Forced air flow through a rectangular channel with 3D turbulence enhancers: visualization of flow structures by laser sheet scattering

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Abstract. In recent times, the design of heat transfer devices is strongly evolving due to both the diffusion of additive manufacturing techniques, that use a wide variety of materials, and Computational Fluid Dynamics (CFD) -based shape optimization techniques. Considering high-aspect ratio rectangular channels, that represent the geometry of heat transfer devices used, among other applications, for batteries cooling systems and compact automotive heat exchangers, the first step of a project towards the design of optimized turbulence enhancers is the validation of the CFD methodology. In particular, since it is important to have a fast-running 3D simulation with physical meaning, several techniques of increasing complexity and computational requirements and times are currently under scrutiny, and their validation is mainly carried out by experiments that measure both local and global heat transfer enhancement. In this context, flow visualization is a powerful tool to get insights of the physical mechanisms that generate convective heat transfer enhancement. In this paper, the setup of a laser sheet scattering method to visualize turbulent structures in a Plexiglas, 1:10 aspect-ratio, rectangular channel ribbed on one of the main surfaces is presented, and results on two different cutting planes are presented for 90° and V-down squared ribs for Re = 500.

1 Introduction

In the complex field of fluid-dynamics, flow visualization has always been crucially important for the understanding of the studied phenomena, from the experiments and drawings of Da Vinci [1], to ongoing studies on the definition of the intricacies related to a seemingly simple phenomenon, yet complex to measure and define, like the laminar-turbulent transition in narrow channels, as described by Sano and Tamai [2]. In particular, narrow rectangular channels are interesting in many heat transfer applications, like turbine blade cooling [3], solar air heaters [4] and, more recently, vehicle battery packs [5].

The research group of the ThermALab laboratory, at Politecnico di Milano, has been carrying out fundamental research on this topic, both with experiments [6], by measuring the global and local convective heat flux in ribbed channels, and CFD simulations [7], aimed at reproducing with good enough accuracy the experimental data. The next stage of this work is to use the methods developed during previous research projects in conjunction with optimization techniques, to find suitable geometries of turbulence enhancers to further increase the heat transfer efficiency. To this end, flow visualization helps comparing the local heat transfer measurements and CFD results, by showing the flow structures which causes the former. Quantitative comparisons with methods such as PIV have been already carried out on selected geometries for detailed analyses, see for example Wang et al. [8], but a fast set-up qualitative method that requires minimum post-processing can also be useful to validate other analysis techniques. To this end, this paper shows how a flow visualization procedure in 1:10 AR channel has been implemented, and first results for 90° and V-down rib configurations.

2 Materials and methods

The channel, made of PMMA, is 2200 mm long, with a 12 mm x 120 mm section. At the middle, a Z-laser ZM18 H3-F-637-lp30 laser (637 nm) is placed on a vertical-moving frame. The channel can be manually rotated along its main axis in order to allow to image both the side and the top of the channel.

The rib section is 4 mm x 4 mm, and a set of three ribs for each trial are glued 80 mm apart on an acetate thin paper, and inserted 1 m deep in the channel, in order to reach a hydrodynamic fully developed flow at the first rib. Two configurations are taken into account, i.e. Rib 90, with straight ribs perpendicular to the mean flow direction, and V-down, with ribs angled by 30° and pointing towards the flow direction. With reference to figure 1, The views presented in this paper are taken among the centerline in the *x-y* plane (side-views), and at 2 mm from the ribbed channel walls, i.e. half a rib height, for *x-z* plane views (top-view), as it is the most decisive section in relation to the local convective heat transfer from the bottom surface.

The flow regulation section is composed by a Bürkert 8802 compressed-air regulating valve, a Endress-Hauser thermal-mass flow meter, and a 7-stage, 30 kPa-head, 5.5 kW-power aspirator. The scheme of the experimental setup is shown in figure 2.

The image acquisition is carried out by means of a Phantom Miro C110 black and white high speed camera, with a maximum frame rate of 4000 fps. Two tracers have been used, i.e. fog, generated by a Lesatec fog generator, which is injected in the whole section by means of a custom manually operated valved pipe, and sulphuric acid (H2SO4) fumes injected locally by means of a Dräger disposable flow testers. The fog is used for visualization from the top, as it better highlights the flow behavior for direct comparison with the heat flux maps between ribs, while the sulphuric acid is preferred in side visualizations.

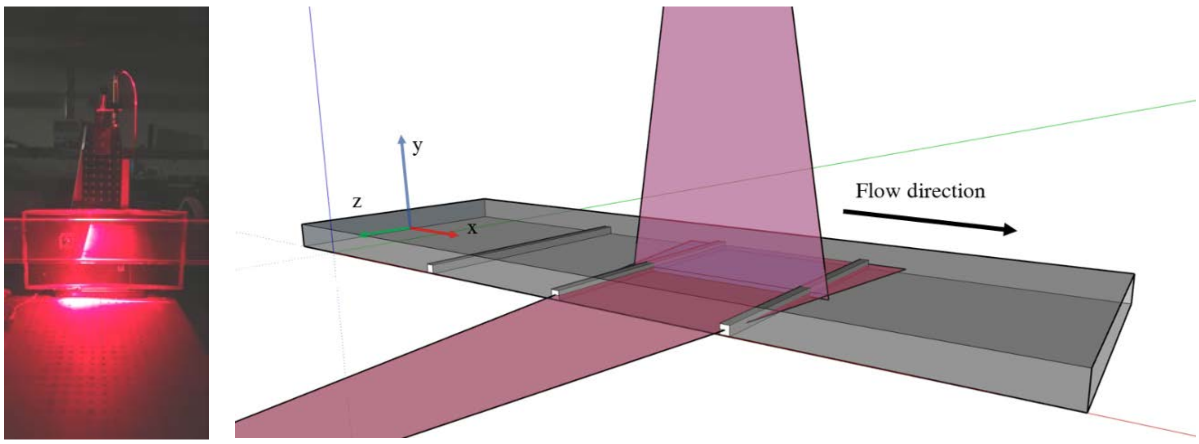


Figure 1. Picture (left) and drawing (right) of the test section.

Due to brightness constraints, the acquisitions within this set of experiments are limited to 200 fps, which allow good quality movies in this context for Reynolds numbers (Re) up to 1000. Higher Re would require a change of laser or both laser and tracer, which will be implemented in future experiments. The Reynolds number of choice for the purpose of this presentation is 500.

A post-processing sequence has been implemented as follows: for each acquired movie, a first image without tracers is collected and subtracted to the whole sequence, in order to filter artifacts as reflections or scattering due to powder particles or scratches. For the selected frames, a contrast and luminosity correction is applied to enhance the local flow features. The air flow is from left to right in all the pictures, which contain a sequence of frames to show the evolution of the flow.

Finally, it should be noted that the choice of the visualization method has been carried out on the basis of available hardware and ease of setup, even though more refined methods in particular regarding a more localized and controllable tracer injection will be likely implemented in later stages. However, the laser sheet scattering allows to precisely select the plane under investigation, which is highly valuable especially in complex 3D geometries which will be studied in the future.

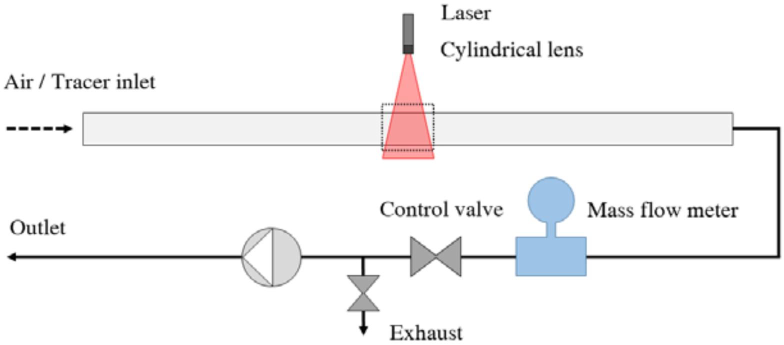
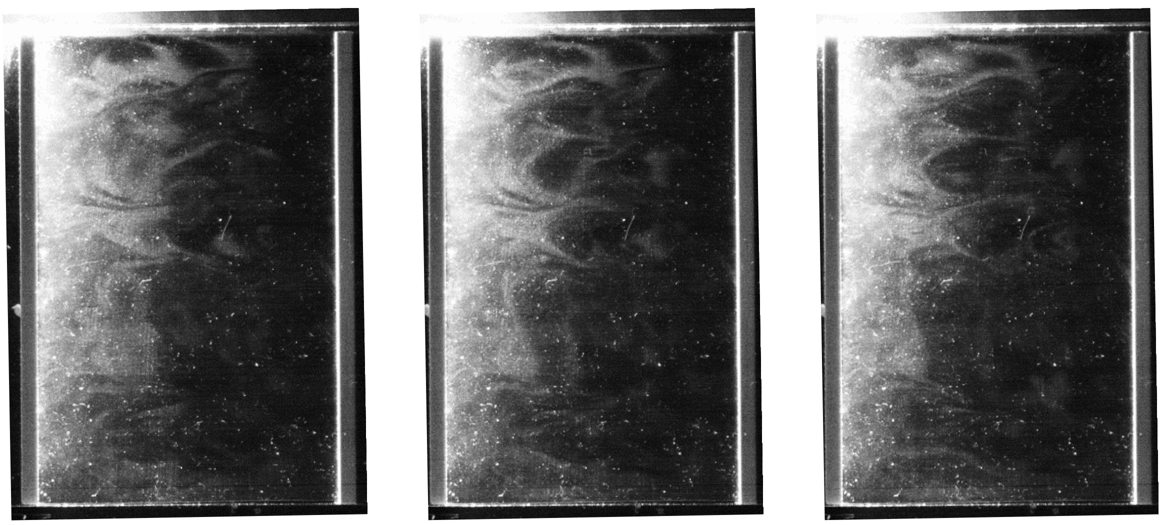


Figure 2. Scheme of the experimental setup.

3 Experimental results

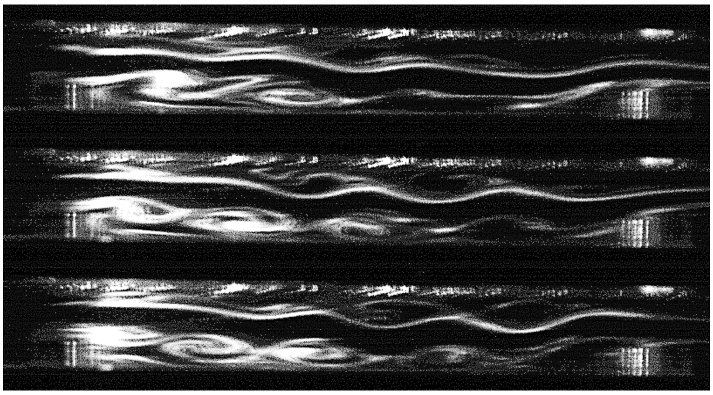
3.1 Rib 90

The visualizations for the Rib 90 configuration highlight the vortex patterns behind the ribs, which are foreseen at Re = 500 by the experimental work of Dushina et al [9], even though in our research do not lead to streamwise noticeable variations of local convective heat transfer, hence temperature for experiment with uniform heating from below as shown in figure 5, as otherwise happens in fully turbulent conditions in the region of reattachment [10]. This phenomenon is probably due to the movement of the vortices along the streamwise direction highlighted in figure 4, while in fully turbulent regime the average recirculation zones are localized.



(a) (b) (c)

Figure 3. Flow visualization for the Rib 90 configuration, top view, Re = 500, fog tracer, sequence of three images 15 ms apart.



(a)

(b)

(c)

Figure 4. Flow visualization for the Rib 90 configuration, side view, Re = 500, H2SO4 tracer, sequence of three images 15 ms apart.

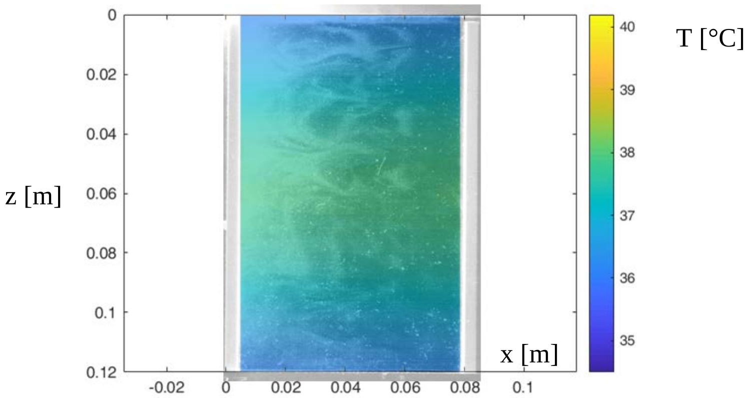
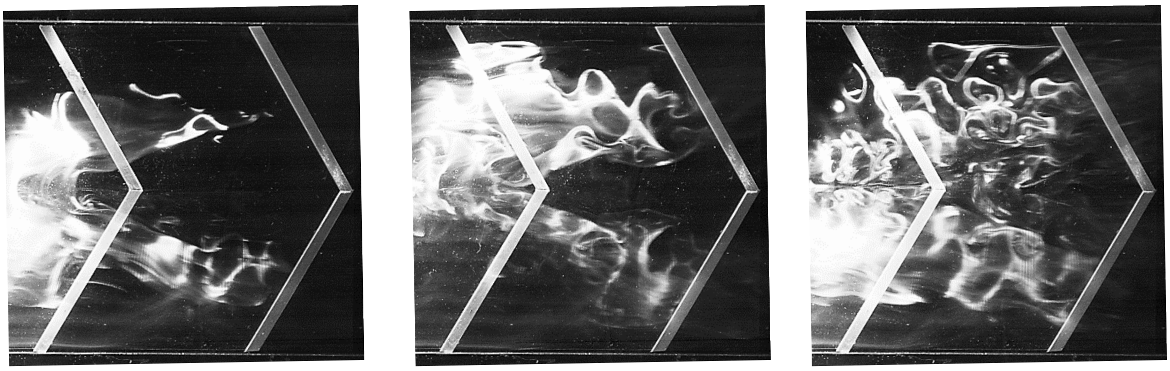


Figure 5. Superimposed temperature field and flow visualization from experiments by the authors at Re = 500, Rib 90 configuration.

3.2 V-down

The V-down configuration causes high flow symmetry, and it is characterized by vortices generated at the edges of the rib, as shown in [11]. Such vortices correspond to local maxima of convective heat transfer, and force the fluid outside the central region, where a minimum of local convective heat transfer, hence higher temperature, is observed, as shown in figure 8.



(a) (b) (c)

Figure 6. Flow visualization for the V-down configuration, top view, Re = 500, H2SO4 tracer, sequence of three images 15 ms apart.

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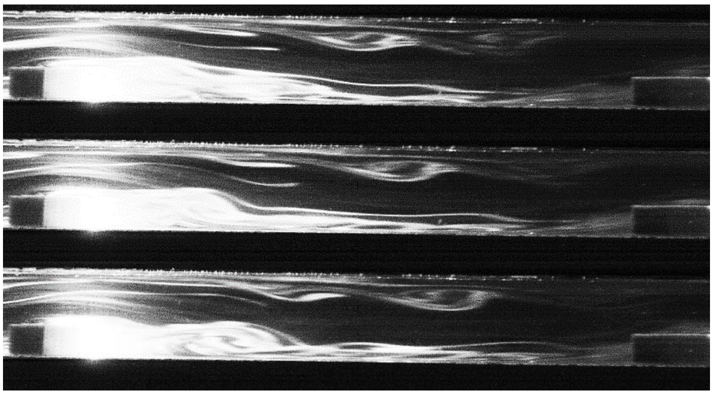

Figure 7. Flow visualization for the Rib 90 configuration, side view, Re = 500, H2SO4 tracer, sequence of three images 15 ms apart.

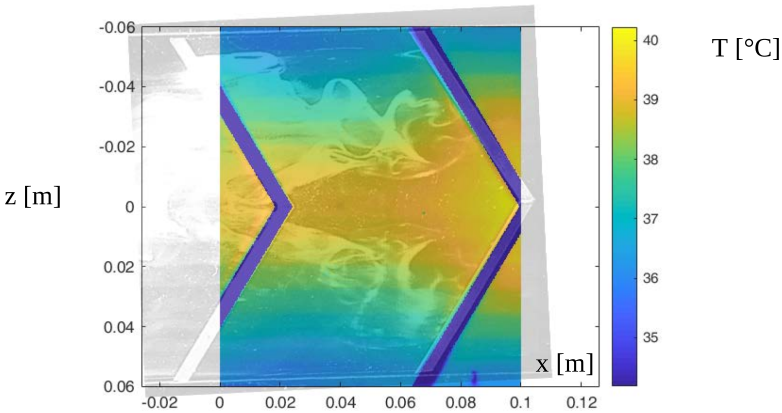

Figure 8. Superimposed temperature field and flow visualization from experiments by the authors at Re = 500.

4 Conclusions

An apparatus and methodology for qualitative flow visualization inside a narrow ribbed channel has been established, with the aim of supporting thermal-fluid-dynamics research aimed at optimizing heat transfer in such geometries. The available equipment allows visualizations for Re up to 1000, while, to perform effective visualizations at higher Re, several enhancements, including the laser source and the camera have to be carried out. The presented images are taken for Re = 500, and highlight the fluid behavior in a transitional flow regime, which interestingly shows, with regards of convective heat transfer distribution, a pattern typical of turbulent regimes for the V-down configuration, while not showing a streamwise difference for the Rib 90 configuration.

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