Convective Heat Transfer Across Rotating Cylinder At Unsteady Laminar Flow Regime

Manoj Kumar Sharma
Department of Mechanical Engineering
PCEM
Bhilai-3, India

Chunnu Lal Dewangan
Department of Mechanical Engineering
ITMUR- School of Engg.and Research
Raipur, India

Puneshwar Verma
Department of Mechanical Engineering
PCEM
Bhilai, India

Abstract- **This paper is devoted to convective heat transfer across the rotating cylinder at unsteady state laminar flow regime.Governing equation Navier-Stroke equation used via the finite volume method for implicit pressure based model. The convective heat transfer calculated at Reynolds number (Re) = 100 and 200 with the range of spin rate (q) = 0 to 2.5 and constant Prandtl number (Pr = 0.7). The results visualize for various spin rate and Re, which show the effect of Nusselt number and local Nusselt number variation around the cylinder surface.**

Keywords- Heat transfer, Rotating cylinder, Nusselt number, Laminar flow.

I. INTRODUCTION

Fluid flow across the bluff body and heat transfer takes place is a greatest area of interest of the researcher. The flow characteristics and heat transport phenomena has wide range of application and engineering practice such as heat exchanger, space heating, seashore structure, cooling of power generating element, cooling electronics instrument etc. Present work has attempted to study the heat transfer across the rotating cylinder at various spinning rate of circular cylinder.

The study of flow across the rotating cylinder involved the numerous of numerical and experimental work at last two decades. The some literatures are, T. Tang et al. [1] has done the numerical study on rotating cylinder at low Reynolds number (Re= 60 and 100) with range of cylinder spin rate 0 to 1. In this paper describes the flow behavior across the rotating cylinder, effect of hydrodynamic coefficient and pressure coefficient on cylinder surface. S. Mittal et al. [2] worked on rotating cylinder at Re = 200 with steady flow regime. High rotational speed of the cylinder at steady flow regime the hydrodynamic forces influenced by Magnus effect. S. Kang [3] done the numerical investigation of steadily rotating cylinder, steady flow regime at Re = 100. The variation of the amplitude of the drag and lift fluctuation and shear rate depend strongly on the rotational direction of cylinder. D.Stojkovic et al. [4] has done the numerical investigation for high spin rate with low and moderate Reynolds number at laminar flow regime. This paper describes the behavior of vortex shedding and variation of drag, lift magnitude. G. E.Karniadakis [5] worked on forced convection heat transfer across the stationary circular cylinder based on energy as governing equation up to Re = 200. This paper investigated temperature distribution and heat transfer for uniform wall temperature and uniform heat flux condition.V Sharma et al. [6] numerically investigated on the heat transfer and effect of prandtl number with various spinning rate at low Reynolds number Re = 1 to 35. The increasing of prandtl number increases the heat transfer rate and decrease with the increasing spinning rate. S.Bijjam et al. [7] has done the numerical study of heat transfer across the cylinder in a confined channel.This paper describes the effect of vortex shedding, drag and lifts characteristics and increases the heat transfer rate with increasing the Reynolds number.

II. NUMERICAL MODELLING

1. Governing Equation

The dimensionless governing equation for two dimensional incompressible, viscous, laminar, unsteady fluid flowswith constant thermo-physical properties of fluid can express as following conservation form:

Continuity Equation

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

Momentum Equation

$$\frac{\partial u}{\partial t}+\frac{\partial (uu)}{\partial x}+\frac{\partial (uv)}{\partial y}=-\frac{\partial p}{\partial x}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \quad (2a)$$

$$\frac{\partial v}{\partial t}+\frac{\partial (uv)}{\partial x}+\frac{\partial (vv)}{\partial y}=-\frac{\partial p}{\partial y}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \quad (2b)$$

Energy Equation

$$\frac{\partial T}{\partial t}+\frac{\partial (uT)}{\partial x}+\frac{\partial (vT)}{\partial y}=\frac{1}{\mathrm{RePr}}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \quad (3)$$

where u and v are velocity component along x and y axis direction in Cartesian coordinaterespectively, t is the time, p is the pressure, T is the temperature, Re (= $\rho U_\infty d/\mu$) is the Reynolds number, Pr (= $\mu C_p/k$) is the Prandtl number, ρ is the fluid density, U_∞ is the free stream velocity, d is the diameter of cylinder, μ is the dynamic viscosity, $C_p$is the heat capacity and k is the thermal conductivity.

The Drag and Lift forces acted on cylinder surface along the x axis and y axis respectively. The Drag and Lift coefficient is combine effect of pressure and viscous coefficient. Lift and Drag coefficients are expressed as following:

$$C_L = C_{LP} + C_{LV} = \frac{2F_L}{\rho U_\infty^2 d} \quad 4$$

$$C_D = C_{DP} + C_{DV} = \frac{2F_D}{\rho U_\infty^2 d} \quad 5$$

where C_{LV} and C_{LP} are viscous lift and pressure lift coefficient respectively and C_{DV} and C_{DP} are viscous drag and pressure drag coefficient respectively.The surface average Nusselt number can be evaluated as follows:

$$\overline{Nu} = \frac{1}{2\pi}\int_0^{2\pi} Nu_\theta d\theta \quad 6$$

whereNu_θ (=$h_\theta d/k$) local Nusselt number on cylinder surface and θ is angular position on cylinder surface.

2. Boundary Condition

Flow over in rotating cylinder the boundary condition shouldbe taken for computational domain as follows:

At inlet: The uniform flow boundary condition used as $u=U_\infty$, $v=0$, and $T=T_\infty$

On cylinder surface: No slip condition assume with u=0, v=0, and $T=T_W$

At outlet: Default boundary condition used as $\partial u/\partial x = 0$, $\partial v/\partial y = 0$ and $\partial T/\partial x = 0$

where T_∞ is the free stream fluid temperature and T_W is the cylinder surface temperature.

3. Computational Grid

Two dimensional computational grid shows in fig.2for numerical simulation of heat transfer across the rotating cylinder.The o-type of structured grid used for this simulation with 100d time of outer domain from cylinder centre. The grids are very fine near the cylinder surface and away from cylinder grid become coarse. The fine grids capture more sufficiently the behavior of fluid flow and it's essential for visualization of results.

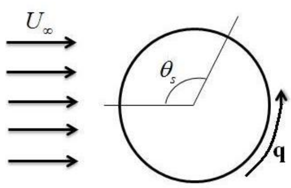

Figure1. Schematics flow across the rotating cylinder

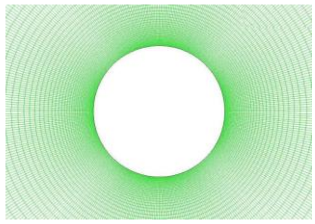

Figure 2. Close view of grid around cylinder

4. Numerical simulation

Simulation for two dimensional heat transports across a rotating cylinder with wide range of spin rate $0 \le q \le 5$at Re = 100 and 200. The solution is based on finite volume method for adopting implicit pressure base model.The cylinder surface is considered as not slip condition with counter clock-wise rotation with uniform dimensionless spinning rate.The working fluid consider as air and the free stream velocity for Re = 100 and 200 are 1 m/s and 2 m/s respectively, the viscosity coefficient is 0.001 Ns/m^2

Validation of numerical code at Re = 100 and 200 used some relevant literature which tabulated below.

TABLE I. VALIDATION CODE FOR RE = 100 AT q = 0

Source	Cd	Nu
Present Work	1.2856	5.0619
R. Golani et al. [8]	1.3063	5.0866
B. N. Rajani et al. [9]	1.3353	--
N. Mahir et al. [11]	1.368	5.179
S. Taunn et al. [12]	1.221	--

III. RESULT AND DISCUSSION

1. Streamline Pattern

The instantaneous streamline patterns (Fig. 3 & 4) are presented to visualization numerical simulation. Initially the cylinder is stationary (q = 0), the unstable vortex shedding formation on downstream of cylinder. The spinning rate of cylinder increases, the symmetry unstable shedding appears on the downstream of cylinder is suppressed along the rotational direction. Two stagnation points formed on the cylinder

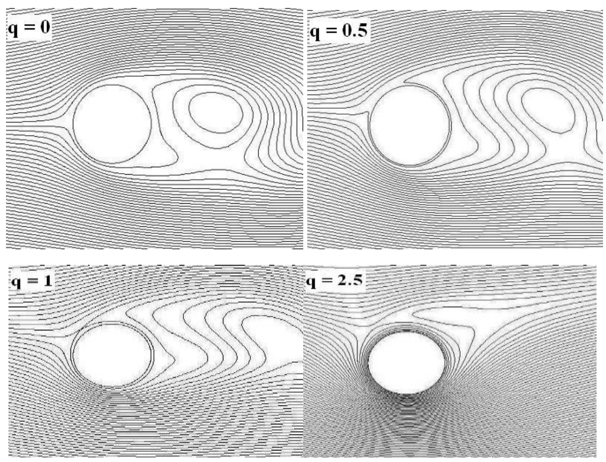

Figure 3.Instantaneous Streamline Pattern at Re = 100

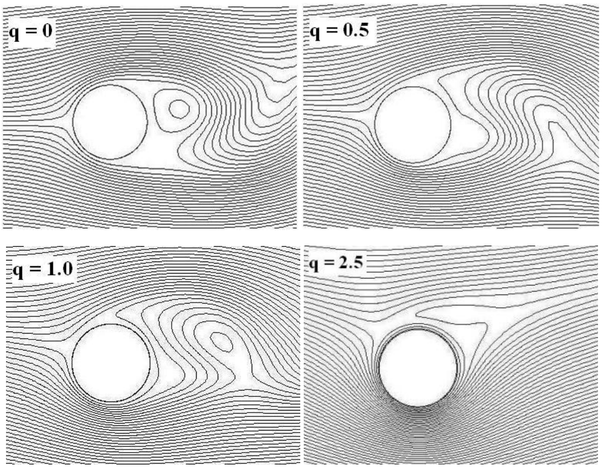

Figure 4. Instantaneous Streamline Pattern at Re = 200

surfacewhich show theseparation and due to high spin rate two stagnation points merge and form a single stagnation point. The rotation of cylinder effected the lift and drag coefficient and Table II show the variation of drag and lift coefficient with various spinning rate for Re = 100 and 200. With the increasing of spinning rate drag coefficient is reduces were the increasing strong amplitude of lift coefficient indicates.

TABLE II. AVERAGE DRAG AND LIFT COEFFICCIENT AT VARIOUS SPIN RATE (q)

	Re = 100		Re = 200	
q	**Cd**	**Cl**	**Cd**	**Cl**
0	1.2856	0	1.2589	0
0.5	1.2295	-1.1920	1.1802	-1.1701
1.0	1.0490	-2.4449	0.9902	-2.4163
2.5	0.2995	-7.6201	0.1924	-7.6177

2. Isotherm Pattern

Instantaneous isotherm patterns for Re = 100 and 200, show in fig.5 and 6.The temperature distribution around the cylinder shows the thickness of thermal boundary layer. The increasing of Reynolds number increase Nusselt number which reduced the thickness of thermal boundary layer. The isotherm pattern visualizesthe heat transfer from cylinder and effect of flow behavior on heat transfer. Increasing spinning rate of cylinder the temperature street is deflecting along the rotational direction which indicates non-uniform temperature distribution around the cylinder surface.

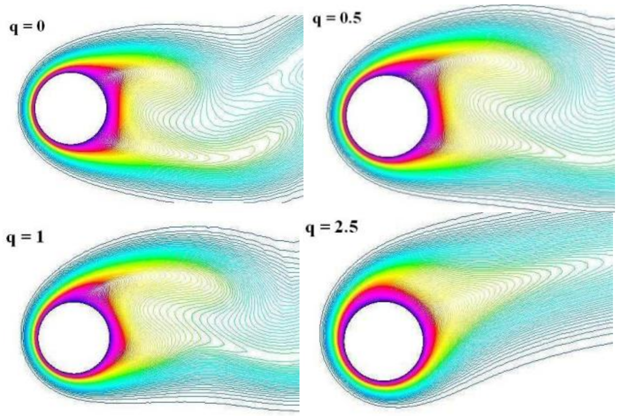

Figure 5. Instantaneous Isotherm Pattern at Re = 100

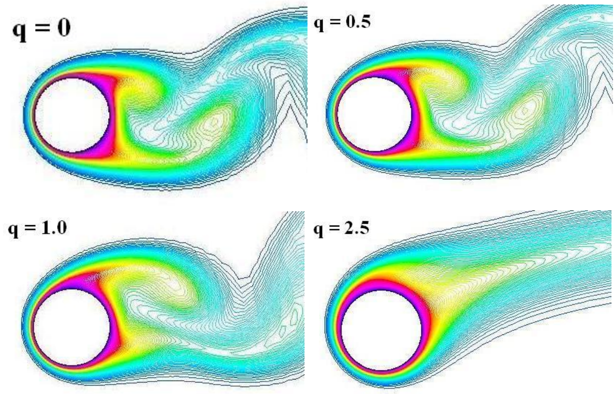

Figure 6. Instantaneous Isotherm Pattern at Re = 200

3. Nusselt number

The Nusselt number shows the amount of heat transport from the cylinder surface. Local Nusseltnumber variation around the rotating cylinder with various spinning rate shows in fig. 7 and 8 for Re = 100 and 200 respectively.The high spinning rate reduced the local Nusselt number andheat transfer rate from cylinder surface were the variation of local Nusselt number around the cylinder surface show the flow behaviors.

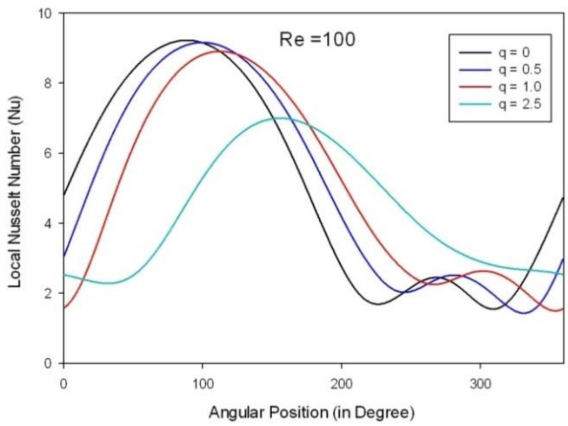

Figure 7. Graph between local Nusselt number and angular position with various spin rate at Re =100

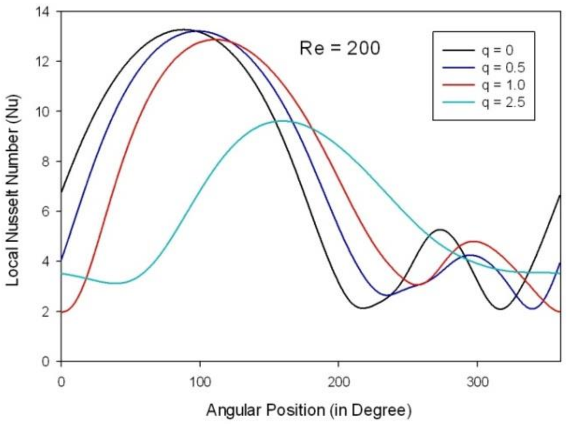

Figure 8. Graph between local Nusselt number and angular position with various spin rate at Re =200

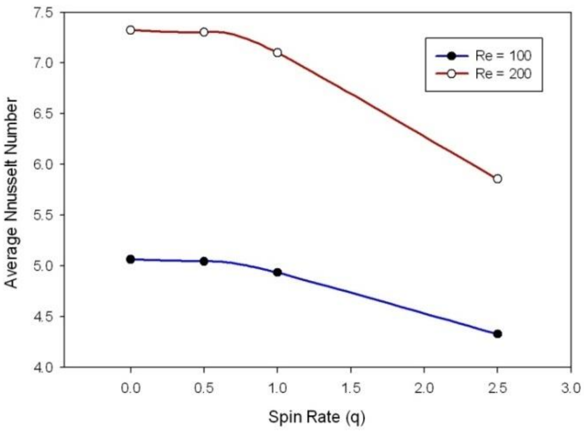

Figure 9. Graph between averageNusseltnumber and spin rate at Re =100 and 200

Local Nusselt number is high on upstream flow regime were local Nusselt number reduced on downstream flow regime.The visualization of flow patterns attached flow indicates the large local Nusselt number and local Nusselt number reduced by the separation of flow from cylinder surface.Fig. show the graph between average Nusselt number and spinning rate of cylinder at Re = 100 and 200.

IV. Conclusion

The present numerical simulation for heat transfer across the rotating cylinder has been carried out under the unsteady state laminar flow regime for Re = 100 and 200. Initially simulated results are comparing with existing experimental and numerical work and good agreement with them. Further simulation work has done at high spinning rate with same simulation code used.The instantaneous flow pattern and isotherm pattern are present for various spinning rate and Reynolds number. The increasing of Reynolds number increases the average heat transfer rate were the high spinning rate reduced the heat transfer from cylinder surface.

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