Access to Space without Energy and Propellant on Board

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Abstract. Laser-driven, in-tube accelerator is a laser propulsion device in which the impulse performance is enhanced by the confinement of the compressible fluid. This paper describes the conceptual origin and state of the art of this technology.

Keywords: Laser ablation, In-tube propulsion, Ram accelerator, Impulse
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INTRODUCTION

At the present state of the art, rocket is the unique tool for terrestrial objects including human beings to reach the space. However, as was imagined even at the era of Jules Verne, there are many other methods having this potentiality. The key issue in the present rocket is that it carries all the propellant and inherent energy on board. This was the breakthrough beyond the older technologies such as power guns, yet on the other hand leads to the limitation of its payload capability. In this paper, referring to related ideas, we discuss how to improve the payload capability of a space launch system beyond the present technical level.

RAM ACCELERATORS

The ram accelerator (RAMAC)[1] is a chemical propulsion device in which a projectile is accelerated in a launch tube that is filled with combustible mixture. The device was invented and its operation was first demonstrated by Hertzberg, Bruckner and Bogdanoff in 1986; Knowlen[2] best contributed to the technical achievements, all in University of Washington. They demonstrated that a projectile obtained a muzzle speed of up to 2.7 km/s through a 16-m-long, four-stage ram acceleration section.[3]

Figure 1 schematically illustrates the operation principle of RAMAC. In the launch tube, combustible mixture, is filled in. The most-frequently used fuel is methane; ethylene and hydrogen are also used. Nitrogen, argon, helium and carbon dioxide are used as diluents. The equivalence ratio is usually higher than unity; the excessive fuel

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acts also as diluent. The specific heat release and the speed of sound of the mixture depend on the mixture component ratio and the fill pressure, which should be tuned to the projectile speed regime.

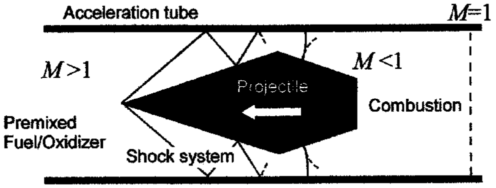
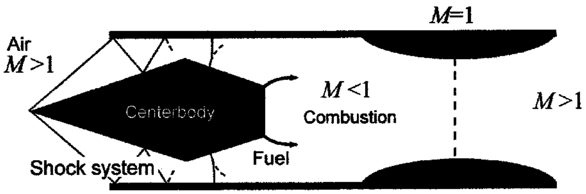
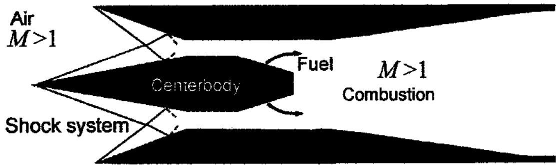


FIGURE 1. Operation principle of ram accelerator in thermally-choked mode

From the viewpoint of fluid dynamics, the flow system over the projectile can be modeled using a control volume in which not only the energy but also the momentum has a source term in the conservation equations called 'generalized Rankine-Hugoniot relations.'[4] Similar relations are applicable to ram/scramjets shown in Fig. 2.



(a) ram jet (subsonic combustion)



(b) SCRAM jet (supersonic combustion)

FIGURE 2. Conventional ramjets

The RAMAC concept is a sophisticated extension of 'in-tube rocket.' The basic idea of the in-tube rocket is to enhance the thrust performance by confining the rocket exhaust gas in a confines space, that is in the launch tube. This idea is transferred the LITA concept which will be described later.

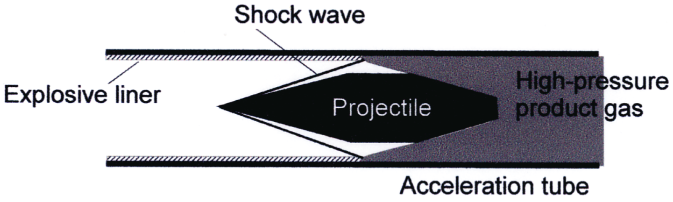


FIGURE 3. Ram accelerator using explosive on tube wall, Higgins[6]

RAMAC-RELATED TECHNOLOGIES

The technical hurdles in RAMAC are (1) the practically-operational regime is quite limited; the system easily experiences the so-called 'unstart.' (2) The oxidization of the projectile due to high-pressure oxygen in the mixture causes serious damage.[3]

Sasoh[5] proposed a 'laser-propelled ram accelerator,' in which thermally-choked operation is attributed not to chemical energy but to laser power. He estimated the propulsive performance of the device; if 1 GW laser power is available, a 100-kg projectile can be accelerated through a 10-km-long launch tube, which can be installed on such high mountain as Mt. Fuji in Japan, up to an orbital speed of 8 km/s. However, as Higgins[6] mentioned in his review paper on RAMAC, such an extremely-high laser power level is far beyond the current state of the art.

Higgins[6] proposed a modification of the RAMAC by utilizing solid explosive in place of gaseous propellant. Explosive segments are placed on the inner wall of the acceleration tube, see Fig. 3. The acceleration tube is filled with low-pressure inert gas; the reflection of the projectile-driven oblique shock wave is expected to induce the ignition of the explosive. Many recognize the effectiveness of this idea, but at the same time for safety reason are reluctant from implementing it. Moreover, ignition delay time of the explosive is not negligible. If the explosive is segmented, it can be ignited from an external source; in this case synchronization between the ignition and the projectile motion becomes a critical issue.

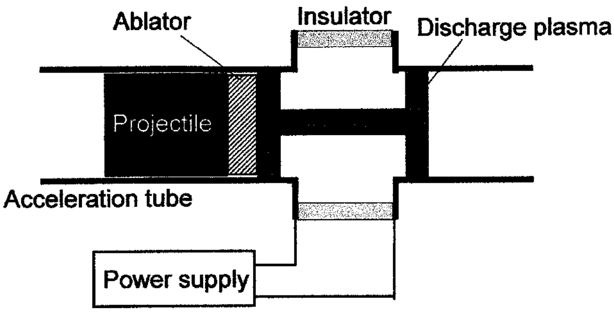


FIGURE 4. Ikuta's cylindrical electrode plasma impulse accelerator (CEPIAC)

Before the era of RAMAC, Ikuta[7] proposed a unique gun named 'Cylindrical-Electrode Plasma Impulse Accelerator (CEPIAC),' see Fig. 4. In CEPIAC, the projectile is accelerated by the ablation pressure which is induced by electrical discharge. The ablator is attached on the rear end of the projectile, is Joule-heated form the back. Except for the energy source, this configuration is similar to the laser-ablative LITA which will be described later.

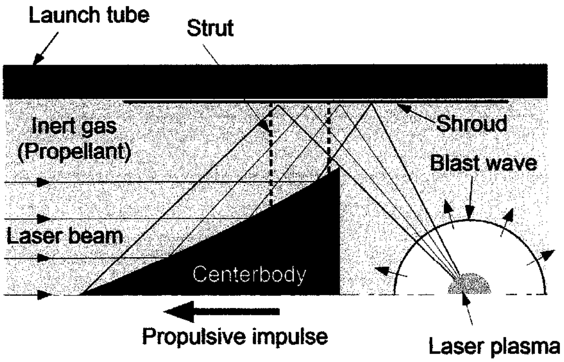


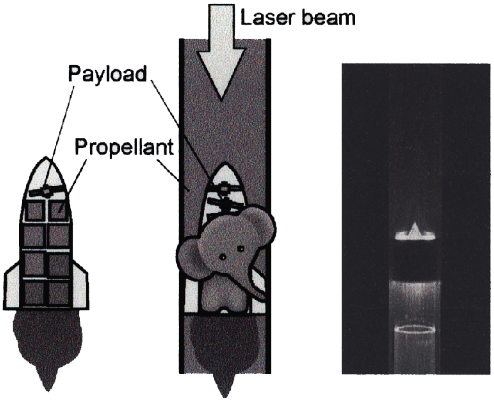
FIGURE 5. Operation principle of LITA-IA (laser beam frontal incidence)

LASER-DRIVEN IN-TUBE ACCELERATOR

LITA-I (Gaseous Propellant)

Sasoh[8] developed a practically-operational device of in-tube propulsion device driven by repetitive laser pulses, named it as 'laser-driven in-tube accelerator (LITA).' The first generation of LITA, LITA-I, utilizes as the propellant inert gas filled in a launch tube.[9,10] Figure 5 illustrates the operation principle of LITA-I.[9] In the launch tube inert gas, such as argon, krypton or xenon, is filled at a prescribed pressure. The end of the launch tube is plugged with ZnSe window which has high transmittance to

10.6-μm wavelength CO_2 laser beam. The laser power is irradiated as repetitive pulses. The laser beam can be introduced either from the muzzle or the breech.



(a)Existing rocket (b)LITA (c) LITA Operation

FIGURE 5. Payload advantage of LITA

In Fig. 5, the optical design of frontal incidence, irradiating from the muzzle end, is shown. The projectile is composed of a centerbody, shroud and struts. The laser beam is reflected on the frontal surface of the centerbody, then is re-reflected on the shroud inner wall, thereby being focused behind. Near the focus, the propellant gas experiences breakdown, then laser plasma is generated as the result of heating during the laser pulse period. The laser plasma expands, driving a blast wave, that is a shock wave accompanied with an expansion region behind. When the shock wave is reflected on the rear surface of the centerbody, a propulsive impulse is generated. We successfully demonstrated vertically launching a 2.15-gram projectile through a 1-m-long launch tube.[9] The demonstration of the LITA operation and its payload advantage published in the campus news of Tohoku University are shown in see Fig. 5.

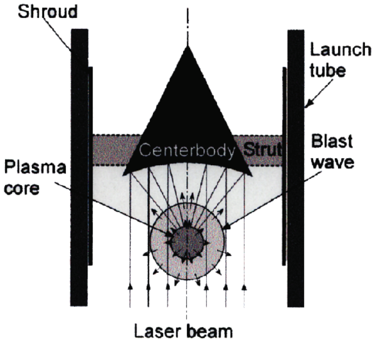


FIGURE 6. Operation principle of LITA-IB (laser beam rear incidence)

The advantage of irradiating laser pulses on the frontal side is to isolate the laser beam from the laser plasma. The life time of the laser plasma is of the order of 10 μs. When the pulse repetition frequency exceeds 100 kHz, the interaction between the laser beam and the laser-induced-plasma becomes critical. However, at the much lower frequency set in the experiment, 100 Hz at a maximum, the plasma and associated flow become settled down -- each pulse causes an independent impulse. The drawback of the frontal incidence is that the laser beam experiences two reflections that cause worse transmission efficiency. Moreover, practically the transmission efficiency strongly depends on the precision of the optical alignment. Then, the rear incidence configuration, LITA-IB, Fig 6, was examined.[10] As was expected, the impulse performance was improved, attaining 1.0 μN/W. The impulse increases linearly with the reciprocal of the speed of sound of the propellant.[10,11]

As well as obtaining interesting propulsion performance, LITA operation provides important research topics in fundamental physics.[12,13] Figure 7 shows framing Schlieren pictures in the processes of the laser-plasma and shock wave interaction. In the frames, the side view of a parabolic mirror shade is seen on the bottom; collimated laser pulse is incident from the top. At *t*=64 μs, a laser plasma is recognized as a radiating ball; an almost spherical shock wave surrounds the plasma. At *t*=144 μs, the reflected shock wave from the parabola is interacting with the laser plasma. The lower half of the plasma has started being deformed from the downward convex to concave shape. This deformation is caused by the baroclinic vortex generation, which appears in the beginning stage of Richtmyer-Meshkov instability,[14,15] which is the most important fluid dynamics problem in implosion physics. Since in this method, a clear interface is generated without any separation membrane the fragments of which cause serious flow disturbance which cannot be isolated from the fluid dynamics instability.

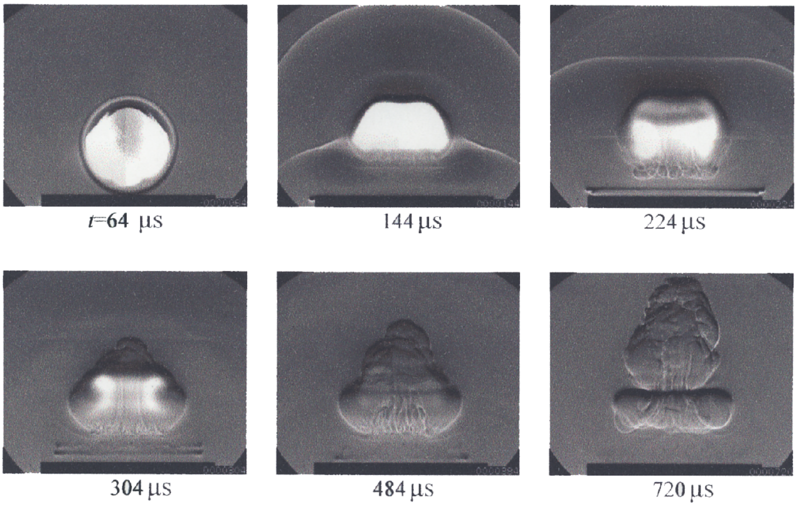
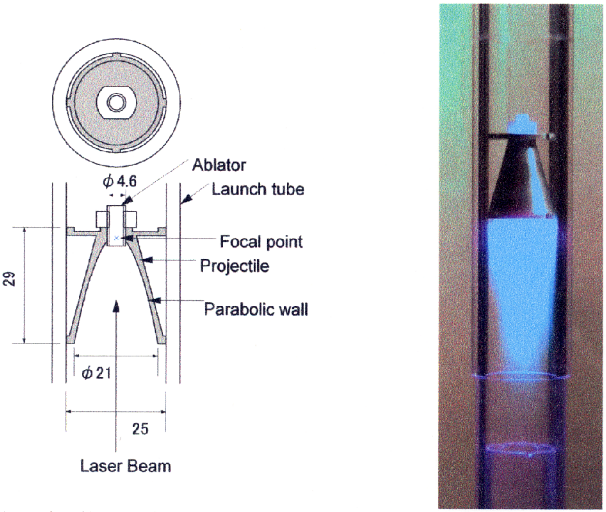

t=64 μs
144 μs
224 μs
304 μs
484 μs
720 μs

FIGURE 7. Richtmyer-Meshkov instability appearing in LITA operation

LITA-II (Ablative Propellant)

In LITA-I, when the projectile gains a high speed, it experiences an in-tube fluid dynamic drag. In such a confined space as in the launch tube, the drag (force on the frontal face) is enhanced as well as the thrust (force on the rear face). Since the drag increases almost linearly with the square of the projectile speed, the achievable terminal speed is limited to a quite low value. In order to solve this problem, LITA of the second generation, LITA-II, has been developed. Figure 8(a) shows the projectile design of LITA-IIA. The projectile gains the propulsive impulse from the laser-ablative gas jet. Initially, the launch tube is evacuated to a low pressure, below 20 Pa in the experiments. Laser beam is sent from the bottom end of the launch tube through a ZnSe window. The mass of the projectile equals 7.1 gram. The lower part of the projectile is shaped as a parabola. The ablator rod (6.4 mm in diameter) made of polyacetal (POM) is placed on the center axis, being threaded to the projectile body. Many works conclude that POM is a good volume absorber to the 10.6 μm CO_2 laser pulse.[16-21] The focus of the parabola is located at 2 mm above the initial lower surface of the ablator. The projectile is supported by eight fins against the inner wall of the acrylic launch tube, four around the focus, the other four around the peripheral of the parabola exit. The parabola acts also as a nozzle to the ablated gas.

As shown in Fig. 8(b), the projectile was successfully launched. In the operation, the upper end is connected to a 0.8-m^3 vacuum chamber that was evacuated down to 20 Pa or lower. The bottom end is plugged. The coupling coefficient exceeded 1.3 mN/W.



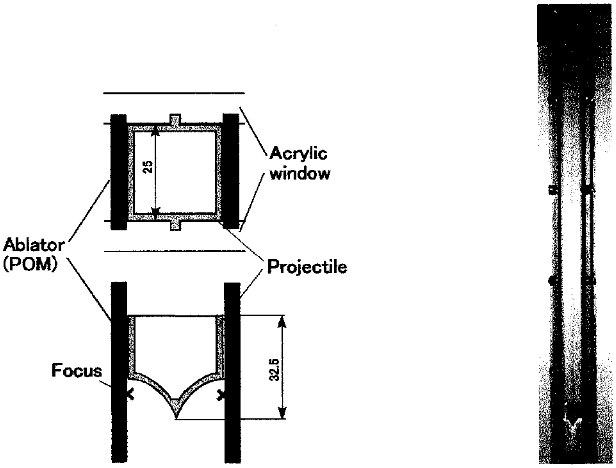
(a) Projectile length unit in mm (b) Snapshot of vertical launch operation

FIGURE 8. LITA-IIA, on-board ablator type

Figure 9(a) shows the design of LITA-IIB, wall ablator type. The projectile is made of aluminum arroy, A7075-T5. The upper body has a 25 mm × 25 mm-suqare ducted cross-section. Its thickness is either 1 mm (5 gram) or 2 mm (8.4 gram). The lower part is composed of symmetric, two-dimentional parabolas. The projectile is held at two guide grooves on the arrylic window. The other opposing two sides are wall made of the ablator, POM. The nominal clearance between the projectile body and the ablator wall is 0.1 mm. The focus of the parabola is located on the ablator surfaces. The effective length of the launch tube equals 0.6 m. The upper end of the launch tube is connected to the vacuum chamber at 20 Pa or lower. The lower end is either plugged or connected to the same vacuum chamber through a differenct duct.

Figure 9(b) shown a snapshot of the vertical launch operation. In the frame, laser ablation is recognized from the emission near the projectile. When the POM wall experiences ablation with linearly-focused laser pulse, abalated gas is ejected from the focus lines almost symmetrically along the normal to the wall. The ablation plumes are reflected on the parabolas, and collimated down along the axis of the launch tube.

We have launched the projectiles with successes; the heavier one only with plugging the lower end, the lighter one even with the evacuated lower end. The corresponding momentum coupling coefficient is of the order of 160 μN/W, the value of which is consistent to Suzuki et al.'s measurement using a impulse balance.[21]



(a) Projectile of wall-ablative LITA (b) Snapshot of vertical launch operation

FIGURE 9. LITA-IIB, wall ablator type

SUMMARY

The in-tube laser propulsion has an important potentiality of high payload capability because neither energy nor propellant needs to be carried on board. The presented experiments have demonstrated that this technology is really feasible, and is further advancing.

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