Numerical Analysis of Interaction Between Single-Pulse Laser-Induced Plasma and Bow Shock in a Supersonic Flow*

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Abstract The interaction of laser-induced plasma and bow shock over a blunt body is investigated numerically in an $M_\infty=6.5$ supersonic flow. A ray-tracing method is used for simulating the process of laser focusing. The gas located at the focused zone is ionized and broken down and transformed into plasma. In a supersonic flow the plasma moves downstream and begins to interact with the bow shock when it approaches the surface of the blunt body. The parameters of flowfield and blunt body surface are changed due to the interaction. By analyzing phenomena occurring in the complex unsteady flowfield during the interaction in detail, we can better understand the change of pressure on the blunt body surface and the mechanism of drag reduction by laser energy deposition. The results show that the bow shock is changed into an oblique shock due to the interaction of the laser-induced low-density zone with the bow shock, so the wave drag of the blunt body is reduced.

Keywords: laser-induced plasma, supersonic drag reduction, bow shock, flow characteristics

PACS: 52.38.-r, 52.50.Jm

DOI: 10.1088/1009-0630/14/8/11

1 Introduction

Using laser energy deposition to reduce the wave drag of a vehicle in a supersonic flow has been paid much attention in recent years [1~5]. The physical mechanism of drag reduction is the interaction of plasma generated by laser energy deposition with the bow shock formed over a blunt body. Therefore, a deep understanding of the effect of laser energy deposition on the reduction of pressure on the front surface of a blunt body is absolutely necessary.

Recently, researchers in China and abroad have begun to study the interaction between laser-induced plasma and bow shock in a supersonic flow. P. Yu GEORGIEVSKY and V. A. LEVIN [6] theoretically studied the dynamic effect of pulsing energy sources on bow shock wave structures for different body shapes. T. SAKAI et al. [7] numerically and experimentally investigated the interaction between laser-induced plasma produced by pulse laser energy deposition and the shock wave over a blunt body at $M_a=3$.

In this paper, the ray-tracing method is used to simulate the process of laser focusing and a numerical study is conducted to analyze the evolution of the flowfield during the interaction of plasma with bow shock in a supersonic flow. Efforts are made to firstly give a satisfactory explanation of the time evolution of the interaction flowfield. Secondly, the time history of pressure, density and temperature distribution along the centerline is calculated. Finally, the wave drag is obtained by integrating the calculated pressure distribution over the body.

2 Physical model and numerical method

2.1 Physical model

The energy conversion model of laser transmission is: a. For a laser, energy is absorbed and scattered by gas, while the intensity of the laser begins to attenuate. Because the free path of scattering is larger than that of absorption, the absorption mechanism plays a major role and the transmission of the laser can thus be described by the radiation transport equation. b. For gas, the energy lost during the laser transmission converts into gas energy, which in turn changes the parameters of the thermodynamic state. The process of fluid flow with laser energy absorbed by gas can be described by the fundamental equations of fluid dynamics with an energy source added into the energy equation [8].

*supported by National Natural Science Foundation of China (No. 90916015)
2.2 Numerical method

The numerical investigations have been performed within the framework of an inviscid perfect gas model on the basis of the 2-D axisymmetric Euler equations written in conservative form. In Cartesian coordinates the equations are:

$$\frac{\partial W}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} = Q,$$  \hspace{1cm} (1)

where, $W$ is conservation variable, $F$ and $G$ are inviscid functions and $Q$ is the energy source, their expressions are:

$$W = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ \rho E \end{pmatrix}, \quad F = \begin{pmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ (\rho E + p)u \end{pmatrix},$$

$$G = \begin{pmatrix} \rho v \\ \rho uv \\ \rho v^2 + p \\ (\rho E + p)v \end{pmatrix}, \quad Q = \begin{pmatrix} 0 \\ 0 \\ 0 \\ Q_L - Q_R \end{pmatrix},$$  \hspace{1cm} (2)

where, $\rho$ and $p$ denote the gas density and pressure, respectively, $u, v$ are the $x, y$ velocity components, $E$ is the total energy of gas per unit volume. $Q_L$ and $Q_R$ are the energy added term due to laser energy absorption by gas and the energy loss term arising from high temperature gas radiation. The expressions of $Q_L$ and $Q_R$ can be found in Ref. [8]. $Q_L$ is a function of laser energy and an inverse bremsstrahlung absorption coefficient, $Q_R$ is a function of the radiator temperature. In this paper, the plasma is produced by a single-pulse laser, so the change of density from laser energy absorption is not considered. In further studies on high-repetition frequency laser energy depositions, the deposition model needs to be improved.

$E$ is defined as:

$$E = e + \frac{1}{2} (u^2 + v^2),$$  \hspace{1cm} (3)

where, $e$ is the internal energy of gas per unit volume.

The equation of state of a perfect gas is used to close the system of gasdynamic equations:

$$p = \rho RT.$$  

2.3 Initial and boundary conditions

Fig. 1 presents the geometry of the blunt body considered in this paper. The blunt body consists of a hemisphere and a cylinder, and this model will be called the sphere-cylinder in the following text. The radius $r$ of the hemisphere is 0.1 m, and the length of the cylinder is 0.4 m. Fixed supersonic inflow conditions corresponding to a standard altitude of 30 km are used on the inflow boundary, and slip wall conditions are applied to the surface of the blunt body. Table 1 gives the gas parameters at 30 km altitude. In numerical simulation the single-pulse laser energy is supposed as 3.25 J, the pulse width at 10 s and the location of laser deposition at $x = -0.2$ m.

Fig. 2(a)~(f) show the calculated pressure, density, temperature contours, relative density, pressure and temperature curve distribution along the centerline (the relative density, pressure and temperature are the ratio of density, pressure and temperature after laser energy deposition to density, pressure and temperature of flowfield), and relative pressure curve distribution along the surface of the blunt body at $t=30 \mu$s, respectively.

From Fig. 2(a), it is found that the blast wave reaches the surface of the bow shock. The transmission wave caused by the interaction between the blast wave and the bow shock reaches the surface of the blunt body, so the pressure along the blunt body surface rises, as can be found in Fig. 2(a) and (f). A bigger low-density region is shown in Fig. 2(b) with a diameter of about 7 cm.

Table 1. Computational parameters

<table>
<thead>
<tr>
<th>Height</th>
<th>Density</th>
<th>Temperature</th>
<th>Pressure</th>
<th>Mach</th>
<th>Specific</th>
<th>number heat ratio</th>
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</thead>
<tbody>
<tr>
<td>30</td>
<td>$1.84 \times 10^{-2}$</td>
<td>226.51</td>
<td>$1.197 \times 10^{3}$</td>
<td>6.5</td>
<td>1.4</td>
<td></td>
</tr>
</tbody>
</table>

3 Results and discussion

The laser beam is focused on some zone in front of blunt body, the gas gets ionized and broken down in this zone and becomes plasma. The absorbed laser energy is changed into internal energy of the plasma. The plasma is coupled with the flow. This transmitting movement of plasma absorbing laser energy is usually called a laser absorption wave [9]. The laser absorption wave moves downstream under the action of supersonic flow, then approaches the surface of the bow shock over the blunt body and begins to interact with the bow shock. The interaction process between the plasma and the bow shock is as follows.

From Fig. 2(a)~(f) show the calculated pressure, density, temperature contours, relative density, pressure and temperature curve distribution along the centerline (the relative density, pressure and temperature are the ratio of density, pressure and temperature after laser energy deposition to density, pressure and temperature of flowfield), and relative pressure curve distribution along the surface of the blunt body at $t=30 \mu$s, respectively.
Fig. 2  Single-pulse laser energy interaction with the bow shock at \( t = 30 \) µs (color online)

Fig. 3  Single-pulse laser energy interaction with the bow shock at \( t = 50 \) µs (color online)

Fig. 3 shows the next phase of flow development at \( t = 50 \) µs. The heated region created by the laser energy deposition begins to interact with the bow shock and the bow shock is deformed due to the decrease in local Mach number, which was called the “lens effect” by GEORGIVSKI and LEVIN [10]. This deformed bow shock can be seen in Fig. 3(a) and (b). From comparison of Fig. 2(c) with Fig. 3(c), the shapes of the
heated region are different and the heated region is compressed, the diameter diminishes from 7 cm to 2 cm. As seen from Fig. 3(c), the compressed high temperature gas does not reach the sphere-cylinder surface. At the same time, the blast wave penetrating through the bow shock reflects off the sphere-cylinder surface. The surface pressure in the neighborhood of the stationary point is decreased because of reverse flows. Surface pressure peaks exist in the vicinity of the reflection line of the blast wave (the point A), which can be seen in Fig. 3(a) and (f).

The results at $t = 70 \, \mu s$ are shown in Fig. 4. These results indicate that the heated region is produced in the region between the deformed bow shock and the reflected blast wave, and has not reached the surface of the blunt body, so the temperature of the surface is not high. From Fig. 4(a), the blast wave is very close to the deformed bow shock. From the Fig. 4(a) and (f), the rarefaction reflections off the surface and the pressure of surface decrease. Outside of the rarefaction fan’s influence, the surface pressure peaks in the vicinity of the blast wave reflection line, and the pressure peak points move away from the stationary point as compared to Fig. 3(a).

The next interaction stage at $t = 90 \, \mu s$ is shown in Fig. 5. At this time, the reflected blast wave moves to the surface of the blunt body, which increases the pressure near the stagnation point (Fig. 5(f)). From Fig. 5(e), the relative temperature distribution along the centerline increases as compared with the previous figures shown in Figs. 2(e), 3(e) and 4(e). The temperature flowfield shows that the heated gas from the central part of the compressed thermal spot begins to penetrate to the sphere surface (Fig. 5(c)). However, this high temperature domain is still behind the repeated reflected blast shock, which moves together with the main flow to the sphere surface.

The results at $t=500 \, \mu s$ are presented in Fig. 6(a)~(f), respectively. At this time, the flowfield structure over the blunt body gradually returns to the steady-state one shown in Fig. 1. From Fig. 6(f), the pressure on the surface is higher than the steady-state one because a compression wave remains when the bow shock moves to the blunt body surface.

The relative temperature curves at different time are shown in Fig. 7. At $t = 30 \, \mu s$ the temperature is higher than that at $t = 0 \, \mu s$ because of the interaction between the laser plasma and the bow shock. At $t = 50 \, \mu s$ the temperature near the stagnation point begins to descend due to the reverse flow, which is consistent with Fig. 3 (c). At $t = 70 \, \mu s$ the low temperature region enlarges. At $t = 90 \, \mu s$ the temperature at the stagnation point rises quickly. The temperature begins to decrease in the following time and returns to the steady-state one (without a laser) at $t = 500 \, \mu s$.

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(a) Calculated pressure, (b) Calculated density, (c) Calculated temperature, (d) Streamlines, (e) Relative density, pressure and temperature distribution along centerline, (f) Relative pressure distribution along the surface of the blunt body

Fig. 4 Single-pulse laser energy interaction with the bow shock at $t=70 \, \mu s$ (color online)
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Fig. 5  Single-pulse laser energy interaction with bow shock at $t=90 \, \mu s$ (color online)

(a) Calculated pressure, (b) Calculated density, (c) Calculated temperature, (d) Streamlines, (e) Relative density, pressure and temperature distribution along centerline, (f) Relative pressure distribution along the surface of blunt body

Fig. 6  Single-pulse laser energy interaction with bow shock at $t=500 \, \mu s$ (color online)

(a) Calculated pressure, (b) Calculated density, (c) Calculated temperature, (d) Streamlines, (e) Relative density, pressure and temperature distribution along centerline, (f) Relative pressure distribution along the surface of blunt body

Fig. 8 shows the drag variation on the front surface of sphere-cylinder body (the red line). The drag at each time is calculated by integrating the pressure along the front area of the model. From Fig. 8, a first sharp increase can be seen at $t = 26 \, \mu s$. After this first increase, at $t = 42 \, \mu s$, the drag begins to reduce because the blast wave reflects off the wall. The second increase is caused by the reflected wave moving to the blunt body at about $t = 80 \, \mu s$. The following reduction is recognized at about $t = 123 \, \mu s$. The third drag increase is followed by the second reduction and then the drag returns to its steady-state value. The drag variation is consonant with the pressure contour evolution.
4 Conclusion

A numerical study is made of the interaction between laser-induced plasma and a bow shock over a sphere-cylinder blunt body in a supersonic flow. The flowfield structure of single-pulse laser-induced plasma interacting with bow shock has been specified. In conclusion, the main process of interaction between laser-induced plasma and bow shock can be divided into four phases. Firstly, following the interaction of the blast wave with the bow shock, the pressure on the surface of blunt body rises. Secondly, with the interaction of the high temperature region with the bow shock, the pressure reduces. Thirdly, the high temperature region moves to the downstream and the pressure rises again. Lastly, the interaction ends and the pressure returns to its original value.

References


(Manuscript received 20 September 2010)
(Manuscript accepted 2 September 2011)
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