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# Unsteady convection heat transfer for a porous square cylinder varying cylinder-to-channel height ratio

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ABSTRACT

The unsteady laminar flow and forced convection heat transfer have been numerically investigated across the porous square cylinder with the heated cylinder bottom at the axis in the channel changing cylinder-to-channel height ratio of 10%, 30%, and 50%. The other parameters include Reynolds number ($50 \sim 250$), Darcy number ($10^{-6} \sim 10^{-2}$), and porosity ($0.4 \sim 0.8$). The pressure drops are also examined for the flow past the porous square cylinder in the channels for all cases. The results indicate that the heat transfer for the square porous cylinder is enhanced as cylinder-to-channel height ratio increases; in particular, the enhancement is more obvious for a higher Darcy number and porosity.


## 1. Introduction

The confined flow configuration at various channel heights is a natural one for heating fluids in many engineering applications. Most of the previous heat transfer studies on channel-confined flow at various channel heights across a square cylinder were done for the forced convection case [1–4]. Sharma and Eswaran [5] showed how the channel-confinement and buoyancy influenced the 2D laminar flow and heat transfer across a square cylinder. Furthermore, forced convection heat transfer in a channel with a porous medium is of considerably technological interest. This is due to the wide range of applications such as LED backlight module cooling system, LED streetlamp cooling equipment, electronic component cooling system, heat exchangers, drying processes, heat pipes, and so on [6–9]. Consequently, there is a need to develop a fundamental understanding of heat transfer phenomena past a square porous cylinder for a channel-confined flow at various channel heights.

Many studies have discussed the characteristics of heat transfer for porous media with various conditions including the Darcy number, porosity, Reynolds number, flow conditions, shape and bodies conditions [10–13]. Huang et al. [14] investigated enhancement of steady-state heat transfer from multiple heated blocks mounted on one wall of a channel by porous covers. Hadim [15] studied steady-state forced convection in a channel with fully and partially porous material, which contained porous layers above the heat sources and was non porous elsewhere. He found that the heat transfer was almost the same as if the channel was totally porous, which was an interesting case since the pressure drop was about 50% lower. They showed that the significant heat transfer augmentation could be achieved through the use of multiple emplaced porous blocks. Wu and Wang [16] investigated the unsteady flow and convection heat transfer for a heated square porous cylinder in a channel. They found that the average local Nusselt number increases as Reynolds number increased; in particular, the increase was more obvious at a higher Darcy number. Oult-Amer et al. [17] analyzed steady-state laminar forced convection cooling of heat generating blocks mounted on a wall in a parallel plate channel. Their results indicated that a significant increase in the mean Nusselt number (up to 50%) was predicted and the maximum temperatures within the heated blocks were compared with the pure fluid case. Jiang et al. [18] solved the problem of steady-state forced convection heat transfer of water and air in plate channels filled with sintered bronze porous media. The convection heat transfer was more intense in the sintered porous plate channels than in non-sintered porous plate channels

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**Nomenclature**

| | |
|---|---|
| $A$ | diffusion matrix of energy equation |
| $B$ | binary function |
| $b$ | height of the cylinder (m) |
| $C_L$ | lift coefficient $[= L/(\rho u_0^2 b/2)]$ |
| $Da$ | Darcy number $(= K/h^2)$ |
| $h$ | channel height (m) |
| $\mathbf{H}$ | pressure gradient matrix |
| $K$ | permeability of the porous material |
| $\mathbf{K}$ | conduction matrix |
| $k$ | thermal conductivity (W/mK) |
| $L$ | lift force per unit length |
| $l$ | channel length (m) |
| $l_D$ | distance from right surface of square porous cylinder to exit plane (m) |
| $l_U$ | distance from inlet plane to left surface of square porous cylinder (m) |
| $\mathbf{M}$ | mass matrix |
| $Nu$ | Nusselt number |
| $\overline{Nu}$ | time-mean Nusselt number $[= \int Nu\,dt/\int dt]$ |
| $p$ | dimensionless pressure $(= p^*/\rho u_0^2)$ |
| $p^*$ | pressure (N/m$^2$) |
| Pr | Prandtl number $(= \nu/\alpha)$ |
| $q$ | heat flux at the bottom surface of the square porous cylinder (=W/m$^2$) |
| Re | Reynolds number $(= u_0 h/\nu)$ |
| $\mathbf{S}$ | diffusion matrix of the momentum equation |
| $t^*$ | time (s) |
| $t$ | dimensionless time $[= t^*/(h/u_0)]$ |
| $T^*$ | dimension temperature (K) |
| $T_0$ | uniform inlet temperature (K) |
| $\widehat{U}$ | intermediate velocity (m/s) |
| $U$ | dimensionless velocity vector components $(U = u/u_0)$ |
| $U$ | $x$-direction dimensionless velocity |
| $u_0$ | uniform inlet velocity (m/s) |
| $u$ | velocity vector |
| $V$ | $y$-direction dimensionless velocity |
| $X$ | dimensionless Cartesian coordinate vector |
| $x^*, y^*$ | Cartesian coordinate |
| $\Delta t$ | dimensionless time increment |
| $\theta$ | dimensionless temperature $[= (T^* - T_0)/(qh/k_f)]$ |
| $\theta_{bw}$ | dimensionless porous cylinder wall temperature |
| $\varepsilon$ | porosity of porous medium |
| $\nu$ | kinematic viscosity of fluid |
| $\rho$ | density of fluid |
| $\Sigma_\alpha$ | surface integration in energy equation |
| $\eta$ | tangential vector |
| $\xi$ | normal vector |

*Superscripts*

| | |
|---|---|
| $n+1, n, n-1$ | $(n+1)$th, $n$th, $(n-1)$th time step |

*Subscripts*

| | |
|---|---|
| p | porous |
| f | fluid |

due to the reduced thermal contact resistance and the reduced porosity near the wall in the sintered channels.

About unsteady vortex flow, Jue [19] used a semi-implicit projection finite element method to solved unsteady two-dimensional flow over a porous square cylinder. He found that as the flow passes a higher permeability cylinder, the vortex shedding occurs later and the shedding period was shorter. Chen et al. [20] numerically investigated the flow past a porous square cylinder based on the stress jump interfacial conditions. Their results indicated that the stress jump interface condition could cause flow instability.

Although the transport phenomena through porous media have been studied, there is little work on unsteady-state convective heat transfer across a porous square cylinder at the axis in the confined channel flow. The purpose of this study is numerically to realize the features of laminar flow across a porous square cylinder with the heated cylinder bottom at the axis in the channel varying cylinder-to-channel height ratio. The numerical method applied here is a semi-implicit projection finite element method which is a powerful numerical method for unsteady incompressible thermal flows [21,22]. This paper investigates how the permeability, porosity, cylinder-to-channel height ratios, and Reynolds number influence the heat transfer under steady-state values and time history of global quantities with vortex shedding involved. The results of this paper may be of interest to engineers attempting to develop thermal control of heat exchangers or electronic devices and to researchers interested in the flow and heat transfer across a square cylinder at the axis in the channel.

## 2. Mathematical formulation

The configuration for the problem in this study is shown in Fig. 1. A two-dimensional, laminar, incompressible, and unsteady flow of a Newtonian fluid past a porous square cylinder with a uniform heat generation mounted on the non- permeable bottom surface is considered here. The channel has a height h and length $l$. The square porous cylinder width is $b$, which is also the dimensionless length scale. The geometric parameters are kept constant at values of $b/b = 1$, $l/b = 20$, $l_U/b = 4$, and $l_D/b = 15$. The fluid enters the channel with uniform velocity and temperature. The flow is modeled by the Darcy–Brinkman–Forchheimer [11] equation in the porous matrix in order to account for inertia and viscous effects. Navier–Stokes equations and energy equation are used for the fluid domain and the thermal field respectively. The following assumptions are used for porous medium [23]. The porous square cylinder is homogeneous and isotropic and completely saturated with a single-phase fluid. The thermo-physical properties of the porous medium are constant, and the effective viscosity equals the fluid viscosity. The effective thermal conductivity of the fluid-saturated porous region is equal to the thermal conductivity of fluid [10].

The dimensionless equations for continuity, momentum, and energy are then expressed as follows:

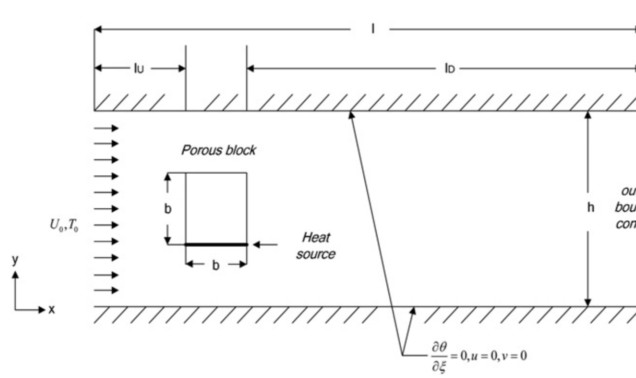


**Fig. 1.** Schematic of the physical domain.