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Wall-mounted perforated cubes in a boundary layer: Local heat transfer enhancement and control

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ABSTRACT

A passive convective heat transfer enhancement device based on perforated obstacles is proposed. The perforation crosses the obstacle from the flow-facing side to the rear side. In this configuration a jet is delivered from the obstacle perforation, thus changing the topology of the wake behind the obstacle. Measurements of the convective heat transfer over a flat plate equipped with perforated wall-mounted cubes are carried out using infrared thermography. Flow fields measurements are performed with Particle Image Velocimetry to address the effect of the perforation (and of the jet issuing from it) on the wake topology and on the heat transfer distribution. A modal analysis is carried out with Proper Orthogonal Decomposition to extract the coherent structures organization and the modifications induced by the perforation of the obstacle. When comparing the results of the perforated cubes with those of a solid cube, it can be observed that perforated obstacles offer a simple solution to obtain a localized increase of the convective heat transfer when the perforation crosses the obstacle creating a jet directed towards the wall. This is obtained at the expenses of a reduced space-averaged heat transfer rate due to a 'lift-up' of the recirculation bubble past the obstacle, which postpones the flow reattachment and reduces the velocity of the reattaching flow. Nevertheless, in case of large perforation angles (thus jet issuing with larger angle with respect to the streamwise direction) this penalty is significantly reduced, providing a local gain in terms of heat transfer rate with almost the same overall heat transfer performances as a solid obstacle.

1. Introduction

The need of cooling objects in compact spaces is fostering the development of advanced heat transfer enhancement strategies since decades. In several fields, such as electronic packaging and turbomachinery, the cooling capabilities are a technology driving factor (see, e.g. [1,2]).

A common solution to enhance the convective heat transfer of a main flow parallel to a wall consists of using vortex generators. The techniques employed to develop such vortices can be bundled into two main groups, according to the definition by Webb [3]: active and passive heat transfer enhancement methods. Active heat transfer augmentation refers to mechanisms in which external power is required. Some common examples are surface or fluid vibration or flow injection. On the other hand, passive methods do not require any external source of power: special surface geometries interact 'passively' with the flow, enhancing the convective heat transfer by promoting the formation of secondary flow structures. There is a wide range of passive cooling methods; some of the most frequently used ones are extended surfaces (such as plain fins), swirl flow devices or roughness elements. Even though active techniques allow for a more effective heat transfer enhancement control, their power requirement and complexity, compared to passive ones [4], makes the latter still very appealing for industrial applications such as turbomachinery cooling.

The inclusion of obstacles and roughness elements is widely used in industrial applications, both due to the increased surface for heat transfer by convection and for the generation of secondary flow structures. The effect on the heat transfer enhancement produced by obstacles with different geometries such as cubes, cylinders, diamonds and semi-spheres was studied by Chyu and Natarajan [5]. The flow around the different obstacles is characterized upstream by a horseshoe vortex, with two legs extending downstream on each side of it. Downstream of the obstacle the values of the Nusselt number are lower, due to the formation of a recirculation region, followed by the reattachment of an impinging flow referred to as arch-shaped vortex. In [5], the authors conclude that the cube geometry provides the highest enhancement

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upstream of the obstacle, which is due to the presence of a strong secondary vortex embedded underneath the primary horseshoe vortex. However, downstream of the cube the augmentation is lower than in other configurations (such as the cylindrical or the pyramidal roughness elements). This is due to the flow separation, which leads to a strong recirculation zone immediately downstream of the cube, as well as to a weaker arch-shaped vortex. The region downstream of the cube is characterized by a recirculation zone with relatively lower heat transfer enhancement, followed by the reattachment region. The reattachment of the separated flow from the top surface occurs at a distance of about 2 cube side lengths from the trailing edge of the obstacle, increasing the local Nusselt number *Nu*, as found by Nakamura et al. [6]. Quite similar results are reported for wall-mounted cylinders by Giordano et al. [7] who showed that the length of the separation region is weakly dependent on the cylinder aspect ratio.

In this work, perforated cubes will be used to improve the convective heat transfer augmentation capabilities of a simple cubic obstacle. The concept of perforated roughness elements or obstacles is common in the industry: perforated fins, for example, have been found to be more efficient than solid ones as they not only reduce the flow blockage but also enhance the convective heat transfer [8]. In essence, square section ribs can be idealized as infinite cubes, in which the spanwise dimension is much larger than the other two. Therefore, a better understanding on the mechanics of the passive heat transfer enhancement using a cube as an obstacle can lead to more efficient design for state-of-art cooling systems.

Perforating the cube has two main advantages from the viewpoint of heat transfer augmentation. The first advantage is the expected reduction of the negative impact of the recirculation zone on the convective heat transfer rate; additionally, the maximum Nusselt number attained is expected to be increased with respect to that of the solid cube configuration due to ejection of fluid through the obstacle. The latter is due to the accelerated flow passing through the hole which, if properly shaped, can act locally as an impinging jet in the wall region immediately past the obstacle. The perforation geometry can be used to tune the distance from the trailing edge of the obstacle at which the maximum *Nu* is attained in the downstream region by means of varying the angle of the jet. Moreover, the Nusselt number maximum is dependent on the distance between the nozzle and the surface [9,10], hence, different perforation configurations can result in different Nusselt number distributions. The assessment of the potential of tuning the local maxima of the Nusselt number can open the door for possible new configurations of cube arrays which may improve the present configurations [11].

Jets are usually considered as an active heat transfer enhancement method [3], and they are widely used as cooling mechanisms in industrial applications such as gas turbines [1]. However, in this case no external power is required as a jet is passively formed due to the difference in pressure between the front face and the recirculation zone where the jet is exiting out of the perforation in the cube. Therefore, the beneficial heat transfer aspects of impinging jets can be attained without introducing any other momentum source into the cooling mechanism.

In order to address the heat transfer capabilites of perforated obstacles, experiments are carried out with Infrared (IR) thermography [12]. Additionally, Particle Image Velocimetry (PIV, [13]) measurements are performed to characterize the flow field features to which the heat transfer enhancement is ascribed. The methodology and the experimental setup are described in Section 2. The results are discussed in Section 3. Proper Orthogonal Decomposition (POD, [14]) is used to provide a modal decomposition of the flow field. Finally, the conclusions are drawn.

2. Methodology

The experiments were carried out in the Göttingen type wind tunnel of the Aerospace Engineering Group at the Universidad Carlos III de Madrid. The wind tunnel has a square test section of 0.4 m $\times$ 0.4 m with a length of 1.5 m; it is capable of reaching a maximum speed of 20 m/s with a streamwise turbulence intensity below 1% of the freestream velocity. Both IR thermography and PIV measurements were performed (not simultaneously) in this work; the experimental setups are sketched in Fig. 1.

A splitter plate with a thickness of 10 mm and located at a distance of 0.1 m from one of the lateral walls of the test section was used in the present experimental campaign. In order to obtain a fully developed turbulent boundary layer, a turbulator strip with a height of a 2.4 mm was placed 75 mm downstream of the leading edge. The boundary layer thickness δ_{99} (here defined as the position at which 99% of the freestream speed is attained) on the plate without cubes was characterized using PIV and was determined to be of 4.4 cm at the point were the cubes were placed. The diagnostic plot approach was used to assess that the boundary layer approaching the obstacles was not reminiscent of the inflow conditions [15].

The perforated obstacles, sketched in Fig. 2, have a base cubical shape with a 10 mm side length *L*. Hence, their height is approximately a quarter of the local boundary layer thickness ($L/\delta_{99} \approx 0.23$). A single cube was mounted over a printed circuit board (PCB) flash mounted on the flat plate, parallel to the incoming flow. A 90° bracket was used together with a level when placing the cube in order to ensure a 0° angle of attack. The solid cube is considered as a baseline configuration to compare the performances of the perforated cubes. Nine different straight perforations, described in Table 1, were analyzed: inlet and outlet exit perforations of 2.5 mm diameter were performed at locations z_{in}

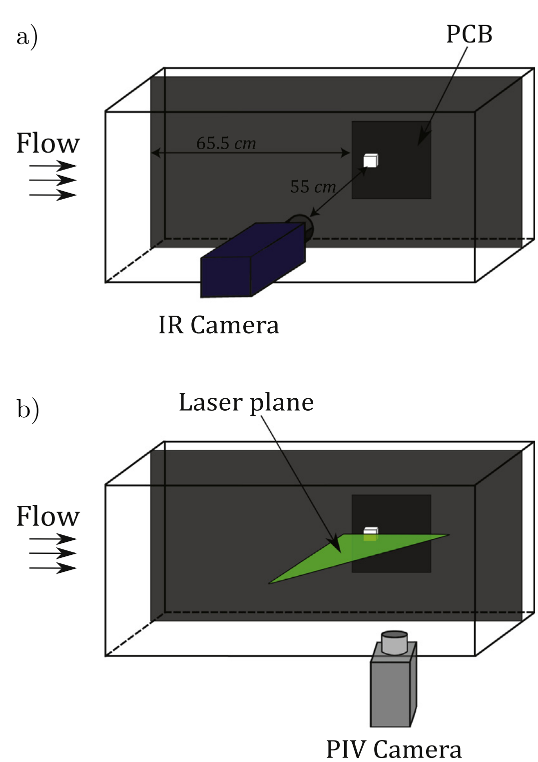

Fig. 1. Sketch of the experimental setup: (a) IR setup for heat transfer measurements, (b) PIV experimental arrangement. IR and PIV measurements were not performed simultaneously.