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Theoretical analysis and numerical simulation of the impulse delivering from laser-produced plasma to solid target*

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A plasma is produced in air by using a high-intensity Q-switch Nd:YAG pulsed laser to irradiate a solid target, and the impulses delivering from the plasma to the target are measured at different laser power densities. Analysing the formation process of laser plasma and the laser supported detonation wave (LSDW) and using fluid mechanics theory and Pirri's methods, an approximately theoretical solution of the impulse delivering from the plasma to the target under our experimental condition is found. Furthermore, according to the formation time of plasma and the variation of pressure in plasma in a non-equilibrium state, a physical model of the interaction between the pulse laser and the solid target is developed. The plasma evolutions with time during and after the laser pulse irradiating the target are simulated numerically by using a three-dimensional difference scheme. And the numerical solutions of the impulse delivering from the plasma to the target are obtained. A comparison among the theoretical, numerical and experimental results and their analyses are performed. The experimental results are explained reasonably. The consistency between numerical results and experimental results implies that the numerical calculation model used in this paper can well describe the mechanical action of the laser on the target.

Keywords: plasma production and heating by laser beams, solid-plasma interactions, impulse, fluid dynamics simulation

PACC: 5250J, 5240H

1. Introduction

When a high-intensity laser irradiates the surface of a solid target, its energy is partly absorbed by the target and the ambient air. The ambient air is ionized directly and so turns into a plasma. And the solid target is ablated and evaporated successively. The evaporated atoms are ionized and become a plasma. The plasma produced in both situations mentioned above has a high temperature and pressure, so it expands rapidly and provides a force for the target. The target obtains an impulse during the plasma expands.[1] Therefore the laser-target system can be used as an advanced propulsive system,[2,3] which is the so-called laser propulsion technique. Comparing it with chemical rocket and electric propulsion that are mature relatively at present, the laser propulsion has many advantages. One is a lower launch cost. The cost is estimated to be only a few hundred dollars, which can afford only to launch a micro-satellite with one kilogram to the anomalistic orbit and are much lower than the cost of ten thousand dollars for a chemical rocket. The second advantage is its high specific impulse compared with the chemical rocket. The specific impulse of chemical rocket cannot exceed 500 s. It has been predicted that the specific impulse of laser propulsion will be tens of times that of chemical rocket. The third advantage is its safety because the aircraft is separated from the energy supply system and working materials. The fourth advantage is its less pollution to environments because the clean and non-contaminative materials can be used as working materials. It has many potential advantages and applications in the field of the laser propulsion, on which many scientists have

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concentrated in recent years. One of the research hotspots is the efficiency of impulse delivering from laser-produced plasma to solid target.[4−11] There exist many difficult problems because they are involved with a series of complex processes such as phase transition of target material and ambient air during the laser's irradiating a target, acutely accompanied with the expansion of plasma and the interactions between plasma and laser, solid target and ambient air. There have been three kinds of main approaches to treating these problems presently. The first one is the experimental approach. This can obtain some useful scaling relations from the analyses of experiment results under different conditions. The advantage of this approach is practicability, but its disadvantage is that it cannot fully understand the mechanism and the detailed process of the impulse coupling between plasma and target. The second one is the theoretical approach. This can obtain some theoretical formulas about impulse with laser intensity by using the interaction theory between laser and material and the fluid mechanical theory and by analysing the process of plasma formation and impulse coupling to the target. The advantage of this approach is that it can reveal the physical essence of impulse delivering from laser-produced plasma to target. But it is difficult to obtain an accurate theoretical formula because of the complexity of the process. Only some approximate formulas can be obtained usually. Furthermore, the results computed by using approximate formulas are much different from the experiment results.[5] The third one is the numerical simulation approach. By theoretically analysing the formation process of laser-reduced plasma and impulse coupling between plasma and target, and by using the fluid mechanical theory and numerical computation methods, one can simulate numerically the evolution of plasma, find the distributions of pressure and temperature in the plasma by integrating the pressure on the target surface with respect to time and area, and finally obtain the impulse coupling to the target. The advantage of numerical simulation is that it can fully understand the mechanism and the detailed process of the impulse coupling between plasma and target through the computational process. However, its disadvantage is that the modelling of mathematics and computation must rely on theoretical analysis and experimental results, which is restricted to the clear describing of actual physical processes.

In this paper, by analysing the creation process of plasma and the laser supported detonation wave with the interaction between laser and solid target, and by using fluid mechanics theory and Pirri's methods, the analytic solution of the impulse delivering from the plasma to the target is obtained approximately, and the impulses are calculated when the laser intensity changes from 10^7 to $10^9\,\mathrm{W/cm^2}$. Based on the theoretical model described above, by analysing the creation process of plasma and the evolution of the inner pressure of plasma in a non-equilibrium state, the physical model for the interaction between pulse laser and solid target is developed. Furthermore, the evolution of plasma and the interaction between laser and target are simulated by using the three-dimensional finite difference method. The numerical solutions of impulse delivering from laser to target are obtained and they accord well with the experimental results.

2. Experimental results, theoretical explanation and numerical simulation of the impulse delivering from laser-produced plasma to solid target

2.1. Experimental results

To study the relation between impulse coupling efficiency and laser power density in the process of interaction of laser with solid target, a high-intensity pulsed Q-switched Nd:YAG laser is focused on the surface of aluminium target with a diameter $\Phi = 12.0\,\mathrm{mm}$ and a thickness $H = 0.5\,\mathrm{mm}$ through a lens with a focal distance $F = 105\,\mathrm{mm}$. The target is hung with a string. It can be regarded as a simple pendulum. Using the photoelectric tachometry, the impulses acting on the target are measured at different laser intensities. The relevant experimental setup and the method of measurement were reported in Ref.[12]. The position of target relative to the lens is shown in Fig.1. The main parameters of laser are as follows: the output energy $E_\mathrm{l} = 0 - 250\,\mathrm{mJ}$ adjustable, the pulse duration $t_\mathrm{p} = 15\,\mathrm{ns}$, and the wavelength $\lambda = 1.06\,\mu\mathrm{m}$. In the experiment, adjusting the relative distance d between the target and the focus of lens, the laser spot radius and its intensity on the surface of target are changed. The relations among laser spot radius, laser intensity on the target and the position of target are shown in Table 1. The experimental result of the

impulse delivering from laser-produced plasma to the target is shown with curve a in Fig.2.

It is shown in Fig.2(a) that the magnitude of impulse on the target is dependent on the laser intensity. When target is between the lens and the focus of lens, the value of d is negative. The closer to the focal point the target is, the higher the laser intensity on the target, and the larger the impulse will be. When the target lies at the focal point, the laser intensity on the target reaches a maximum value and so does the impulse on the target.

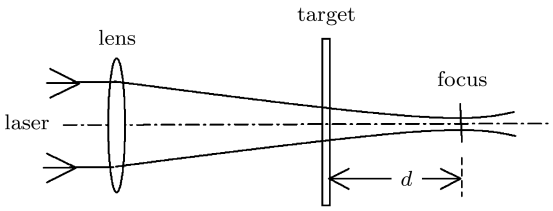


Fig.1. Arrangement for target and lens.

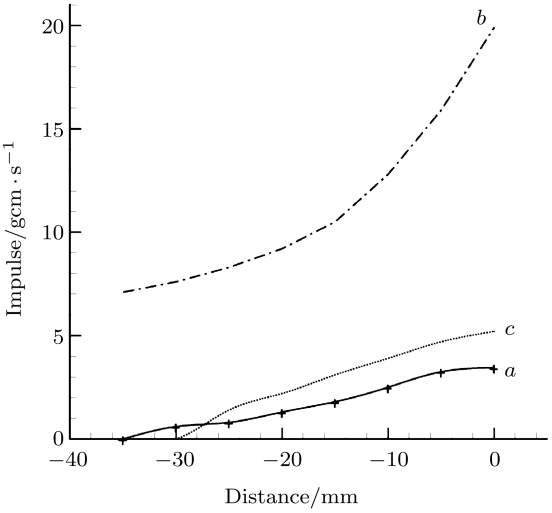


Fig.2. Relation between magnitude of impulse and target position, where a is for experimental results, b for results calculated from the Pirri theoretical model, and c for numerical calculations.

Table 1. Target position, laser spot radius and intensity.

Distance d/mm	–35	–30	–25	–20	–15	–10	–5	0
Radius R_s/mm	2.09	1.83	1.58	1.32	1.07	0.81	0.56	0.50
Intensity $I_0/(10^8\,\mathrm{W/cm^2})$	0.97	1.27	1.70	2.44	3.71	6.47	13.5	17.0

2.2. Theoretical and numerical results

Based on the theory of interaction between laser and material, the explanation of impulse delivering from laser to target can be described as follows: a high-intensity laser beam irradiating the surface of target causes the surface material to vaporize, the evaporated material of target and the air near the target surface are broken down, forming a laser absorption zone. The absorbed laser energy is converted into the inner energy of medium in the laser absorption zone, causing the medium to be ionized rapidly into a plasma with a high temperature and a high pressure. The plasma absorbs the subsequent incident laser energy and expands following the aerodynamics; part of inner energy is converted into the kinetic energy, and the rest is dissipated by radiation, which is absorbed by the solid target and ambient air. If the surface of plasma absorbing the laser energy expands with a subsonic speed, the corresponding wave front is called laser supported combustion wave (LSCW). Because the shock wave caused by the propagation of LSCW is of laser-transparency, the cold air between shock front and LSCW can be ionized, which serves as a transport mechanism, that is, thermal conductivity, heat radiation and diffusion mechanism. It is the transport mechanism that supports the propagations of LSCW and shock front. The sketch of their relative motion is shown in Fig.3(a). For the LSCW, the temperature of plasma is low ($\sim 10^4$ K), while with the increase of the incident laser intensity, the plasma absorbs more laser energy and its surface catches up with the shock front, thus the laser supported detonation wave (LSDW) is created as shown in Fig.3(b). The LSDW propagates with a supersonic speed, and the temperature of plasma is high ($\sim 10^5$ K). The impulse received by the target is the integral of the pressure acting on the target surface by the plasma during LSDW propagation with respect to the action area and time of LSDW propagation. Therefore, solving the propagation rule of LSDW, the impulse received by the target can be determined. But there exist the interaction and the phase-change among the laser, the LSDW, the surface of target, the vapour of target, the air and the plasma, it is difficult to find a theoretical model for describing the propagation rule of LSDW accurately.

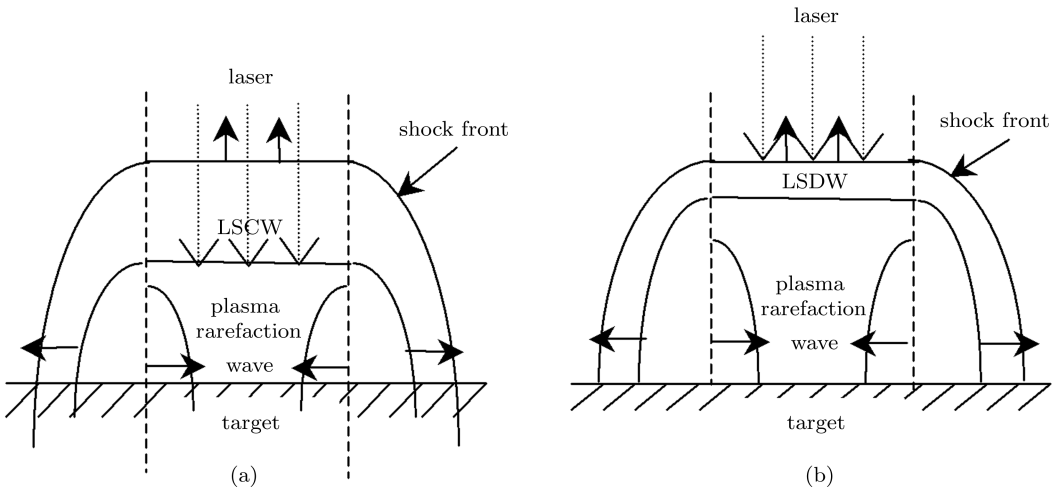


Fig.3. Propagations of laser supported combustion wave (a) and laser supported detonation wave (b).

For describing the propagation feature of LSDW, Pirri [13] assumed that the propagation of LSDW was a one-dimensional motion along the direction of inverse laser propagation. By using the fluid mechanics theory, a simple theoretical model is developed for explaining the impulse delivering from laser to target, with a laser being continuously incident and the LSDW steadily propagating. As the LSDW front coincides with the shock front, the LSDW can be regarded as a strong discontinuous surface without any thickness. And it propagates with a supersonic speed adiabatically. The incident laser energy is absorbed in the LSDW front and causes the shock front to propagate. The shock compresses the air in the front of it, causing the temperature to rise up, and the air to be ionized. The new LSDW front is created, absorbing the laser energy. The LSDW front propagates against the laser direction. Regarding the target vapour and the air as an ideal gas, they can be described by an equation of state. And the isentropic index is not changed during LSDW propagation. The pressure of laser-produced plasma, acting on the target, can be described as follows:[13]

$$p_1 = 4^{1/3}\left(\frac{\gamma+1}{2\gamma}\right)^{2\gamma/(\gamma-1)} \times \left[\frac{(\gamma-1)^2}{\gamma+1}\right]^{1/3} \rho_0^{1/3} I_0^{2/3}, \quad (1)$$

where ρ_0 is the air density without disturbing, I_0 is the laser intensity incident on the target, γ is the isentropic index. For the experimental situation concerning in this paper, we take $\gamma = 1.2$, and $\rho_0 = 1.3 \times 10^{-3}\,\mathrm{g/cm^3}$. Substituting them into expression (1), we can obtain

$$p_1 = 0.16 I_0^{2/3}. \quad (2)$$

The pressure from expression (2) is the stable solution of one-dimensional propagation of LSDW for continuous laser with an intensity I_0. Because a pulse laser irradiating the target has a finite beam radius, Pirri introduced a two-dimensional and finite time revision, that is, the pressure was described by expression (2) in the interval of laser irradiation and decreased after the laser pulse had ended because of lateral and longitudinal expansions of plasma. The plasma expansion produces a lateral (perpendicular to the direction of incident laser) rarefaction wave and a longitudinal (parallel to the direction of incident laser) rarefaction wave, which propagate from the LSDW front to the centre of target. The time of lateral rarefaction wave propagating to the centre of target is

$$\begin{aligned} t_{2\mathrm{D}} &= \frac{R_\mathrm{s}}{c_\mathrm{J}} \\ &= \frac{R_\mathrm{s}(\gamma+1)}{\gamma}\left[\frac{\rho_0}{2(\gamma^2-1)I_0}\right]^{1/3} \\ &= 2.088 R_\mathrm{s} I_0^{-1/3}, \end{aligned} \quad (3)$$

where c_J is the sound speed in plasma behind the LSDW.

The time of longitudinal rarefaction wave propagating to the target is

$$t_\mathrm{z} = t_\mathrm{p} + \frac{D_\mathrm{J} t_\mathrm{p}}{c_\mathrm{J}} = \frac{2\gamma+1}{\gamma} t_\mathrm{p}, \quad (4)$$

where D_J is the speed of LSDW front. Therefore, the duration of pressure described in expression (2) at the target centre is $t \le t_\mathrm{H} = \min(t_{2\mathrm{D}}, t_\mathrm{z})$. When $t \ge t_\mathrm{H}$,

the pressure on the target attenuates following some rule. If $t_{2D} > t_z$, the attenuation follows the planar blast rule as follows:

$$p_2(t) = p_1 \left(\frac{t_p}{t}\right)^{2/3}, \qquad (t_p \le t \le t_{2D}). \tag{5}$$

If $t_z \ge t_{2D}$, the attenuation follows the cylinder blast rule as follows:

$$p_2(t) = p_1 \left(\frac{t_p}{t_{2D}}\right)^{2/3} \frac{t_{2D}}{t}, \qquad (t \ge t_{2D}), \tag{6}$$

where p_0 and p_2 are the pressures of ambient air and plasma, acting on the target surface, respectively. The impulse delivering to target is obtained by integrating the pressure on the target surface with respect to the duration of $p_2 \ge p_0$ and the area of plasma contacting with target surface. Supposing that both laser beam and target are axis-symmetrical, and adopting the cylinder coordinate system, origin point is set at the centre of target surface. The z-axis is directed against the direction of laser beam. r is the distance from integral point to z axis. $p(r,0,t)$ is the pressure distribution on the target surface. $r_0(t)$ is the radius corresponding to $p(r_0,0,t) = p_0$ at time t. t_0 is the time corresponding to $p(0,0,t_0) = p_0$ at the centre of target surface. The impulse delivering to target by the one laser pulse produced plasma is

$$I_m = \int_0^{t_0} \int_0^{r_0(t)} [p(r,0,t) - p_0] r \mathrm{d}r \mathrm{d}t. \tag{7}$$

There does not exist a strict analytic solution for $p(r,\ 0,\ t)$. Pirri[13] considered that the propagations of lateral rarefaction wave and longitudinal rarefaction wave could influence the distribution of $p(r,0,t)$. Based on expressions (3)–(7) and assuming the area of target to be sufficiently large, $p(r,0,t)$ attenuated to p_0 before shock front reaches the edge of target. They deduced some analytic expressions for calculating the impulse in different situations.

If the longitudinal rarefaction reaches the target surface before the lateral rarefaction wave reaches the centre of target surface ($t_0 \ge t_{2D}, t_p \le t_z \le t_{2D}$), then

$$I_m = \pi R_s^2 t_p p_1 \left\{ \frac{t_z}{t_p} + 3 \left[\left(\frac{t_{2D}}{t_p}\right)^{1/3} - \left(\frac{t_z}{t_p}\right)^{1/3} \right] + \left(\frac{t_{2D}}{t_p}\right)^{1/3} \left(\frac{t_0}{t_{2D}} - 1\right) \right\}. \tag{8}$$

If the lateral rarefaction wave reaches the centre of target surface before the longitudinal rarefaction wave reaches the target surface ($t_0 \ge t_{2D}$, $t_p \le t_{2D} \le t_z$), then

$$I_m = \pi R_s^2 t_p p_1 \left[\frac{t_{2D}}{t_p} + \left(\frac{t_{2D}}{t_p}\right)^{1/3} \left(\frac{t_0}{t_{2D}} - 1\right) \right]. \tag{9}$$

By using the experimental parameters corresponding to those reported in this paper, and expressions (8) and (9), the magnitudes of impulse for different laser intensities are calculated as shown with curve b in Fig.2. Comparing curve b with curve a in Fig.2 shows that they have the same tendencies to change with distance, but they have a great difference in magnitude. The analytic results obtained from Pirri's method are much bigger than experimental results. A similar question can be found in Ref.[5]. By analysing the interaction process between laser-produced plasma and target, the difference can be explained as follows. Firstly, as a pulsed laser irradiates the target, some laser energy is consumed in some complex physical and chemical processes such as in the increasing of the temperatures of target and ambient air, in the vaporizing of target material, even in the ionizing of the vapour of target and the ambient air before the LSDW is created. Therefore, the actual circumstance is that the LSDW does not appear at the time ($t = 0$) for laser to irradiate the target, that is, the integral with respect to t cannot begin from 0, but from the time for the LSDW to be created as shown in Eq.(7). Secondly, the pressure in plasma is inhomogeneous at any time t during the LSDW expansion. So the pressure $p(r,\ 0,\ t)$ delivering from plasma to target varies with the variation of r; while in Pirri's method, when deducing expressions (8) and (9) from expression (7), $p(r,\ 0,\ t)$ is regarded as varying with t only the pressure determined from expressions (5) and (6) does not vary with r. Thirdly, because the plasma temperature is much higher than the ambient temperature. There exists the energy loss through heat radiation of plasma.

In order to find an effective method of calculating the magnitude of impulse delivering from laser-produced plasma to target accurately, based on Pirri's method, we suppose that the plasma is created at time t_d instead of $t = 0$, where t_d is obtained as follows:

$$t_d = \frac{I_{0t}}{I_0} t_p, \tag{10}$$

where I_{0t} is the laser intensity threshold at which the LSDW can be detected in our experiment (the laser intensity is between $1.6\times10^8\,\mathrm{W/cm^2}$ and

2.1×10^8 W/cm^2, in this paper, I_{0t}=1.6×10^8 W/cm^2). Based on this formula, the time for the LSDW to be created can be deduced with different laser intensities irradiating the target surface as shown in Table 2. Then expression (7) is rewritten as follow:

$$I_m = \int_{t_d}^{t_0} \int_0^{r_0(t)} [p(r,0,t) - p_0] r dr dt. \qquad (11)$$

Besides the inhomogeneity of $p(r,\ 0,\ t)$ in expression (11), the complexity of plasma expansion can prevent its analytical solution from being obtained. So the fluid mechanics theory is adopted for simulating the expansion of plasma numerically. When $t > t_d$, the LSDW expansion satisfies the equations of fluid mechanics, i.e.

$$\begin{aligned}
&\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z}(\rho u) + \frac{1}{r}\frac{\partial}{\partial r}(\rho v) = 0,\\
&\frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial z}(\rho u^2) + \frac{1}{r}\frac{\partial}{\partial r}(r\rho uv) + \frac{\partial p}{\partial z} = 0,\\
&\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial z}(\rho uv) + \frac{1}{r}\frac{\partial}{\partial r}(r\rho v^2) + \frac{\partial p}{\partial r} = 0,\\
&\frac{\partial E}{\partial t} + \frac{\partial}{\partial z}[u(E+p)] + \frac{1}{r}\frac{\partial}{\partial r}[rv(E+p)]\\
&= \begin{cases} I_0\ (t_d < t < t_p,\ (z,r) \in \Omega), \\ 0,\ \text{otherwise.} \end{cases}
\end{aligned} \qquad (12)$$

The total energy of LSDW in the unit volume can be described as $E = \rho e + \frac{1}{2}\rho(u^2 + v^2)$, where z, r, and t are the space and time coordinates, ρ, u, v, p and e are the mass density, the speeds along the z-axis and the r-axis, the pressure and specific inner energy of LSDW medium, respectively, Ω is the area of target surface irradiated by laser. The initial condition of numerical simulation for Eq.(12) is that when a laser beam with an intensity I_0 irradiates the target, about 40% laser energy in the period from 0 to t_d is converted into the heat energy[14] before the LSDW appears, from which the temperature, the density and the pressure of plasma can be determined. The plasma shape is assumed to be of a cylinder with a cross sectional area equal to the target area irradiated by the laser beam, and a height equal to the molecular free path at a temperature of 10^5 K and a normal density of about 2×10^{-3} cm $\approx$ 20λ.[15] So the initial volume of plasma is $V = \pi R_s^2 \cdot 20\lambda$. Based on expression (12), adopting the second order accurate finite difference scheme[16] for simulating the plasma expansion numerically, the evolutions of temperature, density and pressure in plasma versus space and time can be calculated. Finding $p(r,0,t)$ and substituting it into expression (11) yield, the impulses of plasma, acting on the target with different laser intensities; the results of numerical simulation are shown with curve c in Fig.2.

Table 2. Times for the LSDW to appear and for the plasma pressure to attenuate to p_0 with different laser intensities, obtained from Pirri's theory and the numerical simulation.

Radius R_s/mm	1.58	1.32	1.07	0.81	0.56	0.50
Time for the LSDW to appear t_d/ns	14.1	9.83	6.49	3.71	1.78	1.41
Pirri's attenuating time t_0/ns	2842	3034	3254	3600	4165	7600
Numerical attenuating time t_0/ns	1373	1445	1548	1710	1976	3452

3. Explanation of numerical simulating results

According to the inhomogeneity in plasma revealed from numerical simulation, the results of numerical simulation can be explained reasonably. The pressure distributions in plasma at different times, with a radius of laser beam irradiating the target surface (R_s) being 0.56 mm, are shown in Fig.4, in which the curves are isobaric lines. It is shown from the distribution and the evolution of these isobaric lines that when the laser pulse just ends (corresponding to t = 13 ns (a)), the pressure in plasma is high and uniform, moreover, the pressure gradient on its external surface is very large. The inner pressure decreases gradually with the plasma expanding outward and rarefaction wave propagates inward subsequently. The pressure and its gradient on external surface keep their maxima during the holistic pressure of plasma decreasing. It is such an inhomogeneity of pressure in plasma that causes the pressure in plasma to actually decrease more quickly than those described in expressions (5) and (6). Figure 5 shows the pressure histories at the centre of target surface in the expansion process described in Fig.4. Curve (a) is for the results calculated according to expressions (5) and (6), and curve b is for the numerical results. In numerical

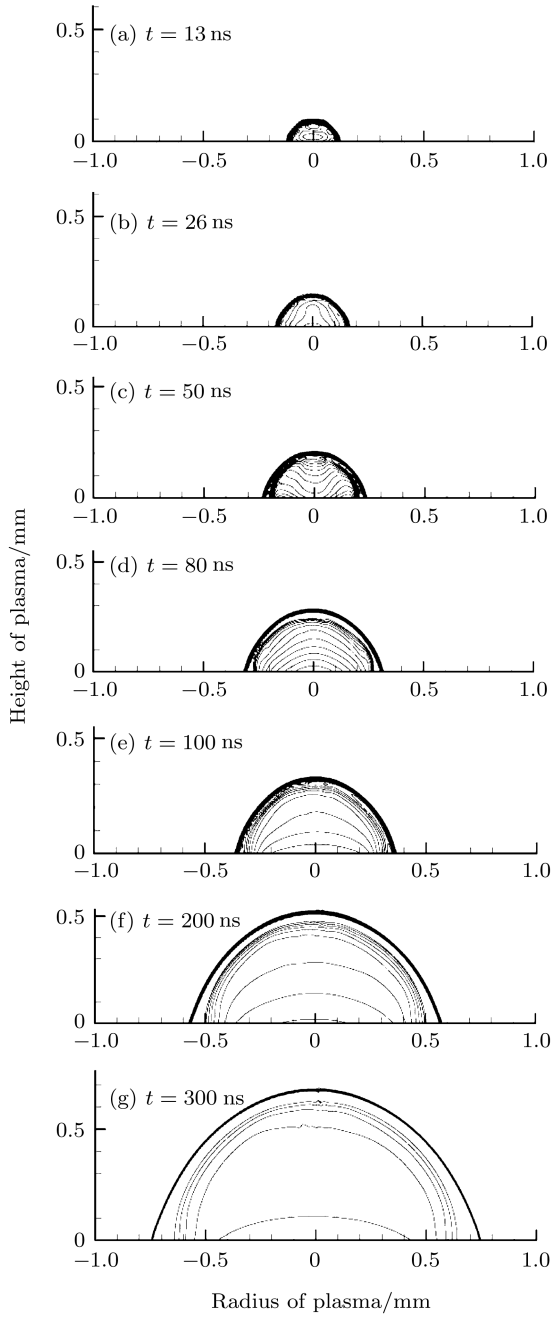


Fig.4. Curves of plasma height versus plasma radium at different times, with $R_s = 0.56$ mm.

simulation, it is assumed that laser energy irradiating the plasma is absorbed entirely by the external surface of plasma that meets the laser beam first after the plasma has been created. All of the energy is converted into the kinetic energy for plasma expansion and the thermal energy for heating and ionizing the air that is close to the external surface of the LSDW front, and then the plasma near the target cannot receive any laser energy. So, the temperature and the density of the plasma in this area will decrease because of lateral and longitudinal expansions. The pressure acting on the target surface will decrease rapidly. In Fig.5(b), this process corresponds to the steepest section of the curve in the initial short interval (0–20 ns). After the laser pulse has ended, the longitudinal expansion speed of plasma changes from accelerative to decelerative. Therefore, there exists a small accumulation of the density on the surface, leading to a tiny increment of pressure appearing on the curve though it decreases rapidly with the time increasing. This tiny change of pressure propagates to the target, causing an inflexion near $t = 20$ ns in curve b. The pressure on the target will decrease slowly subsequently because the gradient of inner pressure of plasma decreases. Table 2 shows two kinds of attenuating time t_0 for the pressure to change from its initial value to p_0 in plasma. One is calculated according to Pirri's formula (5) and (6), and the other is calculated numerically. Comparing the data in Table 2, it is obvious that the plasma pressure obtained from the numerical simulation decreases more quickly than calculated from Pirri's theory for all laser intensities; so the pressure of plasma acting on the target, obtained from the numerical simulations decreases so quickly. Therefore, the impulse on the target, obtained from numerical simulation, is much less than from Pirri's theory. Because the plasma energy loss of thermal radiation and other energy loss are not considered here, the results of numerical simulation are little greater than the experimental results (see curves a and c in Fig.2).

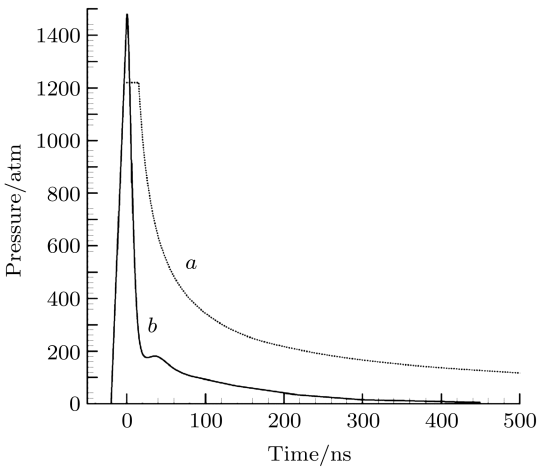


Fig.5. Pressure versus time at the centre of target surface during the LSDW expanding for $R_s = 0.56$ mm, where curve a is for Pirri's results, and b for numerical results.

4. Conclusion

In this paper, based on the theory about the interaction of laser with material and the fluid mechanics, the creation and the expansion processes of plasma in air are investigated. The modified Pirri's formula and the numerical method are used to deal with the inhomogeneous changes of plasma expansion. The impulses delivering from plasma to target are calculated with different laser intensities. The result calculated by using Pirri's theory has the same tendency as the experimental result, but there exists a great difference in value; while the result calculated from the numerical simulation accords with the experimental result well. So, the method of combining the modified Pirri theory with numerical simulation, adopted in this paper, can be used for calculating the impulse delivering from pulse laser-produced plasma to target.

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