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Letter

Numerical investigation on convective heat transfer over two heated wall-mounted cubes in tandem and staggered arrangement

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HIGHLIGHTS

- Laminar convective heat transfer over two heated wall-mounted cubes is investigated.
- Different streamwise and spanwise distances between two cubes in different Reynolds number is studied.
- The finite-volume method is employed to solving the equations.

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ABSTRACT

In this study, laminar convective heat transfer over two heated wall-mounted cubes is investigated. Two cubes, which are under constant heat flux, are placed in different tandem and staggered arrangements on a base plate. This problem is studied for different streamwise and spanwise distances between two cubes in different Renolds number (*Re*), by using finite-volume method. Effects of these parameters are considered on flow and heat transfer characteristics. The results show that the temperature distribution is strongly dependent on flow structure and varies with any change of flow pattern in different arrangements of cubes. In addition, it is observed that the drag coefficient, which is influenced more by pressure forces, in staggered arrangement, is greater than tandem arrangement. Results show that by increasing the spanwise distance the amount of mean Nusselt number (*Nu*) of Cube 2 becomes the same as Cube 1.

Convective heat transfer over wall-mounted cubes is one of applied issues in different fields of engineering. The main applications of this issue are electronic components cooling, flow in heat exchangers, and computation of heat losses at exterior building walls by atmospheric airflow, especially at power plant buildings. Hence, researchers considered study of flow and heat transfer in this geometry as an appropriate model of previously mentioned real examples. There are various experimental and numerical studies in this case. Most of these studies has been surveyed the flow and heat transfer around a single cubic obstacle [1-4]. The main and particular characteristic of flow in this typical geometry is formation of three-dimensional vortices around the cube. The obstacle in the route of the flow creates an adverse pressure gradient, which cause flow separation in upstream of the obstacle. This separated flow appears vortices that wrap around the obstacle and form a horseshoe vortex region. The flow which is conducted over the top surface of the cube, rebounds to the base plate, and creates hairpin vortices in the downstream wake region. Moreover, there are some small vortices in the vicinity of two lateral walls of the cube.

In this geometry, thermal boundary layer is strongly related to local flow structure. Morrise and Garrimella [1] investigated experimentally and numerically the temperature distribution around a cubic obstacle in fully developed water channel flow for $500 \le Re \le 1500$ (laminar) and $10000 \le Re \le 25000$ (turbulence), *Re* is Reynolds number. They observed an increasing wake temperature by increasing *Re* in laminar flow and sub-

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sequently decreasing buoyancy effects. However, in turbulence conditions any influence on the flow structure and wake temperature was not studied.

A numerical study of 2D forced convective flow around a warm square was performed by Yang and Vafaei [2]. In this study, the square was under constant heat flux and placed on a channel wall in a flow with *Re* in the range of 200–2000. The effects of different variables such as square walls height and width and *Re* on flow field and heat transfer were discussed. The results show that the shape and size of obstacles can make an impressive influence on the flow and heat transfer. Moreover average Nusselt number (*Nu*) increases by raising *Re*. Nakamara et al. [3] detailed in an experimental investigation the flow and heat transfer characteristics around a 3D cube on a plate for $4.2\times10^3 < Re < 3.3\times10^4$. By measuring the temperature of the cube surfaces and the base plate, they observed that local heat transfer characteristics are strongly related to the flow properties especially in the horseshoe vortex region. Wang and Chiou [4] described mass-heat transfer around a heated cube in the developed channel flow. They showed that a little change in *Re* changes Sherwood number (*Sh*) distribution on the obstacles surface remarkably. Recently, Rossi and Iaccarino [5] studied in a numerical investigation plume meandering in passive scalar dispersion downstream of a wall-mounted cube. In addition, there are some studies about flow structures around different shapes of obstacles such as semi-ellipsoid obstacle [6], finite wall-mounted square cylinder [7], and a hemisphere wall-mounted [8]. There are some studies about investigations of flow and heat transfer around multiple cubes and most of them focus on tandem arrangement [9-12]. Just a few of them are about staggered arrangement; however, such an arrangement is more similar to real patterns like electronic component boards. Undoubtedly, the flow structure in the cases that are encountered two obstacles is more complicated than one. This is due to the blocking of the first cube (Cube 1) downstream flow by the second cube (Cube 2) and its deviation from the preferred route. So the flow structure is directly related to streamwise and spanwise distances between two cubes. Meinders and Hanjalic [13] in a comprehensive experimental study, described convective heat transfer around two wall-mounted cubes in both tandem and staggered arrangements and in various streamwise and spanwise distances in a turbulent flow. The results show that there are various distributions of heat transfer coefficient on both cubes' surfaces in different arrangements. Flow and heat transfer distribution changes from symmetric state in tandem arrangement to asymmetric state in staggered one. Heat transfer around staggered arrangement of cubic obstacles was simulated in three rows for laminar flow with $100 < Re < 500$, $Pr = 0.7$ by Nakajima et al. [14], *Pr* is Prandtl number. They observed heat transfer coefficient at different surfaces of cubes, which are all under constant heat flux increase with raising *Re*. Flow characteristics in downstream become unsteady at $Re = 400$, however, it is not much observable. Average *Nu* at cubes in the first row is higher than ones in the second row. It gets the minimum value at cubes' surfaces in the third row, because they are placed in thermal boundary layer of leading cubes. The effect of distance between two heated cubes in tandem arrangement in 2D laminar flow was studied by Farhadi et al. [15]. That study showed an average *Nu* increasing by raising streamwise distances. Eslami et al. [16] studied 3D laminar flow around two wall-mounted cubes in various streamwise and spanwise distances. They detailed the effect of different parameters in vortex structures, separation and reattachment points, but did not do any research on the

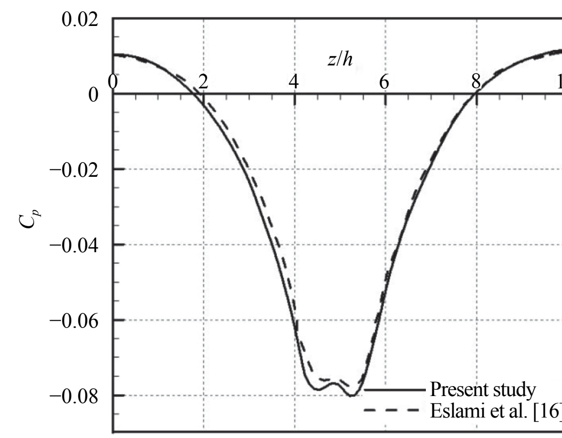

Fig. 1. Comparation of pressure distribution C_p in the present study and the study reported by Eslami et al. [16] on $y = 0.5h$ line, at $x = 0.5h$ plane downstream of Cube 1 in $L = h$ case of tandem arrangement and $Re = 200$.

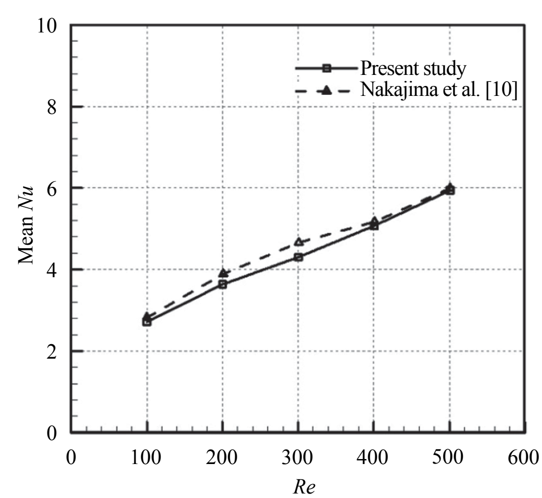

Fig. 2. Comparation of the diagram of mean *Nu* at different *Re* on Cube 2 in $L = 4.5h$ case of tandem arrangement in the present study and the study reported by Nakajima et al. [10]

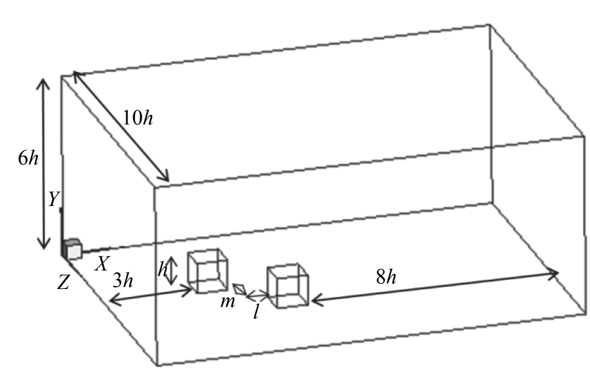

Fig. 3. Geometry of cube arrangement.