Laser Propelled Hypersonic Air-Vehicle

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Abstract

Laser propulsion is a concept in which energy of a thrust producing reaction mass is supplied via beamed energy from an off-board or on-board power source. A variety of laser/beamed energy concepts were theoretically and experimentally investigated since early 1970s. Laser propulsion offers the advantage of both high thrust and high specific impulse; I_{SP} *in excess of 1000s. Other advantages are the simplicity and reliability of the engine set-up, because of fewer moving parts simpler propellant feed system, and high specific impulse. Another major advantage is the reduction in pollution as the major propellant used can be hydrogen, air or water vapor. In this paper we explore the futuristic concept of use of laser propulsion as a main propulsion mechanism for air-vehicles. The thrust is obtained by formation of a Laser Sustained Detonation (LSD) wave of plasma. The vertical thrust is produced by an off-board Repetitive-Pulsed (RP) laser whereas the forward thrust is produced by an On-Board Continuous Wave (CW) laser producing unit. The flight attitude is controlled by the conventional primary flight controls. The possible design of the propulsion units has also been discussed in the paper. There are 3 parabolic retractable attached below the craft and a concave reflector at the rear of the craft. The parabolic retractable reflectors are responsible for the vertical thrust. Whereas the concave reflector at the rear is responsible for the forward thrust. Various calculations involving blast wave, specific impulse, moment coupling co-efficient, lift produced, etc, have been supplied.*

Introduction

Advanced propulsion for the 21st century include the use of beamed energy such as ground based or on-board lasers to provide thrust to a air-vehicle, propelled by a laser induced blast wave. Laser propulsion offers the advantage of both high thrust and theoretically infinite specific impulse I_{SP} at altitudes less than 20 km. Other advantages are simplicity and reliability of the engine because of fewer moving parts, simpler propellant feed system and high specific impulse. Major limitations of this approach are the laser power available, absorption and distortion of the pulsed laser during the vertical take-off and coupling laser power into thrust throughout the flight envelope. The mission requirements are the formation and propagation of the Laser Sustained Detonation Wave and inlet air replenishment. The concept of laser propulsion originates to at least 1972 and is accredited to Kantrowitz.

In our proposed setup there are three parabolic retractable reflectors attached on the lower surface of the air-craft- one below the nose and the other to below the main planes. This will provide a sufficient track area as well as stability during take off. The concept of parabolic reflectors has been deduced from the experimental Lightcraft concepts. On each of these retractable parabolic reflecting nozzles, a laser is fired producing high intensity radiation, which is sufficient to cause an electrical breakdown of a small propellant (air) volume creating a high temperature rapidly expanding plasma. This plasma closely resembles a supersonic blast wave and rapidly exits a supersonic nozzle which gives a high speed vertical lift-off. The speed of the lift-off thrust can be controlled by controlling the intensity and power of the laser incident on the reflectors. The method involved here, for obtaining thrust from this propulsion setup is that, the laser intensity is focused into a gas (air) near the solid surface in order to breakdown the gas (air) and induce a detonation wave transferring momentum to the surface.

For the forward thrust, in the proposed setup, a concave reflecting surface is provided with laser focusing components, preferably optical pipes. An intense laser source is provided on-board the air-vehicle, preferably a high power CO_2 laser. In this Continuous Wave (CW) laser thruster, CW laser is focused onto the concave reflecting surface in a way that, the CW laser from each focusing unit gets reflected back to meet at the focus, of the concave reflector, just outside the cavity enclosed the concave reflector. At the focus the laser intensity is absorbed by the propellant gas (air). This again causes an electrical breakdown of the propellant (air) volume creating high temperature rapidly expanding plasma. The plasma resembling a high speed supersonic blast wave imparts an enormous thrust over the reflector surface; thus imparting momentum to the surface, in turn transferring momentum to the air-vehicle itself. Limitations in this setup are providing the air-vehicle with such an intense laser source on-board and capabilities of the reflector material to withstand the thrust imparted due to the expanding plasma and retain the properties as a reflector.

Major advantages of this concept are- firstly the usage of conventional power-plants for propulsion is completely removed; secondly, with the fast depletion of fossil fuel resources, this concept is the future of aviation industry, because the fuel proposed in this concept provides with extraordinarily high thrust and theoretically infinite specific impulse I_{SP}; thus increasing the overall efficiency of the fuel and greatly decreasing its consumption. Third, the fuels suggested for the proposed laser propelled air-vehicle are hydrogen, water-vapor or simply atmospheric air (up to 20 km altitude). These fuels are not only easily and abundantly available but they also minimize air-pollution which is a major concern with fossil fuels.

Laser Supported Detonation (LSD) Wave

According to Raizer, the basic phenomenon occurring is the ionization of gas, plasma ignition and blast wave propagation. According to the researches done by scientists, such as Pirri and Hettche in the 1960s, it was demonstrated that a focused laser beam from a high power laser source, in a stagnant gas produced electrical breakdown and propagation of a blast or detonation wave.

In the proposed setup for the vertical thrust, initial ionization of the plasma takes place in the gas as a result of focusing the laser beam to higher laser intensities, than the threshold value, thus generating free electrons due to inverse bremsstrahlung effect. According to Brandstein, when the plasma is ignited, its unobstructed length can be estimated by:

$$L=2V_{LSD}t_P \tag{1}$$

Where, L is the initial length of the plasma, V_{LSD} is the detonation velocity and t_P is the laser pulse duration. In this plasma zone, the laser beam energy is absorbed into the gas and L is proportional to the electron mean free path. According to Raizer, the initial absorption wave or Laser Supported Detonation (LSD) wave velocity is given by:

$$V_{LSD} = [2\{\gamma^2-1\}\ \{T/\rho_0\}]^{1/3} \tag{2}$$

Where the maximum heat absorbed or energy released by the wave is given by:

$$q= I/ (\rho_0 V_{LSD}) \tag{3}$$

Also, the pressure generated directly behind the laser supported detonation (LSD) wave front corresponds to the upper Chapman-Jouget point and is given by:

$$P_{CJ} = (\rho_0 V_{LSD}^2)/ (\gamma+1) \tag{4}$$

The flow and thermodynamic variables scaled to a reference point corresponding to a cylindrical blast wave has evolved into a cylindrical shape which corresponds to a plasma ignition to a flat plate. The un-powered Sedov's scaling law used for the present set of conditions for pressure behind the blast wave and the radius of the wave are:

$$(P/P_{REF}) = (t/t_{REF})^{-1};\ (r/r_{REF}) = (t/t_{REF})^{1/2} \tag{5}$$

The specific impulse is given by Simmons and Pirri for this propulsion set up:

$$I_{SP} \approx \{(u^*)^{1/2} E^{1/2}\}/ \{M^{1/4}(t_p-t_s)\, D^*\} \tag{6}$$

Where u^* is the gas sonic injection velocity in the thrust cavity, E is the total laser energy deposited, D^* is the nozzle throat diameter, t_p is the time between the pulses, M is the propellant (air) molecular weight and t_s is the ignition time of the blast wave.

Coming to the horizontal thrust producing unit, the moment-coupling co-efficient is given by:

$$C_m=F/P_{laser} \tag{7}$$

Where F is the thrust generated and P_{laser} is the laser accumulated at focus of the concave reflector.

Now specific impulse given by Yabe and Uchida is:

$$I_{SP} = (\int F dt)/ (g_0 \int m^* dt) = v_p/g_0 \tag{8}$$

Where m^* and g_0 are the propellant mass flow rate and gravity constant respectively, and v_p is the velocity of propulsion. Combining the expressions for moment-coupling co-efficient and the specific impulse, we get:

$$I_{SP}.C_m = (v_p.F) / (g_0.E_{LASER}) \quad (9)$$

Now, $F = m.v_p$,Therefore, $I_{SP}.C_m = [2\{(1/2) m.v_p^2\} / (g_0.E_{LASER})]$

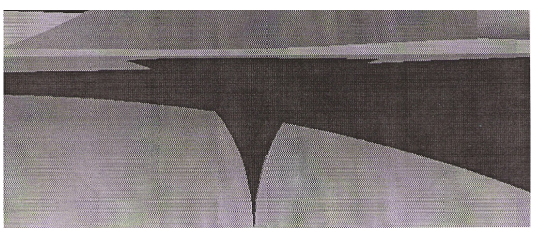
$$\Rightarrow I_{SP} = (1/C_m)\, 2(E_{PROP}/E_{LASER}) \quad (10)$$

where E_{PROP} and E_{LASER} is the kinetic energy of the exhausted propellant (air) and kinetic energy of the laser, respectively. According to calculations from P.K. Wu's work, we get that the total heat transferred to the reflector wall in a depth L of the reflector cavity, is given by:

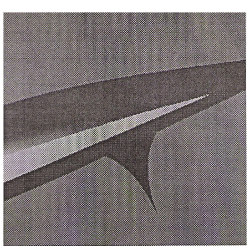
$$Q = 3.5\, Hu\mu mL \quad (11)$$

Where H, u and μ are the stream total enthalpy, velocity and viscosity respectively; m is the mass flow in the space enclosed in the reflector cavity; and L is the depth of the cavity. The co-efficient 3.5 comes from Wu's limited boundary layer calculations.

Suggested Design for the Vertical Thrust Producing Components



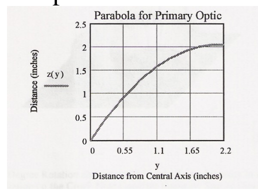
Retractable Parabolic Reflector below the Wing Assembly



Retractable Parabolic Reflector below the Nose

The suggested structure of this component basically consists of a retractable parabolic reflector. The reflector used of is high strength and coated with a solid propellant for initial ignition by inverse bremsstrahlung effect. The solid propellants, with low ionization potential, that can be used are lead or vanadium.

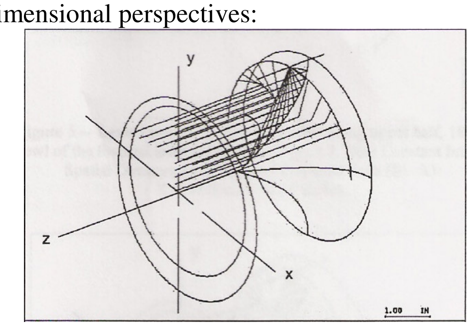
The figure shows the parabola used to construct three retractable parabolic reflectors.



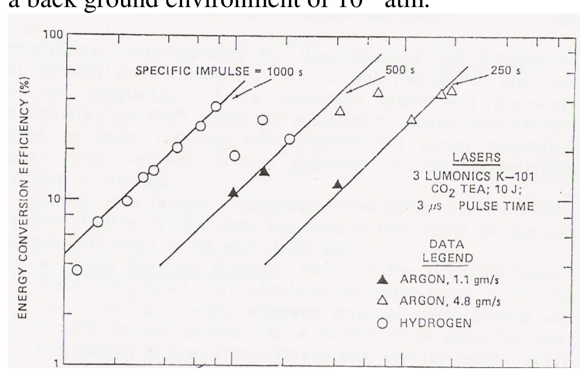
The equation for this relation in units of inches is obtained from Douglas Feikema's:

$$z(y) = 1.9504y - 0.4564y^2 \quad (12)$$

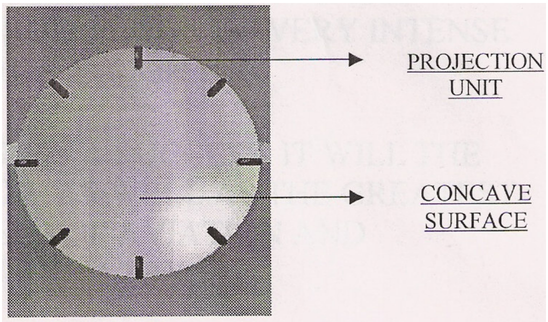
The following figure shows optical system perfectly focused with traced rays in three dimensional perspectives:



The graph below shows the relation between specific impulse and energy conversion efficiency (defined as the ratio of the exhaust kinetic energy per pulse to the laser energy per pulse) obtained with self-focusing parabolic nozzle, with argon and hydrogen propellants, and a back ground environment of 10^{-4} atm.

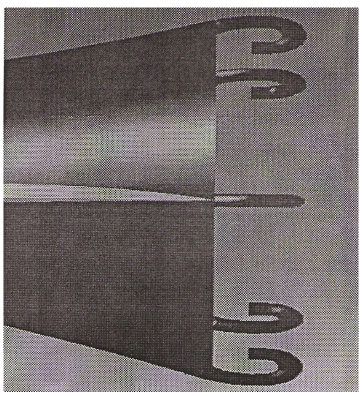


Suggested Design for the Horizontal Thrust Producing Components



The suggested design for this unit consists mainly of three units:

- The On-Board Laser Producing Unit
- The Reflecting Concave Surface
- The Projection Unit for the Laser



1. On-Board Laser Producing Unit:

   This unit comprises any modern Laser Production Mechanism. The required power is almost 100 MW of continuous wave laser. This unit can be placed in the fuselage of the design.

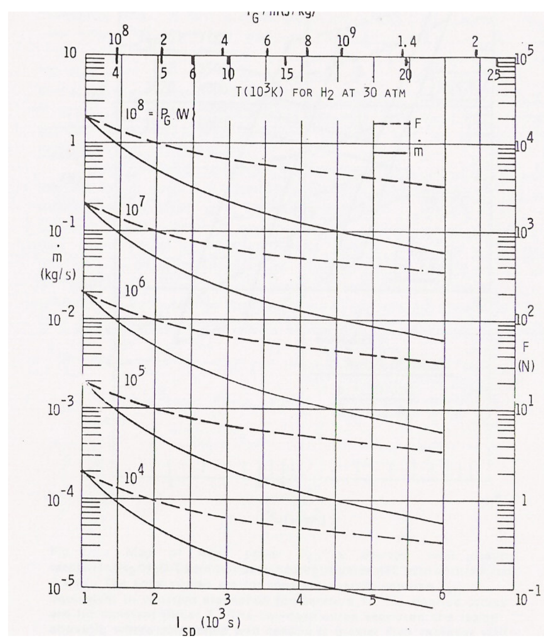
2. The Concave Reflecting Surface:

   This unit is basically a highly reflecting surface. This surface is also made very strong so as to absorb the thrust of the plasma explosion and to transfer the momentum to the craft, without failing throughout the flight envelope. The approximate surface area of this surface can be made to be around $250 m^2$.

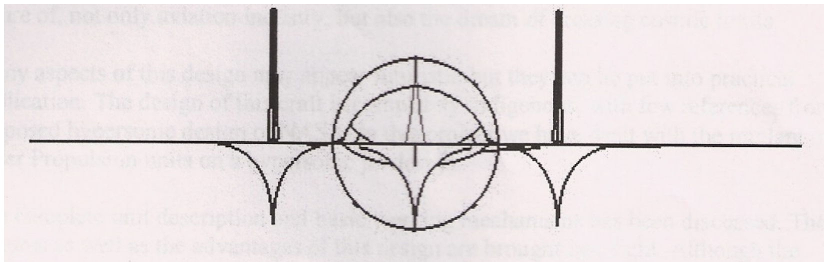
3. The Projection Unit for the Laser:

   This unit comprises of either optical fibers or optical pipes. They are arranged in a way that they focus the laser on the concave surface parallel to the principle axis. As a result the laser intensity is made to converge at the focus.

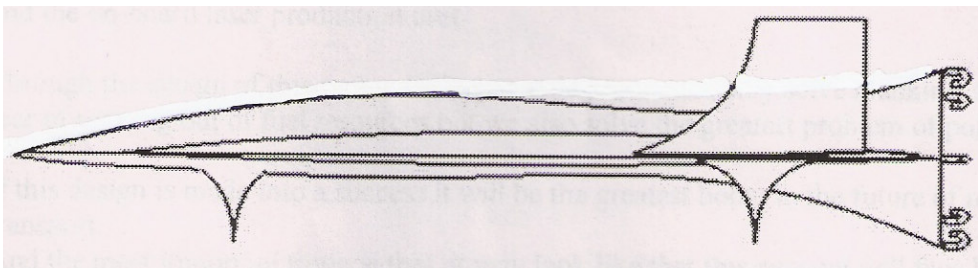
The thruster performance map; relating mass flow rate m, thrust F, specific impulse I_{SP}, and exhaust gas power P_G is provided below:



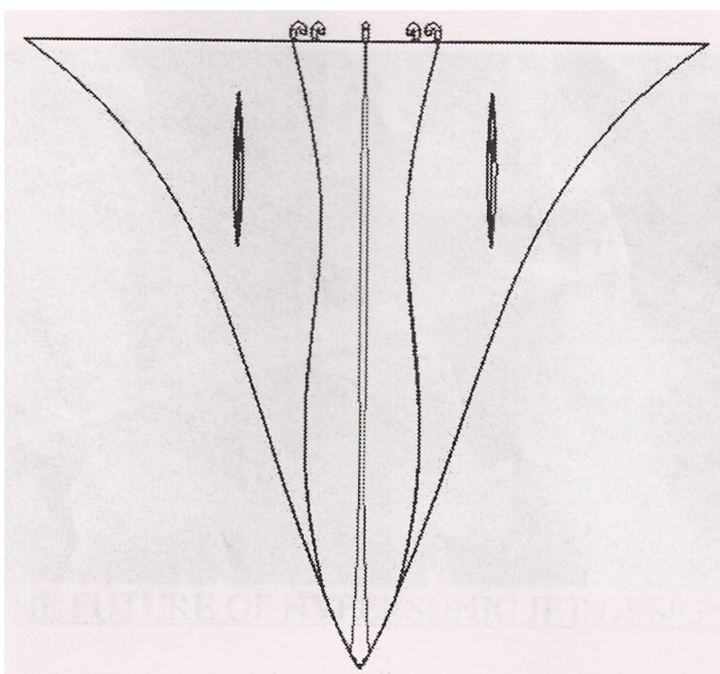
3-View Schematic



FRONT VIEW



SIDE VIEW

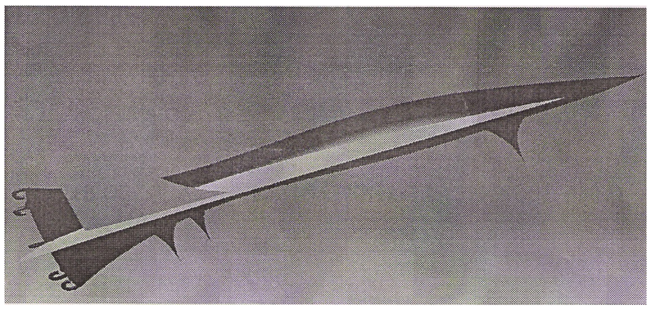


TOP VIEW

Conclusion

The concept of Laser-Propulsion is the future of the aviation industry. With the fast degeneration of fossil fuels from our planet, this propulsion mechanism promises a much reduced and more efficient usage of the fuel. It can also fulfill man's dream to cross cosmic limits at lesser risks and cost. Till date Laser-Propulsion has only been considered for space transportation; but in this paper the application of this propulsion mechanism in for flight within the earth's atmosphere has been enlightened. This is mainly owing to the fact that Laser-Propulsion can use atmospheric air as its propellant till an altitude of approximately 60,000 feet.

The complete unit with suggested working mechanisms has been discussed. There are a number of areas where further research is needed before this design along with its propulsion mechanism can be materialized.



THE PROPOSED DESIGN

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