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Study of influencing characteristics on boundary-layer separation controlled by using DBD plasma actuator with modified model

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ABSTRACT

For more effectively utilizing state of the plasma flow characteristics, to control separation of boundary layer from the subsonic to supersonic, the vortex flow, viscous coupling including shock induced separation, to improve combustion stability and efficiency, thereby minimizing the parasitic resistance and controlling separation bubble issue effectively. Therefore, the main research focus of this paper will be divided into two parts. The first part, the experimental design and measurement will be implemented under atmosphere temperature and pressure conditions, including the actuator for driving the high-voltage AC dielectric plasma between the geometric parameters and the actuating voltage and the relationship between the discharge characteristics of actuator. The second part, we apply the finite volume method to solve the Navier-Stokes equations, and combines the modified physical model of electrostatic field. Through the applied AC voltage and charge density equation for solving Maxwell's equations and the way of obtaining an electric field, investigate the dielectric discharge flow affecting the acceleration effects of normal atmospheric pressure plasma and its impact on the boundary layer flows of thin plate. According to the mentioned above, considering the number of different geometric parameters and different actuator free flow conditions, the impact of physical parameters, for instance, electric potential, electric density and body forces which generated by plasma actuator in computational model, and their further interactions with thin plate boundary layer flow, and then the induced velocity field are discussed in detail.

1. Introduction

The overall design of the system for future hypersonic space flight vehicles, and similar aerial vehicle which combines hypersonic propulsion system, according to the actual flight conditions from subsonic to transonic, and to hypersonic, the boundary layer separation will occur since different flight conditions and high angle of attack in subsonic flow field. When the speed exceeding Mach one, the hyper speed stream will induce the flow characteristic so-called thin layer of shock waves. Which means the shock waves and the wall of vehicle is in the distance that is very close to the boundary layer of scale. Hence, there is viscous interaction phenomenon caused by shock waves and boundary layer interfere (SWBLI) with each other. In addition, the flow temperature increase rapidly due to the hypersonic flow and also increase the thickness of boundary layer which induced by viscous friction more than in low speed flow. Non-viscous flow outside the thicker boundary layer therefore will have a significant impact, so that strengthening the viscous interaction which mentioned before. Thus, not only the boundary layer separation problems in the subsonic flow but also the viscous interaction has a great influence on pressure, lift, drag, and stability on the surface of hypersonic vehicle and propulsion system, and the enhance the friction and heat transfer effects between fluid and solid.

Moreover, due to the thickness of boundary layer accumulates rapidly so that the shock waves generate enough energy, and the pressure gradient will produce separation shocks and induce boundary layer separation. The phenomenon continues further to downstream wedge. At the position behind the angle of wedge, the shock recovers and re-contacts to the surface of wedge, so called phenomenon of reattachment shock. Separation bubble in this process will result in the formation of large-scale pulsations and thus generate separation shock vibrated phenomenon. It will lead to the key components of the vehicle serious vibration and heat load.

1.1. Controlling problems for flow separation and SWBLI

In order to improve the control problems of separation, so far, there are lots of related flow control research at subsonic flow,

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Nomenclature

e	specific internal energy [J/kg]
E	specific energy [J/kg]
F	frictionless flux vector [N/m^2]
h	entropy [kJ/kg]
P	pressure [psi]
r	specific local flux [–]
R	gas constant [J/kg · K]
s	switching function [–]
t	time [s]
T	temperature [K]
u	velocity in x-axis [m/s]
U	vector of conservation variables [N/m^2]
$v_{\max}$	maximum propagation velocity [m/s]
V	volume [m^3]
∂V	unit surface [m^2]

Greek symbols

Δ	difference [–]
ϕ	A potential due to external electric field [N/m^2]
γ	ratio of specific heats [–]
φ	A potential due to net charge density in plasma [–]
ρ	density [kg/m^3]
κ	thermal conductivity [W/m · K]
μ	coefficient of viscosity [kg/s · m]

Index symbols

i,j	step number of individual displacement [–]
K	individual control volume [m^3]
s	average [–]

Mathematical symbols

$\overline{U}$	mean value of conserved variable vector [–]
max	maximum [–]
min	minimum [–]

for example: slats, flaps, vortex generators as well as boundary layer suction and blowing and other control methods. However, these traditional methods will result in additional negative unintended parasitic drag or complex moving parts. For controlling the problems of coupling viscous shock and instability separated flow, some of technical concepts, up to now has been developed success mainly focusing on controlling upstream boundary layer and separation bubble inside. The control methods according to their properties yet mainly divides into two types, active and passive control. Comparing the active and passive control devices, the active control devices has smaller side effects of parasitic drag.

Up to date, most studies show that using active control mode to control the coupling of shock and boundary layer is more desirable than using passive control mode. Which is due to the characteristics of active control mode's design method is when you need to control the boundary layer, it will instantly start up automatically. On the other way, the active control method can also avoid the control device would have been interference coupling flow field, and can achieve the advantage of reducing the resistance at the same time. Over the years about the active boundary layer control methods focus mainly on boundary layer suction and blowing device, and vortex generator jet. Vortex generator jet is used widely in the field of controlling subsonic flow of boundary layer separation. For example, Compton and Johnston [1] study the influence of vorticity by changing the pitch angle and the tilt angle. The results show that the pitch angle between 30° and 60° tilt angle between 60° and 90° can produce the greatest vorticity. The study of Zhang and Collins indicates that embedded vortex generator jets in the boundary layer to control fluid separation is most significant. Moreover, Bueno et al. [2] implement stable and pulse jet vortex generators to obtain controlling of coupling of shock and boundary layer. In which the vortex generator pulsed frequency between 10 Hz and 100 Hz, while using PIV conduct shock and boundary layer interaction phenomenon measurement. The results indicate that boundary layer becomes thicker at the downstream of vortex generator jet, but thinner at the further downstream. However, according to the results, both continuous and pulsed jets can cause the downstream separation shock an offset.

The studies focused on understanding the physical mechanism of coupling of flow separation and separation bubble, and used the method of control fluid to change the scale of separation bubble. Unfortunately, this goal has not yet be reached so far, even though the scale of separation bubble can be further shortened currently, but its frequency broadband instability is still evident. In order to control the problems more effectively, such as mentioned above, subsonic flow separation and compressible flow coupling viscous shock, thereby face effectively to the flight conditions that is more stringent than design conditions, the recent studies have further used the concepts of plasma discharge methods to control the frequency of coupling of separation flow and separation bubble. Plasma flow control is a new concept of flow control technology. Through plasma gas flow control actuation, the energy of electrical field can be transformed into gas molecules momentum or heat of the boundary layer, changing the flow field structure and physical properties of the boundary layer, thereby inhibiting boundary layer flow separation and obtaining continuity of fluid flows.

1.2. Plasma flow control

The flow control of plasma based, especially the actuating element operating in low temperature plasma and at atmospheric pressure, it has many features, such as high bandwidth, no-moving-par actuation, short response time, against corrosion and the mechanical degradation presence in other conventional actuator. To date, magnetohydrodynamic (MHD) drive control is still developing. In order to view the effects of Lorentz force act in the fluid, still require considerable ionization. So the application still has certain difficulty. For a variety of electric discharges method used to control fluid to change the aerodynamics and driven fluid flow researches, in recent years, most of studies are concentrated on dielectric barrier discharge (DBD) and plasma jet.

When the electric field of fluid motion on considering the impact of media on the electric field in the fluid motion, many current phenomena and the interactions between the two bodies produced [3], while for the requirements of precision, energy-saving and miniaturization and other new technological developments, electrohydrodynamics (EHD) has the key advantages of this application, hence in recent years has gradually attention in relevant areas of fluid flow control. For example: Melcher et al. [3] proposed research leaky dielectric related models, and focus on exploring the physical phenomenon of convection within the liquid in AC/DC electric field with a thin layer of liquid droplets. In recent years, Saville [4] had complete review of the relevant research of combining the leakage dielectric medium model and the physical mechanism of the charge generated in its distribution, especially for topologies of structure of spherical and cylindrical geometry.