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Robert J. Harrach
Abraham Szöke
W. Michael Howard

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INERTIAL EFFECTS IN LASER-DRIVEN ABLATION

Robert J. Harrach, Abraham Szöke, and W. Michael Howard

Lawrence Livermore National Laboratory
Livermore, California 94550  U.S.A.

Abstract

The gasdynamic partial differential equations (PDE's) governing the motion of an ablatively accelerated target (rocket) contain an inertial force term that arises mathematically from acceleration of the reference frame in which the PDE's are written, and more physically from the requirement that part of the ablated mass (the deflagration wave zone) needs to be accelerated along with the unablated mass (payload). We give a simple, intuitive description of this effect, and estimate its magnitude and parametric dependences by means of approximate analytical formulas inferred from our computer hydrocode calculations. Often this inertial term is negligible, but for problems in the areas of laser fusion and laser equation of state studies we find that it can reduce the attainable hydrodynamic efficiency of acceleration and implosion by up to 25% for typical conditions.

The efficiency of target acceleration and implosion in laser fusion and laser equation-of-state experiments is ultimately limited by an "inertial drag" effect. This effect can be exhibited most simply within the framework of a rocket model of laser ablation, by writing the rocket equation of motion in the form
\[ M(1+f)\dot{v} = -\dot{M}u_0 \quad , \tag{1} \]

which has the solution (for \( f, u_0 \) constants)

\[ v = \left[u_0/(1+f)\right] \ln(M_0/M) \quad . \tag{2} \]

The corresponding hydrodynamic efficiency of rocket acceleration is

\[ \eta = \frac{Mv^2}{2E_{\text{abs}}} \quad . \tag{3} \]

In these equations \( M \) and \( v \) are the instantaneous values of the (unablated) rocket mass and its center-of-mass velocity with respect to a fixed coordinate frame; the dot represents a time derivative (\( \dot{v} = dv/dt, \dot{M} = dM/dt \)); \( u_0 \) is the velocity of ejected mass relative to the rocket rest frame, and \( E_{\text{abs}} \) is the absorbed energy producing ablation. A relation connecting the rate \( \dot{E}_{\text{abs}} \) that energy is absorbed (burned) with \( \dot{M} \) and \( u_0 \) is \( \dot{M}u_0^2/2 = (0.64)\dot{E}_{\text{abs}} \), where the factor 0.64 corresponds to an adiabatic ablation plasma; for the isothermal case the factor is 0.5.

If \( f=0 \), Eqs. (1)-(3) are the usual rocket equations found in most general physics texts; \( fM \) represents the effective increase in the rocket's inertial mass. The calculations we describe here justify this form for the rocket equations and show that \( f \) is a function only of the specific heat ratio \( \gamma \) of the exhaust gas and the relative thickness of the deflagration wave that drives the ablation.

We analyzed the inertial effect computationally by discarding all non-essential details associated with the laser driver and laser/matter
interaction, imposing instead a prescribed deflagration wave source which advances into the target at a given fixed rate, depositing (liberating) a given quantity of energy per unit of mass traversed. R. Barton's ALE hydrocode [1] is well-suited to such calculations, allowing us to vary, in particular, the deflagration wave thickness from one problem to the next, holding other things equal. For simplicity, we considered only one-dimensional problems in plane geometry. In a given calculation, the target slab was finely divided into some 200 equal-thickness zones and a prescription given for the time when each zone "lights", releasing a given quantity of internal energy in that zone. The lighting algorithm determines both the thickness of the deflagration wave, by the number of contiguous zones which are in the process of burning at a given instant, and the rate that the wave smoothly moves through the accelerating slab.

The computer results show that \( v \) is strictly linearly related to \( \ln(M_0/M) \) for any given deflagration wave thickness, but the coefficient \( u_0/(1+f) \) varies monotonically with this thickness, \( \Delta l_D \), defined as the equivalent thickness of matter spanned by the deflagration wave if the matter were at the solid density \( \rho_0 \):

\[
\Delta l_D = \rho_0^{-1} \int_0^{X_D} \rho(x)dx
\]  

The distance \( \Delta l_D \) must be small compared to the initial target thickness \( l_0 \). It corresponds in the laser problem to the steady state separation \( \Delta l_{as} \) between the ablation and sonic surfaces in the blowoff plasma. From these numerical results for specific cases, we infer that
where $\gamma$ is the usual specific heat ratio ($1 < \gamma \leq 5/3$), $\gamma$ is a logarithmic function of the deflagration wave thickness:

$$y \equiv \ln(\ell_0/\Delta \ell_D) \quad .$$

(6)

and the parameter $y_{\text{max}}$ is defined as

$$y_{\text{max}} = \frac{22.7}{(\gamma-1)0.18} \left(1 - \frac{(\gamma-1)0.48}{1.04}\right) \quad .$$

(7)

The solution, Eq. (5), fits our computations in the range $1 < y < 6$ where they were obtained, and has the correct behavior $f \to 0$ (i.e., the inertial effect vanishes) in the limit of zero deflagration wave thickness $(\Delta \ell_D/\ell_0 \to 0, y \to \infty)$, corresponding to zero separation of the ablation and sonic surfaces. According to Eq. (5) the inertial effect is more pronounced for materials having $\gamma$ nearer unity.

The connection between our results and those of Fabbro, Max, and Fabre [2], derived from their analytical theory of laser-driven ablation, can be made by writing the ablation pressure $P_a \equiv m \dot{v} \ (m = M/\text{area})$ as $P_a = P_{a,0} - P_I$, where $P_{a,0} = \dot{m} \rho_0$ is the uncorrected value and $P_I$ is the inertial correction. We find

$$P_I = \frac{P_{a,0}}{(1+f)} = \begin{cases} 
(1 - \frac{(\gamma-1)0.48}{1.04}) - \frac{(\gamma-1)0.18}{22.7} y & \text{for } 0 \leq y \leq y_{\text{max}} \\
0 & \text{for } y > y_{\text{max}} 
\end{cases}$$

(8)

(where, as before, the top line applies for $y$ between 0 and $y_{\text{max}}$ and the bottom for $y > y_{\text{max}}$) while they get

$$\left(\frac{1+f}{\gamma-1}\right)^{-1} = \begin{cases} 
\frac{(\gamma-1)0.48}{1.04} + \frac{(\gamma-1)0.18}{22.7} y & \text{for } 0 \leq y \leq y_{\text{max}} \\
1 & \text{for } y > y_{\text{max}} 
\end{cases}$$

(5)
Our result shows a stronger dependence on the nature of the ablated plasma, through the factor \( \gamma \).

The hydrodynamic efficiency \( \eta \) [Eq. (3)] goes as \((P_a)^2\); thus the reduction in \( \eta \) due to the inertial drag effect is given by a multiplicative factor \([1 - (P_I/P_{a,o})]^2\), which equals \((1+f)^{-2}\) by Eq. (8) and \([1 - 2\exp(-y)]^2\) by Eq. (9). Setting \( \gamma = 5/3 \), the way our \( \eta \) compares to that of Fabbro, Max, and Fabre for various values [3] of \( \Delta l_D/\lambda_0 \), corresponding to the ratio of mass in the steady-state conduction zone to total initial mass of the target, is indicated in Table I. We predict a comparable reduction in efficiency for small values of the deflagration wave thickness, and less but still quite substantial (up to about 25%) reduction for greater thickness where we expect FMF's result [Eq. (9)] to become inaccurate. Values of \( \Delta l_D/\lambda_0 \) up to 15% or so are typical for the small targets in laser fusion and laser EOS experiments.

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REFERENCES:


[3] The way $\Delta l_D = \Delta l_{as}$ is expected to vary with laser parameters (absorbed intensity, wavelength) is given by FMF's formula (for plane geometry)

$$\Delta l_{as} = (11 \, \mu m) \left( \frac{I_{abs}}{10^{14} \, W/cm^2} \right)^{4/3} \left( \frac{\lambda}{1 \, \mu m} \right)^{8/3} \left( \frac{1 \, g/cm^3}{\rho_0} \right) \left( \frac{A}{22} \right)^{13/6}$$

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TABLE I

\[ [1 - P_I/P_{a,0}]^2 = \text{factor by which inertial effect modifies } \eta \]

<table>
<thead>
<tr>
<th>$\Delta &amp;D/\xi_0$</th>
<th>(FMF)</th>
<th>(present paper, $\gamma = 5/3$)</th>
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<tr>
<td>0.01</td>
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