Effect of Magnus Force on Flow over Cylinder and Heat Transfer Investigation: A Computational Fluid Dynamics Approach

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Abstract. This computational study deals with the forced convection through horizontal cylinder which is performed in the CFD Lab, Department, Mechanical Engineering, GLA University, Mathura. The convective heat transfer coefficient is measured for two different cases stationary cylinder and rotating cylinder. The computational analysis was performed by using commercial CFD package ANSYS-Fluent. This analysis is done because we can’t get the pressure and velocity values in the full domain by using the governing equations. The contours of pressure, velocity and temperature are determined to capture the behaviour of flow throughout the region. Computationally determined values of local heat transfer coefficient are compared with the theoretical values obtained by using governing equations. The effect of the Magnus force is measured on the computational value in such way whether there is any increment in heat transfer coefficient or not. The nondimensional numbers as Nusselt number (Nu), Reynolds number (Re) and Prandtl number (Pr) are used to find the results of heat transfer. It is found that heat transfer is more efficient in case of rotating cylinder in comparison with stationary cylinder. The computationally determined results are found in well agreement with the analytical result.

Keywords: Magnus force, Heat Transfer, Circular Cylinder, CFD, Nusselt number, Prandtl number

1. Introduction

The role of forced convection mechanism can be seen very commonly in everyday life as well as in industrial areas, including designing of heating/cooling systems, heat exchanger simulation, electronic chip cooling, and steam turbines and in many other types of machinery [1-8]. Forced convection is often confronted by engineers during designing or analyzing heat exchangers, pipe flow, and flow over a flat plate at different angles of inclination and at different temperature than the stream also in analyzing the flow over sphere and cylinder [9-12]. Fluid flow over solid bodies commonly arises in practice, and it is responsible for several physical phenomenons for example the drag force acting on the automobiles, power lines, trees, and underwater pipelines. Forced convection is a mechanism in which fluid motion is produced by an external source (like a pump, fan, suction device, etc.). For the effective heat transfer in terms of significant amount of energy the forced convection methods usually
considered [13]. The application of forced convection can also be seen in I.C. engine when water flow through the water jacket to cool the piston cylinder. The coolant used in the journal bearing to remove the extra heat from it also has an application of forced convection through the cylinder. There is also a common problem related to heat transfer from a rotating cylinder which compels us due to its wide range of engineering and industrial applications. The cooling of turbine rotors or electrical motor shafts, cooling of spinning projectiles, drying of paper on rollers in paper industry etc. comes under the same problem [14-116].

Some researchers have done their work on flow over cylinder in order to determine the different parameters during this flow. Manish Mangal, Pritanshu Ranjan and Akshoy Ranjan Paul, (2010) have calculated the reduced drag force in flow over cylinder by placing an upstream rod which reduces drag at the various spacing between the rod and the cylinder for \( \alpha < 5^\circ \) where \( \alpha \) is the angle from stagnation point [17]. A two-dimensional unsteady flow past a square cylinder has been studied numerically for the Reynolds number (Re) considered in the range 50250 so that flow is laminar by Gera.B (2010) [18]. Another study on drag coefficient for the flow past a cylinder is carried out by Monalisa Mallick and A. Kumar (2014) [19]. Muto et al. [20] computationally analyzed the effect of negative Magnus Force on rotating cylinder. They concluded at the Reynolds number in the subcritical or supercritical region, the direction of the lift force follows the Magnus effect to be independent of the rotational speed tested.

2. Governing Equations

The governing equations considered for the analysis of the convective heat transfer coefficient through the flow over cylinder are as follows:

2.1. Continuity Equation

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} = 0
\]  

(1)

2.2. Momentum Equation

\[
\frac{Du}{Dt} = X - \frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{\mu}{\rho} \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right)
\]

(2)

\[
\frac{Dv}{Dt} = Y - \frac{1}{\rho} \frac{\partial p}{\partial y} + \frac{\mu}{\rho} \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right)
\]

(3)

2.3. Energy Equation

\[
\rho c_p \left( u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right)
\]

(4)

2.4. \( k - \varepsilon \) Equation

\[
\frac{\partial \varepsilon}{\partial t} + \text{div} (\rhoue) = \text{div} \left[ \left( \mu_t + \frac{\rho \mu_k}{\sigma_{\varepsilon}} \right) \text{grad} \varepsilon \right] + \rho \mu_t G - \rho \varepsilon
\]

(5)

\[
\frac{\partial \varepsilon}{\partial t} + \text{div} (\rhoue) = \text{div} \left[ \left( \mu_t + \frac{\rho \mu_k}{\sigma_{\varepsilon}} \right) \text{grad} \varepsilon \right] + C_{1e} \rho \mu_k \left( \frac{\varepsilon}{\kappa} \right) - C_{2e} \rho \frac{\varepsilon^2}{\kappa}
\]

(6)

3. Analytical Methodology

A common practice was done by the researchers to nondimensionalized the governing equations and merged the variables which group simultaneously into dimensionless numbers in order to minimize the
total number of variables. There is a dimensionless number named as Nusselt Number which is emerged from this practice for the calculation of convective heat transfer coefficient.

The average Nusselt Number for cross flow over a cylinder is proposed by Churchill and Bernstein (1977)

$$Nu = \frac{hD}{k} = 0.3 + \frac{0.62 \Re^{\frac{1}{2}} \Pr^{\frac{1}{3}}}{1 + 0.4 \Pr^{\frac{1}{3}}} \left[ 1 + \left( \frac{\Re}{282000} \right)^{\frac{1}{2}} \right]$$

(7)

Where, \( \Pr = \frac{\mu c_p}{k} \) And \( \Re = \frac{\rho u D}{\mu} = \frac{u D}{\nu} \)

This equation is valid for \( \Re \Pr > 0.2 \). The fluid properties are assessed at the film temperature which is the average of free stream and surface temperature. The temperature of the air as fluid is kept same as ambient air i.e. 298 K and the temperature is given to the cylinder is 328 K. The properties of air at film temperature which is 313 K i.e. 40°C are taken as following

Table-1 Properties of air at film temperature

| Property                  | Value      |
|---------------------------|------------|
| Density, (kg/m$^3$)       | 1.127      |
| Specific Heat $c_p$ (J/kg-K) | 1007      |
| Thermal Conductivity $k$, (W/m·K) | 0.02662 |
| Viscosity $\mu$, (kg/m·sec.) | 1.918×10$^{-5}$ |
| Kinematic Viscosity $\nu$, (m$^2$/sec.) | 1.702×10$^{-5}$ |
| Prandtl Number $Pr$       | 0.7255     |

4. Computational Methodology

In this section, the whole computational method is described which is employed in the study of convection coefficient of heat transfer through flow over a cylinder.
4.1. Grid Generation

For the analysis of problem grid regarding the study was generated through the widely used software ICEM CFD 15.0. The actual geometry was modeled accurately and the whole geometry was divided into different small meshes for analyzing the problem very close to the actual process. For the two-dimensional analysis, the geometry in the z-direction is considered to be unity.

An area having dimensions 50 D upstream, 50 D downstream and 30 D in lateral direction. The portions of geometry are named as inlet zone, outlet zone, wall-1 zone, wall-2 zone and cylinder zone. A quadrilateral meshing is specified in the domain. An O-grid is specified for the cylinder zone. The first node was at spacing 0.00001 from the surface of the cylinder. An aspect ratio of 2 was utilized subsequently. The data concerning mesh size is as follows:

| Table-2 Mesh Information |
|---------------------------|
| Cells                     | 296212 |
| Faces                     | 593616 |
| Nodes                     | 297404 |
| Partitions                | 1      |
| Cell Zones                | 1      |
| Face Zones                | 6      |

Figure 2 Computational Domain

Figure 3 Quadrilateral meshing in the domain
4.2. Solution Scheme

An implicit algebraic multi grid method of solution is used to converge the results. To achieve the higher accuracy in results the second-order upwind scheme is used in the discretization scheme. Velocity-pressure coupling is fixed by pressure-velocity correlation using a SIMPLE algorithm. Residuals are consistently monitored for continuity, x velocity, y velocity, energy. Convergence of the solution is supposed when the value of residual of energy goes below $10^{-6}$, residual of velocity in the x and y direction goes below $10^{-3}$, residual of continuity goes below $10^{-1}$.

4.3. Boundary Conditions

For obtaining the complete two-dimensional behaviour of flow the component of velocity in the z-direction is considered to be zero for both front and rear plane. Also, the velocity in the y-direction is considered to be zero to suppress any occurrence of any velocity component in the y-direction. On the inflow boundary, velocity in x-direction may vary according to the Reynolds number. The velocity of fluid is taken as 30 m/s. The so-called no-slip boundary condition is provided to the cylinder. On the outflow boundary, the gauge pressure is taken as zero. The characteristic length for Reynolds Number in the case of the cylinder is taken as the diameter D of the cylinder. The rotational speed of 30 rad/sec. is given to the cylinder in order to determine the effect of Magnus force.

Table 3 Boundary Conditions

| Zone       | Boundary Condition       |
|------------|--------------------------|
| Inlet      | Velocity Inlet           |
| Outlet     | Pressure Outlet          |
| Cylinder   | No-slip Condition        |
| Wall-1     | Wall                     |
| Wall-2     | Wall                     |

5. Results

The analytical results for Nusselt number and convective heat transfer coefficient calculated using correlation proposed by Churchill and Bernstine and that calculated computationally are as follows:

Table 4 Comparison between analytical and computational values

| Parameter          | Analytical Value | Computational Value | % Error |
|--------------------|------------------|----------------------|---------|
| Heat transfer      | 85.5723 W/m²·K   | 87.2881 W/m²·K      | 2.00    |
| Nusselt number     | 321.4586         | 327.9045             | 2.00    |
These values are in close resemblance with each other. The average of computational values is taken for the final computational value of heat transfer coefficient and Nusselt number.

| Parameter       | Computational Value without Magnus force | Computational Value with Magnus force | % Increment |
|-----------------|------------------------------------------|-------------------------------------|-------------|
| Heat transfer coefficient | 87.2881 W/m²·K | 108.8791 W/m²·K | 24.735 |
| Nusselt number  | 327.9045                  | 409.0124                          | 24.735     |

The heat transfer coefficient is increased because of the increment in the relative velocity of the flowing fluid over the cylinder. When the first layer of fluid came in the contact of the cylinder wall it acquires the higher velocity at the surface because of rotation of the cylinder.

![Graphical comparison of surface heat transfer coefficient for both the cases](image1.png)

**Figure 5** Graphical comparison of surface heat transfer coefficient for both the cases

![Graphical comparison of surface Nusselt number for both the cases](image2.png)

**Figure 6** Graphical comparison of surface Nusselt number for both the cases
Table 6: Contours without Magnus Effect

| S. No. | Without Magnus Effect |
|-------|-----------------------|
|       | **Pressure Contour**  |
|       | **Velocity Contour**  |
|       | **Temperature Contour** |

Table 7: Contours with Magnus Effect

| S. No. | With Magnus Effect |
|-------|-------------------|
|       | **Pressure Contour** |
6. Conclusions

The CFD analysis of flow over a cylinder concludes the following results:

- The computed value of convective heat transfer coefficient for air is found in close precision with the analytical value.
- The computed value of Nusselt number for air is found in close precision with the analytical value.
- There is a significant increment of approximately 25% in both the values of heat transfer coefficient and Nusselt number considering the Magnus effect.
- It is found that heat transfer is more efficient in case of rotating cylinder in comparison with stationary cylinder.

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Nomenclature

| Symbol | Description                          |
|--------|-------------------------------------|
| ρ      | Density of fluid flowing            |
| u      | Velocity of flow in x-direction     |
| v      | Velocity of flow in y-direction     |
| p      | Pressure in the flow direction      |
| X      | x-direction Body force              |
| Y      | y-direction Body force              |
| T      | Fluid temperature                   |
| T∞     | Free-stream Temperature             |
| T_s    | Surface Temperature                 |
| c_p    | Specific heat of fluid at constant pressure |
| Nu     | Nusselt Number                      |
| h      | Convective heat transfer coefficient |
| L      | Characteristic Length               |
k: Thermal Conductivity of the fluid
Re: Reynolds Number
D: Diameter of the cylinder
Pr: Prandtl Number
μ: Dynamic Viscosity
ʋ: Kinematic Viscosity

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