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Robert J. Harrach
Abraham Szöke
W. Michael Howard

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Lawrence
Livermore
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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 from acceleration of the reference frame in which the PDE's are written. 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 substantially reduce the attainable hydrodynamic efficiency of acceleration and implosion.

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

$$M(1+f)\dot{v} = -\dot{M}u_0, \quad (1)$$

which has the solution (for f , u_0 constants)

$$\dot{v} = [u_0/(1+f)]\dot{m}(M_0/M) \quad (2)$$

The corresponding hydrodynamic efficiency of rocket acceleration is

$$\eta = M\dot{v}^2/2\dot{E}_{\text{abs}} \quad (3)$$

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 ($\dot{v} \equiv dv/dt$, $\dot{M} \equiv dM/dt$); u_0 is the velocity of ejected mass relative to the rocket rest frame, and E_{abs} is the absorbed energy producing ablation. If $f=0$, Eqs. (1)-(3) are the usual rocket equations; 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 γ 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.

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, Δl_D , defined as the equivalent thickness of matter spanned by the deflagration wave if the matter were at the solid density ρ_0 :

$$\Delta l_D = \rho_0^{-1} \int_0^{x_D} \rho(x) dx \quad (4)$$

The distance Δl_D must be small compared to the initial target thickness l_0 . It corresponds in the laser problem to the steady state separation Δl_{as} between the ablation and sonic surfaces in the blowoff plasma. From these numerical results for specific cases, we infer that

$$(1+f) \approx \frac{3(\gamma+1) + y^{2(\gamma-1)}}{[3(\gamma+1)/\gamma] + y^{2(\gamma-1)}} \quad (5)$$

where γ is the usual specific heat ratio and y is a log function of the deflagration wave thickness:

$$y \equiv \ln(l_0/\Delta l_D) \quad (6)$$

Observe that the inertial drag effect vanishes, i.e., $(1+f)$ goes to unity, in the limit of zero deflagration wave thickness ($\Delta l_D/l_0 \rightarrow 0$, $y \rightarrow \infty$), corresponding to zero separation of the ablation and sonic surfaces. Also the effect vanishes for materials having γ approaching 1. This seems plausible from the ideal gas relation $(\gamma-1) = P/\rho \mathcal{E}$, where P is the pressure, ρ

the density, and e the internal energy per unit mass; the ablation pressure generated by the deposition of energy e becomes insensitive to e as γ approaches 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 $P_{a,0} = \dot{m}u_0$ is the uncorrected value and P_I is the inertial correction. We find

$$P_I = \frac{fP_{a,0}}{(1+f)} = \frac{(\gamma-1)}{\gamma} \frac{y^{2(\gamma-1)}}{[3(\gamma+1) + y^{2(\gamma-1)}]} P_{a,0} \quad (7)$$

while they get

$$P_I \approx 2 P_{a,0} \Delta l_{as}/l_0 = 2P_{a,0}e^{-y} \quad (8)$$

The hydrodynamic efficiency η [Eq. (3)] goes as $(P_a)^2$; thus the reduction in η due to the inertial drag effect is given by a multiplicative factor $[1 - (P_I/P_{a,0})]^2$. Setting $\gamma = 5/3$, the ratio of our η to that of Fabbro, Max, and Fabre for various values of $\Delta l_D/l_0$, corresponding to the ratio of mass in the steady-state conduction zone to total initial mass of the target, is shown in Table I. We predict a more drastic reduction in efficiency for small values of the deflagration wave thickness.

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TABLE I

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

$\Delta l_D/l_0$	(FM ²)	(present paper)
0.01	0.96	0.63
0.02	0.92	0.60
0.05	0.81	0.55
0.08	0.71	0.52
0.10	0.64	0.50
0.15	0.49	0.48