and stabilises the flow. This is, perhaps, the first time that such behaviour for the nano-fluid is being reported. Valipour et al. [5] performed numerical simulation of flow-field and heat transfer through a copper–water nano-fluid around circular cylinder has been numerically investigated. Governing equations containing continuity, N–S equation and energy equation have been developed in polar coordinate system. The equations have been numerically solved using a finite volume method over a staggered grid system. SIMPLE algorithm has been applied for solving the pressure linked equations. Reynolds and Peclet numbers (based on the cylinder diameter and the velocity of free stream) are within the range of 1 to 40. Furthermore, volume fraction of nanoparticles (ϕ) varies within the range of 0 to 0.05. Effective thermal conductivity and effective viscosity of nano-fluid have been estimated by Hamilton–Crosser and Brinkman models, respectively. The effect of volume fraction of nanoparticles on the fluid flow and heat transfer characteristics are investigated. It is found that the vorticity, pressure coefficient, recirculation length are increased by the addition of nanoparticles into clear fluid. Moreover, the local and mean Nusselt numbers are enhanced due to adding nanoparticles into base fluid. Sarkar et al. [1] performed numerical simulation of buoyancy driven mixed convective flow and heat transfer characteristics of water-based nano-fluid past a square cylinder in vertically upward flow using a SUPG (Streamline Upwind Petrov–Galerkin) based finite element method. Nano sized copper (Cu) and alumina (Al_2O_3) particles suspended in water are used with Prandtl number (Pr) = 6.9. The range of nanoparticle volume fractions (ϕ) considered is $0 \leq \phi \leq 20\%$. Computations are carried out at a representative Reynolds number (Re) of 100. Effect of aiding and opposing buoyancy is brought about by considering the Richardson number (Ri) range $-0.5 \leq Ri \leq 0.5$. Al_2O_3–water and Cu–water nano-fluids show suppression of vortex shedding at Ri = 0.15. Vortex shedding process is initiated and a completely new phenomenon is discovered when the nano-fluid solid volume fraction (ϕ) is increased. For Al_2O_3–water nano-fluids, at $Ri \geq 0.15$, completely periodic vortex shedding is found for $\phi \geq 10\%$. For Cu–water, shedding is observed for both Ri = 0.15 and Ri = 0.5. At Ri = 0.15 shedding is found at $\phi \geq 5\%$, whereas at Ri = 0.5 it is at $\phi \geq 15\%$. The local Nusselt number increases with increasing ϕ.

It is observed that, a new approach for enhancing heat transfer characteristics by adding the nanoparticles into base fluid was used in few simulation of flow past a circular and square cylinder. To the best of authors knowledge, no work was found on Cu-Water based nano-fluid past an heated elliptic cylinder. Geometry of the flow is showed in Fig.1. The nano-sized copper (Cu) particles suspended in water are used with Prandtl number (Pr) = 6.9. The range of nanoparticle volume fractions (ϕ) considered is $0 \leq \phi \leq 20\%$. Numerical simulations are carried out at a representative Reynolds number (Re) of 100, while Richardson number (Ri) varied in the range from 0 to 1.2.

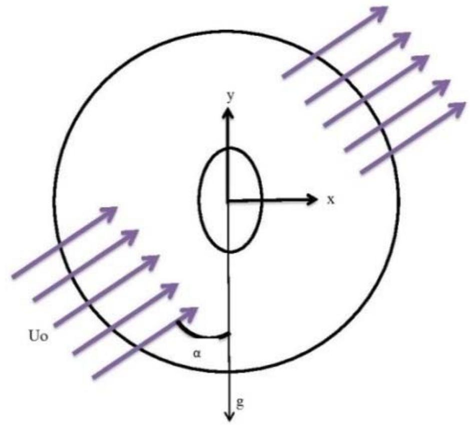


Figure 1: Schematic representation of flow over an elliptic cylinder

II. Mathematical Model and Numerical Scheme

A. *Mathematical Model*

The generic problem of two-dimensional mixed convective flow and heat transfer of water based nano-fluid past a heatThe thermo-physical properties of pure water, alumina and copper at room temperature (see [6 & 7]). We assume Brinkman [8] model for computing effective viscosity of the nano-fluid. The expression for effective viscosity, is given by: $\mu_{eff} = \frac{\mu_f}{(1-\phi)^{2.5}}$ (1)

Effective density of the nano-fluid at reference temperature is given by:

$$\rho_{ef} = \phi\rho_s + (1-\phi)\rho_f \quad (2)$$

Where ρ_s is the density of the solid nanoparticles at reference temperature, and ρ_f is the density of the base fluid at reference temperature. The effective heat capacitance of the nano-fluid at the reference temperature is calculated by the equation given by Xuan and Li [9]. Maxwell–Garnett"s model [10] model has been used for determining effective thermal conductivity of the nano-fluids. It is important to mention here that Maxwell–Garnett"s model and Brinkman model is the basic model for micro-suspension and is restricted to spherical particles only. Accordingly, the present theoretical consideration has been kept simple with the use of basic models available in literature and the effective thermal conductivity and effective viscosity of the nano-fluid is approximated by Maxwell–Garnett model and Brinkman model respectively, within the domain of the single phase formulation approach. Notice that a similar approach was previously used by earlier researchers [11, 7, 12–14] to model the effective thermo-physical properties of the nanoparticle suspension. Such an approach also finds experimental confirmation in the data reported by Xuan and Li [9] for Cu–water and oil–water nano-fluids. Following this, a single phase modelling approach has been adopted in the present study, and the governing equations for single phase flow are extended for nano-fluids [7, 12, 14,]. The thermo- physical properties of the nano-fluids are assumed to be constant. The buoyancy-driven flow from the heated surface interacts with the laminar main flow to yield mixed convection conditions. The governing equations of mass, momentum and energy in non-dimensional form, subjected to Oberbeck-Boussinesq approximation in Cartesian coordinates is given as follows

$$\nabla.\vec{V}=0 \quad (3)$$

$$\left[\frac{\partial \vec{V}}{\partial t}+\left(\vec{V}.\nabla\right)\vec{V}\right]=-\left(\frac{\rho_f}{\rho_{nf}}\right)\nabla p+\left(\frac{\mu_{nf}}{\upsilon_f \rho_{nf}}\right)\frac{1}{\mathrm{Re}}\nabla^2\vec{V}+\left(\frac{(\rho\beta)_{nf}}{\rho_{nf}\beta_f}\right)Ri\theta \quad (4)$$

$$\frac{\partial \theta}{\partial t}+\left(\vec{V}.\nabla\right)\theta=\frac{\alpha_{nf}}{\alpha_f}\nabla^2\theta \quad (3)$$

B. *Numerical Scheme*

The governing equations are discretised on a collocated non-staggered body fitted grid by employing finite difference type of spatial discretisation. A semi-explicit, pressure correction scheme [15], [16] is employed for advancing the discrete solution in time from a given set of initial conditions. The diffusion terms are treated explicitly in [15], [16], however in the present study the diffusion terms are treated implicitly in the predictor step of pressure correction scheme, permitting the use of much larger time steps than permitting by a fully explicit treatment. The concept of momentum interpolation of Rhie and Chow [17] is utilized in order to avoid grid scale pressure oscillations that can result, owing to the decoupling of the velocity and pressure at a grid point in a collocated arrangement. The scheme is conceptually similar to the SMAC algorithm [18-20].

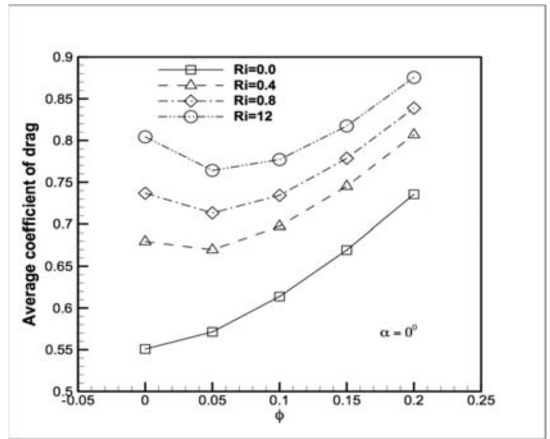


Figure 2 Temporal variation of average coefficient of drag (C_{Davg}) with solid volume fraction (ϕ) of nano-fluid at different Richardson number (Ri) in steady flow regime.

III. Result and Discussion

Numerical simulations are carried out to investigate the effect of nanoparticle loading on the wake dynamics and heat transfer characteristics under buoyancy induced field. Fluid heating affects the evolution of boundary layer produced vorticities that influences shear layer instability and results in degeneration of vortex shedding. Numerical experimentations have been carried out at a representative Reynolds number of 100. The cylinder is maintained at a constant temperature above the ambient temperature over the range of Richardson number of $0 \le Ri \le 1.2$. Cu–water nanofluid is used with Pr = 6.9 and nanofluid solid volume fraction (ϕ) is varied as 0%, 5%, 10%, 15%, and 20%. The results are shown for dynamic steady state conditions. In steady state flow regime, it can be seen that average coefficient of drag (C_{Davg}) increases monotonically with solid volume fraction (ϕ) of nanofluid at Ri=0 but C_{Davg} first decrease and then increases with ϕ at Ri=0.4, 0.8, 1.2 when free stream orientation angle (α) is 0^0 as shown in Figure 2. It can be seen that average Nusselt number (Nu_{avg}) first increase and then decreases with increasing solid volume fraction (ϕ) at Ri=0, 0.4, 0.8 and 1.2 when free stream orientation angle (α) is 0^0 as shown in Figure 3.

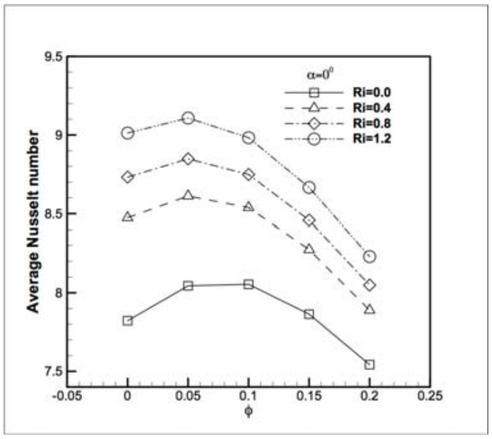
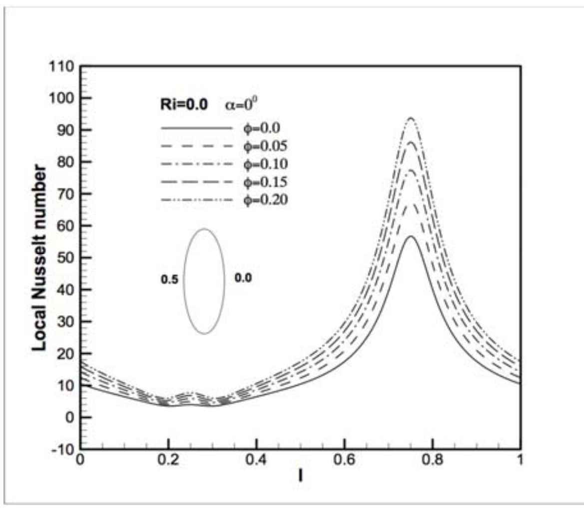
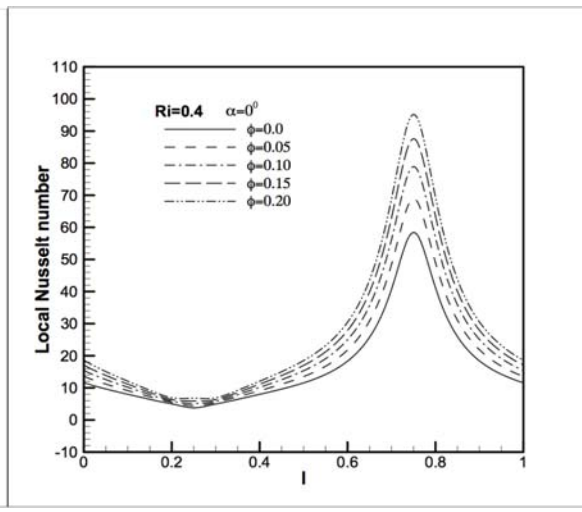


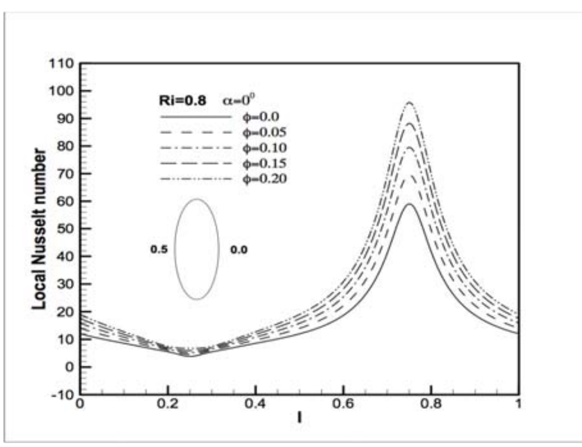
Figure 3 Temporal variation of average Nusselt number (Nu_{avg}) with solid volume fraction (ϕ) of nanofluid at different Richardson number (Ri) in steady flow regime.



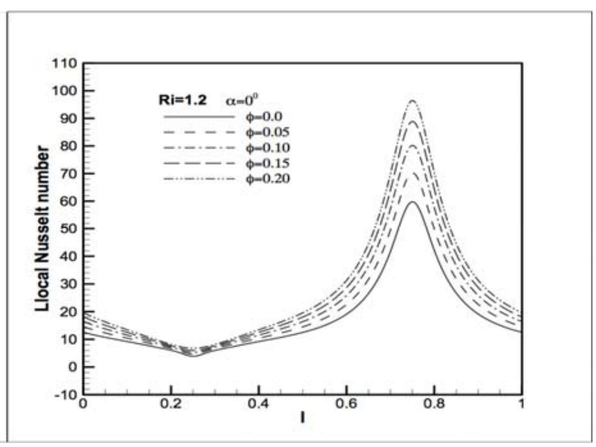
(a)



(b)



(c)



(d)

Figure 4. Variation of local Nusselt number (Nu_l) over the surface of the cylinder with different solid volume fraction (ϕ) of nanofluid at constant Richardson number (Ri) in steady flow regime when free stream orientation angle is 0^o.

Here, we investigate the effect of nanoparticle volume fraction on heat transfer performance of nano-fluid. The quantification of heat transfer is characterised by local and average Nusselt number. For a nano-fluid, the Nusselt number is a function of various factors such as heat capacitance and thermal conductivity of both the base fluid and the nanoparticles, the volume fraction of suspended particles, the viscosity of the nano-fluid and the wake structures. The local Nusselt number computed in this unsteady range is time-averaged over the complete period of vortex shedding cycle. The variation of the local Nusselt number over the cylinder surface for different solid volume fraction (ϕ), is shown in fig.3. Fig 4.(a), (b), (c), and (d) compares the variation of local Nusselt number at Ri = 0.0, 0.4, 0.8 and 1.2 respectively for different nanofluid solid volume fraction (ϕ) when free stream orientation angle (α) is 0^0. It is found that the local Nusselt number increases with increasing ϕ. There is a significant increase in local Nusselt number distribution near the front stagnation region with increasing ϕ. The maximum value of the local Nusselt number occurs at front face of the cylinder facing the incoming flow and decreases gradually over the cylinder surface. This is manifested as higher thermal gradient and accordingly higher local Nusselt number distribution.

IV. Conclusion

Figure Labels: Numerical simulations have been performed to investigate the mixed convective heat transfer and wake dynamics of water-based nano-fluid past an elliptic cylinder in upward parallel flow. At a representative Reynolds number of 100, the results are presented for the range of conditions $0 \leq Ri \leq 1.2$ and $0 \leq \phi \leq 20\%$. For base fluid (ϕ=0) at Ri=0, streamlines shows a small complete symmetric steady recirculation when free stream orientation angle (α) is 0^0. With an increase in nano-fluid volume fraction (ϕ=0.20) size of recirculation zone increases at Ri=0 but increase in the cylinder temperature, associated with increase in the value of Richardson number, the fluid particles in the shear layer are accelerated in the buoyancy field and there is no circulation zone is observed for ϕ=0.20 at Ri =0.4.

References

[1] Sandip Sarkar, Suvankar Ganguly, Amaresh Dalal, "Buoyancy driven flow and heat transfer of nanofluids past a square cylinder in vertically upward flow", International Journal of Heat and Mass Transfer 59 (2013) 433–450.

[2] Mohammad Sadegh Valipour, Reza Masoodi, Saman Rashidi, Masoud Bovand, and Mojtaba Mirhosseini, "A Numerical study on convection around a square cylinder using AL2O3-H2O Nanofluid", Thermal science: Year 2014, Vol. 18, No. 4, pp. 1305-1314.

[3] Suvankar Ganguly, Sandip Sarkar and Amaresh Dalal, "Analysis of Entropy Generation During Mixed Convective Heat Transfer of Nanofluids Past a Square Cylinder in Vertically Upward Flow", Journal of Heat Transfer December 2012, Vol. 134 / 122501-1.

[4] Sandip Sarkar, Suvankar Ganguly, G. Biswas, "Mixed convective heat transfer of nano-fluids past a circular cylinder in cross flow in unsteady regime", International Journal of Heat and Mass Transfer 55 (2012) 4783–4799.

[5] Mohammad Sadegh Valipour, Ariyan Zare Ghadi, "Numerical investigation of fluid flow and heat transfer around a solid circular cylinder utilizing nano-fluid", International Communications in Heat and Mass Transfer 38 (2011) 1296–1304.

[6] R.K. Tiwari, M.K. Das, Heat Transfer augmentation in two-sided lid-driven differentially heated square cavity utilizing nano-fluids, Int. J. Heat Mass Transfer 50 (2007) 2002–2018.

[7] H.F. Oztop, E. Abu-Nada, Numerical study of natural convection in partially heated rectangular enclosures filled with nano-fluids, Int. J. Heat Fluid Flow 29 (2008) 1326–1336.

[8] H.C. Brinkman, "The viscosity of concentrated suspensions and solutions", The Journal of Chemical Physics 20 (1952) 571–581.

[9] Y. Xuan, Q. Li, Investigation on convective heat transfer and flow features of nano-fluids, ASME J Heat Transfer. 125 (2003) 151–155.

[10] J. Maxwell, A Treatise on Electricity and Magnetism, Oxford University Press, Cambridge, 1904.

[11] Y. Xuan, Q. Li, W. Hu, Aggregation structure and thermal conductivity of nanofluids, AIChE J. 49 (2003) 1038–1043.

[12] A.K. Santra, S. Sen, N. Chakraborty, Study of heat transfer augmentation in a differentially heated square cavity using copper–water nanofluid, Int. J. Thermal Sci. 47 (2008) 1113–1122.

[13] S. Sarkar, S. Ganguly, G. Biswas, Mixed convective heat transfer of nanofluids past a circular cylinder in cross flow in unsteady regime, Int. J. Heat Mass Transfer 55 (2012) 4783–4799.

[14] S. Sarkar, S. Ganguly, and A. Dalal, Analysis of Entropy Generation during Mixed Convective Heat Transfer of Nanofluids past a Square Cylinder in Vertically Upward Flow, ASME-J. Heat Transfer 134(12) (2012) 122501–1-8.yx

[40] Z. U. A. Warsi, J. F. Thompson and C. M. Mastin, “Numerical Grid Generation”, 1984.

[15] N. Hasan and S. Sanghi, “The dynamics of two-dimensional buoyancy driven convection in a horizontal rotating cylinder”, Journal of heat transfer, vol. 126, 2004, pp 963-984.

[16] N. Hasan, S. F. Anwer and S. Sanghi, “On the outflow boundary condition for external incompressible flows: A new approach”, Journal of computational physics 206, 2005, pp 661-683.

[17] C. M. Rhie and W. L. Chow, “Numerical study of the turbulent flow past an airfoil with trailing edge separation”, AIAA J. vol. 21, issue 11, 1983, pp 1525-1532.

[18] A. A. Amsden and F. H. Harlow, “The SMAC method: A numerical technique for calculating incompressible fluid flows”, Los Alamos scientific report, LA 4370, 1970.

[19] S. W. Kim and T. J. Benson, “Comparison of the SMAC, PISO and iterative time advancing schemes for unsteady flows”, Computers and fluids, vol. 21, issue 3, 1992, pp 435-454.

[20] L. Cheng and S. Armfield, “A simplified marker and cell method for unsteady flows on non-staggered grids”, International journal for numerical methods in fluids, Vol. 21, issue 1, 1995, pp 15-34.