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RIBLETS IN FULLY DEVELOPED TURBULENT CHANNEL FLOW - AN EXPERIMENTAL CAMPAIGN

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INTRODUCTION

Riblets are well known to reduce the skin friction drag in turbulent flows and have been extensively studied numerically and experimentally in the past. One major experimental contribution was made by Bechert et al. [1], who investigated various types of riblets in an oil channel facility. These oil channel data sets have an accuracy that exceeds all prior air flow investigations. The present contribution aims to extend the available data for the change of turbulent skin friction drag in the presence of riblets through highly accurate measurements in fully developed turbulent air flow. In contrast to oil, the physical dimensions of the riblets are significantly smaller in air but at the same time a much larger range of Reynolds numbers can be covered with the present facility. We investigate three sets of riblets in a Reynolds number ($Re_b = U_b\, H/\nu$) range $3\times10^3 < Re_b < 8.5\times10^4$, where U_b is the bulk velocity, H the channel height and ν the kinematic viscosity.

PROCEDURE

The experimental facility consists of an open-circuit blower tunnel [4] shown in fig. 1. It allows the measurement of small changes in skin-friction drag by evaluating the static pressure at 21 pairs of pressure taps located along the two side walls of a $157\,H$ long channel test section with an aspect ration of 12. The test section is divided into three segments of $38\,H$, $59.5\,H$ and $59.5\,H$ streamwise extent. In the present investigation, the last segment is equipped with riblets on the top and bottom of the channel. The riblet test plates are inserted in such a way that the net channel cross section remains constant. The geometries of the three considered riblelt types are sketched in fig. 2 and the physical dimensions are given in table 1. The last column in table 1 gives the Reynolds number at which the riblets are expected to yield maximum drag reduction.

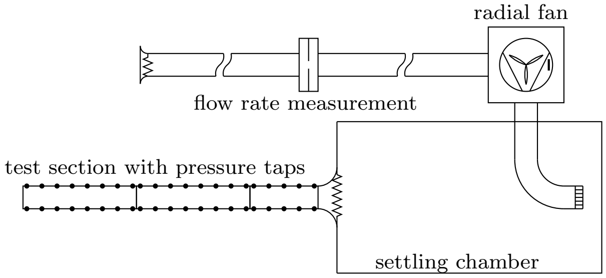

Figure 1: Schematic of the experimental facility.

To cover the whole range in Re_b while maintaining a high measurement accuracy, multiple flow rate measurement devices are used, namely an inlet nozzle and an orifice flow meter designed according to DIN EN ISO 5167, see table 2.

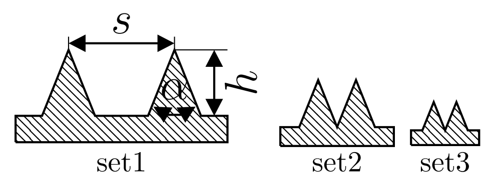

Figure 2: Schematic sketches of the three studied riblet sets.

	$s\,[\mu m]$	$h\,[\mu m]$	tip angle [°]	$Re_{b,\text{opt}}$
set1	614	294	53.5	1.14×10^4
set2	170	160	50	5×10^4
set3	86	83	51	9.7×10^4

Table 1: Parameters of the individual riblet sets.

type	diameter	symbol	approximate range in Re_b
orifice	$60\,[mm]$	○	$3\times10^3 < Re_b < 1.3\times10^4$
inlet nozzle	$74\,[mm]$	⋆	$6\times10^3 < Re_b < 2.4\times10^4$
orifice	$105\,[mm]$	△	$7\times10^3 < Re_b < 3.8\times10^4$
orifice	$150\,[mm]$	□	$3\times10^4 < Re_b < 8.5\times10^4$

Table 2: Different types of flow rate measurement devices used in the experimental campaigns.

RESULTS

Results in terms of skin friction drag reduction are obtained by determination of the c_f-Re_b curve for all three sets of riblets and a smooth reference over the entire Reynolds number range of $3\times10^3 < Re_b < 8.5\times10^4$. Therefore, the pressure-drop along the test section and the corresponding flow rate are assessed by means of high-precision pressure measurements.

The obtained results are converted to the dimensionless friction factor c_f, defined as $c_f = 2*\tau_w/(\rho\, U_b^2)$, where ρ is the density and τ_w the wall shear stress. The resulting c_f-values for all three riblet sets and the smooth reference channel alongside the correlation proposed by Dean [2] are shown in figure 3. The smooth plate reference case shows excellent agreement with the Dean correlation. For the riblet cases, the drag reducing effect and the different design points given in table 1 as a optimal Reynolds number $Re_{b,\text{opt}}$ are clearly visible. For riblet set 1 the drag increasing regime starts around $Re_b = 20.000$.

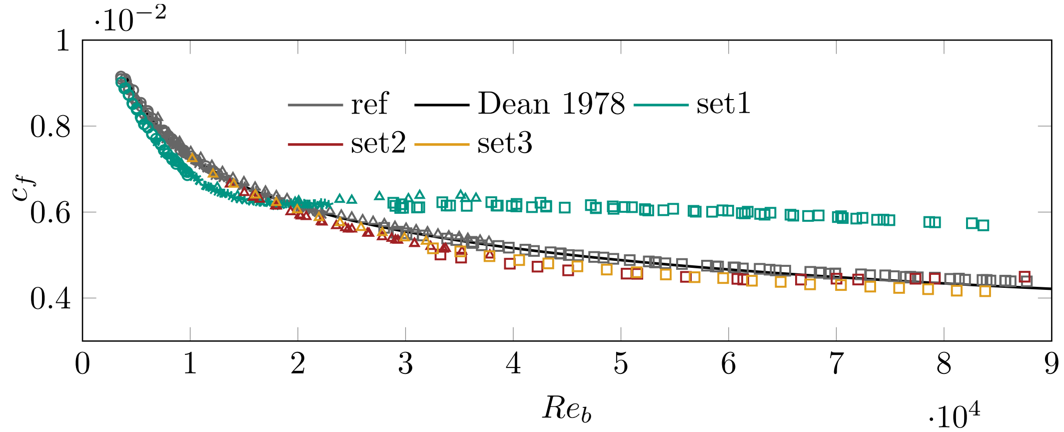

Figure 3: c_f vs. Re_b for smooth reference and riblets. Symbols refer to the flow rate measurement technique as given in table 2.

There appears to exist a Reynolds number region of more less constant c_f across this zero drag change point while a decreasing c_f-value is found for the highest Reynolds numbers.

The classical way to visualize the drag reducing performance of riblets is given by the relative change of wall shear stress τ_w in respect to the smooth reference τ_{w0}. This quantity $\Delta\tau_w$ is plotted in figure 4 as a function of Re_b. In this representation the drag reducing effect is clearly visible and reveals a maximum drag reduction of 6% for set1 and about 7 % for set2 and set3 which is in agreement with the results of [1]. It can nicely be seen that the physically small riblets that are used in the present study have a very broad drag reducing regime in terms of Reynolds number. Actually, the smallest riblet set (set3) only reaches it maximum drag reduction value around the highest Reynolds numbers we investigated and these riblets are expected to reduce drag up to $Re_b = 1.87 \times 10^5$. As it is known in literature, the drag reduc-

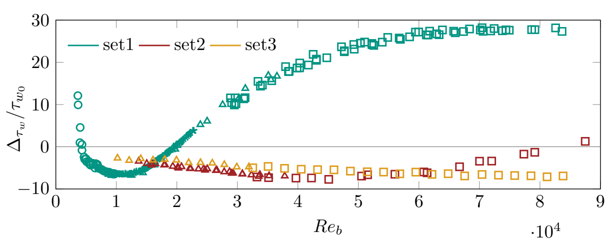

Figure 4: Distribution of $\Delta\tau_w/\tau_{w0}$ in dependence of Re_b.

ing regimes scale well with the dimensionless spanwise riblet spacing $s^+ = s\,u_\tau/\nu$ where $u_\tau = \sqrt{\tau_w/\rho}$. This is shown in figure 5 where the maximum drag reduction $DR_{\max}$ at $s^+ \approx 15$ is confirmed, which is a well documented value in the literature [3, 1]. Due to their geometric similarity, set2 and set3 collapse almost perfectly onto each other in this representation.

Figure 5 also contains an estimate of the initial slope of the drag reducing regime following the suggestion of Lucchini [5] and Bechert et al.[1] for the riblet set 2 and 3. Garcia-Mayoral and Jimenez [3] suggested a correlation for the maximum drag reduction as function of this initial slope. Their suggestion which yields $DR_{\max} \approx 7.9\%$ is also included. Both estimations agree very well with the present data.

The results of this experimental campaign were obtained and reproduced over a time period of more than five years. We demonstrate that it is possible to obtain highly accurate measurements of skin friction drag changes in turbulent air channel flows which have a comparable accuracy of the Berlin oil tunnel measurements but can be carried out in a wider Reynolds number range. We learned that especially the quality of the volume flow rate measurement is crucial for accurate results. The present results will hopefully turn out to be helpful reference data for simulations of turbulent flows over riblets. Finally, the present data document the behaviour of turbulent flow over riblets in the drag increasing regime over a wide Reynolds number range for the first time.

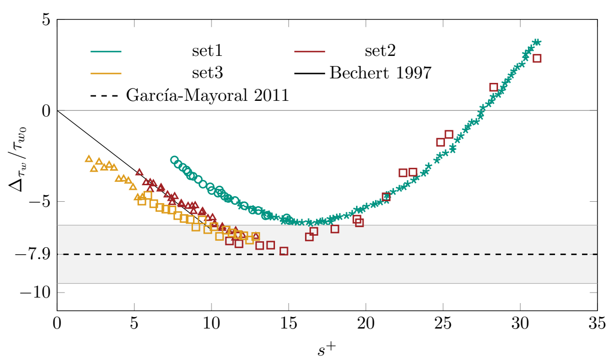

Figure 5: $\Delta\tau_w/\tau_{w0}$ vs. s^+. The initial drag reduction slope is estimated following the procedure of [5] and [1] for the geometrically similar sets 1 and 2. The corresponding maximum drag reduction rate (dashed line) is estimated following the suggestion of [3]. The latter is included jointly with the reported 20 % uncertainty of this estimation.

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