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Experimental PIV study of turbulent flow control by means of a combination of a dimpled surface and blowing through dimples

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This study examines how turbulent flow control is affected by a dimpled surface and blowing through dimples. The flow properties over a dimpled surface under different blowing circumstances were examined using particle image velocimetry (PIV). Velocity and shear stress profiles were measured in the vicinity of the dimpled relief and smooth flat surface for various flow sections along its development direction and then compared. The results show that controlled blowing and surface dimples can successfully change the flow structure, lower turbulence, and improve aerodynamic efficiency. Finding the optimal blowing rate has important ramifications for automotive and aerospace engineering applications.
Keywords: Drag reduction; Combined flow control; Turbulent flow; Dimpled relief; Blowing

1. Introduction

In fluid dynamics, turbulent flow control is an important field of study, especially for applications using aerodynamic surfaces. It has been demonstrated that dimples, which are tiny surface indentations, affect flow properties by delaying flow separation. In order to improve flow performance in a variety of engineering applications, this study intends to investigate the synergistic effects of dimpled surfaces and active flow control by blowing.

By energizing the flow close to the surface, dimples can alter the behavior of the boundary layer and lessen the size of the separation rise that normally occurs at higher angles of attack, as previous studies have shown. By adding high-momentum fluid into the boundary layer, active flow control methods like blowing can intensify these effects and improve flow.

2. Study methodology

2.1 Experimental setup. The experiments were conducted in a closed-loop wind tunnel that Chongqing Lantian Co., Ltd. certified in 2017. (Fig. 1). The wind tunnel has two test sections with octagonal sections. The high-speed flow area is 600*600mm, and the speed is 60m/s, according to the wind tunnel certification passport. The low-speed flow area is 1050*1050mm, the amount of flow homogeneity turbulence in the low-velocity region is 0.02% for V=20m/s and in the high-velocity region is 0.03% for V=60m/s. The turbulence intensity doesn’t exceed 0.5%.

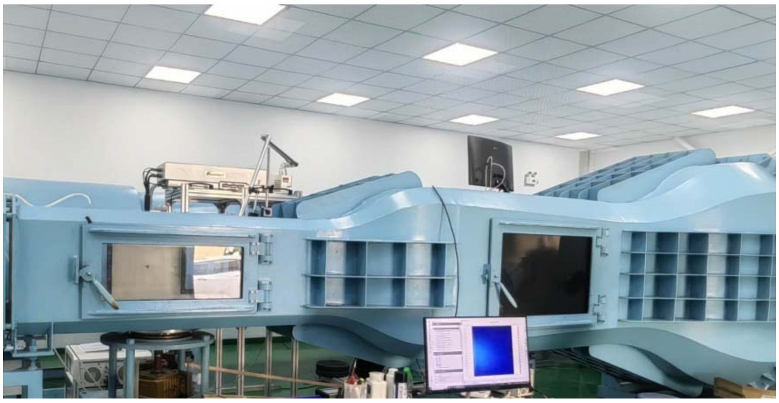

Fig. 1. ZJNU CE TR-PIV system, integrated with the wind-tunnel

A flat plate with an array of dimples was mounted by vertical rod and the magnet, on the floor of the test section. The ellipsoidal dimples had a larger diameter of 30 mm, smaller diameter of 10 mm and a depth of 3 mm, arranged in a single array with a slit or array of holes in them (Fig. 2). The wind tunnel was operated at a freestream velocity range of 5-30 m/s.

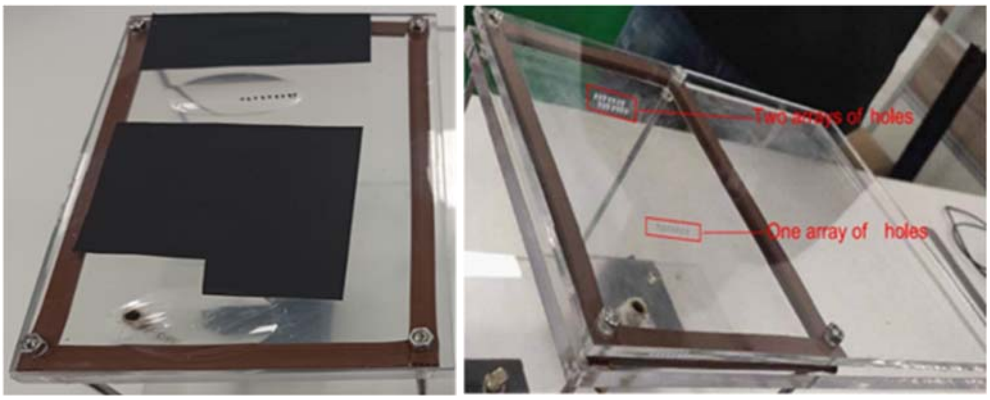

Fig. 2. Two configurations flat plate with ellipsoidal dimple(right) and a flat pate(left)

Dimples and synthetic jets are two interesting techniques utilized to manipulate boundary layers and improve aerodynamic performance. Two methods were utilized for generating steady blowing/periodic blowing-suction (synthetic jet), namely: blowing by the use of compressor (Fig. 3) and periodic air exchange through the surface by the use of speaker (Fig. 4).

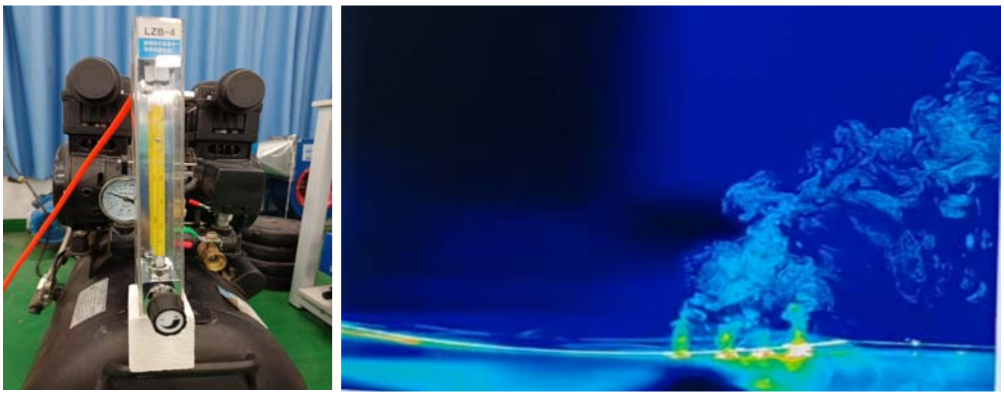

Fig. 3. Compressor, manometer and flow meter employed for providing and regulating the air rate (left) and visualization of blowing flow through the rear part of a dimple (right)

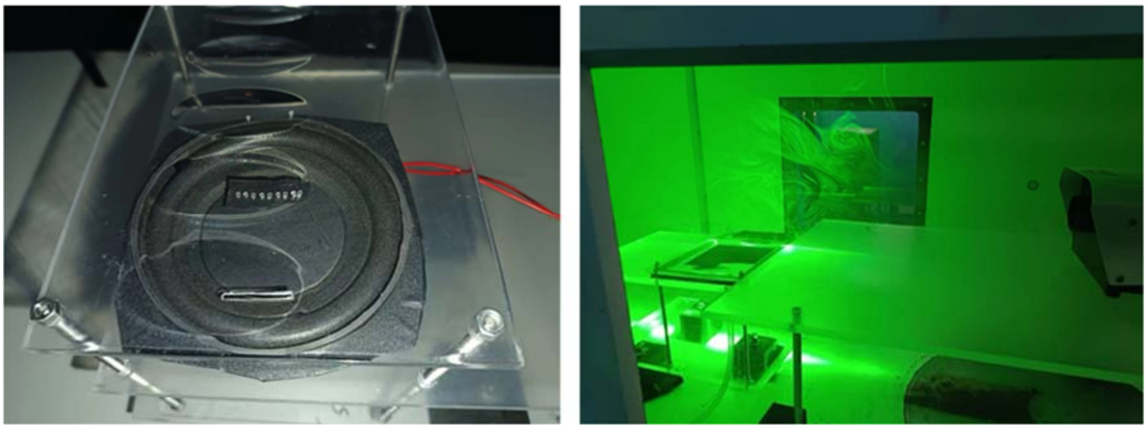

Fig. 4. Testing rig (left) and its set-up in the wind tunnel (right)

2.2 Particle Image Velocimetry (PIV) technique. Particle Image Velocimetry (PIV) as a sophisticated optical method used in many fluid dynamics applications to visualize flow fields and estimate flow velocities was used. PIV allows researchers to examine the velocity distribution and patterns inside a fluid by seeding it with tracer particles and using high-speed imaging to record their movement. This non-invasive technique helps engineers and environmental researchers better understand phenomena like turbulence, mixing, and aerodynamic performance by offering insightful information about intricate flow behaviors.

2.3 Blowing Mechanism. The experiment uses an Arduino micro-controller to control a speaker, which produces sound waves at the desired frequency range. The speaker is mounted under a dimpled plate, creating a synthetic jet of air through holes/slits. The diaphragm moves, creating alternating phases of suction and blowing, resulting in a synthetic jet. Air is then blowed into the bounded space of the testing rig, exiting through holes/slits. Another innovative method for improving fluid flow properties and managing boundary layers in aerodynamics is periodic blowing and suction through surface dimples. This technique energizes the boundary layer, delays flow separation, lowers drag, and encourages mixing, sustaining connected flow throughout a wider range of angles of attack.

2.4 Data analysis. The PIV data were processed to obtain velocity profiles and turbulence intensity. Velocity data analysis with MATLAB enables effective processing, analyze, and visualize fluid flow characteristics. Adjust the code as needed based on a specific data-set and analysis requirements. Flow separation was analyzed by visualizing the streamlines and identifying the separation points, which were marked by a significant drop in velocity.

3. Main results

3.1 Flow Visualization. The PIV results showed distinct changes in the flow structure over the smooth (Fig. 5) and dimpled (Fig. 6) flat streamlined surfaces. Without blowing, the flow exhibited significant separation at the trailing edge of the dimples, characterized by a large vortices' separation. However, with blowing, the flow remained attached longer, effectively reducing the size of the separation vortices and improving flow attachment.

3.2 Velocity profiles. Velocity profiles at various positions downstream of the dimples were obtained. The results indicated that blowing through the dimples increased the mean velocity near the surface, enhancing momentum transfer and reducing turbulence intensity. For instance, at a blowing velocity of 10 m/s, the mean velocity increased by approximately 25% compared to the baseline case (no blowing).

3.3 Turbulence characteristics. The analysis revealed that the combination of dimples and blowing significantly reduced turbulence intensity compared to the baseline case (flat plate without dimples or blowing). The optimal blowing rate was found to be 10 m/s, which provided the best flow control, resulting in a turbulence intensity reduction of about 40% compared to the no-blowing condition. The experimental findings suggest that the combination of a dimpled surface and blowing can be an effective strategy for turbulent flow control. The dimples serve to modify the flow structure, while active blowing enhances this effect by re-energizing the boundary layer. This dual approach can lead to improved aerodynamic performance in applications such as automotive and aerospace engineering.

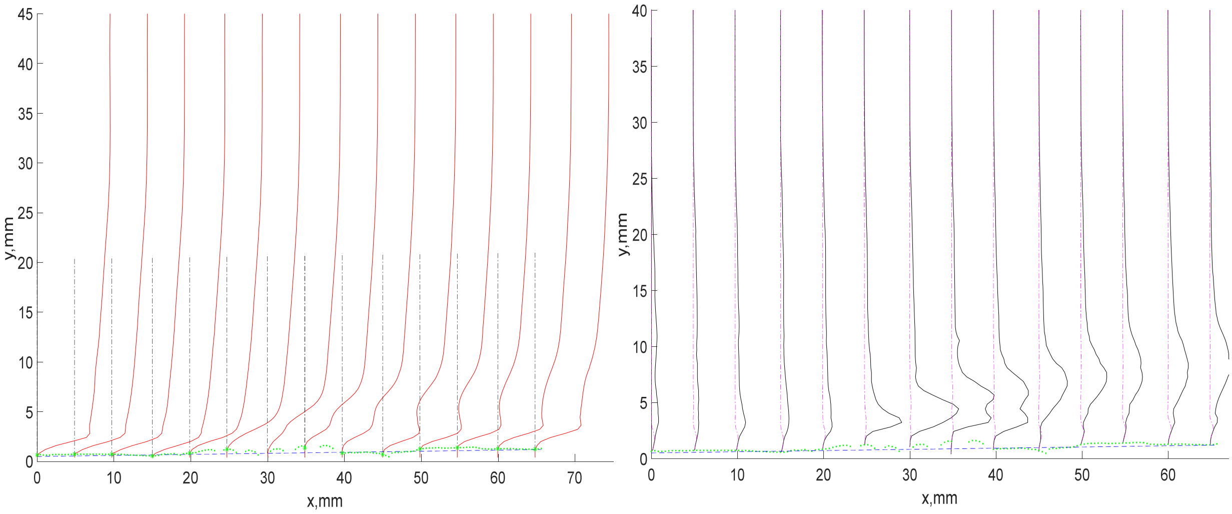

Fig. 5. Velocity profiles (left) and turbulent shear stress profiles (right): measuring place – mid-plane, main flow speed V=10m/s, blowing mode Q=10L/h (smooth flat plate)

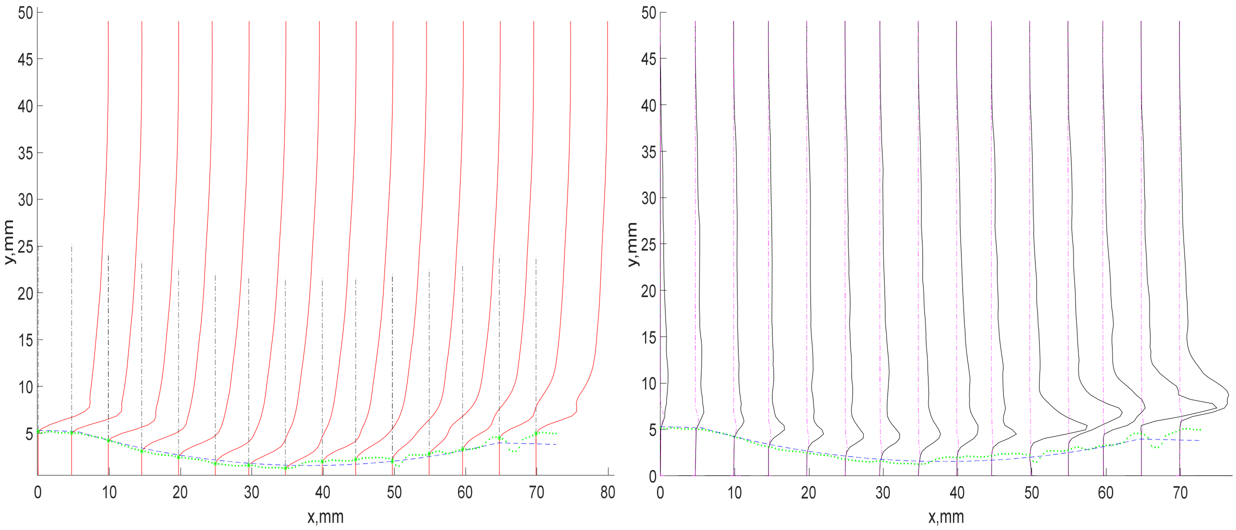

Fig. 6. Velocity profiles(left), and turbulent shear stress profiles (right): measuring place – mid-plane, main flow speed V=10m/s; blowing mode Q=10L/h (dimpled flat plate)

4. Conclusions and further research plans

This study demonstrates the potential of using a combination of dimpled surfaces and blowing for turbulent flow control. The experimental PIV results indicate that this approach can effectively reduce turbulence and improve flow attachment. Further research is recommended to explore the implications of this technique in practical applications and to optimize the design parameters for various flow conditions. Investigating the long-term effects of this flow control method on performance and efficiency could provide valuable insights for future engineering designs. The results indicate that careful optimization of blowing rates is crucial, as excessive blowing may lead to flow destabilization. Future studies could explore the effects of different dimple geometries and arrangements, as well as varying blowing angles and frequencies, to further enhance flow control strategies.

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