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Local heat transfer enhancement around a matrix of wall-mounted cubes using passive flow control: Large-eddy simulations

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ABSTRACT

The purpose of the research reported in this paper was to investigate the influence of attaching vortex generators (VGs) to a surface of a heated cube on flow structures and heat transfer using large-eddy simulation (LES). The cube was located in the middle of a matrix of similar cubes. Two kinds of vortex generators were investigated. The first kind was a simple rib extending in the span-wise direction (VG1) while the second consisted of several of small cubes (VG2). The flow and heat transfer around a cube with vortex generators were compared with the flow and heat transfer around a smooth cube. The LES results showed that the flow in the boundary layer around the cubes with VGs is more turbulent and unsteady than the flow around the smooth cube. More complex structures are generated close to the surface of the cube with VGs, resulting in a considerable increase in the heat transfer coefficient. Local overheating was found behind the rib-shape VG while even distribution of temperature was observed over the surfaces of the cube in the VG2 case. There was a 14% and 17% global increase in the heat transfer coefficient in the VG1 and VG2 cases, respectively.

1. Introduction

When electronic components are attached to a printed circuit, they act, under concentrated heat dissipation conditions, as a strong source of heat which might cause local overheating. It is generally believed that local overheating of integrated circuits (IC) is the major cause of the technical failure of electronic equipment (Meinders and Hanjalić, 2002). Hence, finding a way to efficiently remove heat from these components is crucial for ensuring reliable long-term operations. The production and development of new generations of power electronic components are controlled by an efficient design that removes the heat generated by these components. In general, the heat removal from an integrated circuit is very dependent on the flow structure around it (Niĉeno et al., 2002).

The electronic component is a bluff body and the flow around it is dominant with separation and recirculation regions. The flow around an integrated electronic circuit can be approximated to be similar to that around a cube mounted on a surface. Previous investigations of the flow around a single surface-mounted cube found that different kinds of flow instabilities give rise to different flow structures around the cube. At very low Reynolds numbers, the flow is laminar everywhere around the cube. The flow might separate from the sides of the cube to form separation bubbles that might also be laminar. The flow inside these bubbles circulates, and it might be trapped in place if the bubbles are steady. At a certain critical Reynolds number, the shear layer's instability between the separation bubbles and the exterior fluid (the so-called Kelvin–Helmholtz flow instability) precedes the transition to turbulence and turbulent flow onsets downstream of the separation region. This flow instability is responsible for shedding vortex tubes in a regular fashion to the wake flow behind the cube, distortion of large-scale vortices, production of small-scales and eventually transition from laminar to turbulent flow in the wake. Beyond this critical Reynolds number, the flow is fully turbulent behind the cube. There is also a flow instability in the wake flow behind the cube, which is associated with the shedding of large-scale vortices from the recirculation region to the far wake flow. This flow instability is controlled by the flow Reynolds number and hence the high frequency mode in the shear layers between the recirculation region and the surrounding fluid. The dominant shear layers around the cube make the flow structures very complicated.

Different numerical methods have been used in the past to study the flow around a single cube mounted on a surface. Krajnović and Davidson(2000, 2002) used large-eddy simulation to investigate the flow structures around a surface-mounted cube in fully developed channel flow. In their simulations, the Reynolds number was 4×10^4 based on the incoming mean bulk velocity and the height of the cube. They found that the flow separates from the surface of the cube on the lateral and on the top-side faces. They visualized a horse shoe vortex attached to the mounting surface.

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Cone-like vortices are formed on the top-side face and an arch-like vortex was visualized in the wake flow. These complex flow structures were obtained using different flow simulations. The results were in good agreement with the experimental results of Martinuzzi and Tropea (1993). Yakhot et al. (2006) studied the same cube using direct numerical simulation (DNS) and they observed similar flow structures.

The turbulent flow around multiple cubes is even more complicated. The wake structures from one cube interact with the structures of the next cubes. The flow is characterized by the distance between the cubes and their arrangement in the matrix. The complex topology of the cubes induces the flow to separate and recirculate locally between the mounting surface and the cubes. The shedding of the large-scale structures in the wake flow depends mainly on the Reynolds number of the flow and on the separation distance between the cubes. The flow structures, however, are highly unsteady and three-dimensional.

At present, there are remarkably few studies on the convective heat transfer around a three-dimensional object (Nakamura et al., 2003). Meinders and Hanjalić (1999) experimentally investigated the influence of the relative position of the obstacle on the convective heat transfer from a configuration of two wall-mounted cubes located in a fully developed turbulent channel. They found that the crucial parameter that influences the flow pattern and, consequently, the heat transfer is the longitudinal spacing between the cubes. Meinders and Hanjalić (2002) also carried out experiments in a matrix of equidistant cubes mounted on one of the walls of a plane channel. Their investigation provided reference data on flow and heat transfer relevant to electronics circuitry. They studied an internally heated cube that was placed in the middle of a matrix of identical but non-heated cubes; all were mounted on a constant temperature channel wall (see Meinders and Hanjalić, 2002; Nicěno et al., 2002). The surrounding cubes on the matrix ensured a fully developed flow with periodic boundary conditions. Because of the well-known boundary conditions and their computational simplicity, their case and data were considered as a basis for many computational fluid dynamic simulations made to gain insight into the physics of the flow structures and heat transfer. Verstappen et al. (2000) made a numerical simulation of the turbulent flow and heat transfer in a channel with surface-mounted cubical obstacles without using any turbulent models. They used a $64 \times 64 \times 32$ grid to make a DNS in a domain consisting of one cube mounted at the middle of the matrix. They used a fourth-order discretization scheme. The DNS flow profiles agreed well with the available experimental data. The time-averaged surface temperature agreed well with the experimental data except for at the edges of the cube, where differences up to 10 % exist. Cheng et al. (2003) and Zhong and Tucker (2004) used the experimental data of Meinders and Hanjalić (2002) to compare different simulation techniques (large-eddy simulation (LES), standard k–ϵ Reynolds-averaged Navier–Stokes (RANS) and k–l based hybrid LES/RANS).

Despite the many attempts that have been made to understand the physics of the flow around single or multiple cubes, there have been very few attempts to find a way to enhance heat transfer around the cubes.

In this paper, we investigate the enhancement of heat transfer by altering the turbulent boundary layer. This is done by generating small vortices on the surface of the cube using vortex generators (VGs). Two types of VGs were investigated in this paper. The first type is a simple rib while the second consists of 15 small cubes attached to the top and lateral sides of the large cube. The two vortex generators are mounted at the same position on the top and the lateral faces of each cube in the matrix. The Reynolds number of the flow is 13,000, based on the incoming bulk velocity and the height of the channel. The purpose of the present work is to employ LES to investigate the influence of the vortex generators on the flow structures and the local heat transfer coefficient.

2. Physical model

The physical model is a single heated cube placed in the middle of an equidistant matrix of surface-mounted cubes as shown in Fig. 1. The matrix of cubes is placed on one of the vertical walls of a two-dimensional channel. The matrix consists of a total of 25×10 cubes in the stream-wise and span-wise directions, respectively. The length of the side of cubes, H, is 15 mm. The height of the channel is 51 mm (3.4H). The distance between the centerlines of any two successive cubes in both the stream-wise and span-wise directions is 60 mm (4H). The vortex generators used here are described in Section 5 of this paper.

3. Governing equations

Since the flow is unsteady, an unsteady numerical method for the prediction of the flow and heat transfer is needed. Direct numerical simulation (DNS) is computationally demanding due to the very large number of nodes needed to resolve all the flow scales. The flow around a cube is a typical bluff body flow that is dominated by large separation and recirculation regions. Previous investigations of the flow around bluff bodies showed that Reynolds-averaged Navier–Stokes (RANS) methods give poor results compared to large-eddy simulations (LES). In this paper, LES was employed to solve for both the velocity and temperature fields. In LES, the large-eddies are computed directly and the influences of the small-scale eddies on the large-scale eddies are modeled. The incompressible continuity, momentum and energy equations are filtered using an implicit spatial filter. The resulting filtered equations are:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j}(\bar{u}_i\bar{u}_j) = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu\frac{\partial^2 \bar{u}_i}{\partial x_j x_j} - \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

and

$$\frac{\partial \overline{T}}{\partial t} + \frac{\partial}{\partial x_j}(\bar{u}_j\overline{T}) = \frac{\nu}{Pr}\frac{\partial^2 \overline{T}}{\partial x_j x_j} - \frac{\partial h_j}{\partial x_j}. \tag{3}$$

Here, $\bar{u}_i$, $\overline{P}$ and $\overline{T}$ are the resolved filtered velocity, pressure and temperature, respectively. Owing to the non-linear terms in the momentum and heat equations, the filtered-out small-scale eddies feed back their effects on the large-scale motion through sub-grid scale stresses and heat fluxes. These influences appear as extra terms in the filtered equations, i.e. τ_{ij} and h_j. The sub-grid scale (SGS) stresses, $\tau_{ij} = \overline{u_i u_j} - \bar{u}_i\bar{u}_j$, represent the influence of the unresolved scales, smaller than the filter size, on the resolved ones. The sub-grid heat fluxes, $h_j = \overline{u_j T} - \bar{u}_j\overline{T}$, represent the influence of the unresolved heat fluxes on the resolved ones.

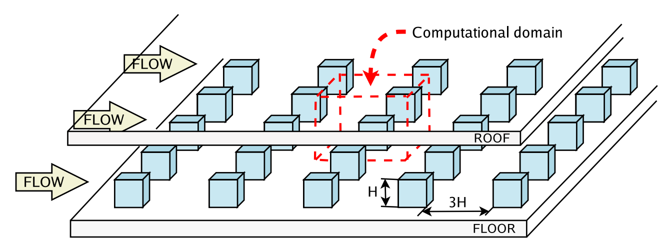

Fig. 1. Matrix of cubes mounted in a channel.