Supersonic Energy Addition for Improving the Performance of Nuclear Thermal Rockets

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October 14, 1999

Nuclear thermal rockets hold much promise for application to lunar and Mars missions. Solid core nuclear rockets have been build and tested as part of the NERVA program almost thirty years ago which demonstrated performance of 820 sec and 250,000 lbs using H_2[1]. During the past ten years interest has been renewed in nuclear rockets and various ideas have been proposed to improve performance. Among these concepts is the idea of adding O_2 in the supersonic region of the nuclear rocket to create an 'afterburner'[2]. This serves to increase the thrust of the nuclear rocket while specific impulse decreases. Another approach to achieving increased nuclear rocket performance is to add energy in the supersonic region using a laser beam propagating from an external source. Energy addition in this way, unlike supersonic combustion has the potential to increase both the specific impulse and the thrust of the nuclear rocket. This is true because the ultimate temperature achieved in the rocket is not limited to the flame temperature of the O_2-H_2 reaction, roughly 3400 K, but is determined by the ability to focus, absorb and contain laser energy. As described in the following paragraphs temperatures significantly higher than 3400 K have been achieved by focusing laser energy in flowing gases.

One way to achieve absorption of radiation in a supersonic region of the flow is by creating a laser sustained plasma (LSP). A thermal plasma provides a source of electrons which absorb radiation through the inverse bremsstrahlung process. As the propellant gas flows through and around the stationary plasma high bulk temperatures are sustained which can be in excess of 15,000 K. Stable laser sustained plasmas have been created and observed in the laboratory at pressures in excess of 1 atm using multi-kilowatt CO_2 gas discharge lasers[3, 4]. A measured value of laser absorption efficiency as high as 86 % has been reported for an argon LSP[3]. Several attempts have been made to model the physical interactions occurring in laboratory LSPs using two dimensional numerical simulations[5, 6]. Although the coupling of laser energy to a plasma has been found to be quite high, the overall propulsion efficiency is not as good. There are several processes that degrade the efficiency. In general, plasma radiation is a significant contributor, and in the case of molecular propellants such as hydrogen, frozen flow losses due to dissociation and ionization are important. A H_2 fueled thruster powered by an LSP has been build and tested[7]. Experiments with LSPs to date have involved subsonic flows. Using a LSP to add energy does not require adding any mass to the flow, which would eliminate the need for the O_2 injection system associated with supersonic combustion. In fact there my be no need to add any additional components to a nuclear rocket which is augmented by laser energy addition using an LSP, if the nozzle itself is used as a focusing mechanism to collect and concentrate a laser beam several meters in diameter[8].

A different approach for energy addition, one that does not utilize a plasma, is the molecular absorption of radiation in the supersonic regime. Adding energy using a molecular absorber involves the excitation of an internal mode such as rotation or vibration of a seed molecule. The seed molecule subsequently transfers its energy to the propellant gas by relaxation collisions. The molecular absorption approach for laser propulsion has been the subject of much theoretical work[9, 10]. The absorption properties of several attractive molecular absorbers for laser propulsion, including SF_6, H_2O and NH_3, have been measured over a temperature range from 500 K to 3000 K at $C0_2$ laser wavelengths[11]. Significant dissociation of these molecules occurs at these temperatures, a diatomic species such as OH can be present at temperatures as high as 5000 K. It is may be possible to rotationally excite OH, formed from the decomposition of H_2O, using a free electron laser source operating in the far infrared region. Unlike many processes which occur in plasmas that trap energy in meta-stable electronic states, vibrational modes and ionization, energy addition using OH at far infrared wavelengths would involve transitions to rotational states which generally have very fast relaxation times. The potential exists to increase the specific impulse of a nuclear rocket, running on hydrogen by adding a few percent of H_2O and expanding the flow isothermally at 5000 K using laser energy addition. The conversion of laser energy to thrust is more efficient than if a plasma were present since all the frozen flow losses asscoiated with a plasma, except dissociation, do not occur. However to avoid losses due to the absorption of laser energy in the plume the beam may need to be introduced into the nozzle from a window in the plenum.

References

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