Physics Letters A 378 (2014) 2672–2682

Contents lists available at ScienceDirect

Physics Letters A

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The characteristics of surface arc plasma and its control effect on supersonic flow

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ARTICLE INFO

Article history:
Received 9 April 2014
Received in revised form 11 June 2014
Accepted 13 July 2014
Available online 21 July 2014
Communicated by F. Porcelli

Keywords:
Surface arc plasma
Discharge characteristic
Supersonic
Shock wave
Flow control

ABSTRACT

The characteristic of surface arc plasma included millisecond and microsecond actuation in supersonic flow is investigated both experimentally and numerically. In the experiment, the discharge characteristic of surface arc plasma in quiescent air and supersonic flow is recorded. The stable oblique shock could be observed with millisecond actuation. And the unstable compressive wave could be also observed with microsecond actuation. In the numerical investigation, plasma actuation is defined as a source term with input power density from discharge V–I characteristic, which is expected to better describe the influence of heating process. The numerical results are coincident with experimental results. In order to confirm the capability of surface arc plasma actuation to control supersonic flow, experimental investigations on control shock induced by ramp and separation of boundary layer induced by impinging shock are performed. All the results demonstrate the control effect of surface arc plasma actuation onto supersonic flow.

1. Introduction

Shockwave is the typical aerodynamic phenomenon in supersonic flow, and if controlled effectively, a series of potential applications can be achieved, such as reducing the wave drag. The wave drag has great influence on the flight performance of the aircrafts and can consume a large proportion of the fuel. Therefore, to reduce fuel consumption and to increase the aircraft range as well as supersonic cruise, the reduction of wave drag has become an important issue. Shockwave-boundary layer interactions (SWBLIs) commonly occur in high-speed flows from the transonic to the hypersonic regime. They can be found in a variety of applications including transonic wings, axial turbines, and mixed-compression inlets. The interaction often results in performance detriments because the boundary layer must negotiate the imposed adverse pressure gradient. The effect of the adverse pressure gradient of the boundary layer can cause separation. These effects (especially the increased unsteadiness and aerodynamic blockage associated with separation) have the potential to reduce system performance significantly.

Shockwave and boundary layer control can be achieved by many mechanical and aerodynamic methods, such as the ramp angle control in supersonic inlet and the vortex generators control in self-adapted wing. Because the mechanical configuration is complex and the flow control response is slow, plasma flow control method has become the research hotspot in the international aerodynamics and thermodynamic field and is expected to bring significant benefits for aircraft such as improved performance and lower cost [1–5]. It has many advantages such as simple structure, flexible control and excitation frequency bandwidth.

The experimental investigation on shock control by plasma aerodynamic actuation was carried out at High Temperature Research Institute in Russian Academy of Sciences [6,7]. The results of experiments showed that, after using the plasma aerodynamic actuation, it could induce weakly oblique shock and reduce the angle and intensity of shock wave in supersonic flow. State University of New Jersey in the United States carried out experimental and numerical studies of shock control by the plasma aerodynamic actuation [8,9]. They applied cylinder model to generate detached shock and employed pulsed microwave discharge to produce plasma. The results of experiments showed that, with plasma aerodynamic actuation, the normal shock intensity at the center place of detached shock was weakened and shock shape was bended. Meyer et al. [10] investigated whether the control process of shock was dominated by the thermal or ionization mechanism through plasma aerodynamic actuation.

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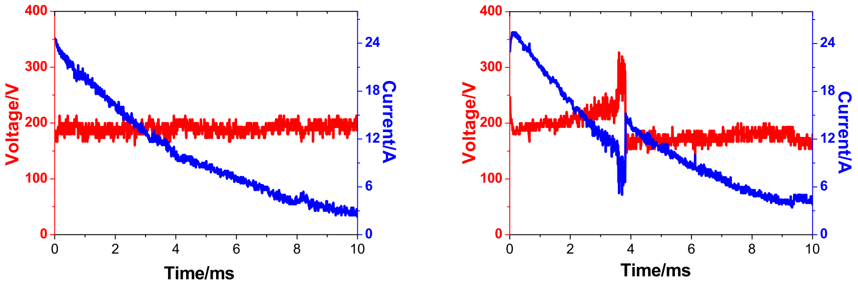
http://dx.doi.org/10.1016/j.physleta.2014.07.016

(a) Surface arc discharge in quiescent air

(b) Surface arc discharge in supersonic flow

Fig. 1. The discharge picture with surface arc plasma.



(a) The V-I plot in quiescent air

(b) The V-I plot in supersonic air

Fig. 2. The V–I plot with discharge voltage of 1 kV.

Recently, localized arc filament plasma actuators (LAFPAs) were developed at the Ohio State University as a means to introduce strong, tailored, high frequency perturbations to flow [11–14]. They forced incoming boundary layer at a frequency close to one of the instability frequencies associated with the reflected shock interacting with the unsteady separation bubble. This resulted in reduction of the separation bubble size and reflected shock unsteadiness. For the mechanism of flow control, they could not reach an agreement between Joule heating effect and unsteadiness manipulation effect. Separation bubble forcing was also performed using a magnetically driven gliding arc to modify static pressure distributions downstream and modulate the flow in the separation region [15, 16]. Using an upstream-directed Lorentz force at low discharge currents (80 mA), it was able to create a local separation bubble for incipient SWBLIs. At higher discharge current (200 mA) and with downstream-directed Lorentz forcing, they were able to demonstrate a considerable reduction in the length scale of the separation bubble. Another approach used a pulsed plasma jet to force an oblique shock on a compression ramp in a Mach 3 flow [17]. It was reported that convection of thermal spots in the incoming boundary layer displaces the oblique shock location upstream, while forcing in the separation bubble did not produce a detectable effect. In addition, the researchers found that, when actuation was used at the upstream of the shock, it was possible to lock the low-frequency instability movement of the shock, effectively reduced the flowing pressure fluctuations near the wall. Flow forcing by repetitive thermal perturbations in NS-DBD actuators was applied for SWBLIs [18]. The main idea of this approach was forcing the flow with high amplitude, high bandwidth perturbations, at a frequency approaching one of flow instability frequencies, thus triggering their subsequent growth in the flow. These results suggest that plasma-induced shockwave-boundary layer flow forcing may have a potential for high-speed flow control applications.

Surface arc plasma actuators have also been developed at the Science and Technology on Plasma Dynamics Laboratory at the Air Force Engineering University in China [19–22]. In the present work, the characteristic of surface arc plasma included millisecond and microsecond actuation in supersonic flow is investigated both experimentally and numerically. Through the modeling of electrical heating, the arc domain is defined a source term with input power density from discharge V–I characteristic, which is expected to better describe the influence of heating process. At last, experimental investigations on control shock induced by ramp and separation of boundary layer induced by impinging shock are performed. All the results demonstrate the control authority of surface arc plasma actuation onto supersonic flow.

2. The discharge characteristics affected by supersonic flow

The shape of arc plasma is shown in Fig. 1 from top view. From Fig. 1(a), we can see that the discharge arc is strongly bounded near the wall surface. The inner layer of discharge arc is white which indicates the plasma temperature is very high, but the outer layer is blue and purple because of its weak discharge intensity. There are three pairs of electrodes in supersonic flow. Compared with quiescent flow, we can observe that arc discharge spreads the whole electrodes areas from Fig. 1(b), which is strongly blown downstream by the supersonic gas flow, and it's a large-area surface discharge near the wall.

2.1. *The discharge characteristics of millisecond actuation*

The design Mach number of the small-scale short-duration supersonic wind tunnel is 3 and its steady operation time is about 60 milliseconds. The test section is rectangular with 100 mm wide and 30 mm high. The gas static pressure and static temperature in the test section are 2813 Pa and 105 K respectively. The groove in the test section lower wall is designed for the plasma actuator fabrication. Plasma actuator consists of a pair of electrodes and the insulating dielectric. The electrodes are made of copper, and flush-mounted on the top wall of the insulating dielectric. The diameter of the electrode is 10 mm. The insulating dielectric is made of BN (Boron Nitride) ceramic.

The plasma power source adopts pulsed DC power source which consists high voltage pulsed circuit, high voltage DC circuit and feedback circuit. The high voltage pulsed circuit breakdowns the gas and this step lasts extremely short time of about 1 microsecond. The second step is the DC hold-up process and maintains about 10 milliseconds.

The electrical parameter measurement system includes DPO4104 oscilloscope, P6015A high voltage probe and TCPA300 + TCP312 current probe for measuring voltage and current.

Fig. 2(a) is the discharge characteristics in quiescent air. This curve contains only the high-voltage DC discharge. When applying