Laser Propelled Spacecraft: Identification of a Suitable Existing Material based on Finite Difference Computation of the Maximum Temperature Obtained

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Abstract - *As the interest in space exploration is increasing, attempts to improve the efficiency of space travel are also underway. One such method of advancement is the laser propelled spacecraft, also known as lightcraft. Lab-scale prototypes have been tested by various agencies and researchers around the world for short flights. For a longer duration of flights, the material of the lightcraft is required to be robust enough to sustain the heat generated from the plasma generation process. This study involves the numerical evaluation of the surface and subsurface temperature at different times of a laser-propelled spacecraft. A finite difference method with an implicit scheme is used to generate the temporal and spatial profile of temperature. The maximum temperature obtained was found to be much lower for Titanium as compared to steel. Such studies are useful for identifying proper working conditions of the spacecraft and hence designing appropriate material.*

1. Introduction

With the space race only getting more competitive with time, scientists all around the world are exploring alternative options for faster and more efficient space travel. One of the major obstacles with improving the efficiency of space travel is the weight of fuel, which subsequently increases the operating cost of the payload [1]. With the existing fuel technology and propellants such as liquid hydrogen [2] and kerosene [3], the cost of launching a satellite in low earth orbit (LEO) could be more than $5000/kg [4]. Also, such propellants (or their source) could be extremely polluting, causing environmental concerns as well. With the ever-increasing demand for communication and surveillance satellites, it could be economically and environmentally challenging to launch enough numbers of these machines.

Using an external power source for pushing the spacecraft could be a potent solution to this conundrum. Laser beam propelled vehicles can be used to launch satellites with the power source located on earth itself [6]. It is basically using a remote power source, which will be located on the ground to propel the spacecraft using electromagnetic radiation beams. This energy can be utilized by the spacecraft either as a heat source for burning the solid fuel or in the case of laser beam propulsion, and the ambient air can be used directly as fuel. Such technology can revolutionize space travel altogether and can open a number of possibilities for mankind. The laser beam propulsion system, in principle, is a ground-based high-power laser system, which constantly supplies the spaceship with energy in the form of laser beams. This beam is pointed at the bottom of the spacecraft, where it is focused in an annular ring shape using a parabolic shroud. This focused beam generates very high temperatures of the order of 10,000 K, which breaks down the air into plasma. This plasma produces a superheated shockwave and pushes the spacecraft ahead. A lip at the shroud or rear end of the spacecraft directs the plasma downwards. Many researchers have also termed such a vehicle as 'Lightcraft' [7].

A Lightcraft laser propulsion system would require a pulsed laser of average power in MW. For demonstration purposes, a spacecraft weighing 50 gm and diameter 10cm was propelled using a 10 KW laser [8] by the Lightcraft Technologies, Inc, (LTI).

Parameter	Value /Range
Diameter of the Lightcraft	300 mm
Diameter of the shroud region	140 mm
Average Laser Power	5, 7.5, 10, 12.5, 15 W
Pulse duration	18 µs
Material	Steel, Titanium (Ti)

This initial flight can go a long way in the commercial development of the technology as a proof of concept. However, even after 20 years of this demonstration, the technology has not evolved much and has to overcome a great deal of obstacles in order to develop as an alternative for the existing liquid fuel rockets. One such obstacle is the selection of shroud material, which experiences high temperatures and pressure due to the breakdown of air and plasma expansion. In this work, an attempt was made to calculate the maximum temperature reached in the shroud of the lightcraft through a finite difference computation method. Also, based on the calculations, a suitable set of properties required in the material are deduced.

2. Materials and Methods

The maximum temperature reached in the body of the lightcraft due to air plasma expansion due to laser propulsion is computed using a finite difference method (FDM) code created in Python. An explicit scheme was used in this work to calculate the temperature assuming 1D heat transfer and a single laser pulse into the surface of lightcraft.

During the flight of lightcraft, the laser is supposed to be aligned accurately with the tail of the vehicle in order to maintain the position of the focus. Since the laser beam is focused in the shape of an annular ring, it has been assumed that the breakdown of air initiates at this location. Therefore, the distance between the point of initiation of the plasma and the surface of the lightcraft would vary with the diameter of the shroud region. The materials used for the study are stainless steel, Titanium, and Aluminum. These three materials have major applications in the aerospace industry and have been used immensely over the years [4]. The geometry of the lightcraft and the laser parameters taken are mentioned in table 1.

The structure of the spacecraft is shown in figure 1. The conical mirror is placed at the lower side of the spacecraft (material) to reflect the incident laser beam. The laser beam focused at the focal length of the mirror and ionized the air at that particular location. This results in the generation of high pressure and high-temperature plasma. This is a very complex process and extremely difficult to model. Therefore, in the present study, a basic single pulse 1-dimensional model is developed by considering various assumptions. Which as follow:

1. Temperature gradient in the X-direction is much higher compared to other directions.
2. Heat loss through radiation is ignored.
3. Material properties are independent of temperature.

In order to solve this problem, the heat conduction equation can be used with the heat generation term. The heat source term is given by full width half maximum (FWHM) laser profile.

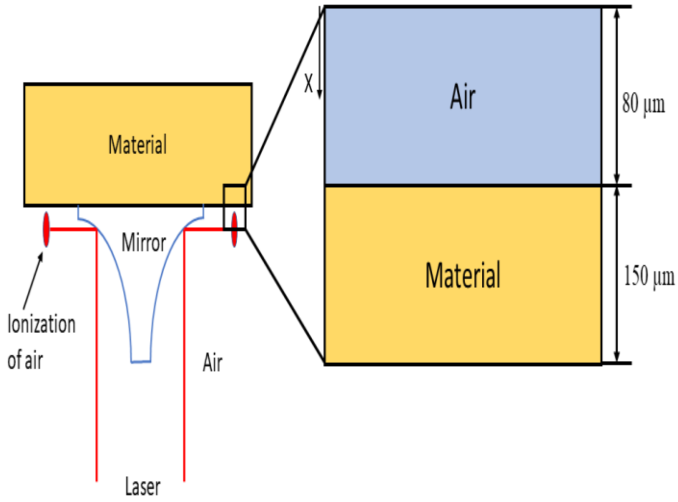

Figure 1 Model description

The discretization of the heat transfer equation is described below:

$$\frac{\rho C}{k}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + Q_{source}$$

Where T is the temperature (K), k is the thermal conductivity of electrodes (W/m.K), ρ is the density of electrode materials (kg/m^3), C is the specific heat capacity of solid material (J/kg.K), and x and y are the coordinates axis. The temporal variation of the laser intensity profile is described by a Gaussian profile with a full width half maximum (FWHM) is given by:

$$Q_{source} = \alpha(1-R)\, I_{max}\, e^{-4ln2\left(\frac{t}{t_p}-\frac{3}{2}\right)^2} e^{-\alpha x}$$

Where α is the absorption coefficient, R is the reflectivity, Imax is the maximum laser intensity at the surface.

$$\frac{\partial T}{\partial t} = \frac{\rho C}{k}\frac{\partial^2 T}{\partial x^2} + \frac{\alpha(1-R)\, I_{max}\, e^{-4ln2\left(\frac{t}{t_p}-\frac{3}{2}\right)^2} e^{-\alpha x}}{\rho C}$$

In the above equation, the term reflectivity can be calculated using the Fresnel equation. It is the ratio of the reflected and transmitted light to the incident light when the light is incident on an interface between different optical media.

The numerical model is based on the finite difference method (FDM) with an implicit scheme, developed using an in-house code in Python. The range of laser parameters is obtained from the preliminary simulations.

3. Results

3.1 Variation of Temperature with depth and average laser power

The temperature of the Lightcraft material, when exposed to laser pulses with different power, was obtained and found to vary a great deal in the starting depth. As depicted in the figure, the maximum temperature obtained is with 15 kW power and is around 34,000 K. Gradually, it reduces with the decrease in laser power, and with 5 kW, the maximum temperature is around 11,000 K. Similarly, we can observe that the maximum temperature obtained in Titanium is around 16,000 K and is maintained till a depth of a few micrometers.

No existing material can handle such high temperatures, and it may appear that the lightcraft technology is not feasible. This analysis is performed for two materials, steel and Titanium, as these two are abundantly used in aerospace applications. Additionally, we must also know the time duration for which such temperature exists on the surface (and small subsurface depth).

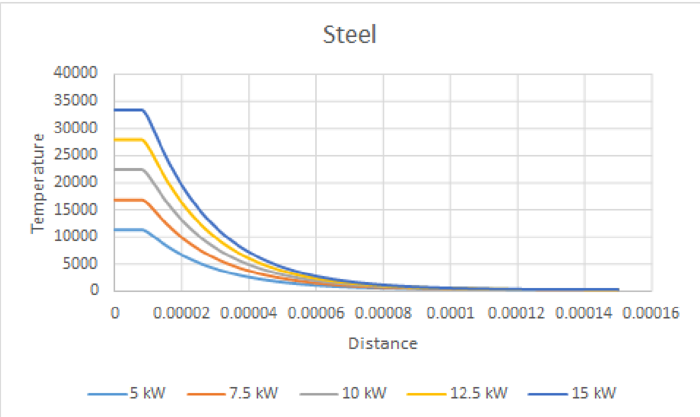

Figure 2 Variation in temperature along with the depth at a different value of power for steel sample

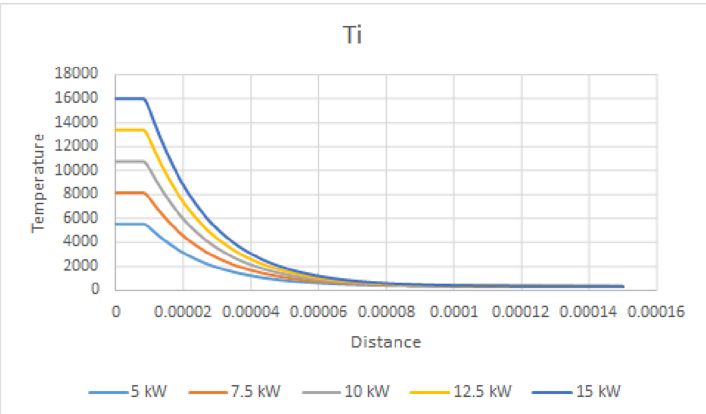

Figure 3 Variation in temperature along with the depth at a different value of power for Titanium sample

3.2 Variation of Temperature with time and average laser power

The data obtained from the numerical simulations were then analyzed and presented in a way to identify the duration of maximum temperatures that the materials are subjected to power levels. All materials have a limit of duration up-till which they can sustain high temperatures, and this analysis will tell us the duration for which the lightcraft material will need to endure high temperatures.

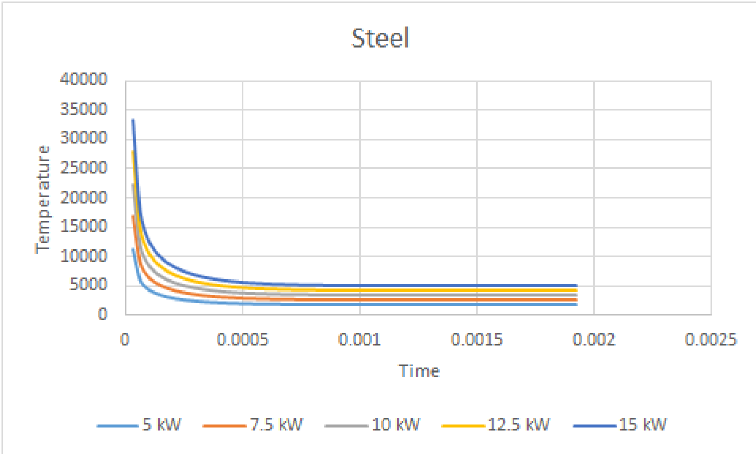

Figure 4 Variation in temperature with time at a different value of power for steel sample

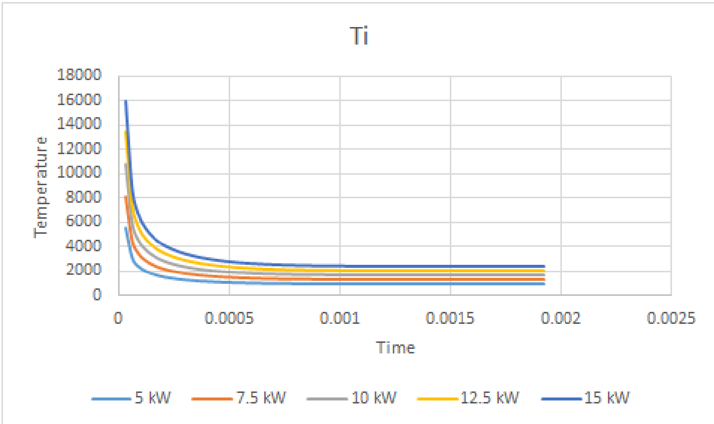

Figure 5 Variation in temperature with time at a different value of power for Titanium sample

It can be observed that the slope is different in both Steel and Titanium and hence the lowest temperature obtained at the end of the laser pulse. This slope or gradient is a function of the conductivity of the materials and hence would certainly vary between Steel and Titanium.

4. Conclusion

Two different metals were evaluated to understand the thermal impact of laser pulses on the material of laser propelled spacecraft or Lightcraft. The temperature as a function of time and space was evaluated using computational methods. A single laser pulse numerical model was developed and coded in Python using the finite difference method and implicit scheme. The heat source was assumed to be a little away from the surface, and hence a layer of air was assumed to be present in between plasma and the lightcraft material. The values of temperature obtained using the FDM model were plotted for Steel and Titanium. The temperature values were plotted at both different times and different depths from the surface. It was observed that the temperature obtained in Titanium was much lower compared to steel.

After this study, we can conclude that, as per the highest temperature obtained, Titanium appears to be a better material for the purpose of a laser propelled spacecraft. However, the highest temperature is still higher, much higher than Titanium's melting point. Such high-power laser beams can't be sustained even by Titanium for a long time, and melting will start with multiple pulses. Therefore, in order to sustain the flight for long durations and till the lower earth orbits in space, some novel material needs to be developed. Also, design changes must be incorporated to improve the efficiency of propulsion and hence promoting the use of lower powered lasers.

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