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On the flow resistance of wide surface structures

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The possibility of skin-friction drag reduction in channel flows due to surface structures is investigated numerically. In this context, surface structures with a high width to height ratio compared to the typical dimensions of riblets are studied in the laminar as well as in the turbulent flow regime. In general, it is found that a reduction of the flow resistance is possible in both flow regimes.

1 Introduction

The application of rib-like surface structures oriented parallel to the flow direction (so-called riblets) as drag reducing device has been investigated intensively in the past decades. It has been shown that riblet-mounted surfaces can reduce the skin-friction drag by up to 10% compared to flat surfaces in turbulent channel flows [2, 4]. In the laminar regime, however, the use of these surface geometries was found to result in drag increase [3]. Using a variational principle for the surface shape, Pironneau et al. [5] were able to show analytically that in the laminar case benefits can only be expected if the surface structures exceed a certain width which scales with the channel height. In the present work structures that obey this particular condition are investigated using an analytical model to predict the flow resistance. Two structures that result in drag reduction in laminar flows are studied in the turbulent regime using direct numerical simulation (DNS).

2 Laminar flow

According to Pironneau et al. [5] drag reduction in laminar channel flow is possible if the ratio of the surface structure width to the mean channel height obeys the condition $l/L > \pi/z$ where $z \approx 1.2$ is the root of $1 - x \tanh x$ (for variable definition see Figure 1). Performing a numerical shape optimization for certain l/L Pironneau et al. [5] show that the optimal shape of these structures is smooth. Within this study we aim to further investigate this type of structures by describing the boundary through a trigonometric function. In Figure 1 a typical structure geometry is shown together with the flow field arising from the structured and the flat reference channel.
Using an analogy between structural mechanics and fluid mechanics, namely the analogy between torsion of beams and fully developed laminar flow in ducts (the governing equation in both cases is Poisson's equation), the pressure drop, and thus the skin friction drag, arising from the curved structures can be estimated by applying Saint Venant's principle [1]. Based on this approach the impact on flow resistance for the variation of all parameters (l, a and b) determining the trigonometric structure is taken into account. The resulting drag reduction for the investigated parameter range is shown in Figure 2. Drag is found to be reduced up to about 50% compared to the flow through a flat channel of the same cross section. In general, it is observed that the drag reduction increases moving to the upper right corner of the contour map representing wide structures that are periodically clamped such that b vanishes, i.e. the structured channel turns into a duct. The results propose an asymptotical behaviour in the drag reduction that can be achieved for large l/L.
Results for classical riblet-like surface structures with sharp corners are shown in Figure 3. Obviously the drag reduction that can be achieved for this type of surface structures is smaller compared to the curved one.

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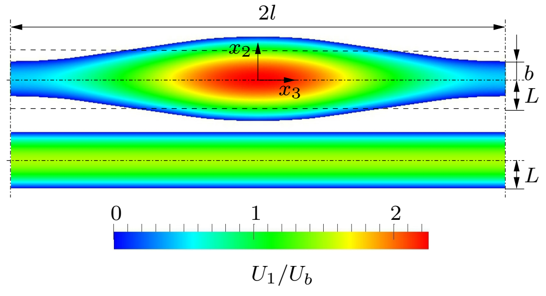

Fig. 1 Numerically predicted laminar flow through a flat channel and channel with wide surface structures: The boundary shape is defined by the function $x_2 = \pm\left((a/2)\cos(\pi x_3/l) + 2b\right)$ with $a/2 = L - b$ (a is the amplitude of the wave). The flow resistance compared to the flat reference channel is reduced by 16% in this example, where $l/L = 8.3$ and $a/(a+b) = 0.59$. Both channels have the same cross section which is indicated by the dashed side walls in the upper figure.

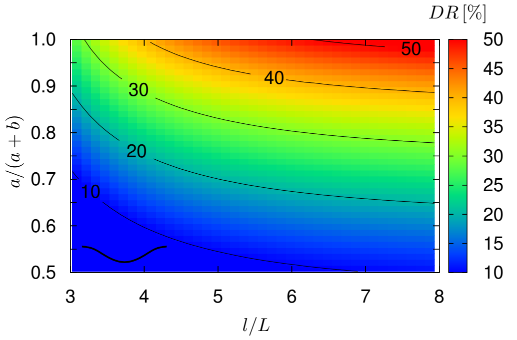

Fig. 2: Curved surface structure: Contour plot of the drag reduction that can be achieved compared to a flat reference channel depending on the parameters a, b, and l that describe the structure geometry.

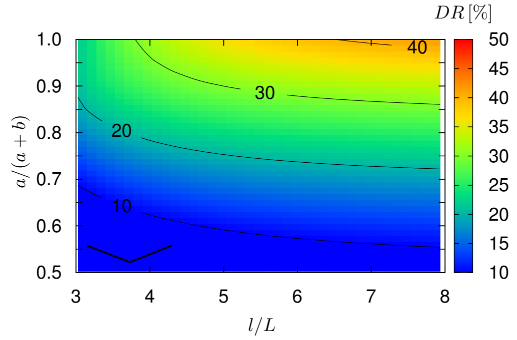

Fig. 3: Riblet-like triangular surface structure: Contour plot of the drag reduction that can be achieved compared to a flat reference channel depending on the parameters a, b, and l that describe the structure geometry.

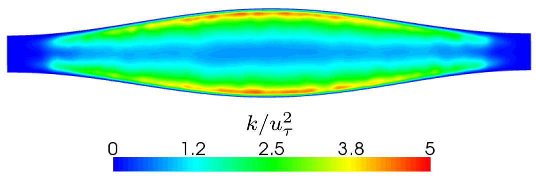

Fig. 4: Duct 1: Turbulent kinetic energy k normalized with the wall friction velocity u_τ.

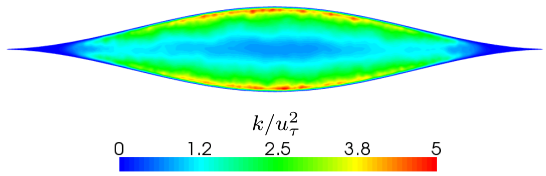

Fig. 5: Duct 2: Turbulent kinetic energy k normalized with the wall friction velocity u_τ.

3 Turbulent flow

In the turbulent flow regime two of the wide surface structures providing drag reduction in laminar flows are investigated at an hydraulic Reynolds-number $Re_h = 4500$ using direct numerical simulation (DNS). In order to limit the computational effort the flow predictions are carried out for duct geometries in both cases. The resulting flow fields are expected to be similar to turbulent channel flows with this surface contour since the flow rate in the location of the small channel height (which is replaced by side walls to form a duct) is significantly smaller than in other locations. The duct shapes and the first preliminary results for the distribution of the turbulent kinetic energy in the ducts are shown in Figure 4 and 5.

For turbulent duct flows it is well-established to use Blasius correlation for the prediction of the flow resistance for different duct geometries [6]. However, the flow resistance based on the present DNS results lies below the value estimated by the Blasius correlation. The reduction is about 10% for duct 1 and 30% in the case of duct 2. The observed tendency proposes a drag-reduction potential for this kind of duct geometries in the turbulent flow regime.

The distribution of the kinetic energy of turbulence k shown in Figure 4 and 5 indicates the reason for the observed reduction in skin friction drag: In the corners of the duct the turbulent activity is very small, which indicates the existance of a laminar flow state in these regions. In general, laminarisation of the flow is the goal of many flow control techniques, since the skin friction drag in a laminar flow is substantially lower than the one of a turbulent flow at the same Reynolds number.

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