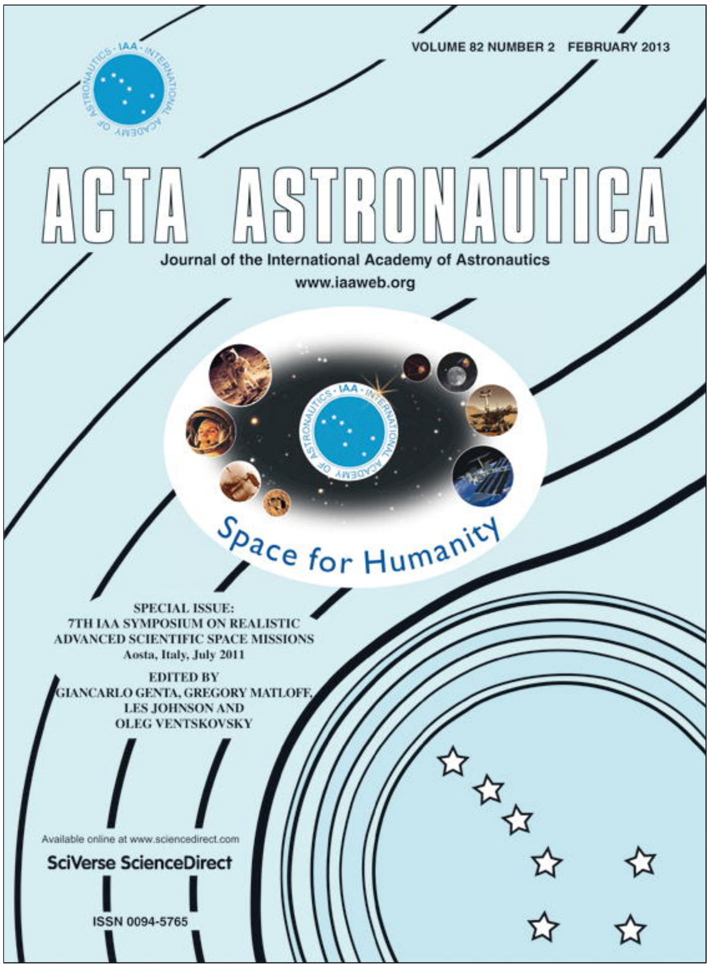
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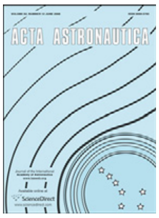

Conceptual study of manned space transportation vehicle using laser thruster in combination with the H-II rocket

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ABSTRACT

This paper describes the conceptual study of a Manned Space Transportation Vehicle (MSTV) using a laser thruster in combination with the H-II Rocket. By combining the use of a laser thruster and H-II Rocket, space trip to the International Space Station (ISS) or a round trip mission around the moon can be performed. Once MSTV with one crew achieves a circular orbit at an altitude of 200 km around the earth (parking orbit) by use of H-II Rocket, MSTV will then put into a circular orbit into an altitude of 400 km (ISS orbit) from 200 km circular orbit by use of the laser thruster. H-II Rocket has the following launch capability with payloads for LEO (300 km): 10 t (H-II A Rocket), 16.5 t (H-II B Rocket). Laser thruster using water propellant, power source for the laser, orbital transfer calculations (to ISS or the Moon) and other practical aspects are examined.

1. Introduction

Nowadays, the space trip business in the private sector aiming at weightless experience is becoming a reality in Europe and the United States. For example, “Space Ship One” or “Space Ship Two” systems are well known at present to the general public.

Now, there are three kinds of space trips such as sub-orbital trip, orbital trip and round trip around the moon that are being prepared for a space trip, which can be purchased through a travel company or an agency. Sub-orbital trips are aimed at a short-duration weightless experience. That is, the carrier-launch aircraft would suspend beneath a carry space vehicle to an altitude of 15 km and then release it. Shortly after release, the space vehicle would fire its hybrid rocket engine and continue on a ballistic ascent to 110 km altitude. The orbital trip would stay at the International Space Station (ISS) or at a space hotel, carrying out earth observation and enjoying the weightless experience. The Soyuz spacecraft has stayed at the ISS from the past to the present. Round trip around the moon is planned where the Soyuz spacecraft is docked with a moon rocket that is assembled in the ISS. After a stay at the ISS or a space hotel, they will go to the moon with the rocket. There are currently seven companies working on space vehicle development for sub orbital trip, six companies are working on space vehicle developments for orbital trips and four companies for round trips around the moon. Although all space vehicles under development are based on a chemical rocket engine system, each company adopts its original launch system. We propose the concept of the Manned Space Transportation Vehicle (MSTV) using a laser thruster in combination with the H-II Rocket for an orbital trip and round trip around the moon. By combined use of laser thruster and H-II Rocket, space transfer can be performed by the following two steps: (1) MSTV with one crew put into circular orbit in an altitude of 200 km around the earth (parking orbit) using H-II Rocket, (2) MSTV is put into

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circular orbit in an altitude of 400 km (ISS orbit) from 200 km circular orbit by using a laser thruster. The H-II Rocket has the following launch capability of payloads for LEO (Low Earth Orbit) at 300km: 10 t (H-II A Rocket), 16.5 t (H-II B Rocket).

Putting a heavy load like an MSTV (5–14 t payload) into the orbit of the ISS or a space hotel directly is technically very difficulty. First, it is required to put an MSTV into the low earth orbit of an altitude of 200 km. Afterwards, the orbital transfer between the 200 km circular orbit to the 400 km circular orbit is performed and finally MSTV arrives at the ISS or a space hotel at an altitude of 400 km. MSTV uses a laser thruster in which speed control is possible to achieve orbital transfer with high precision accuracy.

The external view of the MSTV with a propulsion engine replaced by the laser thruster has a wing type body like the Space Shuttle. Fig. 1 shows an example of a laser thruster. Using steam laser heating, water is preheated and ejected as a supersonic flow that ensures the thermal decoupling of the nozzle wall and the region that is super heated by the laser. MSTV is propelled by the laser propulsion engine, i.e., laser thruster using water as a propellant. The feature of laser propulsion is that both thrust and specific impulse (I_{SP}) can be arbitrarily controlled with laser power density (W/cm^2) [1–9]. Since the exhaust velocity and fluid conditions of a propellant can be controlled by means of combinations using laser parameters such as intensity, wavelength and propellants, the selection between high thrust system and high specific impulse (I_{SP}) system can be easily implemented. The high-precision velocity of MSTV can be precisely controlled by the laser power density. Additionally, since MSTV does not use liquid hydrogen or liquid oxygen but the water as propellant, it is a promising highly safe technology.

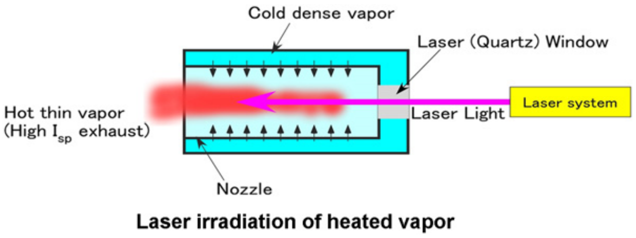


Fig. 1. An example of laser thruster (Propellant: vapour).

In Japan, since there is already an H-II Rocket, which launches a satellite and HTV (H-II Transfer Vehicle), MSTV is launched and put into LEO at 200 km with H-II Rocket. Orbital transfer is performed to arrive at the ISS or a space hotel of LEO 400 km by the laser thruster using water propellant. Basically, rocket driver trajectory for the MSTV is almost the same as that of Japanese HTV (H-II Transfer Vehicle) [10–12].

Details of an MSTV are given below from a viewpoint on the laser thruster, laser power and system design.

2. Manned space mission scenario

The gross weight of the MSTV that is propelled by the laser thruster using water as a propellant assumes temporarily 5t (bodies 3t+water 2t). The mission target is the International Space Station (ISS) with an altitude of about 400 km or a space hotel built in near ISS. MSTV is launched with the H-II Rocket and is directly thrown into a circular orbit at an altitude of 200 km around the earth (parking orbit). Once MSTV is thrown into a circular orbit with an altitude of 200 km, docking to ISS in an altitude of 400 km that will be safely attained by highly precise crew

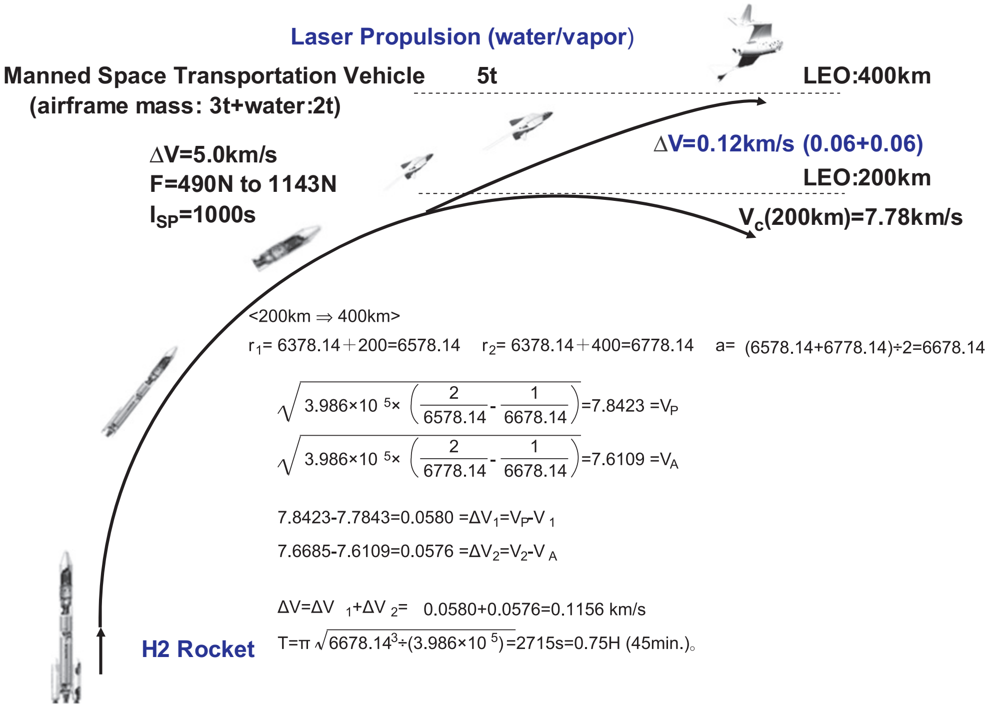


Fig. 2. Launch to LEO (200 km to ISS: 400 km).

operations using a laser thruster in which speed regulation is possible. As shown in Fig. 2, delta $V(\Delta V)$ for the orbital transfer from LEO for moving 200–400 km is 0.0580 km/s. Since circular orbital velocity (V_1) at an altitude of 200 km is 7.7843 km/s and perigee velocity (V_P) thrown into a transfer orbit with an altitude of 400 km is 7.8423 km/s, then the delta V gives $\Delta V_1 = V_P - V_1 = 7.8423 - 7.7843 = 0.0580$ km/s. After orbital transfer, delta V for supplying to a LEO 400 km is made with 0.0576 km/s. Since circular orbital velocity (V_2) at an altitude of 400 km is 7.6685 km/s and apogee velocity (V_A) thrown into a transfer orbit with an altitude of 400 km is 7.6109 km/s, then the delta V gives $\Delta V_2 = V_2 - V_A = 7.6685 - 7.6109 = 0.0576$ km/s. Accordingly, the delta V for orbital transfers from LEO at 200km (circular orbit) to a higher LEO at 400 km (circular orbit) is 0.1156 km/s ($\Delta V = \Delta V_1 + \Delta V_2 = 0.0580$ km/s$+$0.0576 km/s$=$0.1156 km/s; nearly delta $V = 0.12$ km/s). In case that we select specific impulse of $I_{SP} = 1000$s and thrust of $F = 816$N (laser output $P_L = 5000$ kW), the theoretical calculation shows a water amount for consumption of 35.4 kg as propellant and a transition time of 0.75 H (45 min). In the case of re-entry flight, MSTV will decelerate to put into an elliptic orbit (apogee) at an altitude of 100 km from an altitude of 400 km circular orbit using a laser thruster. Similarly, delta V is calculated as -0.087 km/s$=-87$m/s, and a water amount for consumption of 26.5 kg as a propellant is calculated.

Fig. 3 shows the example of a theoretical calculation in the case of the moon sightseeing tour directly: MSTV is put into a LEO 200 km with H-II rocket and after MSTV is transferred to lunar orbit. Required delta V to the Moon is 3.13 km/s. The capability of delta $V = 5$ km/s is held by the propellant of 2 t of water. Fig. 4 shows the overview of orbital course to ISS using H-II Rocket and MSTV. When the space tourism by private business is considered, Fig. 5 shows the outline of the sightseeing tour to the moon via ISS or a Space Hotel. The moon sightseeing at a distance of 384,400 km requires delta $V = 3.13$ km/s, 1368 kg of water and a short Moon sightseeing at a distance of 200,000 km requires delta $V = 3.05$ km/s, 1337 kg of water.

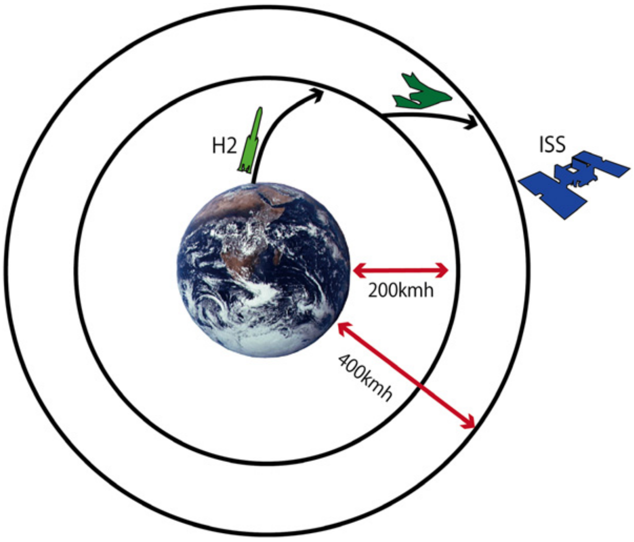
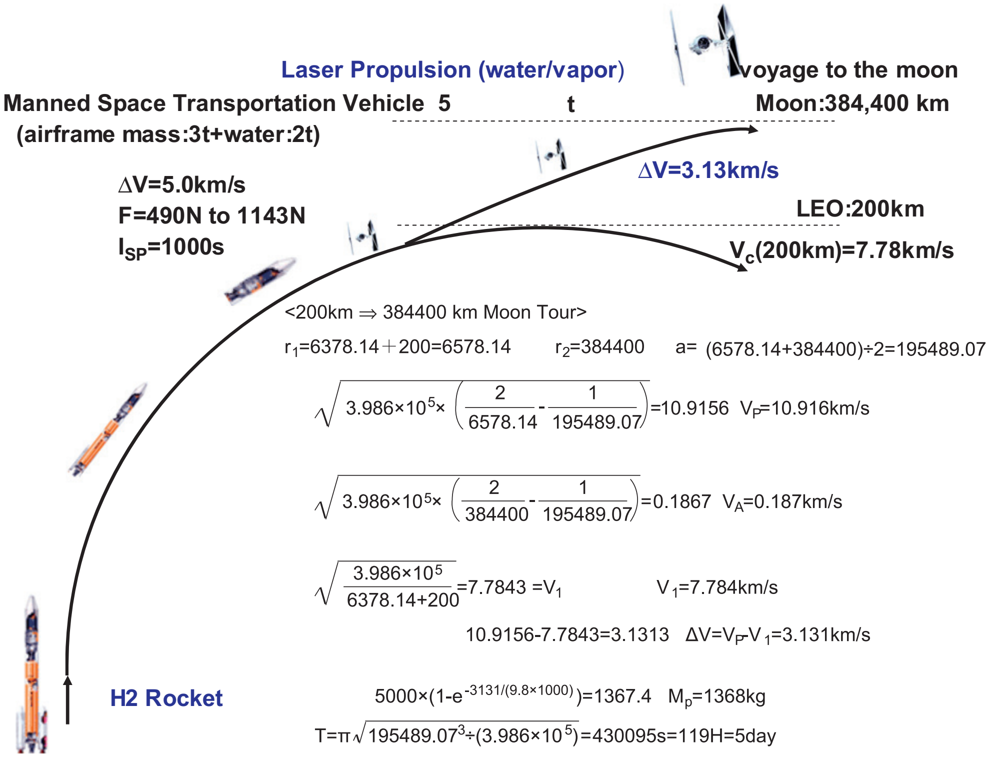


Fig. 4. Launch to ISS by H-II rocket and MSTV.



<200km ⇒ 384400 km Moon Tour>

$r_1=6378.14+200=6578.14 \quad r_2=384400 \quad a= (6578.14+384400)\div 2=195489.07$

$$\sqrt{3.986\times 10^5 \times \left(\frac{2}{6578.14}-\frac{1}{195489.07}\right)}=10.9156 \quad V_P=10.916\text{km/s}$$

$$\sqrt{3.986\times 10^5 \times \left(\frac{2}{384400}-\frac{1}{195489.07}\right)}=0.1867 \quad V_A=0.187\text{km/s}$$

$$\sqrt{\frac{3.986\times 10^5}{6378.14+200}}=7.7843=V_1 \qquad V_1=7.784\text{km/s}$$

$$10.9156-7.7843=3.1313 \quad \Delta V=V_P-V_1=3.131\text{km/s}$$

$$5000\times(1-e^{-3131/(9.8\times 1000)})=1367.4 \quad M_p=1368\text{kg}$$

$$T=\pi\sqrt{195489.07^3\div(3.986\times 10^5)}=430095\text{s}=119\text{H}=5\text{day}$$

Fig. 3. Launch for moon tour.

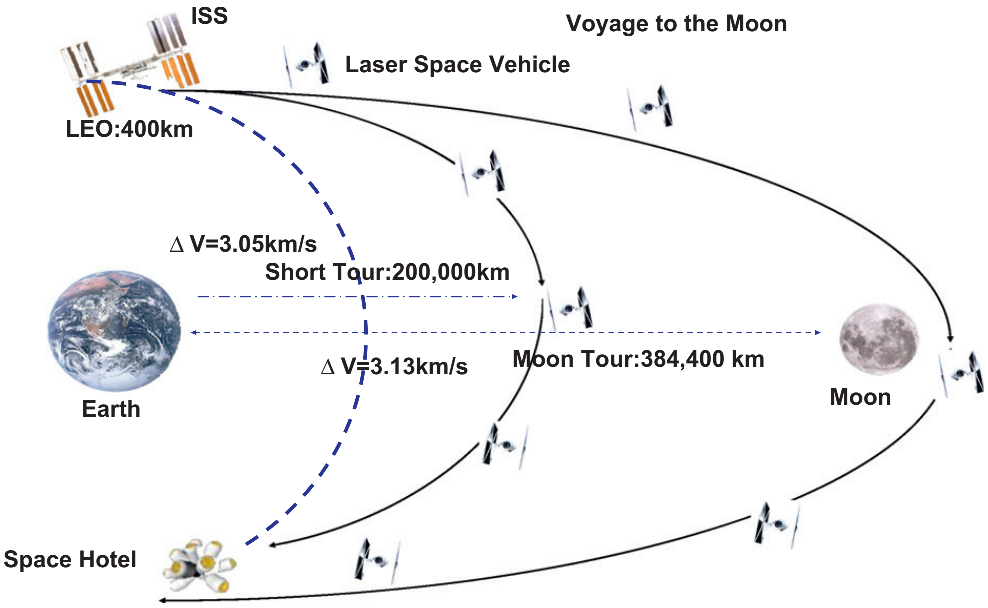


Fig. 5. Moon tour from ISS or space hotel.

3. Laser thruster

Laser generated thrust and the velocity of using ablating gas were measured in a number of laboratory experiments with a wide range of laser intensities and wavelengths on various target (propellant) materials. It was clarified that ablation velocities from 100 m/s ($I_{SP}=10$ s) to 40 km/s ($I_{SP}=4000$ s) are possible by selecting a proper combination of ablating materials and laser conditions, mainly intensity. Laser diodes (LDs), which has made remarkable technical progress in terms of high power generation is supposed to be a suitable choice for an on-board power source. LDs can perform at their best when used in a CW mode and is suitable for generating a low I_{SP} thruster and on the other hand a pulsed laser mode generating high peak power is suitable for high I_{SP} thruster. For instance, if the speed of the exhausting gas is increased, large momentum can be generated with a small amount of propellant mass and large amount of laser energy. On the other hand, if the speed is reduced, the same momentum can be obtained by using smaller laser energy. The former has a condition of the electric propulsion (speed 10 km/s or more of the propulsion gas). In the latter when a large amount of propellant is available and a large thrust is needed, where speed of the exhausting gas is 5 km/s or less will be adopted. In a laser propulsion system, such engine performance can be switched. In laser propulsion technology, velocity and fluid conditions of propellant can be controlled by the energy density of laser radiation by means of the combination of laser parameters such as wavelength, intensity and propellant.

There are two important performance parameters defined for the thrust generation by laser propulsion scheme. They are the specific impulse I_{SP} used in the conventional propulsion scheme and momentum coupling coefficient C_m ($N\cdot s/J=N/W$) specific to laser propulsion: C_m is defined as a ratio of thrust F to incident laser power P_L. It is similar to the thrust electric power ratio (N/kW) of the electric propulsion. Further, similarly to the electric propulsion, the following relation between thrust F and propulsion efficiency η, which is defined as the ratio of propellant kinetic energy to the laser energy, is important:

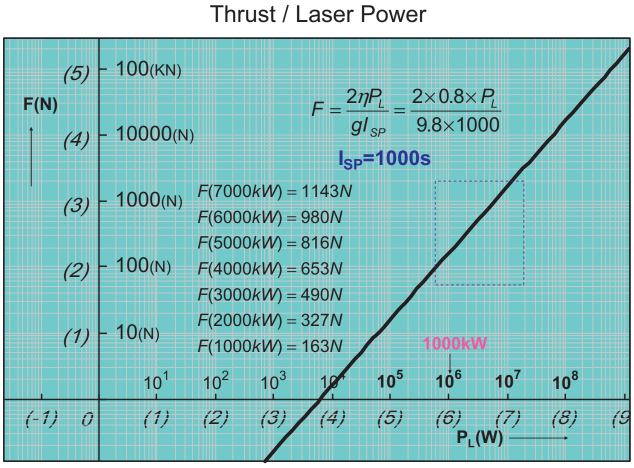


Fig. 6. Relation between thrust and laser power.

$$F=\frac{2\eta P_L}{gI_{SP}} \tag{1}$$

where g is gravitational acceleration and P_L is laser power. We can get the variable thrust by control laser power [5].

Fig. 6 shows a plot of the thrust by $I_{SP}=1000$ s as a function of the laser power. On the order of 500–1000 N thrust can be obtained by the order of 1000 kW laser power as shown within the dotted lines. Fig. 7 shows a plot of thrust by laser power as a function of the specific impulse I_{SP}.

Fig. 8 shows the block diagram of the laser system that switches between an LD pumped continuous laser (CW) and a pulsed laser by ON/OFF control of the laser diode.

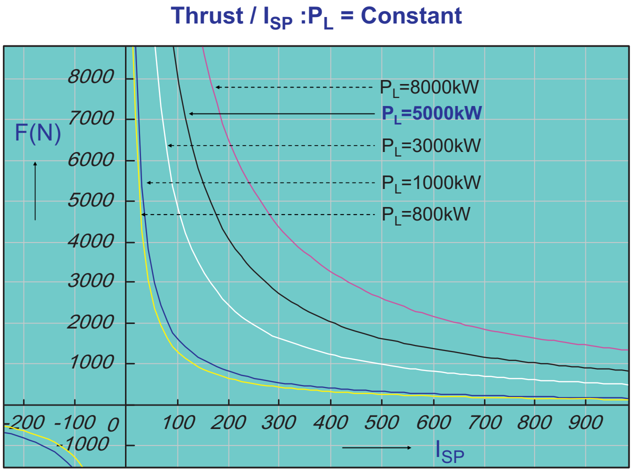


Fig. 7. Relation between thrust and I_{SP}.

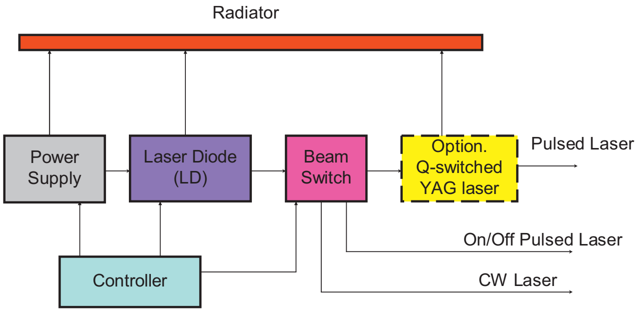


Fig. 8. Laser system block diagram.

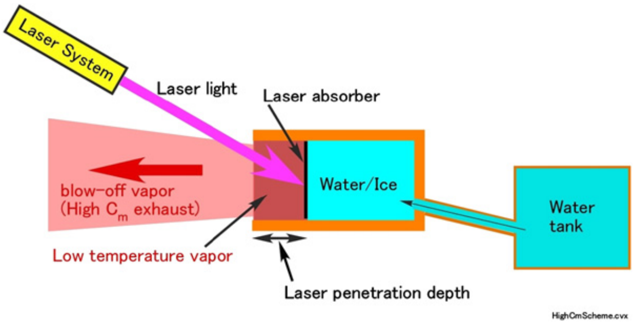


Fig. 9. Laser thruster using water.

In this system we need a CW laser in the main. The laser diode is a continuous oscillation fundamentally and is suitable for the jet generation of gas with a comparatively high thrust/low specific impulse. There is no need for a high peak pulse (i.e., MW) such as mode locking or Q-switching. However, in order to generate a high specific impulse, the pulse operation type laser, which generates a high peak pulse, is suitable. The change-over system with the continuous output mode by the LD realizes a high thrust/low specific impulse and LD excitation Q switched YAG laser pulse output mode that adopts a low thrust/high specific impulse. In consideration of high specific impulse requirement, a dotted Q-switched YAG laser block remains as option.

Since the variable control of thrust and the specific impulse can be performed in relation to laser irradiation conditions (power, power density, a wavelength, pulse width, etc.), they will be controlled only by laser power and laser power intensity (10^7–10^{14} W/cm^2) if a wavelength and pulse width are determined. Control of laser power intensity is performed by position control of a condenser (i.e., control of laser spot size), which adjusts thrust and specific impulse. It has been improved sharply and the electric light conversion efficiency of LD that has attained 75%. The absorption to the water of laser light is determined by a mass absorption coefficient and is dependent on a laser wavelength. As to LDs, since the nozzle length of about tens of cm absorbs the laser wavelength of 1 μm, it seems to be suitable for the nozzle length of a test prototype or practical use for laser thruster (Fig. 1).

Fig. 9 depicts a scheme of using a laser engine driven by water propellant with water/ice laser heating. We adopt this type of laser thruster than aforementioned laser thruster in Fig.1. The engine consists of a nozzle, a water tank, the water or ice stored in the nozzle, a laser system and a laser absorber. CW laser or Pulsed laser radiation irradiates water inside of the nozzle. Water is supplied through a hole in the nozzle from the water tank. The size of the hole, in the order of millimetres is adjusted so that water is kept in the tank by its surface tension and repeatedly renewed after laser irradiation. Almost all of laser light is absorbed with a laser absorber and is changed into thermal energy. The layer of a proper quantity of water has covered the laser absorber, then the thermal energy blows away the layer of this water that is transformed into kinetic energy. In case that high thrust is required, CW laser radiation irradiates water directly. Since temperature is kept low while a large volume of water is simultaneously heated compared with a pulsed laser, injection of the low-temperature propellant of large mass is made. Therefore, the large momentum coupling coefficient C_m is realized and a high thrust is obtained. In the case of pulsed laser, due to its high peak power, the surface of water is rapidly heated and injection of high-temperature propellant of small mass is made. Therefore, a high specific impulse (I_{SP}) is obtained. In other words, selection between a high C_m system and high I_{SP} system can be realized by controlling propellant exhausting velocity. This mechanism corresponds to High C_m with volume absorbers by CW laser and high I_{SP} with surface absorbers by pulsed laser respectively [3–5].

4. MSTV conceptual system design

Very likely conceptual system design based on existing technology is described here. Fig. 10 shows the MSTV specification and Fig. 11 shows the MSTV system block diagram. Thousands of kW is required for laser power source. Recently, Fuel Cell (FC) technology has already made remarkable progress. For example, a Polymer Electrolyte Fuel Cell (PEFC) generates electric power of 100 kW (20 cm by 40 cm by 65 cm and 67 kg) or 85 kW (11 cm by 50 cm by 62 cm and 43 kg) is now in practical use for Japanese motor cars [13–17]. On the other hand,

Major Specifications of MSTV (target)

- **Laser:** High Power Laser Diode (CW/Pulse change-over system)
- **Propellant:** Water
- **Power Source:** 5000kW [Polymer Electrolyte Fuel Cell (PEFC) or laminate type lithium ion battery]
- **Laser Power:** 3700kW
- **Thrust:** 600N (variable:see Fig.6)
- **Specific Impulse (I_{SP}):** 1000s (variable:see Fig.7)
- **Mass:** 14ton (airframe mass:13t+water:1t)
- **Required ΔV:** 0.73km/s > 0.12km/s (LEO200km to LEO400km)
- **WingedVehicle:** 8m (Length) × 5m (Wing span) × 5m (Height)
- **Crew:** 1-3 persons (TBD)

Fig. 10. MSTV specification.

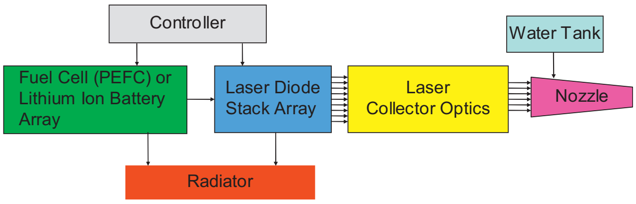


Fig. 11. MSTV system block (high thrust mode).

the lithium ion battery is loaded into the domestic Electric Vehicle at present. It is laminated type lithium ion battery of 95 kW (24 kWh, 182 kg). Also research and development of high-output metal/air battery (metal fuel cell) are carried out as a promising power supply such as Magnesium Fuel Cell and Lithium Fuel Cell. As an evaluation at present, a small lightweight Polymer Electrolyte Fuel Cell (PEFC) is desirable from a viewpoint in the practical use by the domestic car. A lithium ion battery needs lightweight-sizing considerable in weight. Moreover, although the metal fuel cell of magnesium and lithium is in a research trial production stage, it will be strongly expected as a fuel cell of high power and small light weighting in the near future. Concerning high-power laser, 100 kW LD is a stage that can be manufactured by budgetary boost in Japan.

As another important technical aspect, there exists heat transportation and waste heat processing in space. Usually, if it is several MW generation class of heat like a space shuttle or a space station, a big radiator panel is extended and heat transportation is performed locally by the pump type fluid loop. About the radiator, the development of the method of raising coolant temperature using a compressor and Liquid Droplet Radiator is now developed for space use [18]. Thermal Control System (Radiator) is an element indispensable to manned space technology.

MSTV returns from LEO and does not need a mighty thermal protection system like the Hayabusa capsules due to its relatively low-entry speed and thermal environment. In light of one's past achievements; thermal protection system weight for Re-entry of Apollo Spacecraft: 848 kg/(total weight 5806 kg) and Gemini Spacecraft: 144 kg/(total weight 1983 kg), we do a trial calculation as 800 kg with an enough margin. Since re-entry speed 7.6 km/s of MSTV is low as compared to Apollo Spacecraft 10.9 km/s, this estimated weight may be excess. Furthermore, application of feathered configuration such as spaceship 1, 2 needs more consideration. A wing type body is assumed at the time of an earth return from space, such as ISS and a space hotel. In atmosphere re-entry, aerodynamic heating reduction, the cross ranges to a spaceport, etc. is taken into consideration. It is expected a large advantage of using a wing type space vehicle.

Fig. 12 shows the provisional mass analysis of MSTV based on existing technology. Breakdown of mass of 14 t is estimated as follows: mass of laser power source used 50 PEFC (100 kW and 67 kg) generating 5000 kW output is 3.4 t. Another mass including laser system of 1.3 t, hydrogen and oxygen tank for PEFC of 0.5 t, propellant of 1 t, thermal protection system of 0.8 t, radiator of 5 t, crew and air frame of 2 t. Since the launch capability of H-II B Rocket for LEO (300 km) is 16.5 t, MSTV seems to be a margin of 2.5 t weight. The most promising PEFC is manufactured by HONDA and used in FCV (Fuel Cell Vehicle). This PEFC has the following performance: Power 100 kW, Weight 67 kg, Size 20 cm × 40 cm × 65 cm (52 L cubic volume). The 5 MW power is based on the most excellent Honda PEFC using 50 sets in this paper. Also, PEFC manufactured by NISSAN, which is used in FCEV (Fuel Cell Electric Vehicle), is also promising. Its performance is 85 kW power, 43 kg weight and 34 L cubic volume (2011 year's model). On one hand, a 100 kW Laser Diode can also be developed instantly in Japan.

Fig. 13 implies the example of one theoretical calculation in the case of manufacturing MSTV with the present technology. By assuming a MSTV mass of 14 t (body mass 13 t and water of 1 t), $\Delta V = 9.8 \times 1000 \times \ln(14/13) = 0.73$ km/s is obtained. Therefore orbital transfer to LEO 400 km can be reached from 200 km.

Although above-stated mass analysis is just based on present usable technology, therefore MSTV mass is very heavy. However, the progress of the small size and lightweight technology decreases the MSTV weight in the near future.

Mass Analysis of MSTV

Power Supply: 3.4 ton (PEFC:100kW, 67kg × 50) for 5000kW

Laser Diode : 1 ton (LD:100kW, 20kg × 50)

Beam Forming & Focusing Controller: 0.3 ton

Propellant: 1 ton (Water)

Hydrogen & Oxygen with tank (35MPa) for PEFC: 0.5 ton

Radiator: 5 ton (Liquid Droplet Radiator or Water Cooled Radiator)

Thermal Protection System: 0.8 ton

Air Frame: 2 ton

TOTAL 14 ton
(H-II B Rocket Maximum Launch Capacity: 16.5 ton)

Fig. 12. Mass analysis of MSTV by existing technology.

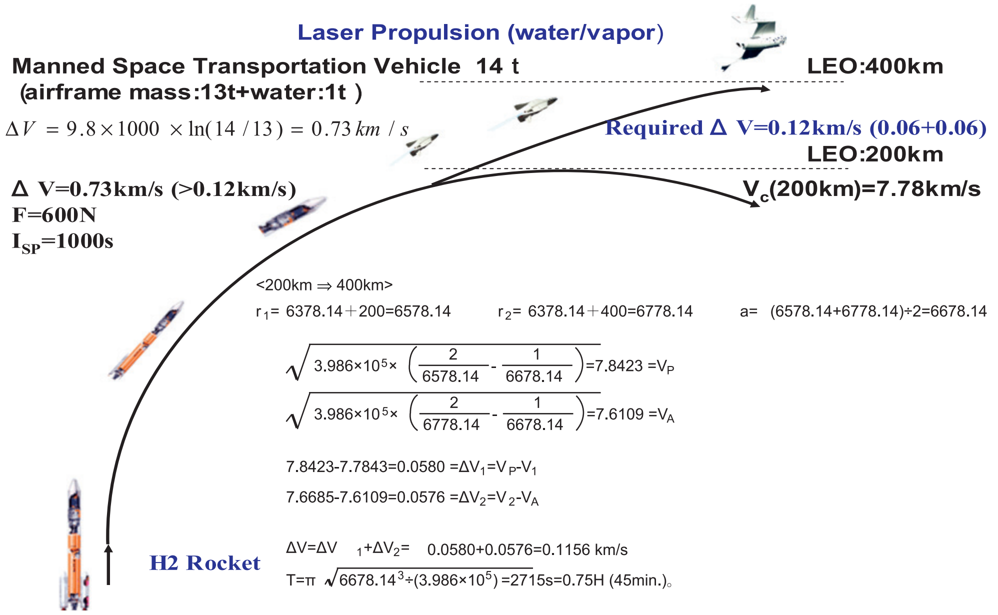


Fig. 13. Implementability by existing technology.

5. Conclusions

The possibility of a Manned Space Transportation Vehicle (MSTV) by using a laser thruster that carries a laser system and laser power supply is investigated. Due to the latest developments of high power laser diodes (LDs) and fuel cells, a laser space vehicle that carries both a laser device with an onboard power supply is feasible. A laser vehicle is no longer constrained by using only a ground-based laser system for generating propulsion. The MSTV can be launched with the H-II Rocket and put into circular orbit in an altitude of 200 km. After that, using a laser thruster, the MSTV is taken from 200 km circular orbit into a higher circular orbit at an altitude of 400 km (ISS orbit).

The MSTV is equipped with the above-mentioned laser engine system that will fly from the space platform, the ISS, and possibly the space hotel before going to the moon. The possibility of making such a sightseeing trip and supporting cargo shipment from the moon's orbit to the surface of the moon can now be seriously investigated. Future work is needed to establish the experimental parameters required to fully develop the MSTV. A full-fledged study and design will currently start by an investigation committee in Japan.

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