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The relation between composition in laser absorption region and ambient pressure*

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In this paper, the compositions in a laser absorption region can be determined from the experiment of laser impulse coupling. When the ambient pressure varies from 9325 to 33325Pa, the compositions are vapour and plasma; while from 35325 to 101325Pa, they are ambient air and plasma. By analysing the relation between the degree of compression and the ambient pressure, the compositions can be determined and the variation of plasma can be explained.

Keywords: laser technology, laser absorption region, ambient pressure, impulse coupling coefficient
PACC: 4255, 4255B

1. Introduction

When a high-power density laser beam is focused on a target, the following events will take place sequentially: the vaporization and ionization of target, the optical breakdown in the ambient air,[1] the plasma absorbing incident laser energy, the air being ionized near the optical breakdown zone, the laser absorption zone moving toward the direction of the incident laser, and the laser supported absorption wave being created.[2] Based on the transmission speed, transmission direction and the character of plasma, the laser supported absorption wave can be converted to the laser supported combustion wave and the laser supported detonation wave (LSDW), as a leading factor in the process of laser impulse coupling to the target. The impulse coupling coefficient is an important factor in judging the laser impulse coupling to target. The impulse coupling coefficient depends on the laser parameters such as power density and incident angle etc., the target parameters such as the area of target and the material of target etc., and the ambient gas parameters such as the composition of ambient gas and the ambient pressure.

The experimental study about the laser impulse coupling coefficient with the variation of ambient pressure was carried out from the 1970s to the 1980s.[3−7] Early experiments focused on the measurement of impulse coupling coefficient.[3,4] Subsequent research turned to the analysis of experimental result.[5−7] Since the 1990s, the research of laser induced plasma, which is created in the process of interaction between laser and target, at different ambient pressures has become a hot point. It is of significance to understand the laser induced plasma.[8−11]

As the laser propulsion serves as one of alternatives to cost-effective low-loading to the upper air and near-earth orbit, the correlation study becomes important. Schall *et al*[12,13] measured the laser pulse and the corresponding impulse coupling coefficient by using a laser with a single pulse energy of 410J and an oscillating frequency of 100Hz. By measuring the impulse coupling coefficient of toroidal shape light craft and bell shape light craft, the impulse coupling coefficient was determined as a function of the laser impulse energy; as an additional parameter the specific mass consumption of Delrin (gram/Joule) was measured for each parameter set, thus the average exhaust rate in vacuum was determined. Sasoh *et al*[14] measured the laser impulse coupling coefficient by changing the pressure in a pipe in the process of laser propelling bullet.

Combining with the research background of laser propulsion in China, Bian *et al*[15−17] gave a laser

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plasma shock wave transmission formula in mediate and far fields and then extended it to the case of non-absolute centric symmetry by adopting basic differential equations or self-simulating motion of one-dimensional unstable flow. Xu *et al*[18] measured the relation between laser impulse coupling coefficient and the ambient pressure, their experimental results indicated that the ambient pressure was closely related to the pressure of LSDW and exerted an influence on the impulse coupling coefficient. Zheng *et al*[19−21] measured the impulse coupling coefficient by using the suction pump and TEA CO_2 laser irradiating the light craft that was hung on a pendulum. Experimental results indicated that impulse coupling coefficient increased eventually with the increase of pressure in the vacuum chamber. When the ambient pressure reached 34.6×10^3Pa，the impulse coupling coefficient attained to a maximum value. And the impulse coupling coefficient decreased with the increase of ambient pressure. Li *et al*[22] used the moving mirror model to study analytically the harmonic generation from solid targets illuminated by intense laser pulses.

In this paper, based on the impulse coupling coefficient at different ambient pressures and the interaction between LSDW and the rarefaction, the variation of adiabatic coefficient with ambient pressure is deduced; the interval of interaction between the rarefaction and the LSDW is calculated. Furthermore, based on the relation between limiting compression ratio and the expanding medium in a laser absorption zone, the variation of plasma in the laser absorption zone is analysed quantitatively. The theoretical analysis of this phenomenon is also made.

2. The briefing of theoretical model

2.1. The rarefaction in the process of interaction between laser and material

When the direction of incident laser is perpendicular to the surface of target, the LSDW will move toward the direction of incident laser. At the same time, because of the expansion of plasma and the flexure of shock wave front, there appears a lateral shock wave. The flow of the LSDW rear is influenced by the lateral rarefaction wave. Once the laser pulse ends up, the LSDW is reflected and propagates to the surface of target; there appears an axial rarefaction wave. Considering the laser impulse transferring to the target, we must count in the interaction between the rarefaction of longitudinal direction and the lateral shock wave. Based on the coherent coefficient of LSDW, we can deduce the interval of lateral rarefaction propagating to a focal centre and the interval of the lengthwise rarefaction propagating to the surface of target.

The movement of lateral rarefaction is shown in Fig.1 where the LSDW and lateral shock wave propagate. Then the lateral rarefaction propagates at a sound speed in the medium of LSDW rear. The interval of lateral rarefaction propagating to the focal centre can be described as[23]

$$t_{2D} = \frac{R_S}{c_J}. \tag{1}$$

In Expression (1), R_S is the focal aperture of Nd:YAG laser; c_J is the sound speed in the medium of LSDW.

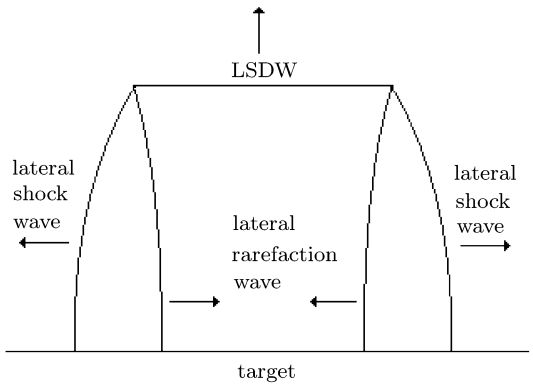


Fig.1. Interaction between lateral rarefaction and LSDW.

The lengthwise rarefaction begins to propagate to the surface of target after the LSDW has propagated as shown in Fig.2. The interval can be described as[23]

$$t_z = t_p + \frac{D_J t_p}{c_J} = \frac{(2\gamma+1)\,t_p}{\gamma}. \tag{2}$$

In Eq.(2), $D_J = \left[2\left(\gamma^2-1\right)\frac{I_0}{\rho}\right]^{\frac{1}{3}}$ is the speed of LSDW; γ is the isentropic index; I_0 is the laser power density; ρ is the air density; t_p is the laser pulse width.

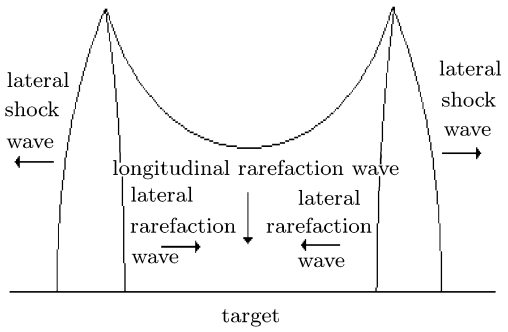


Fig.2. Interaction between longitudinal rarefaction and LSDW.

When the temperature is between 10000 and 250000°K and the air density is between $10\rho_0$ and $10^{-3}\rho_0$ (ρ_0 is the standard density), the inner energy of air can be approached as[24]

$$\varepsilon = aT^{\alpha}V^{\beta}, \tag{3}$$

where a, α and β are the constants; T is the temperature of air; V is the specific volume.

By fitting the experimental result, the constants a, α and β can be determined and thus Eq.(3) can be expressed as

$$\varepsilon = 8.3\left(T^0/10^4\right)^{1.5}\left(\rho_0/\rho\right)^{0.12}$$
$$\text{Equivalent volt/Molecule.} \tag{4}$$

In the process of dissociation, the specific heat increases with air density decreasing. Because the ionization degree increases and the corresponding energy loss increases, $\beta > 0$ and $\alpha > 1$, in addition, the specific internal energy ε, ambient pressure p and the air density ρ can be related to each other by $1 + p/(\rho\varepsilon) = \gamma$, where γ is the adiabatic index. The relation between ρ and γ can be described as

$$\gamma = 0.4\rho^{0.12}/\rho_0^{0.12} + 1. \tag{5}$$

By calculating expressions (1), (2) and (5), the interval of rarefaction can be determined with ambient pressure varying. When the vacuum degree is between -0.092 and -0.042MPa, the interval of lateral rarefaction is smaller than that of lengthwise rarefaction. When the vacuum degree is between -0.042 and -0.000MPa, the interval of lateral rarefaction is larger than that of lengthwise rarefaction. This is the starting point of analysing experimental results.

2.2. The theoretical explanation for high compression ratio

The relation between the specific volume of medium in the LSDW rear and the pressure is shown in Fig.3. The curve $CBJA$ is the Hugoniot curve, which can be expressed as[23]

$$p_1 = \left[2\left(1 - \frac{\rho_1}{\rho_2}\right)^{1/2} 2\left(\frac{\gamma+1}{\gamma-1}\frac{\rho_1}{\rho_2} - 1\right)^{-1} I_0\rho_1^{1/2}\right]^{2/3}. \tag{6}$$

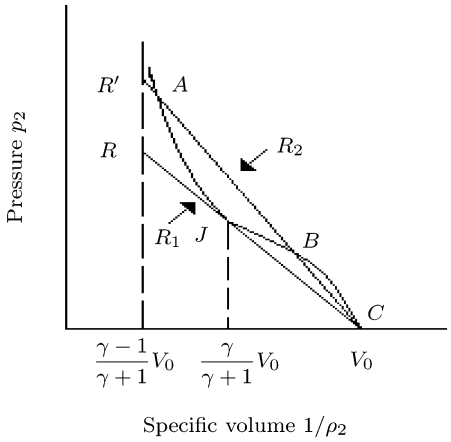


Fig.3. Hugoniot and Rayleigh lines of LSDW.

In Fig.3, straight lines CJR and $CBAR'$ both are the Rayleigh line. The equation of Rayleigh line can be described as follows:[23]

$$p_2 = \rho_1 v_1^2\left(1 - \frac{\rho_1}{\rho_2}\right), \tag{7}$$

where ρ_1 and p_1 are the density and pressure in the LSDW front respectively; v_1 is the LSDW speed; ρ_2 and p_2 are the density and pressure in the LSDW rear respectively; I_0 is the laser power density.

Now we consider the cross points between the Rayleigh line and the Hugoniot line governing the mechanical conservation law. Points A, B, C and J describe the virtual conditions in different terms of interaction between laser and medium. Point J shows the Jouguet state at an ambient pressure of 1atm in the LSDW rear. Point C is the initial virtual state of the medium. Point B is the state on the condition that the speed of medium in the LSDW rear is supersonic. Point A is the state of medium in the LSDW rear on the condition that ambient pressure is less than 1atm.

The evolutionary process of medium in the LSDW rear can be described in Fig.3. Suppose that the medium composed of the ambient material and target is vaporized by laser heating and compressed by the LSDW from Point C to Point R, then it will expand along the Rayleigh line RJC due to the additional energy absorbed from the laser. The medium state reaches Point J when the energy releasing process ends off. The speed of the LSDW satisfies the following formula: $D_{\mathrm{J}} = \left[2\left(\gamma^2 - 1\right)\frac{I_0}{\rho}\right]^{\frac{1}{3}}$.

If the speed of LSDW is equal to D_{J}, after the processes of ionization and absorption, the laser supported absorption wave created by the confluence between rarefaction and shock cannot be created, be-

cause the speed of LSDW is supersonic as compared with that of the medium in the LSDW rear and the flow rate of particles in the LSDW rear is subsonic. The LSDW is attenuated by the rarefaction wave caused by the expanding medium. The virtual state of medium in the LSDW rear reaches Point J, which means that, there does not exist the evolutionary process ($C \to R' \to A$) expressed by the Rayleigh line R_2 (ABC) described in the classical theory.

But when the ambient pressure is low, the evolutionary process changes. There exists the evolutionary process ($C \to R' \to A$) expressed by the Rayleigh line R_2 (ABC). Firstly, from the Rayleigh line, because the ambient pressure decreases, the corresponding speed of LSDW increases. The condition can be expressed by the Rayleigh line R'. Then the medium in LSDW is composed of not only the subsonic particles, but also the sonic particles of target vapour in the Knudsen layer, that is, cross point A between the Rayleigh line R' and the Hugoniot line $CBJA$ can describe a virtual state of LSDW. Point A is near to the asymptotic line $R'R$. Therefore, the compression ratio of LSDW can be defined as $\dfrac{\rho_2}{\rho_1} = \dfrac{\gamma - 1}{\gamma + 1}$.

3. Determination of compositions in laser absorption zone

Because the laser absorption zone lies between the front of LSDW and the target, when the ambient pressure varies, the specific weights of plasma, air and vapour can be changed. This condition is discussed based on the variation of ambient pressure.

3.1. The variation of compression ratio with vacuum degree

The compression ratio of LSDW is the ratio between the density (ρ_1) in the compression zone of LSDW and the density (ρ_0) of the intact gas, that is, $h = \rho_1/\rho_0$.[24] The experimental relation between the compression ratio and the vacuum degree is shown in Fig.4. When the vacuum degree varies from -0.09 to 0.00, the compression ratio changes from 4.5 to 7.6. When the target vapour is a monatomic gas, the isentropic index of the target vapour is 5/3 and the corresponding compression ratio is 4.[25] Therefore, in the case of increasing vacuum degree, the medium in LSDW can be seen as the mixture of air and plasma. The isentropic index of air is 1.4; the corresponding limiting compression ratio is 6. The isentropic index of plasma is 1.2; the corresponding limiting compression ratio is 11. For the vacuum degree varying from -0.07 to -0.06, a jump process is shown in Fig.4; when the vacuum degree varies from -0.09 to -0.07, the limiting compression ratio is less than the limiting compression ratio of air, and it is less than 6. Therefore, the medium in the LSDW rear is the mixture of plasma and target vapour. When the vacuum degree varies from -0.06 to 0.00, because the vacuum degree is more than 6, the medium in LSDW is the mixture of plasma and air. The compositions in LSDW rear are listed in Table 1.

Table 1. The conditions of variations in vacuum degree, composition in laser absorption zone and compression ratio.

vacuum degree/MPa	-0.09	-0.08
compositions in laser absorption zone	plasma, target vapour	plasma, target vapour
compression ratio	4.46835	4.66927
vacuum degree/MPa	-0.07	-0.06
compositions in laser absorption zone	plasma, target vapour	plasma, air
compression ratio	5.30518	6.37151
vacuum degree/MPa	-0.05	-0.04
compositions in laser absorption zone	plasma, air	plasma, air
compression ratio	6.75688	7.17564
vacuum degree/MPa	-0.03	-0.02
compositions in laser absorption zone	plasma, air	plasma, air
compression ratio	7.42908	7.36778
vacuum degree/MPa	-0.01	0.00
compositions in laser absorption zone	plasma, air	plasma, air
compression ratio	7.35209	7.63252

Figure 4 and Table 1 show that with the increase of vacuum degree, the compositions in the laser absorption zone change from plasma and target vapour to plasma and air. There exists a rapid change when vacuum degree varies from −0.07 to −0.06 because the interaction between particles of target vapour is greater than the interaction between molecules of air. When plasma component is greater and greater, the tendency of variation is related to the interaction between electrons and ions, that is, breakdown and recombination. With the further increase of ambient pressure, the neutral molecules reject the recombination of plasma and the compression ratio increases.

The physical explanation for the variation of compositions in the laser absorption zone with ambient pressure is that the ignition of LSDW happens in the target vapour when the ambient pressure is low. With the increase of ambient pressure, the ignition of LSDW happens in air near the target surface.

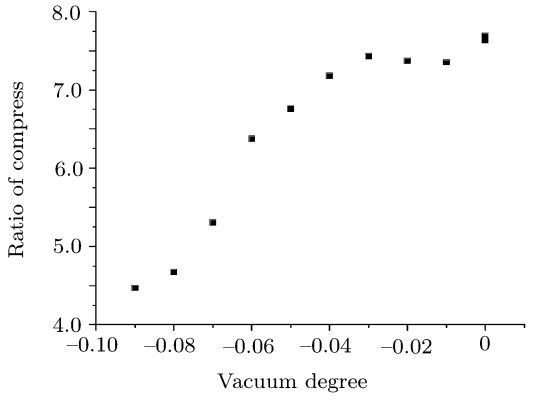


Fig.4. Relation between the compress ratio and the vacuum degree.

3.2. The relation between specific heat and the compositions in laser absorption zone

Because the medium in LSDW rear comprises not only the subsonic particles, but also the sonic particles of target vapour in the Knudsen layer, the compression ratio of LSDW is larger than that of LSDW satisfying the Jouguet condition. Then the limiting compression ratio of LSDW can be described as follows:

$$\frac{\rho_2}{\rho_1} = \frac{\gamma - 1}{\gamma + 1}. \tag{8}$$

Supposing that x is the content of air or vapour in the laser absorption zone, and y is the content of plasma, we have

$$x + y = 1,$$

and

$$\frac{\gamma_x + 1}{\gamma_x - 1}x + \frac{\gamma_y + 1}{\gamma_y - 1}y = \frac{\overline{\gamma} + 1}{\overline{\gamma} - 1}, \tag{9}$$

where γ_x is the specific heat of air or target vapour, and γ_y is the specific heat of plasma.

The relation between vacuum degree and plasma content is shown in Fig.5. When vacuum degree varies from −0.09 to −0.07MPa and from −0.06 to −0.03MPa, the plasma content increases; but when vacuum degree varies from −0.07 to −0.06MPa, the plasma content decreases rapidly, that is, the mechanism of laser absorption is changed. The compositions in laser absorption zone change from the mixture of target vapour and plasma to the mixture of air and plasma. Because the LSDW ignites after air and vapour have absorbed the laser energy, whether the main part absorbing laser energy is target vapour or air, it can exert an influence on the result in Fig.5. When vacuum degree is equal to −0.07MPa, the assumption that there exist plasma and target vapour can hold. When vacuum degree is equal to −0.06MPa, the assumption that there exist plasma and air can be valid. The mechanism of laser absorption is changed when vacuum degree varies from −0.07 to −0.06Mpa, that is, the mechanism of laser absorption changes from the inverse-bremsstrahlung absorption and electron transition to multi-photon absorption and cumulative ionization. It is the physical explanation for the rapid change of plasma when vacuum degree varies from −0.07 to −0.06MPa. When the vacuum degree varies from −0.03 to 0.00MPa, because of the recombination between electrons and ions, the plasma content oscillates.

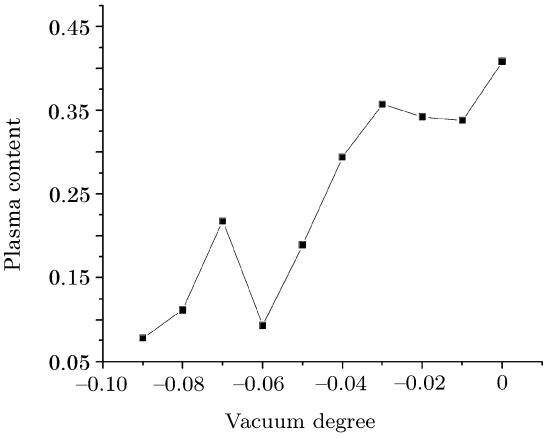


Fig.5. Relation between plasma content and vacuum degree.

4. Conclusion

From the present study we can draw some conclusions as follows:

(1) Because the medium in the LSDW rear comprises not only the subsonic particles, but also the sonic particles of target vapour in the Knudsen layer, the compression ratio of LSDW is the limiting compression ratio.

(2) When the ambient pressure varies from 9325 to 33325Pa, that is, the vacuum degree varies from −0.09 to −0.07MPa, the compositions in the laser absorption zone are vapour and plasma; when the ambient pressure varies from 35325 to 101325Pa, that is, the vacuum degree varies from −0.06 to 0.00MPa, the compositions in the laser absorption zone are air and plasma; the rapid change process of compression ratio, that is, vacuum degree varies from −0.07 to −0.06MPa, can be regarded as the criterion of variation of the compositions in the laser absorption zone.

(3) The physical explanation for the variation of compositions in the laser absorption zone with ambient pressure is that the ignition of LSDW happens in the target vapour when the ambient pressure is low. With the increase of ambient pressure, the ignition of LSDW happens in air near the target surface.

(4) When vacuum degree varies from −0.09 to −0.07MPa and from −0.06 to −0.03MPa, the plasma content increases; the mechanism of laser absorption is changed when vacuum degree varies from −0.07 to −0.06Mpa, that is, the mechanism of laser absorption changes from the inverse-bremsstrahlung absorption and electron transition to multi-photon absorption and cumulative ionization. When the vacuum degree varies from −0.03 to 0.00MPa, because of the recombination between electrons and ions, the plasma content oscillates.

References

[1] Man B Y, Miao Y and Guo X X 1997 *Chin. Sci. Butt.* **42** 1139

[2] Kulikovskii A G and Pashchenko N T 2005 *Fluid Dynamics* **40** 818

[3] Marcus S and Lowder J E 1975 *J. Appl. Phys.* **46** 2293

[4] Duzy C, Woodroffe J A, Hsia J C and Ballantyne A 1980 *Appl. Phys. Lett.* **37** 542

[5] Rosen D I, Mitteldorf J, Kothandaraman G, Pirri A N and Pugh E R 1982 *J. Appl. Phys.* **53** 3190

[6] Bass M, Nassar M A and Swimm R T 1987 *J. Appl. Phys.* **61** 1137

[7] Phipps C R, Turner T P and Harrison R F 1988 *J. Appl. Phys.* **64** 1083

[8] Bickel P, Arenz H, Christiansen J, Eberl E and Kauf M 1994 *SPIE* **2207** 501

[9] Kanevskii M F and Stepanova M A 1994 *SPIE* **2119** 92

[10] Vladimir D Zvorykin 2000 *SPIE* **4065** 128

[11] Bukin O A, Il'in A A, Golik S S and Tsarev V I 2002 *SPIE* **4748** 184

[12] Schall W O, Eckel H A and Mayerhofer W 2002 *SPIE* **4760** 908

[13] Schall W O, Eckel H A and Riede W 2003 *SPIE* **5120** 618

[14] Sasoh Akihiro, Yu Xilong and Ohtani Toshiro 2004 *42nd AIAA Aerospace Sciences Meeting and Exhibit* Reno, Nevada, 1

[15] Bian B M, Yang L, Zhang P, Ji Y J, Li Z H and Ni X W 2006 *Acta Phys. Sin.* **55** 4181 (in Chinese)

[16] Bian B M, Chen X, Xia M, Yang L and Shen Z H 2004 *Acta Phys. Sin.* **53** 508 (in Chinese)

[17] Bian B M, Chen J P, Yang L. Ni X W and Lu J 2000 *Acta Phys. Sin.* **49** 445 (in Chinese)

[18] Xu J B, Lin J D and Liu J 2002 *Explosion and Shock Waves* **22** 285

[19] Zheng Y J, Tan R Q and Wang D L 2005 *High Power Laser and Particle Beams* **17** 979

[20] Zheng Y J, Gong P and Tan R Q 2005 *Chin. J. Lasers* **32** 889

[21] Zheng Y J, Gong P and Tan R Q 2005 *J. Optoelectron. Laser* **16** 624

[22] Li K, Zhang J and Yu W 2003 *Acta Phys. Sin.* **52** 1412 (in Chinese)

[23] Sun C W 2002 *The Effect of Laser Irradiation* (Beijing: National Defense Industry Press)

[24] Zel'dovich Y B and Raizer Y P 1980 *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena* (Beijing: Science Press)

[25] Lu J, Ni X W and He A Z 1996 *The Physics of Interaction Between Laser and Material* (Beijing: China Machine Press)