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An experimental study on the flow characteristics over a micro rib-dimple structured surface

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Abstract

Wind tunnel tests were conducted to characterize the evolution of the turbulent boundary layer flows over a dimpled surface and a rib-dimpled surface. In addition to measuring surface pressure distribution inside the dimple cavity, a particle image velocimetry (PIV) system was used to measure the detailed flow field above and inside the dimple cavity to characterize the turbulent boundary layer flows over the two test plates and the evolution of the unsteady vortex structures inside the dimple cavity. It was found that in comparison with those over a dimpled surface, the rib-dimpled surface was found to have much stronger near-wall Reynolds stress and higher turbulence kinetic energy (TKE) levels at the front portion of the dimple. The micro ribs placed in front of the dimples would generate complex shedding vortices, which further interact with the low-speed recirculating flow structure inside the dimples to enhance the turbulence mixing, therefore increase the heat transfer efficiency indie the dimple, especially at the front portion of the dimple.

1 Introduction

It is well known that the thermal efficiency of gas turbine is highly determined by the inlet temperature. With the growing demands of high inlet temperature, the development of more effective cooling techniques is urgently required for the gas turbine blades and combustion chambers. Dimpled surface, which can significantly enhance the heat transfer by generating strong unsteady vortices and meanwhile maintains a low pressure loss, is a very effective cooling strategy in forced convective heat transfer. A number of studies have been conducted in recent years to investigate heat transfer performance of dimpled surface. Ligrani et al. (2001) and Mahmood et al. (2001) indicated that the vortices shedding from the dimple edge and the flow upwash in the rear region of the dimple are the reasons for the enhanced heat transfer over the dimpled surface. Recently, Zhou et al. (2016) experimentally studied the flow behavior inside the dimple, including the formation and periodic shedding of unsteady Kelvin–Helmholtz vortices in the shear layer over the dimple, the impingement of the high-speed incoming flow onto the back region of the dimple, and the strong upwash flow in the boundary flow to promote the turbulent mixing over the dimpled surface. The heat transfer performance is greatly enhanced by these flow features.

Although the dimple can significantly enhance the convective heat transfer, the detailed experimental and numerical calculations show that at the front portion of the dimple, the heat transfer efficiency is relatively low due to the flow separation and the low-speed recirculating flow inside the dimple cavity. It was found that the heat transfer coefficient of the front portion of a spherical dimple is only 25% or even lower compared to that of the rear region (Ligrani et al., 2001, Rao et al., 2015). In the present study, micro ribs are placed in front of the dimples to induce vortex structures. These vortex structures further interact with the low-speed recirculating flow structure inside the dimples to enhance the turbulent kinetic energy inside

the dimples, therefore increase the heat transfer efficiency over the dimpled surface, especially at the front portion of the dimple.
The experimental study was conducted in a low-speed wind tunnel in Shanghai Jiao Tong University. The experimental Reynolds number (i.e., based on the hydraulic diameter of the dimple and freestream velocity) is in the range of Re=25,000–60,000. The flow characteristics over a micro rib-dimple structured surface are measured by using surface pressure taps and a high-resolution digital PIV system. The surface flow over a conventional dimpled plate is also measured for comparison. The PIV system was used to obtain the detailed characteristics of turbulent surface flows over the test plates to reveal the evolution and interaction of the unsteady vortex structures generated by the micro rib and dimple cavity. The flow field measurements were correlated with the surface pressure measurements to further expound the enhanced effect of micro ribs on the heat transfer efficiency inside the dimple cavity.

2 Experimental Setup

The experimental study was performed in a low-speed, open-circuit wind tunnel located at the School of Aeronautics and Astronautics of Shanghai Jiao Tong University. A rectangular channel was designed to simulate the channel flow inside the internal cooling channel of gas turbine blades. The tunnel has an optically transparent test section of 25mm×150mm in cross-section. The turbulence intensity level of the airflow in the test section of the wind tunnel was found to be about 1.0%.
Figure 1 shows the schematic of a micro rib-dimple structured test plate and a dimpled test plate. As shown in the figure, the two test plates are designed to have the same dimension (i.e., 245mm in length and 130mm in width). Spherical dimples with the same diameter of 20mm and thickness of 4mm are distributed uniformly on both test plates in staggered pattern. For the micro rib-dimple structured test plate, V-shaped ribs with thickness of 1mm are placed in front of the dimples

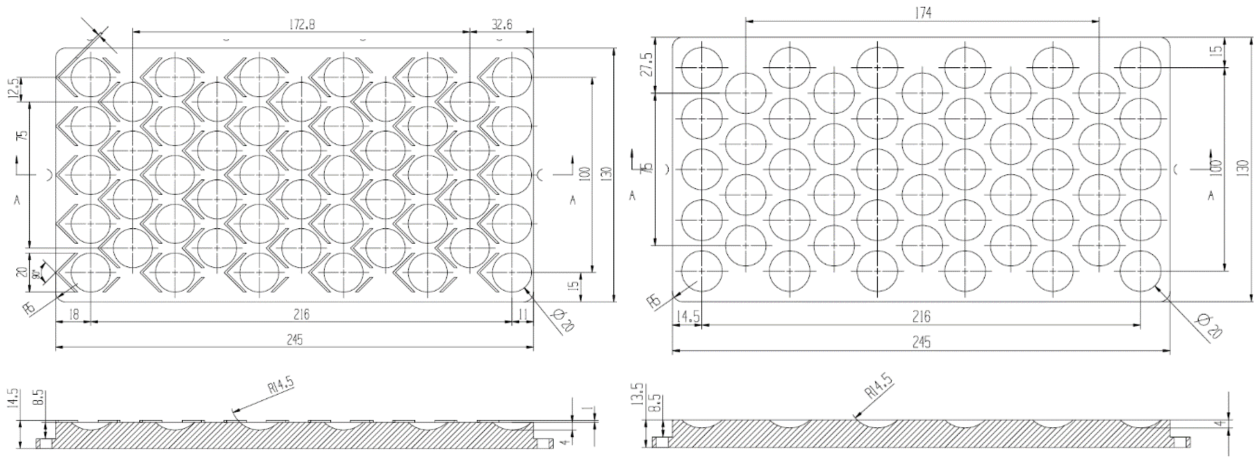
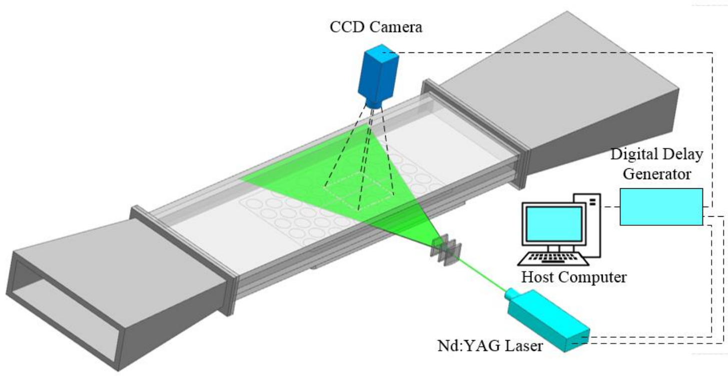


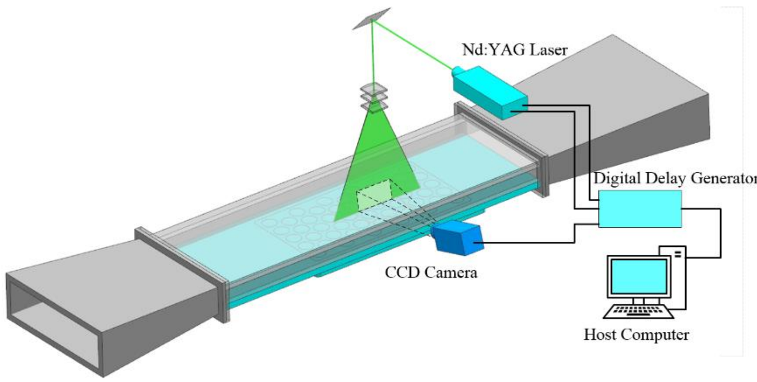
Figure 1: Schematic of the two test plates used in the present study (unit in mm): (a) a micro rib-dimple structured test plate and (b) a dimpled test plate.

A total amount of 15 pressure taps with 0.5mm in diameter for each taps were arranged inside the dimple. The pressure taps were connected to three units of digital sensor arrays (DSA3217, Scanivalve Corp) by using tubing with 1.5mm diameter and 0.2m length for the pressure data acquisition. The precision of the pressure acquisition system is ±0.05% of the 10 in. H_2O full scale range. During the experiments, the instantaneous surface pressure measurement data for each pressure tap were acquired at a data acquisition rate of 300 Hz for 300 s.
In the present study, PIV measurements were conducted to measure the detailed flow field above and inside the dimple cavity, as shown in Figure 2. The incoming airflow was seeded with ~1μm oil droplets. Illumination was provided by a double-pulsed Nd:YAG laser adjusted on the second harmonic and emitting two laser pulses of 380 mJ at the wavelength of 532 nm. The thickness of the laser sheet in the

measurement region was set to be about 0.5mm. A high-resolution 14-bit (2048 pixels×2048 pixels) charge-coupled device (CCD) camera (PCO2000, Cooke Corp) with its view axis normal to the illuminating laser sheet was used for PIV image recording.



(a)



(b)

Fig. 2 Experimental setup for PIV measurements

After PIV image acquisition, instantaneous velocity vectors were obtained by frame to frame cross-correlation of particle images, using an interrogation window of 32 pixels×32 pixels. An effective overlap of 50% of the interrogation windows was employed in PIV image processing. After the instantaneous velocity vectors were determined, the distributions of the ensemble-averaged flow quantities such as averaged velocity, normalized Reynolds Shear Stress, and normalized in-plane TKE were obtained from a sequence of about 300 frames of instantaneous PIV measurements. The measurement uncertainty level for the instantaneous velocity vectors is estimated to be within 2.0%, while the uncertainties for the measurements of the ensemble-averaged flow quantities are estimated to be within 5.0%.

3 Results and Discussion

As shown clearly in Figure 3, the distribution of the surface pressure inside the dimple cavity was found to show significantly different for dimpled surface and rib-dimpled surface. The mainstream flow would separate from the dimpled surface when passing over the front rim of the dimple, which leads to the formation of a recirculation region with relatively low surface pressure at the front portion of the dimple cavity. It can be seen that due to the effect of the flow recirculation flow, the surface pressure distribution is rather flat at the front portion of the dimple cavity. However, for the rib-dimpled surface, the flow downwash caused by the micro rib would significantly affect the recirculation flow inside the dimple. The pressure distribution shown in Figure 3(b) decrease continuously at the front portion of the dimple cavity. It means that the recirculation flow inside the dimple cavity, which induce the pressure distribution, has been weakened significantly.

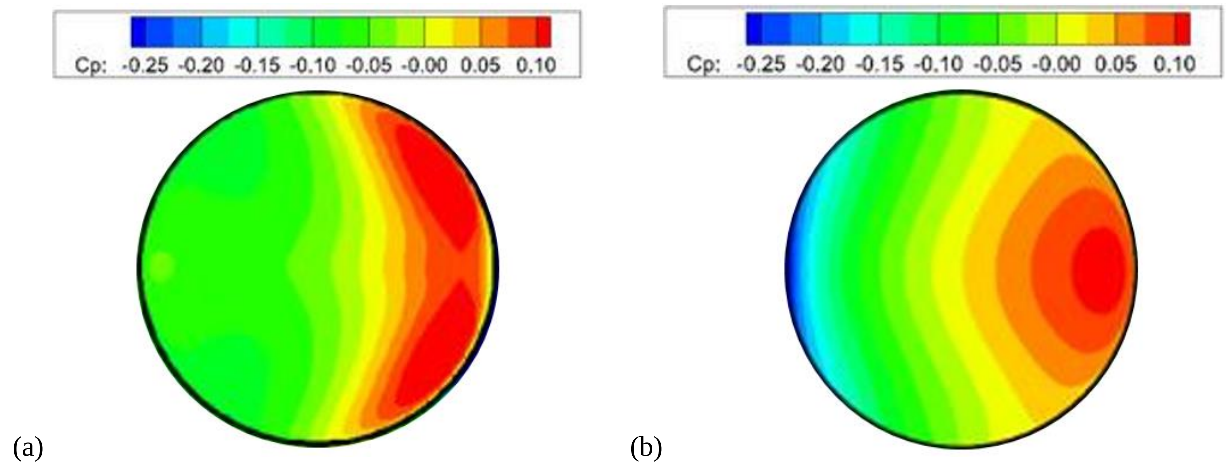


Figure 3: Measured pressure distribution inside the dimple at Re=60000 (a) dimpled surface (b) rib-dimpled surface

Figure 4 shows the ensembles-averaged velocity field for both dimpled surface and rib-dimpled surface. It can be seen that the strong downwash flow induced by the micro ribs can highly improve the turbulent flow structure inside the dimple cavity (i.e., the low-speed recirculating region inside the dimple cavity has almost disappeared). It is believed that the turbulent vortex shedding form the micro rib would move downward significantly after it flows into the dimple, which destroy the original recirculation flow and highly enhance the mixing of the fluids near the wall.

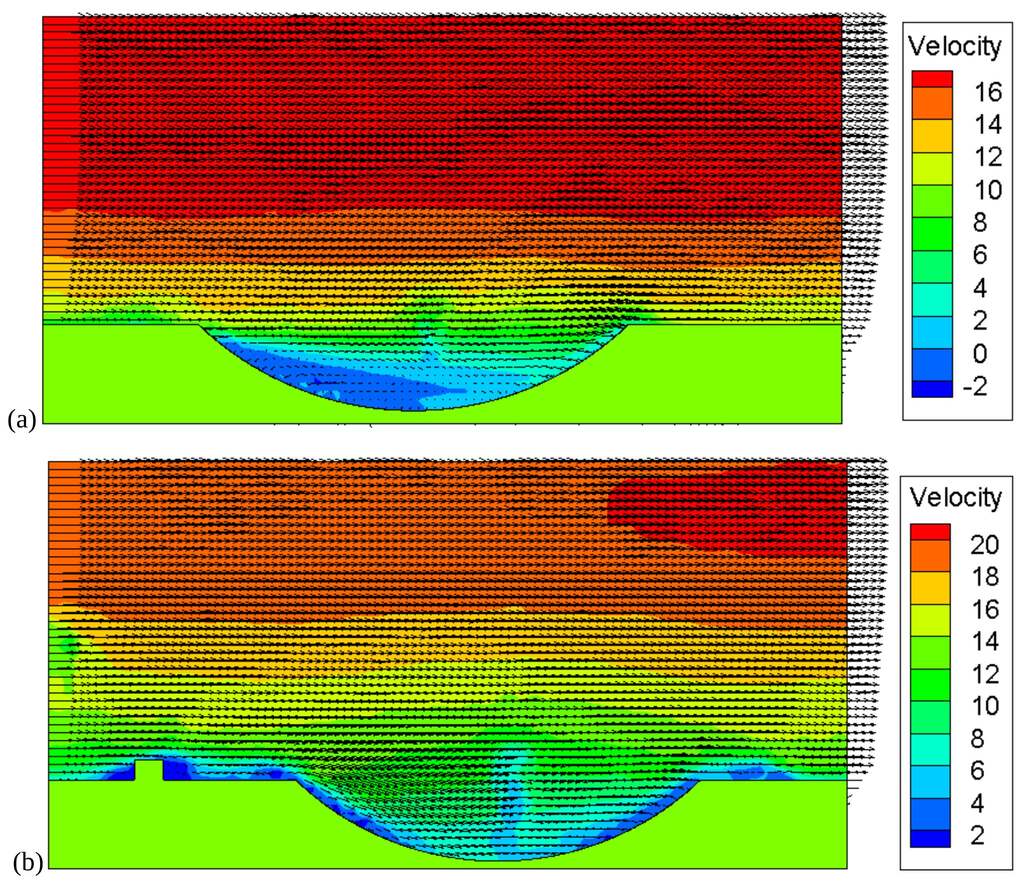


Figure 4: PIV measurement results of the flow field inside the dimple at Re=60000 (a) ensembles-averaged velocity field for dimpled surface (b) ensembles-averaged velocity field for rib-dimpled surface

4 Conclusion

In the present study, an experimental study was conducted to characterize the evolution of the turbulent boundary layer flows over a dimpled surface and a rib-dimpled surface. In addition to measuring surface pressure distribution inside the dimple cavity, a PIV system was used to measure the detailed flow field above and inside the dimple cavity. It was found that the micro ribs placed in front of the dimples would generate complex shedding vortices, which further interact with the low-speed recirculating flow structure inside the dimples to enhance the turbulence mixing, therefore increase the heat transfer efficiency indie the dimple, especially at the front portion of the dimple.

Acknowledgements

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