Laser Original

Scaling Laws for Ablative Compression

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(Received November 16, 1981)

A stationary, plane geometry flow model gives the form of laser-driven ablation fronts and scaling laws for the dependence of implosion parameters on flux limit parameter, laser wavelength and absorbed intensity. The model includes the ionization energy loss. The solutions are compared with the experimental results. The approximate solutions support both numerical calculations and experimental results.

1. Introduction

As it is well known in the laser fusion scheme, the energy transported by electrons from the absorption region into the overdense region is converted into ablation energy and the energy of compression waves which is driven through the reaction of the ablation. It is recognized as important to investigate the hydrodynamic behaviour of laser driven plasmas, our main attention being focused on such a transport region (deflagration region). The investigation gives us information about the inner compressed region as a function of input laser power.

In this paper, the target is considered to consist of a matter with solid density and the compressed region, the deflagration region, and the rarefaction region which are produced by laser irradiation are analyzed. The compressed and deflagration regions are treated being assumed that they are in steady states. The principle is the following:

Consider a cold solid-state target set on laser light, then this target will be heated and set into motion. Because of very high pressure, shock and compression waves, are expected to occur. In such case the physical

description for the flow is: in the initial state the flow is unperturbed cold medium and after the laser light impinges onto the target, the heat plasma will be created and separated from the unperturbed cold medium by a low-temperature zone the density of which is higher than the solid density. This region is called the compressed region. Since in this region the hot plasma electron temperature was measured experimentally for deuterium¹⁾ and is greater than 100 eV, the ionization energy loss should be considered. At first glance, the boundaries between the two regions are discontinuities for physical quantities such as velocity, density and temperature. We call the discontinuous surface (the intermediate region) the shock front.

Following the compressed region, the deflagration region is formed, and we call the boundary between this region and the compressed region the ablation surface. The pressure is characteristically almost constant in the region between the shock front and ablation surface. In the deflagration region, the energy loss due to the ionization is also taken into account. In this region the density is less than the solid density. We should mention here that the shock front propagate inward with different velocities.

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Many workers²⁻⁴⁾ have discussed ablation-driven compression. Most of these previous works²⁾ assumed that the Chapman-Jouguet (C-J) point corresponds to the cutoff density. In this model we assume that the C-J point may not necessarily be the cutoff density.

The paper is arranged as follows. In Sec. 2) we will derive the basic equations considering the three regions, separated by shock front and ablation surface. The energy conservation is discussed including the free streaming flux limit model and the experimental temperature scaling. In Sec. 3) the main parameters in the ablation regime are derived analytically. Also the numerical results and experimental data are presented. Section 4) summarizes the results of this paper, and their implications.

2. Basic Equations and Two Models for Absorbed Energy

It was shown in Sec. 1) that the hydrodynamic high pressure created by laser irradiation and the heat waves propagate. Such waves can be treated as discontinuities across which the equations of conservation of mass, momentum and energy can be applied and in the frame of reference of the wave, as shown in Fig. 1.

2.1. Shock front

The one-dimensional, steady-state equations in a moving reference frame for a laser plasma from a planar target with consideration of the ionization energy loss obey the following conservation laws

mass continuity :

$$\frac{\partial}{\partial x} [\rho(u - \lambda_s)] = 0, \quad (2.1)$$

momentum :

$$\frac{\partial}{\partial x} [\rho(u - \lambda_s)^2 + P] = 0, \quad (2.2)$$

Fig. 1. Distinguishes three regions on the plasma during the implosion process.

energy :

$$\frac{\partial}{\partial x} \left[\left\{ \frac{1}{2} \rho(u - \lambda_s)^2 + \rho e \right\} (u - \lambda_s) + P(u - \lambda_s) \right] + I n(u - \lambda_s) \delta(x) = 0, \quad (2.3)$$

where ρ (n) is the fluid mass (number) density, u is the fluid velocity, P is the pressure, λ_s is the shock front speed, $e = \frac{1}{\gamma - 1} \frac{P}{\rho}$ is the internal energy per unit mass (assume that the conventional specific heat ratio $\gamma = \frac{5}{3}$ is constant throughout the reaction) and I is the ionization energy per unit mass.

Equations 2.1~2.3 state that the balance across the shock front boundary by mass continuity, momentum and energy, respectively. The first term in Eq. (2.3) represents the change

in the kinetic energy, the second term represents the contribution of the internal energy e and both terms arise from transport of energy across the shock front boundary and the third term comes from the rate of working by stress.

Using the conventional relation $P = n(1 + Z) \times T$ for compression and $\rho \sim A m_p n$ where $Z = n_e/n$ is the effective charge (n_e is the electron number density), T is the temperature, A is the mass number and m_p is the proton mass. By arranging these equations the jump conditions across the shock front can be found as:

$$\frac{P_1}{P_0} = \frac{\frac{\rho_0}{\rho_1} - 4 + 2I \frac{n_0}{P_0}}{1 - 4 \frac{\rho_1}{\rho_0}} \quad (2.4)$$

$$\frac{\rho_1}{\rho_0} = \frac{1 + 4 \frac{P_1}{P_0}}{\frac{P_1}{P_0} + 4 - 2I \frac{n_0}{P_0}}, \quad (2.5)$$

$$\frac{u_1}{\lambda_s} = 1 - \frac{\rho_0}{\rho_1}, \quad (2.6)$$

where the subscripts 0 and 1 denote the initial state and the compression state, respectively.

The strong shock limits are obtained when $P_1 \gg P_0$ and have the simple form $\frac{\rho_1}{\rho_0} \sim 4$, where the ionization energy loss effects are neglected.

Numerical solutions at the shock front are shown in Fig. 2, i.e. shock Hugoniot curve. It is shown that the ionization energy loss is considerable in a strong shock limit case.

Fig. 2. Shows the numerical solution of the conservation eqs. at the shock front.

2.2. Ablation surface

In this region we take into account the heat conduction effects. Using the jump conditions at the ablation surface the following equations can be held:

$$\rho_1(u_1 - \lambda_a) = \rho_2(u_2 - \lambda_a), \quad (2.7)$$

$$\rho_1(u_1 - \lambda_a)^2 + P_1 = \rho_2(u_2 - \lambda_a)^2 + P_2, \quad (2.8)$$

$$\left[\frac{1}{2} \rho_1(u_1 - \lambda_a)^2 + \frac{3}{2} n_1(1 + z_1) T_1 + p_1 \right] \times (u_1 - \lambda_a) = \left[\frac{1}{2} \rho_2(u_2 - \lambda_a)^2 + \frac{3}{2} n_2(1 + z_2) \times T_2 + P_2 + n_2 I_2 \right] (u_2 - \lambda_a) + Q_2, \quad (2.9)$$

and the Chapman-Jouguet deflagration condition is

$$c_2 = \sqrt{\frac{P_2}{\rho_2}} = u_2 - \lambda_a, \quad (2.10)$$

where λ_a is the ablation front speed, Q_2 is the heat flux and c_2 is the sound speed and the subscripts 1 and 2 for all physical quantities refer to the states ahead and behind of the ablation surface, respectively. Rearranging these equations the pressure and density ratios at the ablation front can be given as:

$$\frac{P_2}{P_1} = \frac{1}{2 - \frac{\rho_2}{\rho_1}}, \quad (2.11)$$

$$\frac{\rho_2}{\rho_1} = 1 - \sqrt{1 - \frac{P_1}{n_1(1 + z_2) T_2}} \quad (2.12)$$

$$\approx \frac{P_1}{2n_1(1 + z_2) T_2} \ll 1$$

Since the mass density ρ_1 is much greater than the mass density ρ_2 , it is clear that the ablation pressure is almost about twice of the pressure near the C-J point.

The ablation front speed is given by

$$\lambda_a = u_1 + \sqrt{\frac{P_1 - P_2}{\rho_1 \left(\frac{\rho_1}{\rho_2} - 1 \right)}} \quad (2.13)$$

2.3. Energy conservation

In order to obtain a complete set of equations, one needs considerable information about the absorbed energy flux near the cutoff density, primarily one needs two additional equations.

First the energy increase in the whole system is the sum of the three terms, the energy increase in the whole compressed region, the energy increase in the rarefaction region (because of the isothermal expansion follows the deflagration) and the third term due to the ionization energy loss.

The energy increase in the compressed region is given by

$$\begin{aligned} \epsilon_{\text{comp.}} = & \left[\frac{1}{2} \rho_1 u_1^2 + \frac{3}{2} n_1 (1 + z_1) T_1 \right] | \lambda_s - \lambda_a | \\ & - \frac{3}{2} n_0 (1 + z_0) T_0 \lambda_s \end{aligned} \quad (2.14)$$

The first term in the right part of equation (2.14) is the kinetic energy of a particle passing through the shock front, the second term is the internal energy of a particle in the whole compressed region and the last term is the internal energy of a particle at rest.

The energy increase in the isothermal expansion is given by

$$\epsilon_{\text{iso.}} = \int_{-\lambda_a t}^{\infty} dx \frac{d}{dt} \left[\frac{1}{2} \rho u^2 + \frac{3}{2} n (1 + z) T \right] \quad (2.15)$$

$$\text{where } u = \frac{x}{t} + c_2,$$

$$\rho = \rho_2 \exp \left[- \frac{1}{c_2} \left(\frac{x}{t} + \lambda_a \right) \right]$$

and the point $x = -\lambda_a t$ corresponds to the Chapman-Jouguet point.

Therefore, the energy increase in the whole system is equal to the absorbed intensity I_a , i.e.

$$I_a = \epsilon_{\text{comp.}} + \epsilon_{\text{iso.}} + n_0 I_1 | u_0 - \lambda_s | + n_1 I_2 | u_1 - \lambda_a | \quad (2.16)$$

In Eq. (2.16) the last two terms represent the increase in the ionization energy.

Second, two models are considered here, the free streaming flux limit model and the experimental temperature scaling.

At sufficiently high temperature and low density, heat flux may saturate in the overdense region, namely the heat flow can not exceed the maximum free streaming flux, thus in such a case a reasonable added equation (free streaming fluxlimit model) for the solution is

$$I_a = f n_c T_2 \left(\frac{T_2}{m_e} \right)^{1/2} \quad (2.17)$$

where f is a dimension less number^{2,5,6)} which can be determined from the microscopic phenomena in the cutoff region, n_c is the cutoff density and m_e is the electron mass. Equation (2.17) states that the energy transported by the electron is balanced with the absorbed energy flux I_a at the cutoff region. A reasonable added equation (the experimental temperature⁷⁾ scaling) for the solution is

$$T_2 = 2.28 (I_a \lambda^2)^{1/4} \quad (2.18)$$

Since the temperature T_2 is proportional to $I_a^{2/3}$ in the case of free streaming flux limit model and to $I_a^{1/4}$ in the case of experimental temperature scaling, for the given range of I_a the free streaming flux limit model covers a wide range of the temperature T_2 than that for the experimental temperature scaling. For reasonable value of flux limit parameter (say $f=0.5$) at I_a 10^{14} W/cm² the free streaming flux limit model gives temperature higher than that for experimental temperature scaling. In other words, the heat flux becomes greater in the case of free streaming flux limit model than that for experimental temperature scaling. While at $I \sim 10^{15}$ W/cm² experimental temperature scaling gives heat flux greater than that for the free streaming flux limit model (see Fig. 3).

Fig. 3. Comparison between free streaming flux limit model and experimental temperature scaling.

3. Approximation Solutions and Numerical Results

Before proceeding to the numerical solutions it is necessary to know the main parameters in the ablation regime such as the ablation pressure, mass ablation rate, hydrodynamic efficiency, and so forth. This section deals with these in greater detail to estimate these parameters analytically and numerically. We will consider the two models, i.e. the free streaming flux limit model and the experimental temperature model. The analytic solutions are also helpful in interpreting the numerical solutions and experimental data.

3.1. Approximation solutions

From Eq. (2.13) one can obtain $u_1 - \lambda_a = c_1 [\frac{\rho_2}{2\rho_1}]^{1/2} \ll c_1$, it means that the particle velocity u_1 is of the order of the ablation front speed λ_a . If the absorbed energy flux is of the order of 10^{15} W/cm², then the ionization energy loss can be neglected. Also assume strong shock limits, therefore the energy increase

in both two regions, compression and rarefaction regions are

$$\dot{\epsilon}_{\text{comp.}} \approx \sqrt{3} P_1 c_1; \quad \dot{\epsilon}_{\text{iso.}} \approx 2.75 P_1 c_2$$

respectively.

The ablation pressure P_a is the pressure of the hot plasma at the ablation front (the term ablation is used because the pressure is associated with the ablation of heated plasma from solid target). According to Eq. (2.16) the pressure exerted on the target can be written as

$$P_1 \approx P_a \approx 3.72 \times 10^{-12} \sqrt{\frac{A}{(1+z_2)T_2}} I_a, \quad (\text{Mbar}) \quad (3.1)$$

Here the electron temperature in units of eV and I_a in units of W/cm².

In the practical units for the free streaming flux limit model and experimental temperature scaling are

$$P_a \approx 15.11 \left(\frac{A}{1+z_2} \right)^{1/2} I_a^{2/3} f^{1/3} \lambda^{-2/3}, \quad (\text{Mbar}) \quad (3.1a)$$

$$P_a \approx 12.5 \left(\frac{A}{1+z_2} \right)^{1/2} I_a^{7/8} \lambda^{-1/4}, \quad (\text{Mbar}) \quad (3.1b)$$

, respectively. Where I_{a14} is the absorbed laser intensity in units of 10^{14} W/cm². These formulas suggest that reducing λ will increase P_a as $\lambda^{-2/3}$ in Eq. (3.1a) and as $\lambda^{-1/2}$ Eq. (3.1b). The experimental temperature model gives a large ablation pressure. The ablation pressure is greatest where the electron temperature T_2 is greatest and Z_2 is smallest. If the plasma ablation rate decreases the temperature rises and absorption drops, allowing more energy to reach the ablation front and thereby increasing the ablation rate.

Comparing our model with the rocket model⁸⁾ (the integration of the equation of motion of a rocket model gives the mass ablation rate $\dot{m}$ as

a function of the velocity and mass at any time) the mass ablation rate can be given by

$$\dot{m} = \rho_1 |u_1 - \lambda_a|, \quad (3.2)$$

in the practical units are

$$\dot{m} \approx 3.14 \times 10^5 \left(\frac{A}{1+z_2} \right) I_{a14}^{1/3} f^{2/3} \lambda^{-3/4} \quad \text{g} \cdot \text{cm}^{-2} \text{sec}^{-1}, \quad (3.2a)$$

for the free streaming flux limit model, and

$$\dot{m} \approx 2.15 \times 10^5 \left(\frac{A}{1+z_2} \right) I_{a14}^{3/4} \lambda^{-1/2} \quad \text{g} \cdot \text{cm}^{-2} \text{sec}^{-1} \quad (3.2b)$$

for the experimental temperature scaling.

It appears that the mass ablation rate is greatest in the case of the experimental temperature scaling rather than the free streaming flux limit model.

Our definition for the hydrodynamic efficiency η_H is based on the ratio between the sum of energy increase in the compressed region $\varepsilon_{\text{comp}}$, plus the ionization energy loss in the compressed region to the energy increase in the whole system ε_{tot} .

$$\eta_H = (\varepsilon_{\text{comp}} + n_0 I_1 |u_0 - \lambda_s|) / I_a \quad (3.3)$$

therefore,

$$\eta_H \approx 0.05 \rho_0^{-1/2} \left(\frac{A}{1+z_2} \right)^{3/4} f^{1/2} \lambda^{-1} \quad (3.3a)$$

for the free streaming flux limit model, and

$$\eta_H \approx 0.04 \rho_0^{-1/2} \left(\frac{A}{1+z_2} \right)^{3/4} I_{a14}^{5/16} \lambda^{-3/8} \quad (3.3b)$$

for the experimental temperature scaling, where ρ_0 in units of $\text{g} \cdot \text{cm}^{-3}$. In the case of the free streaming flux limit model the hydrodynamic efficiency does not depend on the laser flux intensity but the wavelength dependence is strong. Since the energy increase in the compressed region is proportional to $P_1^{3/2}$ and because P_1 is proportional to $I_a^{2/3}$ in the case of free streaming flux limit model and to $I_a^{7/8}$ in the case of experimental temperature scaling, the

hydrodynamic efficiency does not depend on I_a in the case of free streaming flux limit model while it is proportional to $I_a^{5/16}$ in the case of experimental temperature scaling. The exhaust of low temperature gives high efficiency (see Fig. 7).

The pressure acting on the solid is the sum of the two components, thermal and momentum transfer. So that the mechanical power P_M for this system can be defined as follows:

$$P_M = \left(\frac{1}{2} \rho_1 u_1^2 + P_1 \right) u_1 \quad (3.4)$$

Therefore, the resulting scaling laws for the free streaming flux limit model and for the experimental temperature scaling are

$$P_M \approx 1.27 \times 10^{13} \rho_0^{-1/2} \left(\frac{A}{1+z_2} \right)^{3/4} I_{a14} f^{1/2} \lambda^{-1}, \quad (\text{w/cm}^2) \quad (3.4a)$$

$$P_M \approx 9.61 \times 10^{12} \rho_0^{-1/2} \left(\frac{A}{1+z_2} \right)^{3/4} I_{a14}^{21/16} \lambda^{-3/8} \quad (\text{w/cm}^2) \quad (3.4b)$$

, respectively.

The absorbed intensity dependence of this mechanical power is stronger for the experimental temperature scaling than the free streaming flux limit model.

The shock Mach number M_1 (in the compressed region) for both the free streaming flux limit model and the experimental temperature scaling are given by

$$M_1 \approx 4.59 \rho_0^{-1/2} (A/T_0)^{1/2} \left(\frac{A}{1+z_2} \right)^{1/4} \times I_{a14}^{1/3} f^{1/6} \lambda^{-1/3}, \quad (3.5a)$$

and

$$M_1 \approx 4.17 \rho_0^{-1/2} (A/T_0)^{1/2} \left(\frac{A}{1+z_2} \right)^{1/4} \times I_{a14}^{7/16} \lambda^{-1/8} \quad (3.5b)$$

, respectively.

And the corresponding Mach number M_2 in the

ablation region is given by

$$M_2 \approx 0.04 \rho_0^{-1/2} \left(\frac{A}{1+z_2} \right)^{3/4} f^{1/2} \lambda^{-1}, \quad (3.6a)$$

$$M_2 \approx 0.03 \rho_0^{-1/2} \left(\frac{A}{1+z_2} \right)^{3/4} I_a^{5/16} \lambda^{-3/16} \quad (3.6b)$$

It is apparent that the plasma flows subsonically into the deflagration region and supersonically in the compressed region.

Finally, from Eq. (2.12) the number density n_2 at the C-J point for the two models are

$$n_2 \approx 7.8 \times 10^{21} \frac{A^{1/2}}{1+z_2} f \lambda^{-2}, \quad (3.7a)$$

$$n_2 \approx 4.42 \times 10^{21} \frac{A}{1+z_2} I_a^{5/8} \lambda^{-3/4} \quad (3.7b)$$

It seems that the number density n_2 at C-J point is greater than the cutoff density. The wavelength dependence of the number density n_2 is stronger in the case of the free streaming flux limit model than the experimental temperature scaling. Because the density number n_2 at C-J point depends on P_1/T_2 (see Eq. (2.12)) it does not depend on the absorbed intensity I_a in the case of the free streaming flux limit model, while it is proportional to $I_a^{5/8}$ in the case of the experimental temperature scaling.

3.2. Numerical results

This section describes numerical calculations performed with both the free streaming flux limit model and the experimental temperature scaling. Numerical calculations are performed for the Eqs. (2.4)~(2.18) in order to estimate the main parameters of the ablation. We consider CH_2 , Al and SiO_2 as examples. Experimental data from the Institute of Laser Engineering⁷⁾ (ILE), Naval Research Laboratory⁹⁾ (NRL) and Rutherford Laboratory¹⁰⁾ (RL) are presented also.

On the basis of the numerical calculations and experimental results and the discussion

pertaining thereto we propose the following inference conclusion.

Figure 4 shows the numerical results and available experimental data for ablation pressure

Fig. 4. a, b and c ablation pressure as a function of laser intensity or absorbed intensity showing calculated values and experimental data taken from various laboratories.

as a function of laser intensity or absorbed intensity; a), b), and c) compare the numerical calculations for both the free streaming flux limit model and the experimental temperature scaling with ILE data, NRL data and RL data, respectively. Figure 5 shows the numerical results and available experimental data for mass ablation rate as a function of laser intensity or

Fig. 5. a and b show mass ablation rate as a function of laser intensity or absorbed intensity showing calculated values and experimental data taken from various laboratories and c show mass ablation rate as a function of absorbed intensity for Al, SiO₂ and CH₂.

absorbed intensity, a) compares the numerical calculations for both models as a function of laser intensity with ILE data, b) compares the numerical calculations for both models as a function of absorbed intensity with RL data and c) compares the dependence of the mass ablation rate on the charge Z.

According to these comparisons ILE and NRL results are in good agreement with both the free streaming flux limit model and the experimental temperature scaling, but RL results are in good agreement with the free streaming flux limit model. It is apparent that agreement is quite good at $\lambda=1.06 \mu\text{m}$, but poor at longer and shorter wavelength. The results are generally reasonable at higher pressure. As it is expected for large z the mass ablation rate is large (see Fig. 5c).

Figure 6 presented the dependency of the ablation pressure on the flux limit parameter f . This dependence follows the removal of energy by ions from the absorption region near the cutoff density at a rate proportional to the incident laser intensity. Figure 7 illustrates the numerical calculations for hydrodynamic efficiency η_H and ablation temperature T_2 as a function of absorbed intensity. It is clear that the exhaust of low temperature gives high efficiency. Figure 8 shows the numerical calculation

Fig. 6. Shows ablation pressure as a function of the flux limit parameters (solid line for absorbed intensity = 10^{15} W/cm^2 and dashed line for absorbed intensity = 10^{14} W/cm^2).

Fig. 7. Shows the hydrodynamic efficiency η_h and the temperature T_2 as a function of absorbed intensity.

Fig. 8. Shows dependency of the mechanical power P_M and the number density n_2 on the absorbed intensity.

for the mechanical power and the number density at the C.J point as a function of absorbed intensity. It is apparent that the number density at the C.J. point is larger than the cutoff density.

The approximation solutions given in Sec. 3 support these expectations in both numerical calculations and experimental results.

4. Conclusion and Discussion

The scaling with laser wavelength of the laser generated ablation is a potentially significant factor in laser driven implosion and compression studies. This model includes the ionization energy loss in plane geometry assuming a steady-state. The free streaming flux limit model and experimental temperature scaling are considered. Analytical and numerical modelling of the ablation parameters such as ablation pressure, mass ablation rate hydrodynamic efficiency, and so forth in this paper has included the flux limit parameter, laser wavelength and absorbed intensity. The solutions are compared with the experimental results. Both numerical and approximation solutions show reasonable agreement with experimental results from various laboratories. The agreement is quite good at $\lambda = 1.06 \mu\text{m}$, but poor at shorted wavelength. At higher pressure the results are reasonable. The ablation pressure is greatest where the electron temperature T_2 is greatest and Z_2 is smallest. In the case of the experimental temperature scaling the mass ablation rate is greater than that in the case of the free streaming flux limit model. The hydrodynamic efficiency does not depend on the laser absorbed intensity in the case of the free streaming flux limit model, but the wavelength dependence is strong. The exhaust of low temperature gives high efficiency. The information of this paper shows that the experimental temperature scaling is the most satisfactory available for ILE and NRL experiments data. RL experimental data and free streaming flux limit model show reasonable agreement.

Acknowledgments

The authors thank Prof. C. Yamanaka, Dr. H. Nishimura, Dr. K. Mima and Dr. T. Yabe for a useful discussion of the results.

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