Experimental Thermal and Fluid Science 60 (2015) 148–156

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Effect of hydrophobicity on turbulent boundary layer under water

Hu Haibao [a], Du Peng [a], Zhou Feng [b,*], Song Dong [a], Wu Yang [b]

[a] School of Marine Science and Technology, Northwestern Polytechnical University, Xi'an 710072, People's Republic of China
[b] State Key Laboratory of Solid Lubrication, Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China

ARTICLE INFO

Article history:
Received 2 March 2014
Received in revised form 19 June 2014
Accepted 9 August 2014
Available online 6 September 2014

Keywords:
Hydrophobic surface
Turbulent boundary layer
Drag reduction
Slip
Bursting event

ABSTRACT

Turbulent flow field on hydrophobic surface is measured in the gravitational low-speed water tunnel using hot-film anemometer. The mean velocity profile shows that hydrophobic surface has an apparent influence on the distribution of the turbulent boundary layer in the near-wall region ($y^+ < 80$). The turbulence intensity and friction on hydrophobic surface are also decreased. In this study, drag reduction rate up to 14.2%, and slip length up to 18.290 μm are obtained. In view of the importance of the bursting events to the production of turbulent kinetic energy and Reynolds stress, the energy distributions of flow data at $y^+ = 20$ (right in the buffer layer) are analyzed based on continuous wavelet transform (CWT), and the relation between the maximum value of energy and the bursting events is established. By proposing a new detecting method, phase averaged waveform of ejections and sweeps of the bursting events are extracted and analyzed. The results demonstrate that the intensity of the bursting events is decreased and the time scale is extended. Therefore, we concluded that hydrophobic surface decreases the turbulent fluctuations, by weakening the bursting events, and so decreases the Reynolds stress and wall friction in boundary layer, and finally results in macroscopic drag reduction in turbulence. At last, the prospect of hydrophobic drag reducing technology is discussed.

© 2014 Elsevier Inc. All rights reserved.

1. Introduction

Hydrophobic surface combines both chemical properties and topological micro-features of solid surface, and its being able to reduce drag has drawn general interests in recent years [1–3]. Hydrophobic surfaces are known to have a slip boundary condition on the wall which can support a shear-free air–water interface because of the properties of low surface energy and micro-structures [4,5]. It is expected that this slip will lead to drag reduction in both laminar and turbulent regimes.

Although intensive investigations have been made for laminar drag reduction [6,7], in turbulence, flow turns unsteady and the drag reducing mechanism will be more complicated and harder to discover. Numerical investigations have indicated that the structure of a turbulent wall-bounded flow in water can be significantly affected when the solid surface is hydrophobic. The earliest computational study was performed by Min et al. [8,9]. They studied the effects on turbulent flow field of streamwise and spanwise slip and reported that the streamwise slip decreased the drag, while the spanwise slip increased the drag [8]. Another investigation of them demonstrated that the slip effect had a significant impact on flow stability and transition to turbulence [9]. Fukugata [10] proposed an explanation of hydrophobic drag reduction in the turbulent flow regime that small alterations in momentum transfer within the viscous sublayer can have a significant impact on the entire turbulent boundary layer. The drag reducing effect of hydrophobic surface in turbulence has also been observed in many experimental investigations [11–13]. Woolford et al. [14] measured turbulent flow in a hydrophobic channel treated with a Teflon coating with Reynolds numbers ranging from 4800 to 10,000. The results showed that hydrophobic surfaces with the ribs and cavities aligned with the flow yielded an 11% decrease in the friction factor while the same surfaces aligned in the transverse direction caused a modest increase in the friction factor. Daniello et al. [15] studied the drag reduction in turbulent flows over hydrophobic surface and discovered that the onset of drag reduction occured at a critical Reynolds number, where the thickness of the viscous sublayer approached the scale of the hydrophobic micro-features. The recent developments of the effect of hydrophobicity on turbulence above are all inspiring. However, the distribution of the turbulent flow field over hydrophobic surface and the drag reducing mechanism is still not fully discovered and needs further investigations.

The wavelet transform is a powerful tool for signal-processing. It has also been used to analyze the vortical structures in turbulence, including urban turbulence [16], jet flow [17], atmospheric surface layer [18], boundary layer flow [19] etc. Camussi [20]

---

* Corresponding author.

E-mail addresses: huhaibao@nwpu.edu.cn (H. Haibao), zhouf@lzb.ac.cn (Z. Feng).

http://dx.doi.org/10.1016/j.expthermflusci.2014.08.013
0894-1777/© 2014 Elsevier Inc. All rights reserved.

promoted a technique based on wavelet transform to analyze bidimensional velocity fields obtained by particle image velocimetry (PIV), and validated to velocity vector in different flow conditions and turbulence levels. Roussel et al. [21] extracted coherent vortices in three-dimensional (3D) homogeneous isotropic turbulence with high precision based on wavelet decomposition of the vorticity field and a subsequent thresholding of the wavelet coefficients. Onorato [22] studied the statistical properties of the streamwise velocity fluctuations in a fully developed turbulent channel flow through the probability density function of the wavelet coefficients, and found that the intermittency features were dependent on the distance from the wall. Therefore, identifying the vortical structures over hydrophobic surface using wavelet analysis is a promising way to investigate the effect of surface hydrophobicity, which has not been caught too much attention.

In this paper, we conducted experimental measurements of the turbulent boundary layer using hot-film anemometer to investigate the macroscopic drag reducing effect and the acting mechanism of surface hydrophobicity. Moreover, the processes related to the bursting events in turbulence are extracted and investigated using wavelet analysis. Based on the observation in the experiment, some weaknesses limiting the practical application of hydrophobic surface are discussed, and a few significant suggestions are proposed for the prospect of hydrophobic drag reducing technology.

2. Experimental details

Experiments in this study were carried out to measure the flow field of the turbulent boundary layer in a gravitational low-speed water tunnel. Fig. 1(a) and (b) shows the photo and sketch of the water tunnel, respectively. Driven by the water level difference between the water tank and water storing basin, the water successively flows through the stabilizing section, contracting section, experimental section and electromagnetic flowmeter. Water pump is used to pump the water back into the water tank so that the water can be circulated. Flexible connection is added between each two sections to avoid the vibration of the water pump disturbing the flow field in the experimental section. To change the water speed, we can adjust the switching valve and water pump. Two criterions can be used to verify whether the water is steady, one is the number of the water speed shown on the electromagnetic flowmeter, and the other is the stability of the water in the level observing section. The size of the experimental section is 1.2 m × 0.2 m × 0.2 m, and fully developed boundary layer flow can be achieved in this section. Through repeated measurements, the water speed in this experimental system can be adjusted continuously from 0 to 1.0 m/s, the systemic error of the electromagnetic flowmeter is less than 1.0%, and the turbulence intensity in the center of the experimental section is less than 2.0%. So, the level of the external disturbance is low, and the water tunnel is capable of precise measurement of the flow field of the turbulent boundary layer.

The "IFA 300" constant-temperature anemometry system of TSI Company is used to measure the flow field of the turbulent boundary layer. It is a bridge and amplifier circuit that controls a tiny wire or film sensor at constant temperature. As the fluid flow passes the heated sensor, the amplifier senses the bridge off-balance and adjusts the voltage to the top of the bridge, keeping the bridge in balance. The voltage on top of the bridge can then be related to the velocity of the flow. This system can automatically adjust the frequency response, whose maximum value is over 300 kHz, so it is capable of capturing very high frequency fluctuations of turbulence. In this study, a single-sensor hot-film probe (model "1218–20 W") is selected, so we can only get one dimensional data of the flow signals. Although one dimensional signal can not reflect planar or spatial vortex structures, through properly data processing, the change of the flow field can still be extracted and discovered. Before the experiment, the hot-film probe is calibrated to adjust to the environment, and the measuring error of the velocity using hot-film probe is less than 1.0%. The experimental apparatus is shown in Fig. 2. The experimental plate lies on the bottom of the experimental section. The experimental plate has two parts, the black part is the hydrophobic surface, the white part and the sandpaper (40 grit) attached on it are used to accelerate the flow transition from laminar to turbulent flow. The size of the black and white part are 0.4 m × 0.18 m and 0.2 m × 0.18 m, respectively. Three brackets whose length is 0.03 m are used to support the two parts and guarantee the horizontal level. We define the start of the experimental plate as the original point. The mean flow is in the x-direction, the wall-normal direction is y and the spanwise direction is z. The hot-film probe is placed at the position $x = x_0$ upon the experimental plate in the x direction and in the middle of the experimental plate in the z direction to measure the turbulent boundary layer. In the experiment, x_0 is 0.5 m (5/6 of the experimental plate). The probe is fixed on the movable end of the coordinate frame and stretches into water through a test hole on the top. The moving error of the coordinate frame is less than 0.01 mm, which sufficiently satisfies our testing requirement of the turbulent boundary layer under water. In the experiment, the sampling frequency f_c is set to 50 kHz, and the sampling time is set to 10.24 s.

The large area fabrication of hydrophobic surface is a technical difficulty in both experimental research and practical application. This difficulty has been overcome in this study. A copper plate model of 0.4 m × 0.18 m area is prepared as the fundus of hydrophobic coating. The fabrication of our hydrophobic surface is as follows.

It has long been known that hydrophobicity can be achieved by reducing the surface energy and increasing the surface roughness. To reduce the surface energy, we coated the flat plate with

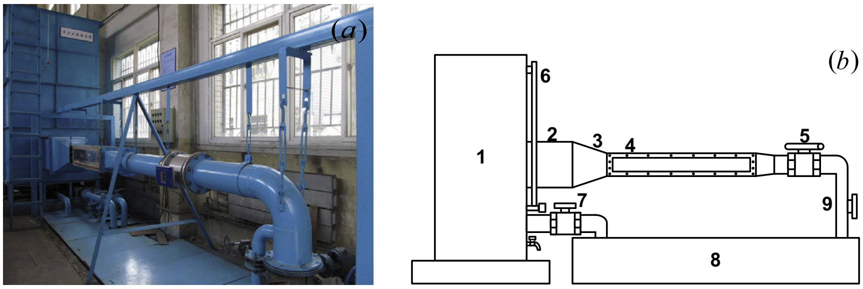

Fig. 1. (a) Photo and (b) sketch of the gravitational low-speed water tunnel, which consists of (1) water tank, (2) stabilizing section, (3) contracting section, (4) experimental section, (5) electromagnetic flowmeter, (6) level observing section, (7) water pump, (8) water storing basin and (9) switching valve.

Download English Version:

https://daneshyari.com/en/article/7052400

Download Persian Version:

https://daneshyari.com/article/7052400

Daneshyari.com