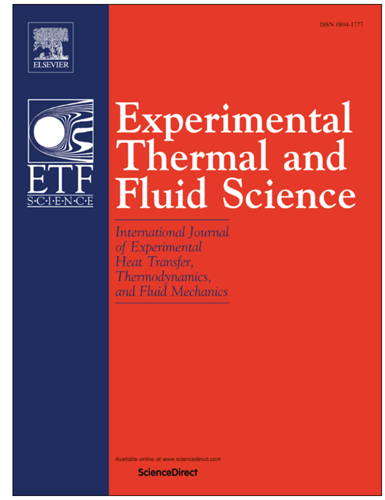

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Turbulent channel flow over riblets with superhydrophobic coating

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Abstract

The performance of riblet surfaces after applying a superhydrophobic coating (SHC) is evaluated by planar particle image velocimetry (PIV) measurement at riblet tip spacing of s^+ = 8.6, 17.3 and 34.6 (normalized using wall unit). The three riblet sizes correspond to an undersized (small drag reduction), an optimum (maximum drag reduction), and an oversized (drag increase) riblet, respectively. All the experiments are carried out in a turbulent water channel flow at constant Re_H = 4,360 (based on channel height H and average velocity). The superhydrophobic layer is formed by spray coating of micro/nano particles with a thickness of ~1λ (wall unit). The results show smaller mean velocity over the s^+ = 8.6 and s^+ = 17.3 riblets when coated with the superhydrophobic layer at near-wall region of y^+ < 15 while the mean velocity over the s^+ = 34.6 riblet with SHC is larger relative to the non-coated counterpart. The SHC increased $\langle u^2 \rangle$ over the s^+ = 8.6 and 17.3 surfaces while $\langle u^2 \rangle$ reduced over the s^+ = 34.6 surface in the near wall region of y^+ < 40. A smaller $\langle v^2 \rangle$ value is observed in the near-wall region (y^+<50) of all three riblets upon applying the SHC while the reduction is smaller for smaller riblets. The $\langle v^2 \rangle$ peak also shifts away from the wall upon coating the s^+ = 34.6 riblet. The Reynolds shear stress over s^+ = 8.6 and s^+ = 17.3 riblets is not considerably different relative to the superhydrophobic coated counterparts while a large reduction of $\langle uv \rangle$ is observed at y^+< 30 after coating the s^+ = 34.6 riblet. The estimation of drag reduction (DR) based on weighted integral of $\langle uv \rangle$ shows 6.0% and 10.1% reduction of drag over the s^+ = 8.6 and s^+ = 17.3 riblets after the SHC process, respectively. SHC on the oversized s^+ = 34.6 riblet improves the performance from 9.0% drag increase (DI) over the non-coated surface to 1.2% DR, equivalent to 10.2% reduction of drag upon coating the riblet. The larger improvement of oversized riblets (s^+>30) is associated with the effectiveness of the SHC in the larger riblet valley and consequently attenuation of ejection and sweep motions. The SHC broadens the operation range of larger riblets, which are easier to manufacture.

Keywords:

Riblet surface, superhydrophobic surface, particle image velocimetry, turbulent water channel flow

1 Introduction

High skin-friction in turbulent flows leads to large energy consumption in transport applications such as oil pipelines, marine vessels, and aircrafts. Drag reduction (DR) techniques such as polymer additives [1], microbubbles [2], superhydrophobic surfaces [3], and riblets [4, 5] have been explored to increase the performance of these systems. Among these techniques, those that do not require any energy input, such as riblet and superhydrophobic surfaces, are of particular interest.

Riblets are microgrooves aligned in the streamwise flow direction that can reduce the skin-friction component of drag by up to ~10% [4, 6]. Their performance strongly depends on their size relative to the flow scales expressed as a non-dimensional scale s^+ defined as $s^+ = s\, u_\tau / \nu$. Here, s is the cross-flow spacing between successive riblet tips, ν is the kinematic viscosity, and u_τ is the friction velocity over a smooth surface exposed to an identical flow rate [6]. Walsh [7] observed DR when s^+ < 30 with maximum DR in the range of s^+ = 15 to 20. Bechert *et al.* [6] investigated a variety of groove shapes and observed increase of the DR until s^+ ~ 17 followed by smaller DR until it turned into DI at around s^+ = 30. García-Mayoral and Jiménez [8] suggested the square-root of groove cross-section A^+_g to characterize the optimum geometry for maximum drag reduction. Their analysis showed maximum drag reduction occurs at A^+_g = 10.7 with 10% scatter in the data collected from variety of geometries.

Several investigations associated riblet DR with the shift of the streamwise vortices away from the wall and reduction in their spanwise meandering. Streamwise vortices are known to contribute to positive turbulent production through sweep and ejection motions [9]. Suzuki and Kasagi [10] conducted a detailed analysis of the turbulent flow in the riblet valley and observed impediment of energy transfer from streamwise to spanwise

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