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Forced Convection Around a Solid Cylinder

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Abstract

Efficient thermal management is a critical challenge in many engineering applications, where optimizing forced convection can significantly enhance system performance and reliability. However, understanding the influence of flow conditions on convection patterns around solid geometries remains a complex problem. This study investigates the forced convection flow around a solid cylinder under varying Reynolds numbers (Re = 1, 10, 20, 40) using COMSOL Multiphysics software. By transforming dimensional equations into dimensionless forms, simulations reveal the evolution of streamline and velocity patterns as flow transitions from laminar to more complex dynamics. The findings provide valuable insights into the relationship between flow behaviour and velocity performance. This study demonstrates the capabilities of COMSOL Multiphysics in thermal system analysis and sets the foundation for future research on more intricate geometries and varied flow parameters.

1. Introduction

Understanding forced convection mechanisms is fundamental in engineering design to optimize energy utilization and ensure system reliability. Forced convection, driven by external forces such as fans or pumps, enhances heat transfer efficiency compared to natural convection. Forced convection has been extensively studied in various configurations and geometries to understand its influencing parameters. It revealed that heat transfer may be categorized based on the interaction between surface heat flow and temperature different as a driving factor. The first study of convection heat transfer was conducted by [1], who studied about the history of heat transfer to provide historical perspectives on the influences of Newton's law of cooling on the development of heat transfer theory published in 1701. Then, another study focused on forced convection flow and heat transfer along a flat plate within a porous medium, observing their influence on heat transfer and fluid flow characteristics [2]. Another researcher investigated how nanoparticle motion and movement affected heat transmission in a horizontal stream covered with a porous media, and they discovered that when the Schmidt number rose, the wall temperature gradient reduced, and therefore the local Nusselt number also decreased [3]. Additionally, the researcher discussed the consequences of forced convection involving a water-alumina-based nanofluid at a high Reynolds number within a square cavity that contains a rotating disk operating at a unit speed and suggested that recirculation movement of the disk can affect the temperature distribution in the channel [4].

A solid cylinder is an important geometric shape used in heat transfer analysis, especially in applications including conduction, convection, and radiation. Understanding the heat transfer characteristics of a solid cylinder is important for various engineering problems, such as thermal management in mechanical systems, design of heat exchangers, and material processing. In addition, solids transmit heat more efficiently than liquids or gases because their particles are closer together. This makes, solid as the best heat conductor [5]. It was discovered by a study that evaluates the numerical investigation to analyse mixed convective heat transfer within a square enclosure that was divided into two layers, featuring a rotating circular cylinder positioned at the centre of the cavity. The findings demonstrated that with an increase in the Darcy number, Rayleigh number, and solid volume fractions, will affects the rise of the intensity of the flow, the steepness of the temperature gradient, and the average Nusselt number (Nu) irrespective of the cylinder radius [6]. Another study researched the investigation of flow and heat transfer from an isolated square cylinder sustained at a constant temperature. It was discovered that the mean Nusselt number gradually increased with increased in Reynolds number and Darcy number [7]. Another study indicated a numerical simulation to analyse magnetohydrodynamic (MHD) mixed convection induced by a rotating circular solid cylinder within a trapezoidal enclosure containing a Cu-water nanofluid saturated with a porous medium [8].

Existing research has study about fluid flow and forced convection heat transfer around a solid cylinder wrapped with a porous ring [9]. Their research aims to replicate previous analysis by focusing on both solid and porous region while applying Finite Volume Method (FVM). In contrast, the objective of the present study is to analyse forced convection around a solid cylinder by focusing on solid region and applying Finite Element method (FEM) in COMSOL Multiphysics software.

Nomenclature	
D	Cylinder diameter
u, v	Velocity component in r, θ direction respectively
r	Radial coordinate
Re	Reynolds number
Pr	Prandtl number
P	Pressure
R	Cylinder radius
Greek symbols	
ρ	Fluid density
θ	Cross-radial coordinate
μ	Dynamic viscosity
Subscripts	
s	Solid
W	Wall
v	Viscous force
∞	Free stream

2. Methodology

Fig. 1 illustrates a square geometry of the studied problem, where it comprises a long circular cylinder with the diameter of D. The top and bottom walls are fully insulated, with the right and left walls kept at different temperatures. Besides, the left wall will be the inlet for the external force with the temperature of T_∞ and the right wall will be the outlet side. The laminar flows across the solid cylinder at a constant temperature of T_w. The parameters that were used for the research will be the Reynolds number, with the value of Re = 1, 10, 20, and 40.

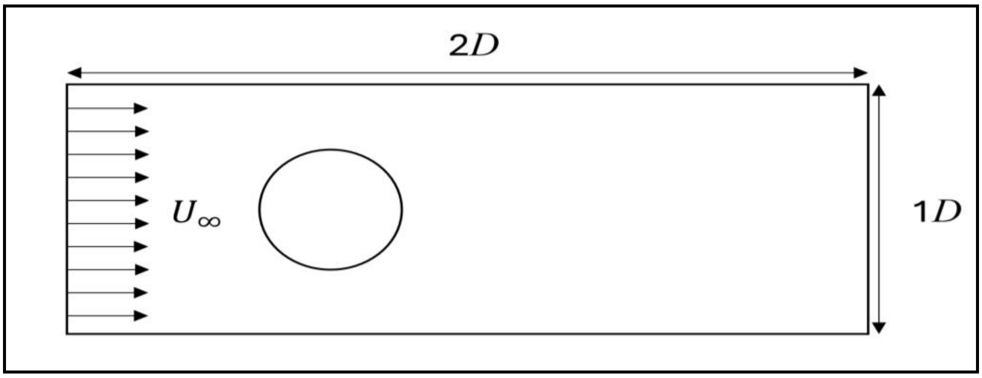


Fig. 1 The physical model configuration

The governing equations (1) to (3) by [9] are shown below:

$$\frac{\partial}{\partial r^*}(r^* u^*) + \frac{\partial v^*}{\partial \theta^*} = 0 \tag{1}$$

$$\rho\left(\frac{v^*}{r^*}\cdot\frac{\partial u^*}{\partial \theta^*} + u^*\frac{\partial u^*}{\partial r^*} - \frac{v^{*2}}{r^*}\right) = -\frac{\partial p^*}{\partial r^*} + \mu\left(\frac{\partial^2 u^*}{\partial r^{*2}} + \frac{1}{r^*}\frac{\partial u^*}{\partial r^*} + \frac{1}{r^{*2}}\frac{\partial^2 u^*}{\partial \theta^{*2}} - \frac{2}{r^{*2}}\frac{\partial v^*}{\partial \theta^*} - \frac{u^*}{r^{*2}}\right) \tag{2}$$

$$\rho\left(\frac{v^*}{r^*}\frac{\partial v^*}{\partial \theta^*} + u^*\frac{\partial v^*}{\partial r^*} + \frac{u^* v^{*2}}{r^*}\right) = -\frac{1}{r^*}\frac{\partial p^*}{\partial \theta^*} + \mu\left(\frac{\partial^2 v^*}{\partial r^{*2}} + \frac{1}{r^*}\frac{\partial u^*}{\partial r^*} + \frac{1}{r^{*2}}\frac{\partial^2 u^*}{\partial \theta^{*2}} + \frac{2}{r^{*2}}\frac{\partial u^*}{\partial \theta^*} - \frac{v^*}{r^{*2}}\right) \tag{3}$$

The equations (1) to (3) are converted into their dimensionless form by using the following set of variables

$$r^* = rR \qquad \theta^* = \theta \qquad u^* = uU_\infty$$
$$v^* = vU_\infty \qquad p^* = p\rho U_\infty^2 \qquad T = T(T_w - T_\infty) + T_\infty \tag{4}$$
$$R_e = \frac{\rho U_\infty D}{\mu} \qquad P_r = \frac{v}{\alpha}$$

where there are components of fluid kinematic viscosity, fluid density, thermal diffusivity of fluid, dynamic viscosity, cylinder diameter, and pressure.

$$\frac{\partial}{\partial r}(ru) + \frac{\partial v}{\partial \theta} = 0 \tag{5}$$

$$\left(\frac{v}{r}\frac{\partial u}{\partial \theta} + u\frac{\partial u}{\partial r} - \frac{v^2}{r}\right) = -\frac{\partial p}{\partial r} + \frac{2}{\mathrm{Re}}\left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} + \frac{1}{r^2}\cdot\frac{\partial^2 u}{\partial \theta^2} - \frac{2}{r^2}\cdot\frac{\partial v}{\partial \theta} - \frac{u}{r^2}\right) \tag{6}$$

$$\left(\frac{v}{r}\frac{\partial v}{\partial \theta}+u\frac{\partial v}{\partial r}+\frac{uv}{r}\right)=-\frac{1}{r}\cdot\frac{\partial p}{\partial \theta}+\frac{2}{\mathrm{Re}}\left(\frac{\partial^2 v}{\partial r^2}+\frac{1}{r}\cdot\frac{\partial v}{\partial r}+\frac{1}{r^2}\cdot\frac{\partial^2 v}{\partial \theta^2}+\frac{2}{r^2}\cdot\frac{\partial u}{\partial \theta}-\frac{v}{r^2}\right) \tag{7}$$

The requirements for boundary conditions are as follows:

Surface of the solid cylinder

$$u_2 = v_2 = 0$$

Inlet section (Uniform flow)

$$0 < \theta < \frac{\pi}{4}\ ,\ u_1 = -cos\theta,\ v_1 = sin\theta$$

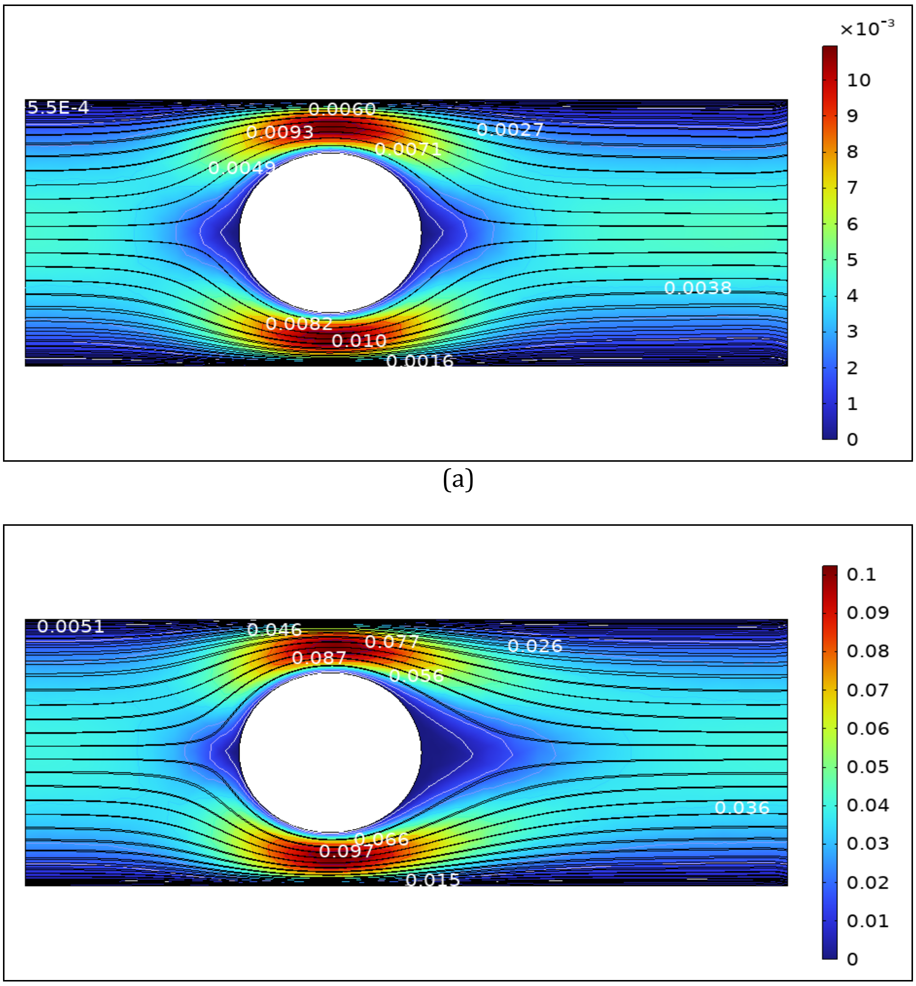
Upper and downer boundaries (infinity boundary condition)

$$\frac{\partial u_1}{\partial r} = 0, \frac{\partial v_1}{\partial r} = 0$$

3. Results and Discussion

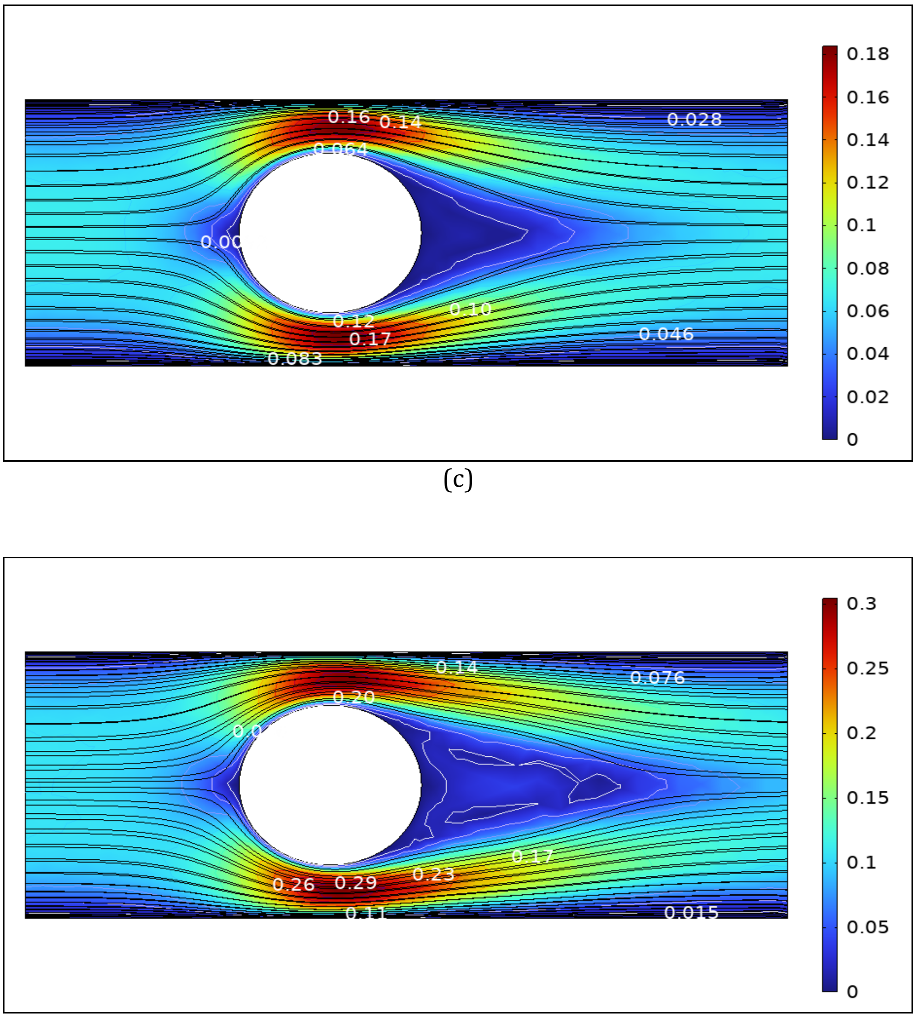
The Reynold number is set to 1, 10, 20, and 40. It represents the fluid flow velocity at a constant temperature. The forced convection behaviour in a square shape with a solid cylinder was examined. The reason these values were selected is that Re = 1, 10, 20, and 40 influence the convection effect at a constant initial temperature.

3.1 Streamlines and Velocity



(a)

(b)



(c)

(d)

Fig. 2 Streamlines and velocity various Reynolds number, Re

The effect of Reynolds number on the streamlines and velocity around cylinder is illustrated in Fig. 2 for the case of various Reynolds number, Re: (a) Re = 1; (b) Re = 10; (c) Re = 20 and (d) Re = 40. For Fig. 2(a) Re = 1, it shows that the flow around the cylinder is smooth and entirely laminar with no observable disturbances. There is no flow separation or vortices development downstream after passing the solid cylinder. This occurs because viscous forces dominate over inertial forces, ensuring a highly stable and predictable flow pattern. Besides, the velocity values near the cylinder are lower due to the dominance of viscous forces, which slow down the fluid near the surface.

Fig. 2(b) displays the streamlines for Re = 10. It shows that the flow begins to exhibit slight changes when the Reynolds number rises to 10. Even though the streamlines remain mostly laminar, the downstream area exhibits minor irregularities. In addition, the velocity values increase in the free-stream region but decrease near the cylinder due to viscous drag. These changes are at an early stage to flow separation and the shift towards complex flow pattern begins with this.

Fig. 2(c) shows the streamlines for Re = 20. The streamlines behind the cylinder indicate noticeable flow separation and a wake region begins to form. The levelling advantages of viscosity are overcome by expanding inertial forces, resulting in this wake area. In the downstream area, the split flow produces small vortices that break the flow's symmetry. In addition, the velocity values near the cylinder's surface are low, especially in the wake region. In the free-stream region, the velocity increases significantly, indicating that inertial forces are becoming more dominant. It is evident that the flow dynamics are become increasingly complex and unstable, even if the flow is still laminar.

Fig. 2(d) demonstrates the streamlines for Re = 40. The streamline pattern changes dramatically. A bigger wake region forms behind the cylinder as the flow divergence becomes more noticeable. The streamlines demonstrate that the flow has greatly departed from the cylinder's surface due to the dominance of inertial forces. Furthermore, the velocity values in the recirculating region are lower due to the reverse flow caused by separation. However, the velocity in the free-stream region is higher, reflecting a greater influence of inertial forces over viscous forces.

4. Conclusion

Efficient thermal management is a critical challenge in many engineering applications, where optimizing forced convection can significantly enhance system performance and reliability. This study investigates the forced convection flow around a solid cylinder under varying Reynolds numbers (Re = 1, 10, 20, 40) using COMSOL Multiphysics software.

Key findings reveal that at low Reynolds numbers, the flow remains stable, with streamlines wrapping smoothly around the cylinder and low velocity near the surface due to the no-slip condition. Early signs of flow separation are observed downstream as Reynolds numbers increase, transitioning the flow toward more complex dynamics. These transitions highlight the interplay between streamline patterns and velocity distributions, offering insights into the mechanisms governing forced convection. This study demonstrates the capabilities of COMSOL Multiphysics in analysing thermal phenomena and suggests further exploration of the effects of variable parameters, such as initial temperature values or additional influencing factors, to better understand and optimize forced convection processes.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design, solve the governing equation, analysis, and interpretation of results****: Nur Azizi Hilman Mohd Yusoff, Muhamad Ghazali Kamardan;* ***draft manuscript preparation****: Nur Azizi Hilman Mohd Yusoff, Muhamad Ghazali Kamardan. All authors reviewed the results and approved the final version of the manuscript.*

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