Summary of the research activity:

Experimental investigation of the flow field in rectangular cooling channels provided with low aspect-ratio pin-fins and flow at low Reynolds number

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Ph.D. thesis discussed on the 26th of May 2009 – Tutor: Prof. Pietro Giannattasio

Objectives

The pursuit of the optimal design of a cooling system requires the maximum heat transfer performance with acceptable coolant pressure losses and the fulfilment of the constraints of the specific application. In particular, modern heat sinks for electronic components or microelectronic circuits are heat transfer devices in which high thermal loads are coupled with important requirements of small dimensions and low noise emissions. These cooling systems are usually composed by rather narrow rectangular channels in which a liquid coolant flows at very low velocity and short pin-fins are used to guarantee high heat transfer performance. These latter devices are installed on the channel walls in order to increase the wet surface and to actively promote the agitation and turbulence of the coolant flow. An efficient use of pin-fins requires a deep knowledge of their impact on thermal and flow fields, but at the present it is quite difficult to find in literature useful information concerning the typical operating conditions of these heat transfer promoters. Moreover, the strong complexity of the flow field that establishes in the cooling channel is challenging also for modern numerical codes, the validation of which is made difficult by the lack of an accurate experimental data-base.

Therefore, the present research activity is aimed at providing a detailed experimental characterization of the flow field around heat transfer promoters of different shape in realistic flow conditions. In particular, the present study analyzes the topology and the dynamics of the separated flow structures that develop around single obstacles with circular, square, rhomboidal and triangular base, characterized by a low aspect-ratio ($AR = height/diameter = h / d = 1.09$) and installed in a narrow channel with rectangular cross-section ($width / height = b / h = 6.67$). Distinctive features are the confinement of the pins at both ends, the low Reynolds number ($Re = U_B\, d/\nu = 800, 1800, 2800$; U_B = *bulk flow velocity in the channel*), the high core flow turbulence intensity and the presence of thick undeveloped boundary layers on the channel walls.

Experimental apparatus and procedure

The experiments have been performed in a test rig (see Fig. 1.A) consisting of a closed circuit that allows an accurate control of both temperature and mass flow rate of the water that feeds the test section. This latter (see Figs. 1.B and 2.A,B) consists of a rectangular channel completely machined out of Plexiglas in order to provide full optical access for the application of the Particle Image Velocimetry (PIV) technique. Its ends are connected by means of flanges to short aluminium ducts having the same internal cross section of the channel. The aluminium ducts enter inside the cylindrical walls of two settling tanks (R1 and R2 in Fig. 1.A) so as to provide inlet and outlet sections characterized by abrupt contraction and expansion, respectively. At the centre of the duct and at a limited distance from the inlet section, different types of obstacles (see Fig. 2.C) can be installed. The obstacles extend over all the height (*h*) of the channel and they have the same characteristic cross-sectional diameter (*d*). The present channel geometry, in particular the obstacles aspect-ratio and the type of the inlet and outlet sections, has been selected in order to reproduce a practical configuration of liquid cooling channels, such as the heat sinks used in the electronic devices.

The investigation of the flow field around the obstacles has been carried out by means of two-dimensional PIV measurements performed in several horizontal and vertical planes located in the symmetry planes of the channel and at different elevations from the lower wall of the duct (see Figs. 2.A,B). The data allowed the three-dimensional flow fields to be reconstructed and the time evolution of the main flow structures to be captured.

Results

In view of the low Reynolds numbers considered, the flow that approaches the obstacle is characterized by thick boundary layers that are still developing on the channel walls. Moreover, due to the perturbations induced by the abrupt channel entrance and the limited entry length, the free stream turbulence intensity is rather high ($Tu \approx 7\%$). These flow conditions do not allow the development of a laminar flow at $Re = 800$ and trigger the flow into transition to a turbulent regime at $Re = 1800$ and 2800.

The characteristics of the perturbed inlet flow have been shown to play a very important role in the development of the separated structures in front of the obstacles, i.e., the horseshoe vortex system produced at the wall-obstacle junctions. In particular, contrary to the expected behaviour from the data in literature for similar geometries and flow regimes, the horseshoes turn out to be perturbed by vorticity bursts from the incoming boundary layers, leading to aperiodical vortex oscillations at $Re = 800$ or to break-away, core fluid inrush and secondary vorticity eruption at the higher Reynolds numbers (see Fig. 3). The latter instabilization process, usually observed at higher flow regimes, has been previously reported in literature to be a particularly effective mechanism of heat transfer enhancement.

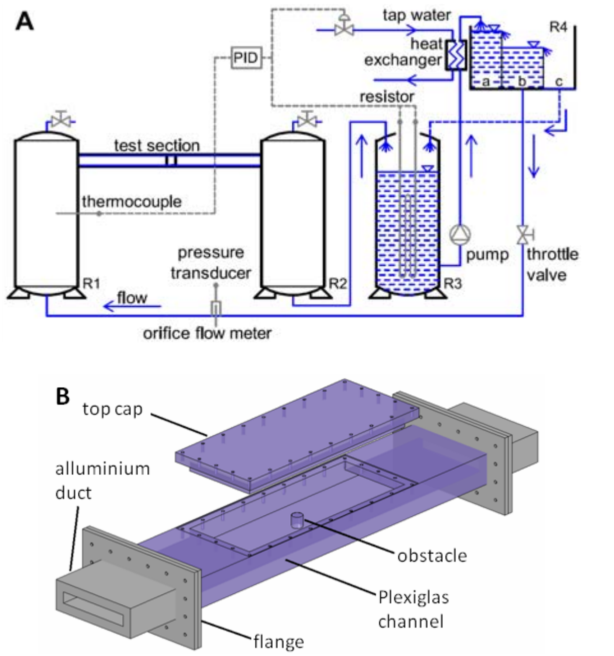

Figure 1: (A) Schematic of the experimental apparatus and (B) view of the test section.

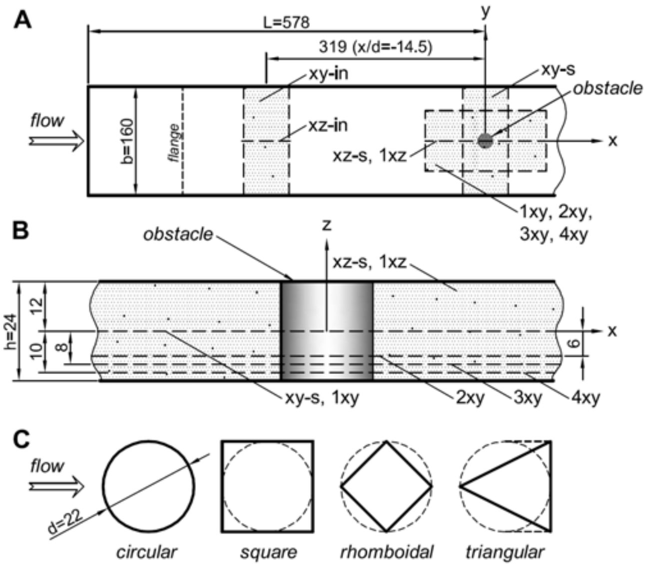

Figure 2: Test section: position of the PIV measurement planes, (A) xy view, (B) xz view; (C) cross-section of the investigated obstacles (measures in mm).

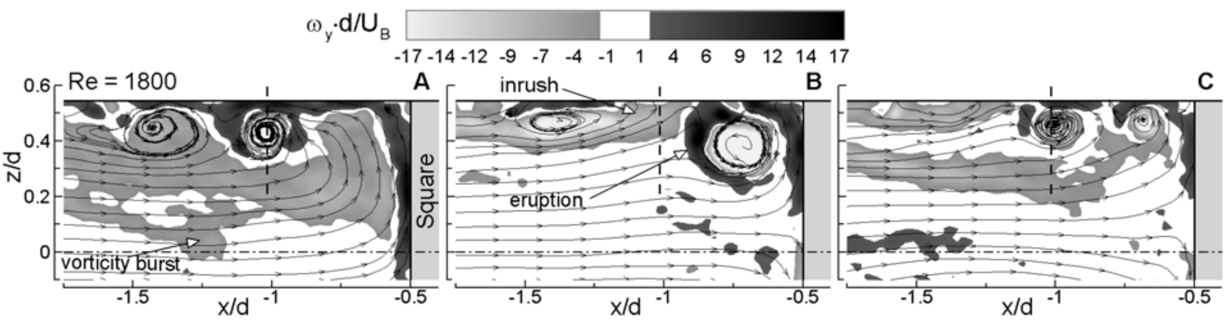

Figure 3: Instantaneous vorticity fields and stream-tracers in the upper half of plane 1xz in front of the square obstacle for $Re = 1800$: (A) $t = 0\,s$, incoming perturbation; (B) $t = 1\,s$, effect of the vorticity burst, (B) $t = 1.25\,s$, break-away of the primary vortex.

In the present investigation, the commented instabilization of the horseshoe vortices is rather strong in front of the square pin. In the case of the circular obstacle the vortex dynamics is similar but the lower blockage effect of the pin leads to a decrease of about 30-40% in the vortices size and induced velocity fluctuations. Concerning the rhomboidal and triangular pins, which exhibit a sharp edge on the frontal surface, the reduction in the intensity of the separated structures is even more evident and well defined cases of break-away and inrush have been documented only for the rhomboidal pin at $Re = 1800$ and 2800.

Because of the low aspect-ratio, the wake downstream of the obstacles turns out to be highly three-dimensional and influenced by streamwise oriented vortical structures produced at the wall-obstacle junction. From the time averaged point of view, the recirculation bubbles are affected by a span-wise mass transport from the channel walls to the horizontal symmetry plane (see Fig. 4). The fluid comes back to the walls along the obstacle rear surface and inside the shear layers. This behaviour is rather evident at $Re = 800$ where the span-wise flow extends over all the channel height.

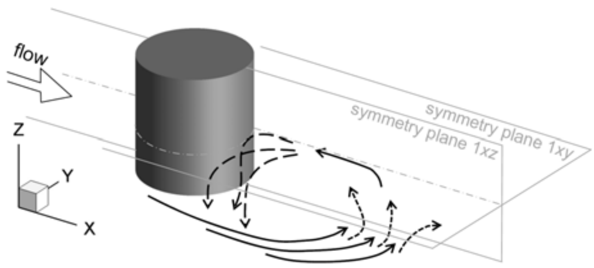

Figure 4: Mass transport mechanism downstream of the obstacle.

When looking at the time evolution of the flow structures in the wake another interesting behaviour is observed. The combination of span-wise flow, low Reynolds number and high free stream turbulence gives rise to an unexpected competition between two opposite vortex shedding modes. The first one, regular, is revealed by a typical alternate vortex shedding (see Figs. 5.A,C), while the second one, irregular, is characterized by the development of intense secondary structures and the decoupling of the shear layers (see Fig. 5.B). At the lowest flow regime this latter phenomenology is by far the main one for all the obstacles (see Fig. 6). At increasing Reynolds number the persistence of the irregular shedding mode reduces, but with a trend strongly dependent on the obstacle shape. In particular, the rhomboidal pin sheds regular vortices in most cases already at $Re = 1800$, while the square pin is almost insensitive to the change in the Reynolds number.

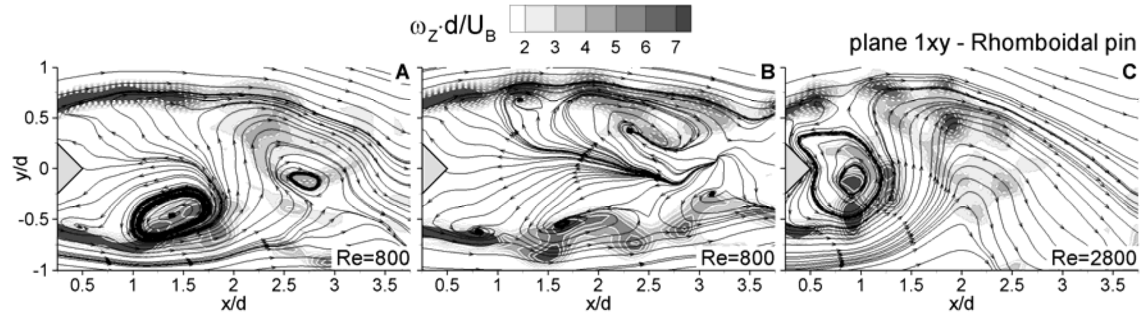

Figure 5: Instantaneous flow fields in plane 1xy downstream of the rhomboidal pin at $Re = 800$ and 2800: examples of regular (A and C) and irregular (B) vortex shedding. Dashed contours denote negative vorticity.

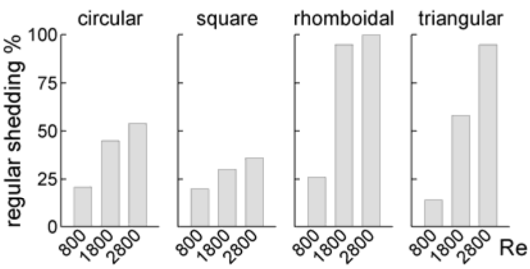

Figure 6: Percentage of regular shedding events.

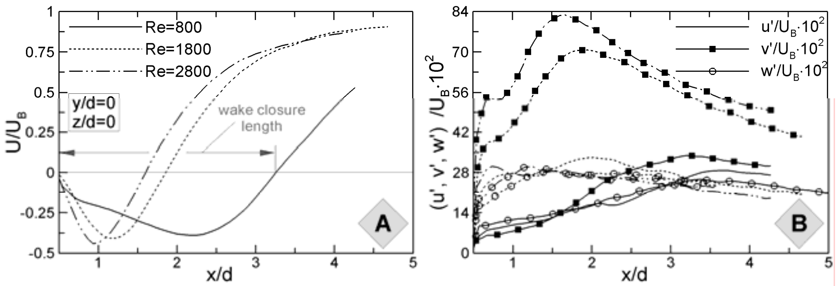

Figure 7: Profiles of (A) mean streamwise velocity and (B) velocity fluctuations along the channel axis for the rhomboidal pin.

These strong differences in the vortex shedding mode have important effects on the time averaged characteristics of the wake (see the example in Fig. 7). In particular, at $Re = 800$, where all pins shed predominantly irregular vortices, all the observed recirculation regions extend considerably downstream, very low values of velocity fluctuations are measured inside the wakes and no dominant peak is found in the frequency spectrum of the fluctuating velocity. On the contrary, when the regular shedding prevails, the wake extension is dramatically reduced, very high velocity fluctuations are found in the cross-wise direction and the dominant frequency of the vortex shedding is in agreement with the one expected for similar obstacles at the same Reynolds number but for higher aspect-ratios.

Conclusions

A detailed and accurate experimental investigation of the flow structures around single heat transfer promoters of different shape has been performed. The peculiar geometrical and flow conditions, such as low aspect-ratio, low Reynolds number and high free stream turbulence, resemble the real working conditions of practical applications. These conditions have been shown to give rise to unexpected or unusual flow structures that are not predictable from the present literature, which mostly refers to stereotyped flow configurations. In particular, a strong instabilization of the horseshoe vortex system has been observed in front of the square and the circular pins already from $Re = 1800$. Downstream of all the obstacles at $Re = 800$ the wake is highly three-dimensional and an irregular vortex shedding mode prevails against the regular alternate phenomenology. The persistence of the irregular mode is strongly dependent on the obstacle shape and it produces remarkable effects on the mean wake characteristic lengths. The most favourable flow characteristics for the heat transfer augmentation have been observed in front of the square obstacle and downstream of the rhomboidal and triangular pins.

The results of the present research, when coupled with an appropriate thermal characterization of the investigated configurations, will provide a solid interpretative basis for the heat transfer mechanisms that determine the performance of practical devices, which will be useful to define more rational design criteria. Finally, the present measurements represent a wide and accurate data-base for the validation of numerical codes under challenging flow conditions.