Impulse Dependence on Propellant Condition in a Laser-Driven In-Tube Accelerator

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The laser-driven in-tube accelerator is a unique laser propulsion device, in which a projectile is accelerated in a launch tube with the power of repetitive laser pulses. The impulse is enhanced owing to a confinement effect, and the type and fill pressure of the propellant gas are tunable to the thrust performance. We have conducted operation experiments using a 25-mm-bore launch tube with a laser energy from 2.4 to 3.5 J/pulse at a laser-pulse repetition frequency of up to 70 Hz. The 3-gram projectile has a centerbody; as a parabolic mirror, its base focuses an incident laser beam to a spot on the center axis. Three monoatomic gases (i.e., argon, krypton and xenon) are examined as the propellant. The momentum coupling coefficient is measured from a condition that the time-averaged impulse is balanced with the gravitational force onto the projectile. The measured impulse characteristics are analyzed by referring to scaling relations that are obtained from dimensional analysis and pressure histories measured for the launch tube. In accordance with the dependence of the impulse generation period, the measured impulse is in inverse proportion to the propellant speed of sound. For a fill pressure up to about 100 kPa, the impulse sharply increases as the fill pressure increases, while it becomes saturated for higher pressures. Those performance characteristics are analyzed by estimating the overpressure level and the duration time of the impulse generated by the laser-driven blast wave.

Key Words: Laser, Propulsion, Impulse, Speed of Sound, Shock Waves, Scaling Effect

Nomenclature

a : speed of sound = $\sqrt{\gamma RT_0}$
 C_m : momentum coupling coefficient, the ratio of impulse to input laser energy
 $\bar{C}_m$: dimensionless momentum coupling coefficient, defined by Eq. (8)
 d : diameter of projectile base
 E : laser energy per pulse
 F_g : friction force due to flow viscosity between projectile and launch tube wall
 F_i : solid-to-solid friction force at the interface between projectile and launch tube wall
 f : laser pulse repetition frequency
 f_h : minimum value of f for projectile lift-off
 g : gravitational acceleration
 I : local impulse, integral of local pressure in respect to time
 J : propulsive (total) impulse to projectile, integral in respect to time of force, which in turn is an integral of local pressure in respect to area
 M_s : shock Mach number = U_s/a_0
 m : projectile mass
 P : pressure

P_0 : propellant fill pressure
 R : specific gas constant
 r : distance from projectile base to laser beam focus
 T : temperature
 t : time measured from initiation of laser pulse
 U : projectile speed
 U_s : shock speed
 x : one-dimensional spatial coordinate
Greek symbols
 α : function, Eqs. (5), (8), (10) and (12)
 χ : scaled distance defined by Eq. (6)
 Δ : Error, Eq. (3)
 ΔP : overpressure from P_0
 γ : specific heat ratio
 ρ : density
 τ : characteristic duration time

Subscripts

0: initial value
s: shock wave

1. Introduction

Laser propulsion consists of generating a propulsive impulse from laser energy. Since a vehicle does not need to carry a power source on board, its payload capability can be superior to those of existing propulsion technologies. After Kantrowitz proposed this concept in 1972,¹⁾ experimental impulse performance,^{2–6)} vertical launch capability^{3–5,7–9)}

and various applications^{10,11)} have been examined. Pirri et al.²⁾ successfully realized the operation of what they called a 'laser-powered pulsejet,' in which a parabolic shell acted both as a reflector for focusing a collimated laser beam to a narrow region and a nozzle for the air. Myrabo et al.³⁾ designed a 'lightcraft' for laser-powered launch. It is mechanically stable for laser-beam alignment. Using a 10-kW class CO₂ laser, they successfully launched the lightcraft to an altitude as high as 71 m.⁷⁾ The technology of laser propulsion also involves important fundamental physics such as beam-matter interaction and shock-wave dynamics related to a laser-induced blast wave.

Here, we discuss the launch of a projectile initially at rest with a repetitive pulse (RP) laser. A pulsed laser beam is focused behind the projectile. If the local laser beam intensity exceeds a threshold value, free electrons are produced through an electron avalanche, thereby further enhancing laser beam absorption. The energy that is absorbed by the electrons is also redistributed to heavy particles through collisions. In this way, a high-pressure plasma core is created around the focus during the laser pulse irradiation period, and then expands and drives a blast wave.¹²⁾ On the projectile base, the pressure increases when the blast wave is reflected. As a result of this increased pressure, a propulsive impulse is generated. With laser pulses being repetitively irradiated, impulses are also repetitively produced, thereby yielding a thrust as their time-averaged value.

In most of the existing laser propulsion technologies, an object is accelerated in an open space.^{3–5,7)} However, in the Laser-driven In-Tube Accelerator (which will hereafter be referred to as 'LITA') developed at Institute of Fluid Science, Tohoku University,^{6,8,9,13–15)} a projectile is accelerated in a confined space; that is, in a launch tube, see Fig. 1. The launch tube is filled with an inert gas that acts as the propellant. A pulsed laser beam is focused on the projectile base, causing breakdown and laser energy absorption in the propellant. The projectile experiences an impulse from a blast wave that is driven by a laser-generated inflating plasma core. The types and fill pressure of the propellant are tunable for favorable impulse performance. The impulse onto the projectile base is increased due to reflections of the blast wave against the launch tube wall ('confinement' effect¹⁴⁾). As well as this favorable performance, LITA has the following practical advantages over other laser propulsion devices:

1) Unlike propulsion in an open space, additional devices for the trajectory tracking and attitude control of a projectile are not necessary; and 2) the danger against laser beam hazard, noise, vibration and air pollution are vastly alleviated.

On one hand, the impulse generation mechanisms in LITA involve many fundamental physical problems, while on the other hand, as was found by Sasoh et al.,¹⁵⁾ such a simple performance characteristic that the impulse was in inverse proportion to the speed of sound was experimentally obtained, although under a limited number of examined operation conditions. The propellant fill pressure, P_0 , is another important parameter in optimizing the performance characteristics and minimizing the associated cost of the launch system. This paper aims at examining detailed dependencies of an impulse on propellant conditions, and at understanding the associated flow physics and scaling effects through experimental and theoretical considerations.

2. Apparatus

Experiments have been conducted using a highly repetitive pulse CO₂ transversely excited atmospheric (TEA) laser (wavelength; 10.6 μm). In this study, the repetition frequency was set to 70 Hz. Figure 2 shows the laser power history in a single pulse, which is measured using a photon drag sensor (Hamamatsu, B749, rise time; 1 ns, effective sensing diameter; 5 mm). The power has two peaks. The first, and primary one, has a full-width at half maximum of 120 ns and contains about 40% of the total energy for the first 300 ns. The second one has a lower peak value and a longer duration period. The total duration of the laser pulse irradiation is at the order of 3 μs .

The beam output from the laser covers a cross-sectional area of a 30 mm $\times$ 30 mm square. It lies horizontally in a steel-walled room, is weakly focused using a ZnSe convex lens (focal length; 3 m), and is deflected to the axis of the vertically installed launch tube using two molybdenum plane mirrors. The schematic of the whole launch tube assembly is shown in Fig. 3a, and the detailed assembly around the projectile in Fig. 3b. The launch tube is made of acrylic and is 0.5 m in length. The projectile is initially located at about 100 mm above an NaCl window at the tube bottom. The tube section below the projectile initial location is made of aluminum, and its inner diameter (24.6 mm) is

Fig. 1. Schematic illustration of LITA operation.

Fig. 2. Laser power history measured using photon drag sensor set at the center of the laser beam cross-section, laser energy; 2.6 J.

Fig. 3. Launch tube assembly (unit: mm).

slightly smaller than the outer diameter of the projectile shroud (25.0 mm). Above the projectile, the launch tube (acrylic portion, inner diameter; 25.3 ± 0.1 mm) has a loose fit to the projectile shroud. The overpressure on the launch-tube wall at an axial location of 15 mm below the initial location of the focus is measured, and simultaneous observation is conducted to determine if the projectile lifts off or not. The pressure transducer (PCB 113A21, rise time; $1 \mu\text{s}$) is flush-mounted on the inner surface of the launch-tube wall. The laser beam is sent to the launch tube through the NaCl window. The upper end of the launch tube is plugged with a brass flange. In order to accurately measure the laser energy input, the laser beam cross-section is shaped through a 16-mm-dia. circular aperture so that it fits to the projection of the projectile base that is 16.2 mm in diameter. The effective value of the incident laser energy, which ranges from 2.4 J/pulse to 3.5 J/pulse, is obtained accordingly. The laser energy input is measured using an energy meter (Gentic ED-500LIR).

A schematic illustration of the projectile is shown in Fig. 4. The projectile is comprised of a centerbody, three struts and a shroud. The latter two components are found practically useful for stabilizing the in-tube attitude. They are all made of aluminum alloy, A7075-T6, and are connected together with epoxy adhesive. The laser beam can be supplied either from the front^(6,8,13,14) or rear side of the projectile. Yet, in the present experiment, thrust performance was always better in the latter case than in the former. Therefore, data only for rear incidence will be presented in this paper. The projectile mass is 3.0 g. The fore side of the centerbody consists of a cone with a half apex angle of 30 degrees. The base of the centerbody is lathed as a parabola. Its focus is located at an axial distance of 7.9 mm down the peripheral of the base.

Fig. 4. Projectile, (unit: mm) Upper; Side cross-sectional view; Lower; View from the bottom.

3. Method and Conditions of Experiment

3.1. Estimation of momentum coupling coefficient

The quantity that is most commonly used to evaluate the performance of a laser propulsion device is the momentum coupling coefficient, C_m . This is defined as the ratio of the propulsive (total) impulse, J , that the projectile experiences to the laser energy input, E . When time-averaged, C_m is equivalent to the ratio of the thrust to the laser power input. This quantity is convenient for comparing propulsive performances among devices of different dimensions and different laser-power input levels from the viewpoint of flow physics. Note here that C_m has the same dimension as the reciprocal of a velocity, that is [s/m].

In the present experiments, C_m is measured in projectile vertical launch operations. The time-averaged equation of projectile motion is expressed by

$$m \frac{dU}{dt} = C_m f E - mg - F_i - F_g \quad (1)$$

The first and second terms on the right-hand side of Eq. (1) designate a time-averaged propulsive impulse; that is, a thrust produced by laser pulses and gravitational force, respectively.

The third term is a frictional force due to the solid-solid contact at the interface between the projectile and the launch-tube wall. This force is expressed as the product of a friction coefficient and normal force to the interface. In principle, since in the vertical launch, the component of gravitational force normal to the interface does not exist, this term is negligible. In practice, however, the projectile can cant within an inclination angle that is smaller than 0.92 degrees, which is determined by the clearance between the projectile shroud and the launch-tube wall, and the shroud aspect ratio. Because the center of gravity of the projectile exists in the upper part of the shroud, about 6.5 mm

from the upper edge, a resultant moment onto the projectile due to the friction force between the edges of the shroud and the launch-tube wall stabilizes the in-tube attitude of the projectile. Therefore, in estimating the force balance between thrust and gravitational force, F_i can be neglected.

The fourth term, F_g , is caused by the gas viscosity in Couette flow through the clearance between the shroud and the launch-tube wall. In the experiment, with f and E set constant, laser operation is started and the projectile is watched to see if it rises to the top or not, then the laser is stopped. If yes, f is decreased, and if not, it is increased. In this way, it is possible to find the minimum value, f_h , for projectile lift-off with a given E . Under this condition, the projectile almost hovers in the launch tube; F_g decreases with decreasing flow velocity relative to the projectile, the projectile acceleration on the left-hand side of Eq. (1) also drops; and the thrust is approximately balanced with gravitational force, mg ; thereby experimentally determining C_m by

$$C_m = \frac{mg}{f_h E} \quad (2)$$

By differentiating Eq. (2), the error in C_m , ΔC_m , is given by

$$\frac{|\Delta C_m|}{C_m} = \frac{|\Delta f_h|}{f_h} + \frac{|\Delta E|}{E} \quad (3)$$

In the present experiments, the resolution of the laser-pulse repetition was 5 Hz. The range of f for projectile lift-off ranged from 40 to 70 Hz, corresponding to 7 to 13% error due to the first term on the right-hand side. The second term, corresponding to shot-to-shot uncertainty of the laser-pulse energy, is 8%. Overall, the error in determining C_m ranged from 15 to 21%, depending on the value of f .

In the present experiment, the length of the launch tube is 0.5 m. After the plasma core is produced, laser-driven blast waves propagate towards both ends of the launch tube. The waves then reflect off of the respective ends and propagate back towards the projectile. As a result of the interaction with the projectile, both transmitted and reflected waves are observed; thereby more complicated wave interactions follow. The average time interval for each blast wave to travel back and forth between the projectile and the launch tube ends is estimated by dividing the launch tube length (0.5 m) by the propellant's speed of sound. For xenon at a temperature of 290 K, this interval becomes about 3 ms. In the present experiment, the highest laser pulse repetition frequency was set to 70 Hz, corresponding to an interval of 14 ms. Therefore, in an interval between successive laser pulse irradiations, several reflected waves reach the projectile from both the top and bottom ends. The duration time of a vertical launch experiment is at the order of 500 ms, which is much longer than the above-mentioned characteristic time for the wave travel. Therefore, the impact of such reciprocal waves on thrust performance is assumed to be averaged out during the operation, and is neglected in the calculation of thrust performance.

4. Impulse Characteristics

4.1. Scaling consideration

Before analyzing experimental results, let us discuss the similarity and scaling effect of the impulse characteristics. We deal with the unsteady motion of an inviscid, compressible flow of calorically perfect gas. The propulsive (total) impulse, J , that the projectile experiences is generated as the time integration of the force which, in turn, is obtained as the spatial integration of the overpressure primarily over the centerbody. For point-source explosion, as is discussed by Sedov¹⁶⁾ from dimensional analysis, J is expressed by:

$$J = \alpha_1 \left(\frac{\rho_0 E}{r} \right)^{1/2} d^2 \quad (4)$$

$$\alpha_1 = \alpha_1 \left(\gamma, \frac{d}{r}, \chi, \text{ geometry, orientation} \right) \quad (5)$$

$$\chi = \frac{r}{\left(\frac{E}{P_0} \right)^{1/3}} \quad (6)$$

where, χ is a dimensionless quantity, the ratio of the distance between an explosion source and the body surface to a characteristic distance associated with the source energy. α_1 depends on χ only when the ambient pressure, P_0 , has a significant relation to the blast wave motion, otherwise the blast wave motion asymptotically follows a self-similar solution for $\chi = 0$. Using the equation of state,

$$P_0 = \rho_0 R T_0 = \frac{\rho_0 a_0^2}{\gamma}, \quad (7)$$

Eq. (4) is transformed to

$$\begin{aligned} \bar{C}_m &\equiv a_0 C_m = \frac{a_0 J}{E} = \alpha_1 \chi^{3/2} \left(\frac{d}{r} \right)^2 \gamma^{1/2} \\ &\equiv \alpha_2 \left(\gamma, \frac{d}{r}, \chi, \text{ geometry, orientation} \right) \end{aligned} \quad (8)$$

Since α_2 is independent of a_0 , C_m is in inverse proportion to a_0 . $\bar{C}_m$ is a dimensionless quantity corresponding to the present scaling relation. The effect of fill pressure, P_0 , reflects through a dependence on χ , the formulation of which, however, is not known to this specific problem.

In the same way, a local impulse, I , which is the time-integral of the local pressure, has the following scaling for point explosion:¹⁶⁾

$$I = \alpha_3 \left(\frac{\rho_0 E}{r} \right)^{1/2} \quad (9)$$

$$\alpha_3 = \alpha_3 \left(\gamma, \frac{d}{r}, \chi, \text{ geometry, orientation, location} \right) \quad (10)$$

Transforming Eq. (9) in the same manner as that for Eqs. (4) to Eq. (8), the following scaling relation is obtained:

$$I = \frac{\alpha_4 r P_0}{a_0} \quad (11)$$

$$\alpha_4 = \frac{\gamma^{1/2} \alpha_3}{\chi^{3/2}} \quad (12)$$

In the following subsections, we discuss the experimentally measured impulse characteristics in reference to the above scaling relations. Along with the momentum coupling coefficient, C_m , which is measured in the vertical launch shown in Fig. 2a, we analyze the histories of the static pressure that is measured at 15 mm below the focus along the launch-tube wall, see Fig. 3b. Although the primary impulse is exerted on the base of the centerbody, the pressure there cannot be readily measured because it also acts as the reflector of the laser beam. Instead, we discuss pressure histories measured on the launch-tube wall near the focus in terms of their link to the scaling relations of Eqs. (8) and (11).

4.2. Effect of propellant's speed of sound

In this study, monoatomic gases (i.e., argon, krypton and xenon) are selected as the propellant mainly for the following two reasons: (1) Due to their high specific heat ratios, high thrust performance is expected, and (2) the characteristics in shock-compressed state can be modeled as a calorically perfect gas, in which a specific heat ratio remains constant, thereby simplifying performance analyses. The propellant conditions set in the present experiments are listed in Table 1.

Figure 5 uses double-logarithmic coordinates to show the relationship between C_m and the propellant's speed of sound, a_0 , for constant fill pressures, P_0 . As will be shown later relating to Fig. 7, for each gas at fill pressures from 100 kPa to 300 kPa, the measured C_m became constant within the resolution of the measurement. As is seen in Fig. 5, at

Table 1. Conditions of propellant.

Propellant	Type	Ar	Kr	Xe
	a (m/s) at $T_0 = 293$ K	319	220	176
	P_0 (kPa)		10–300	
Laser	E (J)		2.4–3.5	
	f (Hz)		30–70

Fig. 5. C_m vs. a_0 .

Broken line: $C_m \sim 1/a_0$, for argon at $P_0 = 25$ kPa the projectile does not lift-off even at 70 Hz.

each fill pressure, C_m is almost in inverse proportion to a_0 .[‡] This is consistent with the scaling relation of Eq. (8) if α_2 is independent of a_0 . In order for this relation to hold, the effective value of the laser pulse energy input to the gas, E , and χ should be independent of the propellant gas type.

Figures 6a and 6b show the histories of overpressure, ΔP , measured on the launch-tube wall. Each history has several pressure oscillations, among which the highest overpressure, $\Delta P_{\max}$, is obtained in the first positive pressure pulse. This pulse is caused by the reflection of an incident laser-driven blast wave. The proceeding pressure oscillations are due to proceeding wave reflections in the launch tube. The reader should note that when ΔP variations for different gases are plotted onto the $a_0 t$ coordinate, see Figs. 6c and 6d, they almost coincide with each other. This implies that the local impulse, I , in Eq. (11) is proportional to the reciprocal of a_0 . This condition is realized if E , χ and α_4 are independent of a_0 .

From the above results, it is concluded that E is effectively independent of a_0 . We will now discuss the shock-wave dynamics appearing under this condition. In the inviscid, compressible flow of calorically perfect gas with a given geometry, shock-wave reflection patterns and post-shock pressures are determined only by an incident shock Mach number, M_s .¹⁷⁾ As seen in Fig. 7a, the post-shock pressure, $\Delta P_{\max}$, and hence the local shock Mach number, M_s , are almost independent of a_0 . In such cases, the wave diagrams plotted on $x - a_0 t$ coordinates become similar, see Fig. 8a. However, when plotting the diagrams onto an $x - t$ coordinate, as shown in Figs. 8b and 8c, the corresponding local shock speed, U_s , scales with a_0 , and the duration time of each event, τ , is inversely proportional to a_0 . For a low a_0 , the pressure event takes a long time (Fig. 8b), and for a high a_0 , a short time (Fig. 8c). The impulse due to this pressure event, I , is the time integral of ΔP . For example, the impulse due to the first positive pressure pulse is equal to the hatched area in Figs. 8b or 8c. It is scaled with the reciprocal of a_0 in accordance with the variation in τ . In the present experiment, this principle is well utilized; using xenon as the propellant, C_m as high as 290 N/MW, at the highest level of laser propulsion using only a gaseous propellant, is obtained.

Now, let us estimate a duration time in measured pressure events. Here, let the characteristic duration time for impulse generation, τ_1 , be defined by:

$$\tau_1 \equiv \frac{\left(\int \Delta P dt \right)_{\max}}{\Delta P_{\max}} \quad (13)$$

As seen in Figs. 6a and 6b, τ_1 is regarded as an effective duration time of the first positive overpressure pulse. The relationship between τ_1 and a_0 are plotted in Fig. 7b. As is predicted in the above discussions, τ_1 is almost proportional to

[‡]This dependence was first reported in Ref. 15, and was discussed based on a one-dimensional shock tube relation. In the following discussions with further experimental data, the relevant mechanisms will be much better understood.

Fig. 6. Variations of ΔP after a single laser pulse irradiation.
 τ_1 is defined by Eq. (13), $E = 3.5$ J.

Fig. 7. Dependence of quantities related to launch-tube wall pressure on a_0 , Kr, $E = 3.5$ J.

Fig. 8. Illustration of local impulse dependence on a_0 for one-dimensional wave reflections on the wall.
 Solid line: shock wave; Broken line: Expansion wave.
 Reflected Expansion waves are not drawn.

the reciprocal of a_0 .

Therefore, we have confirmed that both α_2 estimated from the impulse performance and α_4 estimated from the over-pressure history on the launch-tube wall are independent of a_0 . This is consistent with the assumption that the effective laser energy input to the gas does not depend on the prop-

Fig. 9. $\bar{C}_m$ vs. P_0 .

pellant types. Under this condition, the duration time for propulsive impulse generation is inversely proportional to a_0 , with the overpressure amplitude remaining unchanged. In order to unify the impulse performance among the present propellant types, a dimensionless momentum coupling coefficient, $\bar{C}_m$, is useful because it is independent of a_0 .

4.3. Effect of propellant fill pressure

Next, we discuss the dependence of propulsive impulses on the fill pressure, P_0 . In Eqs. (8) and (11), the impact of P_0 on α_2 and α_4 occurs based on their dependencies to χ . However, an explicit formulation is not readily obtained in closed forms. Here, we discuss them based on experimental data.

Figure 9 shows the experimentally measured relationship between $\bar{C}_m$ and the propellant fill pressure, P_0 . As seen in the previous subsection, within the experimental uncertainty, $\bar{C}_m$ is independent of the propellant types. For $P_0 < 100$ kPa, $\bar{C}_m$ is an increasing function of P_0 . For larger P_0 , it becomes saturated. In practical application at a ground-based facility, the fill pressure dependence that obtains the highest impulse performance at the atmospheric pressure level is favorable because the mechanical load on the launch tube is kept moderate, and the construction cost as well as the consumption of the propellant are reasonably low. Although this dependence looks simple, the dependence of α_2 on P_0 is not yet clear.

Figure 10 shows the histories of the overpressure measured on the launch-tube wall. As is plotted in Fig. 11a, $\Delta P_{\max}$ is an increasing function of P_0 . However, the higher P_0 rises, the lower the ratio $\Delta P_{\max}/P_0$ becomes; the weaker the shock wave, see Fig. 11b.

In Fig. 11c, the local impulse, I_1 , the time integral of the overpressure during the first positive pulse, see Figs. 8b and 8c, is plotted as a function of P_0 . For scaling in respect to the speed of sound, the local impulse is multiplied by a_0 . There exists a contradiction between the measured momentum coupling coefficient, $\bar{C}_m$, of Fig. 9 and this scaled, local impulse, $a_0 I_1$. For $P_0 > 100$ kPa, on one hand, $\bar{C}_m$ saturates. On the other hand, $a_0 I_1$ is still an increasing function of P_0 , although it becomes slightly saturated. As seen in Eqs. (10) to (12), α_4 depends both on χ and the location

Fig. 10. Histories of ΔP for various P_0 measured after a single laser pulse irradiation, $E = 3.5$ J.

of the pressure measurement. While α_2 in Eq. (8) is obtained by spatially integrating a local impulse over the projectile surface, α_4 is measured from a local impulse on the launch-tube wall. Because the relevant pressure wave interactions involve nonlinear characteristics of compressible fluid dynamics, quantitative local impulse characteristics depend on the location of measurement. Hence, the fill-pressure dependence cannot be well reproduced from the pressure history measured on the launch-tube wall. Regardless, both $\bar{C}_m$ and $a_0 I_1$ are increasing functions of P_0 for $P_0 < 100$ kPa, and become less sensitive for even higher fill pressures.

$a_0 \tau_1$ as a function of P_0 is plotted in Fig. 11d. It ranges from 6.5 to 10 mm. Note that this range is on the order of the distance from the focus for the laser beam to the center-body base.

5. Conclusions

The impulse performance and its generation mechanisms in LITA operation have been analyzed based on vertical launch performance, the characteristics of an overpressure on the launch-tube wall, and dimensional analyses. In relation to the duration period, the propulsive impulse is in inverse proportion to the propellant's speed of sound. Therefore, a dimensionless momentum coupling coefficient, $\bar{C}_m$, becomes a useful quantity for performance evaluation. $\bar{C}_m$ increases as P_0 increases up to about 100 kPa, and then saturates for higher fill pressures. Since the dependence of the local impulse on P_0 is location dependent, the measured propulsive performance characteristics could not be quantitatively reproduced from pressure histories measured on the launch-tube wall. In practical applications on/near the ground, working around the atmospheric pressure level is favorable because the launch tube and related facilities can have thin walls, and an intensive pumping system, either for compression or evacuation, is not necessary; thereby saving on facility construction cost and running cost including propellant gas.

Fig. 11. Fill pressure dependencies, $E = 3.5\text{J}$.

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