Darcy Forchheimer Flow in an Open Channel with a Cylindrical Heater and Porous Matrix – Galerkin Method

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Abstract

In the design of electronic equipment such as servers, computers, or power supplies, open cavities may contain heated components like microprocessors or power transistors. This investigation considers the flow of a Newtonian fluid in an open rectangular cavity with porous material and a heated cylindrical obstacle under the influence of a uniform magnetic field. The novelty of the investigation is to analyse the effect of the magnetic field on the flow strength and rate of heat transfer from the obstacle embedded in the non-Darcy porous rectangular channel. The solution of the flow problem has been obtained by employing the Finite Element Method via COMSOL Multiphysics, and the effect of various parameters on heat transfer and flow strength has been demonstrated with the help of contours. The augmented values of the Reynolds number resulted in the creation of a stronger vortex, while the Hartmann number decayed the fluid velocity. The fundamental principles of fluid dynamics and heat transfer in open cavities with heated obstacles are used to design, optimise, and ensure the safety and efficiency of various systems.

Keywords: Darcy-forchheimer, Porous medium, Lorentz force, Channel Flow, Finite Element Method.

AMS Classification Code: 35Q30, 76M10, 35Q35, 76W05, 76D05

1. INTRODUCTION

The study of fluid flow around obstacle arrays is a well-known issue in fluid dynamics, with several industrial applications. Offshore structures include oil and gas pipelines on the seafloor that are impacted by currents and waves, piers and bridge pilings, cooling towers, control rods in nuclear reactors, skyscrapers, chimney stacks, suspension bridges and other structures. Farhany et al. [1] examined the fluid flow problem in an open trapezoidal cavity with an elliptical obstruction under the effect of the Lorentz force and discovered that the flow velocity decreases with increasing Reynolds number and the rate of heat transfer in the system can be increased by adjusting the Reynolds number. MHD unsteady flow around two circular obstacles was studied numerically by Rashidi et al. [2], the aim of the investigation was to analyse the impact of magnetic on the strength of the vortex near the circular obstacles. They found that higher strength of magnetic field is required to attain steady state from transient state flow. Das and Ahmed [3] analysed the impact of magnetic field on the flow behaviour of a Newtonian fluid flowing in an open channel having porous and non-porous region attached adjacent to each other. The impact of Lorentz force on the flow behaviour in a curved channel having solid cylinder was investigated by Raza et al. [4].

2. MATHEMATICAL FORMULATION AND SOLUTION METHODOLOGY

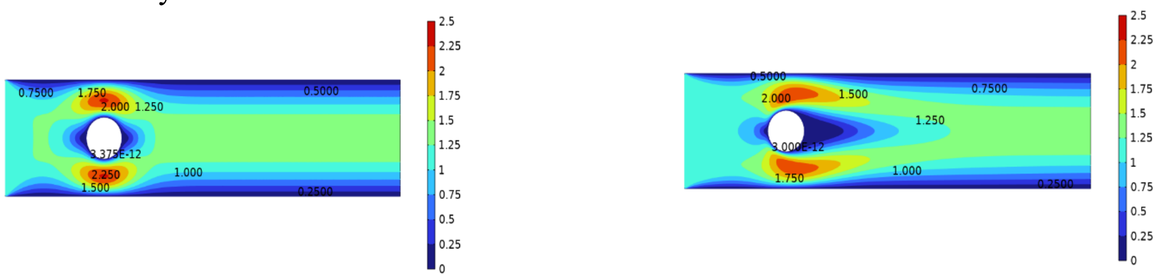
Consider a steady two-dimensional flow of a Newtonian fluid in an open channel having porous material and cylindrical heated obstacle. The cold fluid with temperature T_c enters the channel from the left side of the channel and the outlet is provided at the right side of the channel. The upper and lower walls are assumed to be isothermal and the temperature of the cylinder is assumed to be T_h ($T_h > T_c$). The cylindrical obstacle is assumed to be heated with temperature T_h. Uniform magnetic field of strength B_0 is applied normal to the surface of the channel. The Boussinesq approach is applied to the density variation while the rest of the physical characteristics are assumed to remain constant. The governing equations considered in the analysis are: modified Navier-Stokes equation and energy conservation equation with appropriate boundary conditions.

The dimensionless equations are numerically solved using the Galerkin finite element method (FEM) approach. In the current computational investigation, a nonuniform triangular grid mesh was used. A partial refinement technique has been used at each zone that requires a higher mesh to capture the data, such as around the circular obstacle. This technique has been used to reduce the high computational requirements that are needed in the case of using a uniformly fine mesh.

3. Results and Discussion

A mathematical model is developed to study the impact of the of the magnetic field on heat transfer and flow in an open cavity with porous material and a heated circular cylinder. **Figure 1 (a)** and **(b)** illustrate the impact of Reynolds numbers ($Re = 0.1$) and ($Re = 150$) on the velocity magnitude at $Ha = 1.5$. Physically, the application of a magnetic field resists the motion of the fluid due to a resisting force called the Lorentz force. This force acts oppositely to the direction of flow. While the Reynolds number is the ratio of the inertial force to the viscous force, Augmented values of the Reynolds number result in a decreasing viscous force or an increased inertial force. Physically, $Re < 1$ signifies the dominance of the viscous force over the inertial force. Figure 1 (a) corresponds to the contours of velocity at $Re = 0.1$, in this case, the viscous force is dominant, due to which a higher velocity is reported near the surface of the cylinder. While for $Re = 150$, the higher velocity region extends towards the outlet due to a higher inertial force, as depicted in **Figure 1 (b)**. **Figure 2 (a)** and **(b)** illustrate the impact of Reynolds numbers ($Re = 0.1$ and $Re = 150$) at $Ha = 100$. The augmented values of Ha resulted in the creation of a larger lower velocity region near the circular obstacles due to the higher resistive force.

The implication of Reynolds number $Re = 0.1$ and $Re = 150$ on the isothermal contours has illustrated in **Figure 3 (a)** and **(b)**. At higher Reynolds number, flow tends to become turbulent, enhancing mixing due to which the temperature gradients within the fluid degrades. As a result, the temperature distribution becomes more uniform across the flow. In **Figure 3 (b)** it is observed the temperature of the heated cylinder does not spread evenly in the channel, while at lower Reynolds number ($Re = 0.1$), the temperature of the cylinder spreads all over the cylinder.



(a) **(b)**

Fig. 1: (a) Impact of $Re = 0.1$; (b) $Re = 150$ on velocity magnitude at $Ha = 1.5$.

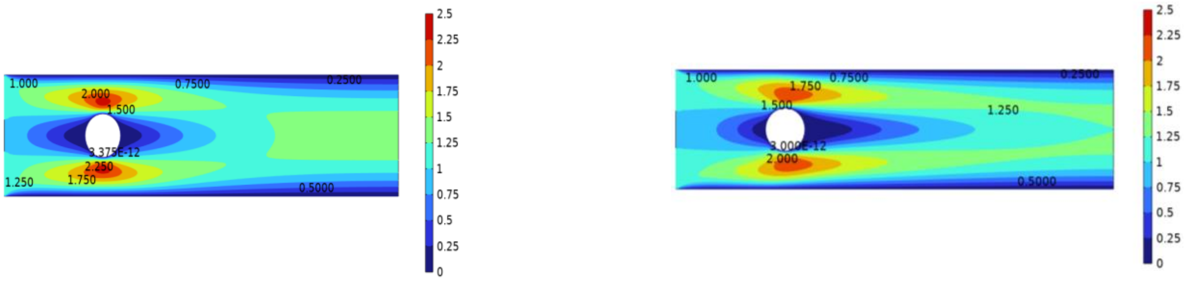


Fig. 2: (a) Impact of $Re = 0.1$; (b) $Re = 150$ on velocity magnitude at $Ha = 100$.

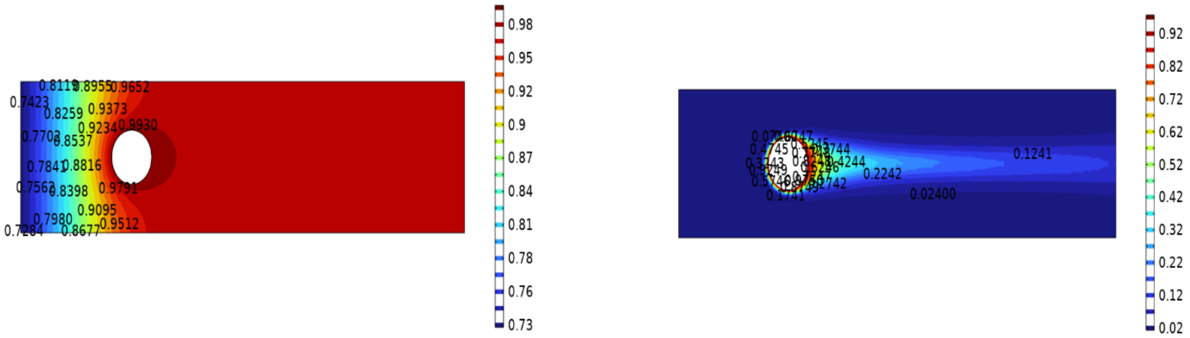


Fig. 3: (a) Impact of $Re = 0.1$; (b) $Re = 150$ on isothermal contours at $Ha = 100$.

4. CONCLUSION

The two-dimensional steady flow of a Newtonian fluid in an open channel with a porous matrix and a heated cylinder under the influence of Lorentz force has been investigated. The impact of Reynolds number and Hartmann number on flow behaviour has been studied and illustrated with the help of contours. The solution to the flow problem has been obtained by using COMSOL Multiphysics. The key findings of the investigation are as follows:

1. The Reynolds number plays a significant role in the alteration of flow patterns. Higher values of the Reynolds number resulted in the creation of a larger vortex but stronger one near the cylinder.
2. Application of a magnetic field resulted in the decay of fluid velocity, thus creating a larger and weaker vortex near the cylinder.
3. A higher Reynolds number obstructs heat transmission from the surface of the cylinder.

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