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TURBULENT DRAG REDUCTION DUE TO ELECTROSTATIC FLOCKING SURFACE WITH GROOVES

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INTRODUCTION

It is well known that the riblet, which consists of microgrooves or microfences on the bounding surface aligned with mean flow direction with small transverse spacing, is one of the most popular and widely accepted passive control methods used for a wall-bounded turbulent flow [3]. Riblets work as a longitudinal fence to reduce skin-friction drag by impeding spanwise movement of longitudinal vortices during sweep events and reduce the friction drag up to about 10% for the wall-bounded flow [1, 3].

For the engineering and industrial applications, a new technique is further needed to achieve the higher turbulent drag reduction as an alternative to the riblet. A hairy surface may be one of the promising candidates from the standpoint of seeking an idea from natural creatures such as the riblet which is an idealized model of shark skin. Itoh et al. [2] achieved the drag reduction ratio up to 12% due to the seal fur for a wide range of Reynolds numbers. However, there are few studies on the turbulent drag reduction due to the artificial fur surface, as long as we know.

In this study, we propose a new drag-reducing method using the electrostatic flocking surface with grooves. The pressure loss and flow rate in the rectangular water channel flow was measured to evaluate the relation between the friction factor and the Reynolds number and the drag reduction ratio. The obtained results were compared with those of smooth surface and uniform electrostatic flocking surface without grooves.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experiments were conducted in a rectangular channel made of acrylic resin with a channel width $W = 140$ mm, nominal channel height $H^* = 30$ mm, and total channel length of $3,650$ mm consisting of four sections (see figure 1 and [2] for details). The tap water, with the temperature kept constant by a heat exchanger, was circulated by a centrifugal pump. The flow rate was controlled by the pump with an inverter power source and a valve, and measured by two electromagnetic flowmeters for large and small flow rates. The upstream two sections of the channel, I and II, were in the developing region of 2,000 mm long, and the downstream section III was in the measuring region of 1,000 mm long. The channel-aspect ratio of the present duct was $W/H^* = 4.67$. The upper and lower walls of section III were test plates of $900 \times 180 \times 15$ mm, which were convertible, while the side walls were fixed and smooth.

The friction factor was obtained by measuring the pressure loss between the locations at a streamwise interval of 700 mm in section 3. Two kinds of pressure transducers (GE Druck Co. Ltd., LPM5381 and LPM5481) whose full scales were from 200 to 5,000 Pa and linearity was ±0.25% were used for measurements of pressure loss.

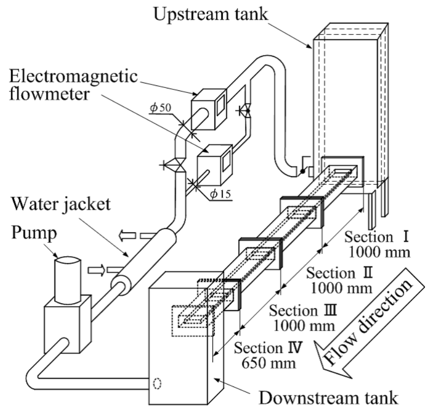

Figure 1: Experimental apparatus.

Smooth surface made of acrylic resin plates and a set of plates adhered by sheets of electrostatic flocking surface with or without grooves were tested. Figure 2 shows the photograph of the cross section of the electrostatic flocking surface with grooves under dry condition, which was captured by a digital camera (EOS 7D, Canon Ltd) with a macro lens. The horizontal and vertical directions correspond to the spanwise and wall-normal directions, respectively. The height of the flocking is $h = 1$ mm, and the lateral rib spacing is $s = 2$ mm, and thus the shape factor was $h/s = 0.5$. At this moment, the shape of rib is not sharp. It is also noted that the present shape is not optimal for the blade-type riblet [1].

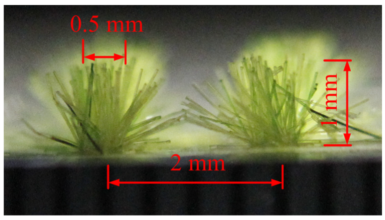

Figure 2: Photograph of electrostatic flocking surface with grooves under dry condition.

RESULTS

In this study, it is difficult or impossible to directly measure the channel height, the distance between the upper and lower plates for the electrostatic flocking surfaces, where the channel height is not constant due to the roughness of protrusions. For an accurate evaluation of friction factors, it is essential to estimate the channel height as accurately as possible, since the friction factor evaluated varies approximately with the cube of a channel height for the duct flow. Hence, the effective channel height H was introduced and defined as the distance between the upper and lower plates at which the measured friction factor agreed with the laminar theoretical relation between the friction factor λ and the Reynolds number Re for a smooth surface in the laminar flow region ($Re < 2,000$) (see [2] for details). The Reynolds number Re is defined as follows:

$$Re = \frac{d_h U_a}{\nu}, \tag{1}$$

where $d_h = 2HW/(H+W)$ is the hydraulic diameter (W: channel width = 140 mm), $U_a = Q/(HW)$ is bulk velocity (Q: flow rate), and ν is kinematic viscosity.

Figure 3 shows the relation between the Reynolds number Re and the friction factor λ for the smooth surface. The laminar theoretical relation ($\lambda = 1.17 \times 64/Re$) and the turbulence empirical relation ($\lambda = 1.06 \times 0.3164 \times Re^{-0.25}$), taking into account the channel-aspect ratio ($W/H^* = 4.67$ in the present study), are also indicated in the figure. The effective channel height H for the smooth surface was evaluated to be 30.3 mm in the laminar flow region. Adopting this value, in the turbulent flow region, the data for smooth surface agree well with the turbulent empirical relation. On the other hand, the effective channel heights for the electrostatic flocking surfaces with and without grooves was 27.7 and 29.9 mm, respectively, which indicates that the virtual origins of the electrostatic flocking surfaces are located downward from the top of electrostatic flocking furs.

Figure 3 also shows the relation between Re and λ for the electrostatic flocking surfaces with and without grooves. In the turbulent flow but smaller Reynolds number region within about $Re = 10^4$, the friction factors for both electrostatic flocking surfaces with and without grooves are smaller than that of the smooth surface, i.e., the turbulent drag reduction could be obtained (see figure 4). The drag reduction ratio DR is defined as follows:

$$DR = \frac{\lambda_{\mathrm{smooth}} - \lambda}{\lambda_{\mathrm{smooth}}} \times 100, \tag{2}$$

where $\lambda_{\mathrm{smooth}}$ is the friction factor on the smooth surface. Note that the drag reduction ratio DR is evaluated at the fixed Reynolds number Re. The maximum drag reduction ratio for the electrostatic flocking surface without grooves is about 15%, which is comparable with the seal fur surface (cf. Itoh et al. [2]). For the electrostatic flocking surface with grooves, the maximum drag reduction ratio up to about 20% could be obtained around $Re = 5,000$, which is larger than that of homogeneous electrostatic flocking surface.

At the large Reynolds number here, the friction drag for both electrostatic flocking surfaces with and without grooves is much larger than that of smooth surface, i.e., the value of DR is negative (see figure 4). This friction drag increase is due to the roughness effect of electrostatic flocking surfaces as well as the riblet. Figure 5 shows that the equivalent relative sand roughness (k/d_h) is 0.013 and 0.019 for the electrostatic flocking surfaces with and without grooves, respectively.

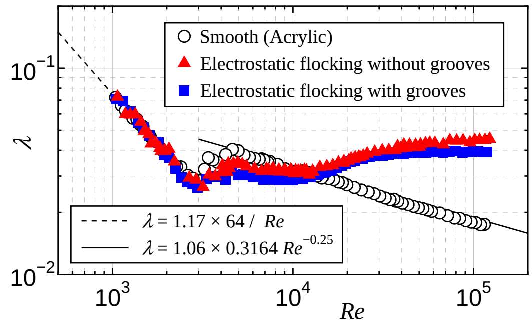

Figure 3: Friction factor vs. Reynolds number.

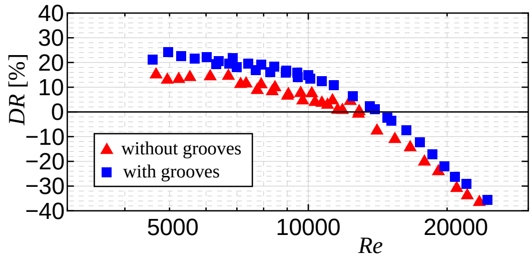

Figure 4: Drag reduction ratio vs. Reynolds number.

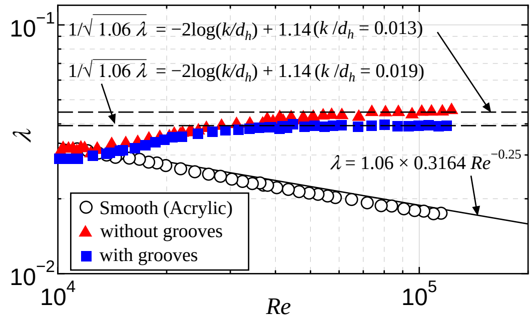

Figure 5: Effect of roughness at $Re > 10^4$.

CONCLUSION

In the present study, the drag-reducing ability of electrostatic flocking surfaces with and without grooves was investigated by measuring the flow rate and the pressure drop along the channel in the rectangular water channel flow. The present study revealed that the electrostatic flocking surface with grooves had sufficient potential to provide a larger turbulent drag reduction than previous standard riblets, although the Reynold number region for the effective drag reduction is limited to the narrow region from the transient to early turbulent flows.

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