EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER OVER DRAG-REDUCING RIBLETS

Mathieu Creyssels & Christian Nicot
Laboratoire de Mécanique des Fluides et d'Acoustique, CNRS, Ecole Centrale de Lyon, France

Abstract The effect of longitudinal and drag-reducing riblets on heat transfer in a turbulent boundary layer is investigated. Systematic previous studies of turbulent flows over 'V'-shaped riblets have shown that a drag-reducing regime is observed when the height of the ribs and their spacing are approximately 15 in wall units [8, 1]. The experimental results presented here indicate that drag-reducing riblets surfaces are also heat-transfer reducing surfaces and suggest that the so-called Reynolds analogy remains valid even with microgrooves over the boundary wall.

STATE OF THE ART

It has been long established that in most cases roughening a surface exposed to a turbulent stream of fluid increases skin friction compared to a smooth surface. Additionally, for heated or cooled surfaces, the increase in heat transfer caused by roughness elements is usually less than the corresponding increase in shear stress. The aim of this work is to investigate the possibility to obtain a surface that enhances the heat transfer while reducing the turbulent wall-shear stress. If it is possible, such particular surfaces would be useful to improve the overall performance of various heat transfer devices such as heat exchangers.

It has also been shown experimentally [8, 1] that wall surfaces with micro-grooves, so-called riblets, in turbulent boundary layers lead to a net drag reduction, up to 10 %, in spite of a substantial increase in the wetted surface, so that riblet-covered surfaces are potential candidate for new passive heat transfer equipments. While the effect of riblets on skin friction is no longer a matter of debate, it is quite different for heat transfer [7]. Previous experimental results showed a heat transfer increase together with a skin friction reduction, indicating an apparent breakdown of the 'Reynolds analogy'. [8, 3] reported a heat transfer enhancement by as much as 10 % and [5] up to 30 % in the drag-reducing regime of the riblets. However, using a nonlinear $k - \epsilon$ model, [2] observed for drag-reducing riblets surface a heat transfer coefficient lower than that on a smooth surface and this result has also been confirmed by means of direct numerical simulation at a Reynolds number $\mathrm{Re}_\tau = 180$ [7].

EXPERIMENTAL SET-UP

The flat and profile support used to study the development of the turbulent boundary layer is 150 mm long, 75 mm wide and is placed inside a horizontal plane and free jet, as sketched in Fig. 1. The shape of the support has been carefully designed in order to avoid any transition to turbulence from its downstream edge, even when placed in a laminar outer flow. The effects observed here are not due to the triggering of the transition by the outer turbulence, but to the outer fluctuations upon the already developed turbulent boundary layer. The support is placed at 25 cm from the 1 cm wide and 30 cm long nozzle of the jet. The external velocity of the incoming flow is parallel to the surface of the profile and can be varied from 4 to 12 m/s, representing a range of Reynolds number between 3×10^4 and 9×10^4 based on the distance from the leading edge of the support to the middle of the heat flux sensor.

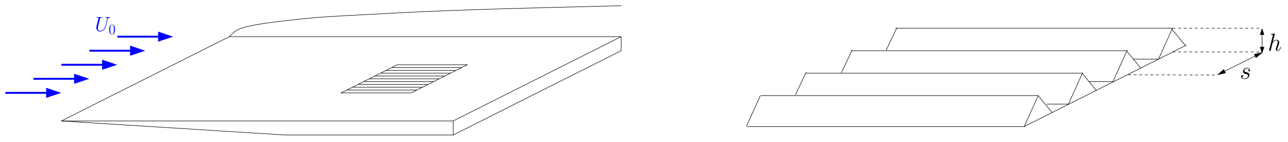

Figure 1. (a) Sketch of the experimental setup. (b) Geometry of riblets configuration studied and definition of the height h and the spacing s of the ribs. Two riblets surfaces are used: the first one with $h = 130$ μm and $s = 400$ μm, the second one with $h = 380$ μm and $s = 800$ μm.

To measure the capacity of the turbulent flow to cool a hot plate, a inhouse-built heat flux sensor was carefully incorporated inside the support at 10 cm from the leading edge. Its upper surface sits flush with the top surface of the support profile. The heat flux sensor has a very compact and robust design, it consists of a copper plate, the upper side is in contact with the turbulent flow and can be micromachined in order to draw ribs. Copper plate is chosen because of its good thermal conductivity that ensures the utmost temperature homogeneity. The height of the ribs (h) was selected to force the riblets surface to be in the drag-reducing regime that is:

$$5 < h_+ = hu_\tau/\nu < 30$$

ν is the kinematic viscosity of air and the wall-shear velocity u_τ is derived from the streamwise velocity profile measured with a hot-wire anemometer over the test surface.

For increasing the copper plate temperature, a heating foil is glued on its underside and the power input (P) is directly measured with high precision. Temperatures are measured through type E thermocouples. Three of them are inserted in the copper plate and another is placed inside the air jet as a reference (T_{air}). Then, we define the Nusselt number by:

$$\mathrm{Nu} = \frac{P - P_{\mathrm{loss}}}{\lambda(T_{\mathrm{Cu}} - T_{\mathrm{air}})L},$$

where λ is the thermal conductivity of air and $L = 25$ mm is the size of the heat flux sensor. As for the heat losses (P_{loss}), they are measured with quite good precision in order to obtain accurate values of the Nusselt number.

RESULTS

First, the heat-transfer coefficient is measured as a function of the free-stream velocity for a heat-flux sensor with a smooth copper plate, which gives us a baseline Nusselt number (Nu_0). Then, the experimental procedure is repeated for a second heat-flux sensor with riblets inserted in a second support profile and finally the Nusselt numbers of this riblet surface are directly compared with those of the previous smooth surface (see Fig. 2).

Surprisingly, the heat transfer data from the riblets of this present study exhibit a behavior very much like previous data on skin friction results from the original work of Bechert *et al* [1]. When the height of the ribs is less than 15 in wall units, both Nusselt number and skin friction are reduced over the riblet surface (up to 4 %), whereas this reduction becomes a net increase of both heat transfer and drag as soon as $h_+ > 15$.

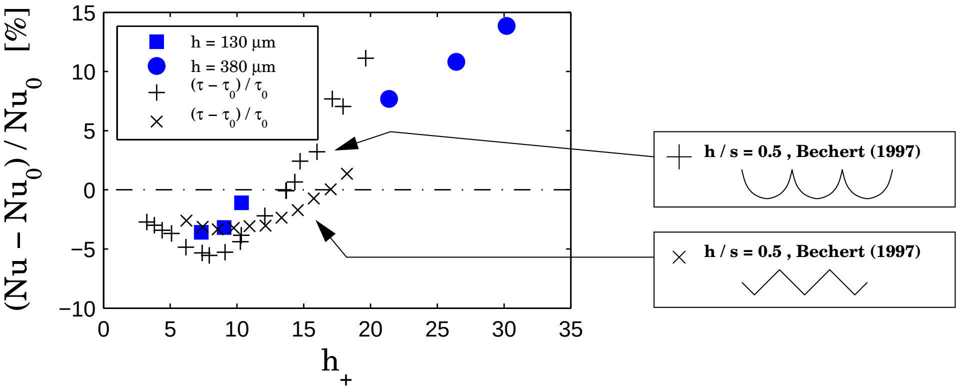

Figure 2. Heat transfer for present study and skin friction from [1] as a function of the height of the ribs measured in wall units $h_+ = hu_\tau/\nu$.

The results obtained here for the heat transfer over riblets agree very well with those reported in numerical studies [2, 7] and also with the experimental measurements of skin friction from [1], confirming that the Reynolds analogy remains valid even for drag-reducing riblets. It just means that the skin friction can be evaluated by measuring the heat transfer coefficient, which offers two significant advantages: first, the use of a high-precision mechanical balance is avoided and secondly, high-frequency heat flux sensors already exist (see for example [6, 4]) and permit statistical studies of the heat flux and thus of the skin friction close to the wall.

References

[1] D. W. Bechert, M. Bruse, W. Hage, J. G. T. van der Hoeven, and G. Hoppe. Experiments on drag-reducing surfaces and their optimization with an adjustable geometry. *J. Fluid Mech.*, **338**:59–87, 1997.

[2] M. Benhalilou and N. Kasagi. Numerical prediction of heat and momentum transfer over micro-grooved surface with a nonlinear kappa-epsilon model. *Int. J. Heat Mass Transfer*, **42**(14):2525–2541, 1999.

[3] K. S. Choi and D. M. Orchard. Turbulence management using riblets for heat and momentum transfer. *Exp. Therm. Fluid Sci.*, **15**:109–124, 1997.

[4] http://www.taosystem.com/.

[5] A. M. Lindemann. Turbulent Reynolds analogy factors for nonplanar surface microgeometries. *J. Spacecraft*, **22**(5):581–582, 1985.

[6] E. Sanz, C. Nicot, R. Point, and F. Plaza. Study of transition from laminar to turbulent boundary layer on a tilted flat plate using heat transfer measurements. *J. Thermal Sci.*, **16**(2):186–191, 2007.

[7] E. Stalio and E. Nobile. Direct numerical simulation of heat transfer over riblets. *Int. J. Heat and Fluid Flow*, **24**:356–371, 2003.

[8] M. J. Walsh and L. M. Weinstein. Drag and heat-transfer characteristics of small longitudinal ribbed surfaces. *AIAA Journal*, **17**(7), 1979.