PIV experimental research of drag reduction mechanism by superhydrophobic-riblet wall surfaces

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Abstract This study reports skin drag reduction of turbulent boundary layer (TBL) flow over a unique superhydrophobic-riblet wall surface, which combines two passive drag-reduction approaches of superhydrophobic surface and riblet wall. Time-Resolved Particle Image velocimetry (TR-PIV) experiments were carried out in a water tunnel. The Reynolds number based on the momentum thickness and free stream velocity was \( Re_\theta = 1451 \). It compared mean velocity and turbulence intensity profiles in the cases of natural flat plate (P), superhydrophobic surface (SH), riblet wall (R) and superhydrophobic-riblet wall surface (SR). The friction velocity fitted by logarithmic law region of the mean velocity profile shows distinct drag reduction superiority of SR surface. The topology and evolution of coherent structures were observed by using the approaches of conditional extraction and phase average. Then, the connection between the outer layer structures and skin drag reduction rate was addressed, by stressing the distinctive dynamic features of the turbulent structures over different surfaces.

Keywords: turbulent boundary layer, superhydrophobic, riblet, TR-PIV

1 Introduction

Riblets surfaces were studied from the investigation of micro-structures on the shark skin. An optimum drag reduction value of 9.9% was found on blade-shape riblet wall with \( s^+ = 17, h^+/s^+ = 0.5, \tau^+/s^+ = 0.02 \), where \( s^+ \), \( h^+ \) and \( \tau^+ \) denote grooves width, height and blade thickness in viscous units, respectively [1]. A better characteristic length which is the square root of the groove cross-section \( l g^+ \) was used to measure drag reduction effect of the riblet wall, and the best drag reduction value was obtained at \( l g^+ \approx 10.7 \) [2]. The superhydrophobic structure was inspired by the lotus leaf surface. Superhydrophobic surfaces are surfaces with static contact angle \( \theta_c > 150^\circ \) and rolling angle \( \alpha < 10^\circ \).

2 Experimental methodology

Femtosecond laser was used to engrave oriented structures which are about 35μm width and 15μm thickness \( \text{U type micro-grooves on the } 130 \text{ mm } \times \text{130 mm aluminum plate surface. After the fluoration treatment, a robust superhydrophobic surface with static contact angle } \theta_c = 153^\circ \text{ is obtained, which could not be wetted at } Re_\theta = 2586 \text{ in experiments. An aluminum plate with dimensions of } 3.7 \text{ m } \times \text{0.59 m } \times \text{0.01 m (length } \times \text{width } \times \text{height) was fixed within a } 4.1 \text{ m } \times \text{0.6 m } \times \text{0.7 m (length } \times \text{width } \times \text{height) water tunnel to obtained a fully developed TBL. The shooting area was 3.1 m downstream of a 3 mm diameter trip wire which was fixed 20 mm downstream of the leading edge. The free stream velocity is 0.273 m/s. The number of velocity instantaneous fields is 16430 and the sampling frequency is 300 Hz.

3 Results

Fig.1a shows the mean velocity profiles which are normalized by their respective \( u_\tau (\bar{u}^+ = \bar{u}/u_\tau \) and \( y^+ = yu_\tau/v \) using a Clauser chart fit. The basic parameters of each wall condition are listed in Table 1. Here, \( \delta \) is the TBL thickness, \( u_\tau \) is the friction velocity and DR is the ratio of reduced resistance. By comparing the streamwise turbulence intensity \( (u'_{rms}/u_\infty) \), wall-normal direction turbulence intensity \( (v'_{rms}/u_\infty) \) and Reynolds shear stress \( (u'v'_{rms}/u_\infty^2) \) of each case in Fig.1b and Fig.1c, three drag reduction cases show lower values in near wall region clearly. It indicates that SH, R and SR could mitigate the large-Reynolds-stress-producing events in low wall-normal position. It is worth noting that SR shows minimum values in both the streamwise turbulence intensity and Reynolds shear stress. That is consistent with its best drag reduction effect.

Extended Abstract ID:186
Fig. 1 (a) Mean velocity profiles; (b) turbulence intensity; (c) Reynolds shear stress

Table 1 Summary of the basic experimental parameters

<table>
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<tr>
<th></th>
<th>δ (mm)</th>
<th>Re_τ</th>
<th>Re_θ</th>
<th>u_τ (m/s)</th>
<th>DR (%)</th>
<th>s+</th>
<th>lg+</th>
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</thead>
<tbody>
<tr>
<td>P</td>
<td>44.2</td>
<td>570</td>
<td>1451</td>
<td>0.01237</td>
<td></td>
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<tr>
<td>SH</td>
<td>45.5</td>
<td>565</td>
<td>1437</td>
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<td></td>
<td></td>
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<tr>
<td>R</td>
<td>44.3</td>
<td>551</td>
<td>1460</td>
<td>0.01194</td>
<td>6.9</td>
<td>23</td>
<td>15.1</td>
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<tr>
<td>SR</td>
<td>47.1</td>
<td>526</td>
<td>1542</td>
<td>0.01073</td>
<td>24.8</td>
<td>21</td>
<td>13.6</td>
</tr>
</tbody>
</table>

The Linear stochastic estimation (LSE) [3] results of conditional averaging flow fields of P, SH, R and SR at y = 0.076 (where δ corresponds to the TBL thickness) are presented in Fig. 2(a)-(d), respectively. By connecting vortex cores (red point) and stagnation points (blue point), the inclination angles of hairpin vortex packages could be seen, which are 8.5°, 10.8°, 13.7° and 14.5° corresponding to Fig. 2(a)-(d), respectively. Compared to the LSE result of P, LSE results of SH, R and SR show more consecutive and larger zones of uniform momentum (UMZ) under the yellow connecting line. The low-momentum UMZs on SH, R and SR performance as uniform ejection events, while UMZ on P performances as alternating ejection events and sweeping events. And the sweep event contributes most of the wall shear stress.

Fig. 2 Linear stochastic estimation results of different surfaces conditions

Acknowledgements This work is supported by the National Natural Science Foundation of China (Grant No. 11732010, 11572221, 11872272, U1633109, 11802195) and the National Key R&D Program of the Ministry of Science and Technology, China, on “Green Buildings and Building Industrialization” through Grant No. 2018YFC0705300.

References

