Numerical simulation for the influence of injected laser power on plasma drag reduction

Z Liu¹, Z G Dou², H Huang² and J Fang¹

¹Department of Postgraduates, the Academy of Equipment Command and Technology, 3380 Post box, Huairou Beijing 101416, China
²Department of Basic Theories, the Academy of Equipment Command and Technology, 3380 Post box, Huairou Beijing 101416, China

E-mail: liuzhun0@gmail.com

Abstract. Laser plasma drag reduction is a new method to reduce the wave drag of hypersonic flight. Inject laser power is an important parameter. An appropriate laser power should be chosen when laser power was injected to achieve the best drag reduction effect via the minimum laser power. The effect of inject laser power on the performance of laser plasma drag reduction when incoming flight Mach number is 6.5 and at 30km altitude was simulated numerically. The result indicates that the drag can be effectively reduced by energy injection in the upstream flow. The larger the inject power is, the smaller the drag of the blunt body obtained. The energy injection can also influence the pressure and temperature on the surface of blunt body. When laser energy injected, high pressure region on the surface moves to the back of the hemisphere, the pressure of stagnation point decreased. There are two peaks of temperature on the blunt surface, one is the stagnation point and the other is the high pressure region. Temperature of the surface after high pressure region is lower comparison to the condition that no energy injected.

1. Introduction
The wave drag of aircraft can be reduced effectively by inject laser energy into the hypersonic incoming flow. Myrabo, et al., first suggested that add energy to support the Directed-Energy Air-Spike (DEAS) ahead of the craft to reduce wave drag[1]. The drag of the aircraft may be greatly reduced is mainly due to that energy deposition could break the structure of bow shock on the craft surface and weak oblique shock formed, aerodynamic resistance due to the pressure difference between front and back of the craft. Besides, it changes the velocity direction of incoming flow, guide airflow to the periphery of aircraft, also made the drag reduced.

Laser plasma drag reduction has been investigated in some countries, and mainly concentrated in Russia, the United States and so on. Myrabo, et al., had experimental and computational investigation about the drag of blunt body in different inject energy[2]; David Riggins, et al., investigated blunt body drag reduction using focused energy deposition numerically[3]; Meiliang Mao, et al., had study the relation between positions of laser energy injection and the drag the blunt body suffered by solve viscous Navier-Stokes equations numerically[4].

Using laser plasma to reduce the drag of aircraft is an efficiency method, but related research is not extensive developed in our country, especially for drag reduction performance optimization. The inject power of laser is an important parameter among performance optimization. When laser energy

Published under licence by IOP Publishing Ltd
injected, we need to choose appropriate power, and expect to achieve best drag reduction performance by inject minimum energy. Thereby, base on previous work by others, this paper numerical simulated the effect of laser energy injection to the blunt body drag when \(Ma=6.5\), the relation between injected laser power and laser plasma drag reduction performance has been researched. Through comparing the results, we can find that higher injection laser power made the blunt body suffered less resistance. But, if the power is too high, the efficiency of the laser energy significantly dropped. We expect that this work can provide assistance for the future experimental study to choose appropriate inject laser power.

2. Computation Methodology and Parameter Definition

2.1. Parameter Definition
Two parameters can be defined to provide insight into the usefulness of the energy deposition concept[5]. The first one is \(R\), which is the normalized drag; the second one is \(S\), which is power effectiveness.

\[
R = \frac{D_{\text{mod}}}{D_{\text{ref}}} \quad \quad (1)
\]

\[
S = \frac{(D_{\text{ref}} - D_{\text{mod}})V_{\infty}}{\phi} = \frac{D_{\text{ref}}V_{\infty}}{\phi} (1 - R) \quad \quad (2)
\]

In these expressions, \(\phi\) is the injected power, \(V_{\infty}\) is the velocity of the incoming flow. \(R\) is \(D_{\text{ref}}\) divided by \(D_{\text{mod}}\), which means the actual drag obtained with the flowfield modification divided by the drag of the body without any flowfield modification (the reference case). \(S\) is the ratio of the propulsive power savings due to flowfield modification divided by the power required to modify the flow, or the energy deposition rate.

2.2. Computation Methodology
Aerodynamic was described by Euler gasdynamic equations and viscosity was not considered. The gas equation of state was under the air model of high-temperature equilibrium gas[6]. The equations were solved by using a Roe scheme of second order space accuracy and a MUSCL approach.

The energy is deposited upstream of the blunt body on the centerline axis. Assume that Laser energy deposited instantaneously, laser focus in the fire region, a high temperature and pressure region was formed. Laser energy was equal distributed to each computation grid. When the injected energy in the fire region grids exceeds the breakdown threshold of air, the air in this region was breakdown, and laser plasma generated.

2.3. Computation Condition
The blunt body used for computation is composed by a hemispherical nose which diameter is \(D=10\text{cm}\) and a cylinder which diameter is 10cm. The solutions use a 400×300 grid. The computation configuration and boundary conditions was show in Figure 1. “Inflow” is the supersonic inflow boundary condition; “Outflow” is the supersonic outflow boundary condition. Incoming flow comes from left side of x-axis to the right side. Fire region was in the upstream of the blunt body, the distance between blunt body and center of the fire region is \(2D\). The fire region is rectangular, which length is \(0.1D\), width is \(0.05D\). Because the computation model is axisymmetrical, the fire region is a cylindrical region essentially.
3rd International Photonics & OptoElectronics Meetings (POEM 2010) IOP Publishing
Journal of Physics: Conference Series 276 (2011) 012026 doi:10.1088/1742-6596/276/1/012026

3. Results and Discussion

3.1. Flowfield without laser energy injection

According to the shock wave theory, for each incoming Mach number $Ma$, there is a maximum flow turning angle $\alpha_{\text{max}}$. Because the model is a blunt body, when the hypersonic flow near its surface, the turning angle approach to $90^\circ$, and this angle exceed $\alpha_{\text{max}}$, the shock wave detach the blunt body surface. We could consider that the front of the detached bow shock as a normal shock. When the incoming flow penetrated normal shock, its velocity decelerated to subsonic, and the pressure increased sharply, the blunt body suffered great wave drag.

The computation result indicates that intensive bow shock will be formed ahead the nose of the blunt body, as shown in Figure 2. In order to obtain steady state field and stable drag of the blunt body, compute time was set to 250$\mu$s. The drag of blunt body suffered was about $D_{\text{ref}}=247.17$N. This drag was the reference drag. The distance between the bow shock and the surface of blunt body is about 0.0075m. The highest pressure, in the stagnation point, was about $6.50\times10^4$Pa, about 54 times of the environmental pressure.
Figure 2. Pressure Contours of steady flow field at mach 6.5.

Lobb had investigated the relationship between the front face of the shock wave and the stagnation point distance in stable condition [7]:

\[
\Delta = 0.41D\left(\frac{\gamma - 1}{\gamma + 1}\right)M^2_a + \frac{2}{\gamma + 1}M^2_a
\]

in the equation, \(\Delta\) is the distance between the front face of the shock wave and the stagnation point, \(D\) is diameter of craft, \(\gamma\) is specific heat ratio, \(M_a\) is Mach number of incoming flow.

According to the expression, substitute the computation conditions, we can obtain that

\[
\Delta = 0.41 \times 0.1 \times \left(\frac{(1.4 - 1) \times 6.5^2 + 2}{(1.4 + 1) \times 6.5^2}\right) = 0.007642m
\]

Compare to this result, the numerical simulation result differ approximately 1.9%. So, it is feasible to simulate the aircraft wave drag in hypersonic stream by this program.

3.2. The effect of inject power to the drag of the blunt body

After the steady flow field build, the laser energy was input into the incoming stream ahead the blunt body. The computation compared the effect to the blunt body drag when inject energy power is 1kW, 2kW, 5kW, 10kW, 20kW, 50kW. Energy was continuous injected after steady flowfield has been established, that is, after 250 \(\mu\)s. Compare to the condition when no energy injection, the drag of the blunt body suffered obvious decreased, the decreased level related to inject power.

Table 1 provides a comprehensive listing of 6 energy power performance with values \(R\) and \(S\):

| \(P/kW\) | \(D_{mod}/N\) | \(R\) | \(S\) |
|---------|----------------|------|------|
| 1       | 207.94         | 0.841| 76.93|
| 2       | 202.80         | 0.820| 43.51|
| 5       | 188.70         | 0.763| 22.93|
| 10      | 153.71         | 0.622| 18.33|
| 20      | 102.66         | 0.415| 14.17|
| 50      | 67.90          | 0.275| 7.03 |
If the inject energy power increase, the blunt body decreased. When inject power is 50kW, the drag of the blunt body suffered is 27.5% of the base drag. Figure 3 shows the normalized drag, power effectiveness when in different inject power.

![Figure 3. Curves of normalized drag and power effectiveness to inject power.](image)

Fig 3 indicates that the drag of the blunt body dropped as the inject energy power increased; if the power is higher than 20kW, the tendency of drag decreasing is gently. As the inject power increase from 1kW to 10 kW, power effectiveness dropped sharply; if the power is higher than 10kW, power effectiveness dropping tend slowly. So, lower power is expected to get higher power effectiveness, but if the inject energy power is too low, the decrease of blunt body drag is inconspicuous.

3.3. Analysis of the computation result
The curves of drag vs. time under different inject energy power is shown is Figure 4.

![Figure 4. Curves of drag vs. time.](image)

When no energy added, the drag of the blunt body kept stable (1–250µs). As energy begin to add in, an inverse impulse act on the blunt body surface, the drag increase at first, and then decrease rapidly. The decrease speed depends on the input power, if higher power is injected (50 kW for example), the drag drop almost vertically; if lower power is injected (10 kW for example), the decline of the drag is a little slowly. And if lower power is added in, the drag will reach a minimum value, and then resume to a higher level, for an example, the inject power is 1kW, the blunt body drag will get the
minimum value at 577µs, and the value is 87.0N, then, it resume to 207.9N; if the inject power is 50kW, the drag continuous decrease, and will get the minimum value at 557µs, the minimum value is 39.7N, and then reach a stable drag near 67.9N. So, if low power is injected, a minimum drag will be reached, but it can’t maintain a better drag reduction performance.

The flowfield of the blunt body periphery under 5kW injected power is shown in Figure 5. In the laser energy focus region, laser supported denotation wave (LSDW) is generated, as shown in Figure 5a. The LSDW propagate to the surface of blunt body surface, and then penetrate the bow shock, an inverse thrust acted on the blunt body, the drag increase. Then, because the high temperature and low density region of the denotation wave interior, the pressure of the stagnation point decrease, the top of the bow shock move ahead, until the structure of the bow shock is destroyed (Figure 5 b). At last, the flowfield of the blunt body periphery get stable again, and a structure like oblique shock is formed (Figure 5 c).

![Figure 5. Pressure contours of flow field in different times.](image)

Figure 6 shows the stable flow field under different inject power. The laser focus region is like a small “wedge” in the flow field. The high temperature and low density region formed by the LSDW cause the top of the bow shock move ahead, and transform to oblique shock (main shock). A triangle front separation region formed in the oblique shock, its top is behind the fire region. The velocity direction of incoming stream which far from the axis is changed, but the incoming stream which near the axis will penetrate the oblique shock into the separation region, and a second shock will be formed in the oblique shock (secondary shock). When the inject power increase, the main shock get more intensive, the front separation region get larger, and the secondary shock weakened.

![Figure 6. Pressure contours of flow field under different inject power.](image)

The pressure and temperature in axis and blunt body surface under different inject power is shown in Figure 7.
Figure 7. Pressure and temperature in axis and blunt body surface under different inject power.

When laser energy add in, the high pressure region on the blunt body surface move toward back of the hemisphere (Fig 5, Fig 6), the pressure of stagnation point decrease, from greater than 60kPa drop to near 10kPa. The highest pressure in the blunt body surface decreased as the inject energy power increased. In the back part of the blunt body, the influence of the inject power to surface pressure is much less than in the nose of the blunt body. There are two peaks of the temperature of body surface, one peak is the temperature of the stagnation point, higher than no energy added in, and increased as the inject power increased; the other peak is the region which pressure is the highest in the surface. The surface temperature drop rapidly after the second temperature peak and it is lower than no energy added in.

Myrabo et al. give a formula of the optimization laser energy power when radius of the LSDW is constant[8]:

\[ P = 2(\gamma + 1)\alpha^\gamma pc_0R^2Ma \]  

In the equation, \( \gamma \) is specific heat ratio, \( \alpha \) is numerical coefficient, \( \alpha = 0.937 \) for \( \gamma = 4/3 \), \( p \) is pressure, \( c_0 \) is local sound velocity, \( R \) is radius of the denotation wave, \( Ma \) is Mach number of the incoming flow. From Figure 5 we can see that when the denotation wave propagates to the blunt body surface, its radius is about 0.035m. From the formula, the theoretical optimization power is about 15kW. From Figure 3 we can see that when inject laser power is 15kW, the normalized drag is small and the power effectiveness can hold in about 15.

4. Conclusions

The drag of the blunt body obvious dropped by injecting energy into the hypersonic incoming flow. This paper investigates the variation of the blunt body drag under different injected laser power by numerical simulation, and summarize as follows:

- Higher inject power can get better drag reduction effectiveness, when injected power is 50kW, the drag of the blunt body drag is 27.5% of the base drag;
- Less injected power can get higher power effectiveness, when injected power is 1kW, the power effectiveness reach 76.93;
- When the hypersonic incoming inflow penetrates the oblique shock, the pressure and temperature of the blunt body surface changed obviously. High pressure region moves towards the back of the blunt body nose, and the highest pressure decrease as the injected energy power increase. The temperature of the stagnation point will be higher compare to no energy add in, but the temperature behind the high pressure is lower than the temperature when no energy add in.
So, in the experimental investigation, the inject power should be appropriate chosen between normalized drag and power effectiveness to expect use least injected energy to save most propellant. At the same time, the variety of the pressure and temperature should also be considered.

References
[1] Myrabo L N 1978 Solar-Powered Global Air Transportation AIAA Paper No.78-0689
[2] Bracken R M, Hartley C S, Mann G, Myrabo L N, Nagamatsu H T, Shneider M N and Raizer Y P 2003 Proc. of 1st Int. Symp. on Beamed Energy Propulsion, 2003 485-96
[3] Riggins D W, Nelson H F and Johnson E 1999 AIAA Journal 37 460-7
[4] Mao M L, Dong W Z and Deng X G 2001 ACTA Aerodynamica Sinica 19(2) 172-6
[5] Riggins D W, Barnett J T and Taylor T 2003 12th AIAA Int. Space Planes and Hypersonic Systems and Technologies (Norfolk Virginia 15-19 December 2003)
[6] Li Q, Hong Y J and Cao Z R 2006 Explosion and Shock Waves 26(6) 550-5
[7] Lobb R K 1964 The High Temperature Aspects of Hypersonic Flow 519-527
[8] Myrabo L N and Raizer Y P 1994 25th AIAA Plasmadynamics and lasers Conf. (Colorado 20-23 June 1994)