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Technical Note

# Mixed convection heat transfer from confined tandem square cylinders in a horizontal channel

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ABSTRACT

This paper presents a numerical study on the two-dimensional laminar mixed convective flow and heat transfer around two identical isothermal square cylinders arranged in tandem and confined in a channel. The spacing between the cylinders is fixed with four widths of the cylinder and the blockage ratio and the Prandtl number are fixed at 0.1 and 0.7 respectively. The mixed convective flow and heat transfer is simulated by high accuracy multidomain pseudospectral method. The Reynolds number ($Re$) is studied in the range $80 \leqslant Re \leqslant 150$, the Richardson number ($Ri$) demonstrating the influence of thermal buoyancy ranges from 0 to 1. Numerical results reveal that, with the thermal buoyancy effect, the mixed convective flow sheds vortex behind the cylinders and keeps periodic oscillating. The variations of characteristic quantities related to flow and heat transfer processes, such as the overall drag and lift coefficients and the Nusselt numbers, are presented and discussed. Furthermore, the influence of thermal buoyancy on the fluid flow and heat transfer are discussed and analysed.



## 1. Introduction

The flow around bluff bodies has been a subject of considerable interest to the scientists and researchers for several decades due to its numerous engineering applications such as compact heat exchangers, cooling towers, solar collection systems and electronic cooling. The fluid flow patterns are even more complex for multiple square cylinders positioned closed to each other considering their interactions. Furthermore, the flow is strongly affected by the thermal buoyancy, particularly in the cases of low velocity flow and large temperature difference between the bodies and the ambient fluid. In these cases, the thermal buoyancy effect is characterized by the dimensionless parameter Richardson number, which represents the strength of free convection in comparison with the forced convection. Therefore, a large number of investigations on the thermal buoyancy affected flow and heat transfer from circular and square cylinders, involving various computational domains, configurations and parameter ranges, have been performed.

Focusing on the aiding or opposing air thermal buoyancy effect, the flow and heat transfer over a circular cylinder and a square cylinder are numerically studied by Gandikota et al. [1] and Sharma and Eswaran [2] and Sharma et al. [3] respectively. The effects of other parameters such as blockage ratio $B$ [4], nanofluids [5], turbulent flow [6] are investigated numerically. Sarkar et al. [7] numerically studied the influence of cylinders' location on the flow and heat transfer in unconfined vertical medium. For the two cylinders in tandem arrangement in a vertical channel, the steady mixed convective flow around the cylinders with the fixed spacing of four widths of cylinder dimension and blockage ratio $B = 0.25$ is numerically studied by Chatterjee [8], while the spacing effect on the flow is investigated by Lu et al. [9]. The mixed convective flow over multi cylinders is numerically performed by Chatterjee et al. [10]. The main conclusions of these investigations can be summarized as that the aiding buoyancy suppresses the flow separation while the opposing buoyancy facilitates the flow separation.

For the cross thermal buoyancy effect, it has been of a hot topic for the researchers. Without the confine of channel, i.e. in the unbounded medium, Biswas and Sarkar [11] investigated the cross thermal buoyancy effect on the vortex shedding process over a circular cylinder. Sarkar et al. [12] simulated the unsteady nanofluids flow across a circular cylinder at two Richardson numbers 1 and −1. Chatterjee and Mondal [13] simulated the mixed convective flow past a square cylinder for $5 \leqslant Re \leqslant 40$, $0 \leqslant Ri \leqslant 2$ and $Pr = 0.7$. Subsequently, Chatterjee and Mondal [14] studied the flow around tandem square cylinders with various spacing ratios as $50 \leqslant Re \leqslant 150$; Chatterjee and Raja [15] investigated the flow over an in-line row of square cylinders. Within the confine of a horizontal channel, the effects of Richardson number [16], Prandtl

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**Nomenclature**

| | |
|---|---|
| $B$ | blockage ratio, $d/H$ |
| $C_d$ | drag coefficient, $2 \times \left(\int_A^B p dy - \int_C^D p dy\right) + 2/Re \left(\int_B^C \partial u/\partial y dx + \int_A^D \partial u/\partial y dx\right)$ |
| $C_l$ | lift coefficient, $2 \times \left(\int_A^D p dx - \int_B^C p dx\right) + 2/Re \left(\int_C^D \partial v/\partial x dy + \int_A^B \partial v/\partial x dy\right)$ |
| $C_p$ | pressure coefficient, $2p$ |
| $d$ | width of cylinder |
| $\mathbf{e}$ | unit vector, (0, 1) |
| $g$ | gravitational acceleration |
| $G$ | spacing between cylinders |
| $Gr$ | Grashof number, $g\beta\Delta\theta d^3/v^2$ |
| $h$ | local heat transfer coefficient |
| $H$ | width of computational domain |
| $k$ | thermal conductivity of fluid |
| $n$ | index of iteration |
| $N$ | total number of iterations in one period |
| $Nu$ | overall Nusselt number |
| $Nu_l$ | local Nusselt number, $hd/k = -\partial\theta/\partial\mathbf{n}$ |
| $\mathbf{n}$ | unit normal vector |
| $p$ | dimensionless pressure |
| $Pr$ | Prandtl number, $v/\alpha$ |
| $Re$ | Reynolds number, $U_{max}d/v$ |
| $Ri$ | Richardson number, $g\beta\Delta\theta d/U_{max}^2 = Gr/Re^2$ |
| $t$ | dimensionless time |
| $u$, $v$ | dimensionless velocity components |
| $U_{max}$ | the maximum velocity at the inlet |
| $\mathbf{u}$ | velocity vector, ($u$, $v$) |
| $x$, $y$ | directions of Cartesian coordinate |
| $X_d$ | downstream distance |
| $X_u$ | upstream distance |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | thermal diffusivity of fluid |
| $\beta$ | coefficient of volume expansion |
| $\nu$ | kinematic viscosity of the fluid |
| $\theta$ | dimensionless temperature |
| $\tau$ | pseudo time |

*Subscript*

| | |
|---|---|
| rms | root-mean-square |

*Superscript*

| | |
|---|---|
| $\bar{}$ | period averaged |

number [17] and power-law fluid [18] are numerically performed for the mixed convection flow around a single square cylinder. Moreover, for the tandem square cylinders, Chatterjee and Amiroudine [19] studied the steady mixed convective flow at four widths cylinder-to-cylinder spacing in horizontal channel with the following conditions: $1 \leqslant Re \leqslant 30$, $0.7 \leqslant Pr \leqslant 100$, $0 \leqslant Ri \leqslant 1$ and $B = 0.1$.

From the above literatures, it can be summarized that only the one numerical investigation [19] has considered the cross buoyancy effect on the flow around tandem square cylinders in a horizontal channel, moreover, the flow is steady and the inlet flow is uniform. However, to the authors' best knowledge, no open report has focused on the unsteady flow around tandem square cylinders and heat transfer in confined space, which represents numerous equipments of similar configuration used in energy conversion and transportation environments. Acknowledging the theoretical and engineering importance of this issue and the scarceness of related investigations, this paper presents a comprehensive study on the mixed convective flow and heat transfer over tandem square cylinders in horizontal channel with high accuracy multidomain pseudospectral method. The blockage ratio and Prandtl number are fixed at $B = 0.1$ and $Pr = 0.7$ respectively, while the Reynolds number $80 \leqslant Re \leqslant 150$ and the Richardson number $0 \leqslant Ri \leqslant 1$.

## 2. Mathematical model and numerical methods

### 2.1. Governing equations and boundary conditions

The non-dimensional governing equations for the two-dimensional incompressible mixed convection with Boussinesq approximation can be expressed in the following forms.

$$\nabla \cdot \mathbf{u} = 0$$
$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla p + Re^{-1}\nabla^2\mathbf{u} + Ri \times \theta\mathbf{e}$$
$$\frac{\partial \theta}{\partial t} + (\mathbf{u} \cdot \nabla)\theta = (Re \times Pr)-^{1}\nabla^2\theta \quad (1)$$

The reference variables used in the nondimensionalization are: the cylinder width $d$, the maximum inlet velocity $U_{max}$, the reference pressure$\rho U_{max}^2$, and time $d/U_{max}$.

Fig. 1 shows the computational domain and the employed boundary conditions. The upstream and downstream distances are selected as $X_u = 5d$ and $X_d = 15d$ respectively, according to the articles [14,19]. The lateral distance between the top and bottom lateral boundaries is $H = 10d$ (blockage ratio $B = 0.1$) and the spacing between the cylinders is fixed at $G = 4d$. The boundary conditions are described as follows.

At the inlet boundary, $u = 1 - (1 - (2y/H))^2$; $v = 0$; $\theta = 0$.

At the outlet boundary, $\partial u/\partial x = 0$; $\partial v/\partial x = 0$; $\partial\theta/\partial x = 0$.

At the lateral boundary, $u = 0$; $v = 0$; $\partial\theta/\partial y = 0$.

On the surface of the square cylinders, $u = 0$; $v = 0$, $\theta = 1$.

The pressure at the inlet boundary follows homogeneous Neumann condition ($\partial p/\partial \mathbf{n} = 0$), while the Dirichlet condition ($p = 0$) is applied at the outlet. On the wall boundaries, the pressure is determined by setting the second normal derivative to zero ($\partial^2 p/\partial \mathbf{n}^2 = 0$).

### 2.2. Discretization and solution method

The spatial discretization is performed by the high accuracy multidomain Chebyshev pseudospectral method [20–26]. The whole domain is first decomposed into 15 subdomains

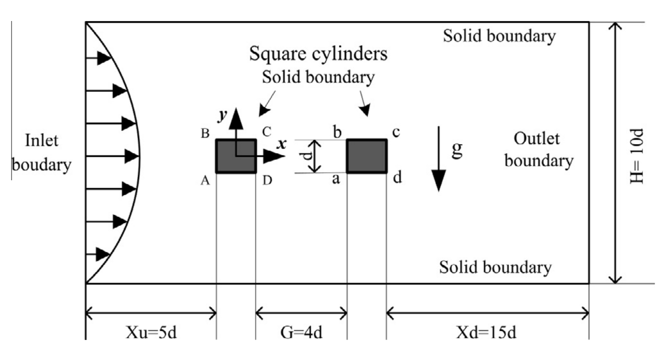


**Fig. 1.** Schematic diagram of the computational domain and boundary conditions for the mixed convective flow around tandem square cylinders in a horizontal channel.