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Flow structure generated by laser-induced blast wave propagation through the boundary layer of a flat plate

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ABSTRACT

Laser energy deposition generates localized flow structures that can be used as flow control devices in high-speed flows. In the present study, the interaction between a laser-induced blast wave and an incoming laminar boundary layer on a flat plate was experimentally investigated at a Mach 5 flow with three different unit Reynolds numbers. A hemispherical laser-induced blast wave (LIBW) is induced by focusing a 532 nm pulsed Nd:YAG laser beam on the surface of the plate. The hemispherical shaped fore wave front of the LIBW is locally transformed to an oblique shape, which results in a laser-induced oblique shock wave (LIOSW). As LIOSW propagates through the laminar boundary layer increases its thickness. With laser energy deposition near the leading edge of the flat plate, the LIOSW interacts and influences the leading edge shock wave (LSW). This interaction could contribute to the modulation of the LSW in scramjet intakes. A weak shock limb generated at the shape transition point of the LIBW or thermal spot due to laser-induced gas breakdown causes the boundary layer perturbation. The geometrical pattern produced due to the interaction between the LIOSW and the disturbed boundary layer remains similar to itself as it grows with time as well as at different local Reynolds numbers, 2.2×10^5 to 5.7×10^5.

1. Introduction

Laser energy deposition is an emerging technique to improve the aerodynamic performance of high-speed vehicles, and it has potential for various applications such as drag reduction [1,2], shock wave modification [3,4], and a controllable perturbation device for boundary layer transition studies [5]. Laser energy deposition can improve scramjet engine efficiency, thereby enabling the high-speed flying vehicles to operate at a wide range of Mach numbers. Scramjet engine efficiency deteriorates at an off-design flight Mach number by modulating the leading edge shock because shock waves impinging within the engine inlet at a certain angle can only be achieved at a predetermined flight Mach number [6]. A numerical work by Macheret et al. [7] suggests that energy addition can be used to increase efficiency and performance at off-design flight Mach numbers. Drag reduction is directly related to more efficient transportation and less emission of harmful gases. When considering energy deposition upstream of a blunt body at a Mach 5 freestream flow, the bow shock wave interaction with the low density spot generated by energy deposition induces counter rotating vortices due to the baroclinic instability, which interact with the boundary layer of the blunt body, contributing to drag reduction [8].

Understanding of shock wave boundary layer interaction (SWBLI) is important for the improvement of aerodynamic performance. Complex flow features, such as: impinging oblique shock waves, normal shock wave reflections, and ramp flows are all present in a high-speed vehicle even without laser energy deposition. Laser energy deposition induces a blast wave and low density thermal spot, which results in complex SWBLI. Yan et al. [9] numerically investigated the effect of pulsed laser energy deposition on a normal shock–boundary layer interaction in the intake of an engine, and they showed that the normal shock wave moves towards upstream due to laser energy deposition. According to an experimental investigation [10], laser energy deposition can delay the shock induced separation over a flared cylinder. Tamba [11] and Iwakawa [12] showed that the boundary layer oscillation was significantly altered by the laser pulse duration.

The interaction of a blast wave with a boundary layer can have many complicated flow features. In the present study, experiments were conducted to understand the interaction between the laser-induced blast wave and the incoming laminar boundary layer on

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Table 1
Experimental conditions.

Unit Reynolds number Re_{unit} [m^{-1}]	Total pressure P_t [kPa]	Total temperature T_t [K]	Freestream pressure P_∞ [kPa]	Mach number
11.0×10^6	547.75	372.3	1.03	5.0
13.0×10^6	640.62	375.5	1.23	5.0
14.4×10^6	719.9	375.5	1.36	5.0

a flat plate at a Mach 5 freestream flow. High-speed Schlieren photography was employed as the flow diagnostics technique. The laser induced blast wave was located at four different axial locations along the centerline of the plate. The flow structures due to the interaction were compared at three different unit Reynolds numbers.

2. Experimental setup

The experimental investigations were conducted at Mach 5 freestream flow with unit Reynolds numbers of 11.0×10^6, 13.0×10^6, and 14.6×10^6 m^{-1}, in an intermediate high supersonic blowdown wind tunnel. This wind tunnel consists of a high pressure vessel, an electrical heater, a setting chamber, an axisymmetric Mach 5 nozzle, a test section, a diffuser, and a vacuum tank. The stable Mach 5 flow is maintained up to 7.5 seconds. The flow properties and wind tunnel configuration are presented in Refs. [13–15]. The flow conditions are shown in Table 1. A flat plate model with its upper surface located on the nozzle centerline, was supported by a sting. The leading edge of the flat plate was sharp edge with the lower surface chamfered by 12°.

A Q-switched 532 nm pulsed Nd:YAG laser was used to deposit energy into a boundary layer of the plate. The laser beam (203 mJ/pulse with pulse width of approximately 4 ns) is introduced into the test section from the top window of the tunnel using a laser guide arm. In the present experiments, a combination of three lenses was used as suggested by Schmisseur et al. [5,16]. The combination of the lenses enables focusing the laser beam into a smaller spot to obtain higher energy density even at the same laser beam energy level. The 25.4 mm concave lens with focal length of −100 mm expands the laser beam, then the 50 mm diameter convex lens with 250 mm focal length collimates the beam expansion. The laser beam is focused into a small spot at the focal position of the third convex lens. All of the optical lenses and the top window were coated with antireflective coating for a wavelength of 532 nm. The laser beam was focused on the flat plate at various streamwise positions along the model centerline. The laser focal positions were $L = 10$, 20, 30, and 40 mm downstream of the leading edge of the flat plate.

To visualize the unsteady phenomena, high-speed Schlieren photography with a standard Z-type optical arrangement was employed. The optical system consists of a 300 W continuous xenon arc lamp for light source, two 203 mm parabolic mirrors with focal length of 1829 mm, and a high-speed camera (Photron, Fastcam SA-1.1). A horizontal rectangular slit in front of the light source creates a light spot that illuminates the first parabolic mirror. The light beam is then collimated by the first mirror and passes through a quartz side window. A second parabolic mirror reflects the collimated beam after the beam passes through the test section and the opposite quartz side window. A horizontal knife-edge is located at the focal point of the second parabolic mirror. The high-speed camera recorded the images at 90 kfps with an exposure time of 1 µs. An offset angle between the collimated light beam and the light path from the light source to the first/second mirrors was set at 10 degrees to prevent coma aberration.

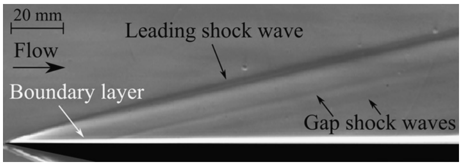

Fig. 1. The Schlieren image of the Mach 5 flow with $Re_{unit} = 13.0 \times 10^6$ m^{-1} over the flat plate without laser energy addition.

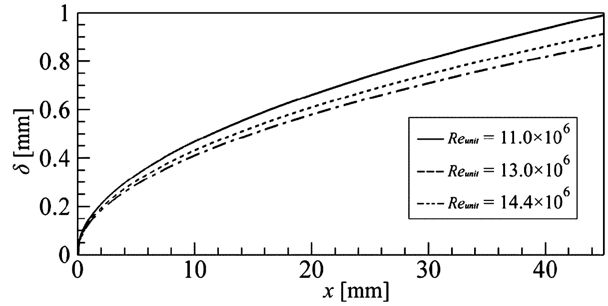

Fig. 2. Theoretical prediction of boundary layer thickness on the flat plate in Mach 5 flow.

3. Results and discussions

3.1. Flow structure without laser energy deposition

Fig. 1 shows the flow structure over the flat plate without laser energy addition. A leading shock wave (LSW) generated from the leading edge of the flat plate is slightly curved in the vicinity of the leading edge due to viscus interaction. When hypersonic flow passes over the flat plate, the large displacement thickness of an initial boundary layer from a leading edge makes a virtual body. This virtual body refracts the incoming inviscid flow and consequently induces a slightly curved oblique shock wave [17,18]. The weak compression waves are induced by a gap of the pressure taps along the model center line and would hardly affect the flow over the flat plate. The white region above the flat plate indicates the boundary layer growing in thickness gradually with distance. Namely, it is laminar boundary layer. To calculate the boundary layer thickness, a theoretical prediction is employed. Based on velocity distribution in a compressible laminar boundary layer on an adiabatic flat plate, thickness of the laminar boundary layer δ is predicted as;

$$\delta = \xi \cdot \sqrt{\frac{\nu_\infty \cdot x}{U_\infty}} \quad (1)$$

According to Schlichting [19], a non-dimensional parameter $\xi \approx 15.5$ for Mach 5 flow corresponds to a local velocity of $0.99U_\infty$. Where, U_∞, ν_∞, and x are the velocity, the kinematic viscosity, and the streamwise surface distance from the leading edge, respectively. The subscript "∞" refers to the freestream conditions. The theoretical predictions of boundary layer thickness, shown in Fig. 2, indicate thinner boundary layer which is almost similar to boundary layer thickness on the Schlieren image (Fig. 1). In the present unit Reynolds numbers, boundary layer thickness grows up to approximately 1 mm at the laser focal region of 40 mm from the leading edge. The relation between boundary layer thickness and laser-induced flow structure is discussed later.

3.2. Laser-induced flow structure

Laser energy deposition on the flat plate generates a blast wave that induces a localized flow perturbation. Fig. 3 shows the typical Schlieren images of the laser focusing at 40 mm from the