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S1_5 The microwave thermal rocket engine

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Abstract

This paper describes the microwave thermal rocket, which uses microwave energy provided by an external power source to heat a propellant. We derive the important performance characteristics of such an engine, including the relationship between mass flow rate into the engine and both thrust and exhaust velocity. Specific applications of the technology are compared to conventional rockets and resistojets, and it is discovered that the engine would be useful for manoeuvring in space, but not in a launch vehicle. This paper discusses a design similar to that described in US patent 6993898.

Introduction

A rocket engine works by expelling material (a propellant) in one direction, which through conservation of momentum gives a force that pushes the rocket in the opposite direction. In conventional chemical rockets, the kinetic energy of the propellant is supplied through the exothermic reaction of a substance (the fuel), the exhaust products of which form the propellant. In a microwave thermal rocket, the fuel is separate from the propellant. The fuel's energy is instead converted to electricity and then to microwave energy, which heats the propellant and causes it to expand out of the rocket's exhaust (fig. 1).

Theoretically any wavelength of light can be used to drive such a rocket engine, provided that A) the light can be produced efficiently, and B) a practical propellant can be found that is opaque to it. Current technology allows for highly efficient conversion of electrical power into microwave energy with newly developed magnetrons rated to about 75% efficiency (ϵ) [1] and an obvious propellant fluid is water, which is of course non-toxic, easy to store, has a high specific heat and is fairly dense.

The first section of this paper will derive the thrust and exhaust velocity produced by a microwave thermal rocket.

Theory

The accelerating force (F) on a rocket-propelled vehicle is given in eq. (1):

$$F = \dot{m} v_{ex} \qquad (1)$$

where $\dot{m}$ is the mass flow rate in kilograms per second and v_{ex} is the exhaust velocity of the propellant as it leaves the engine. The exhaust velocity of a rocket is affected by the pressure difference across the exhaust plane of the nozzle, but improving performance through managing this difference is beyond the scope of this paper. For the following discussion, such effects will be neglected.

A measure of the efficiency of an engine is how much change in velocity (Δv) it can produce from a given amount of propellant. The Tsiolkovsky relation gives this explicitly as

$$\Delta v = v_{ex} \ln R, \qquad (2)$$

where R is the ratio between initial and final rocket mass. We can see that for the same fraction of mass consumed as propellant, a higher exhaust velocity means higher Δv and correspondingly higher fuel efficiency.

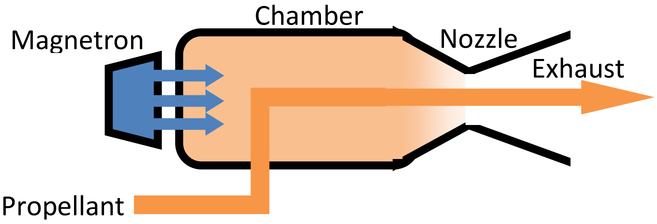

Figure 1: Microwave rocket engine schematic

Given that the exhaust temperature will be much higher than the ambient temperature, we cqn assume that the exhaust velocity is equal to the thermal energy transferred to the propellant by the microwaves. This is related to the thermal energy (E_{th}) of each individual molecule by eq. (3).

$$v_{ex}^2 = \frac{2E_{th}}{\mu m_h}, \qquad (3)$$

where μm_h represents the average relative atomic mass of the propellant multiplied by the mass of a hydrogen atom.

Assuming that on average every molecule in the chamber receives an equal amount of thermal energy from the microwaves, we can relate microwave power P to molecular flow rate $\left(\frac{dN}{dt}\right)$ in molecules per second and then mass flow rate:

$$P = \frac{dE}{dt} = \frac{dN}{dt} E_{th} = \frac{1}{\mu m_h} \frac{dm}{dt} E_{th}. \quad (4)$$

With E as total chamber energy. Rearranging eq. (4)'s expression for thermal energy and substituting into Eq. (3) gives

$$v_{ex} = \sqrt{\frac{2P\mu m_h}{\mu m_h} \frac{1}{{dm}/{dt}}} = \sqrt{\frac{2P}{\dot{m}}}, \quad (5)$$

with μm_h cancelling out. This can be substituted into the thrust equation (1) to give

$$F = \dot{m}\sqrt{\frac{2P}{\dot{m}}} = \sqrt{2P\dot{m}}. \quad (6)$$

We now have equations for both the thrust and the exhaust velocity of the rocket, as a function of microwave power.

Discussion

We now apply the above equations to a practical situation, to see how a microwave rocket would compare to current electrical and chemical propulsion systems.

The idea of using electrical energy to heat a propellant is nothing new. A resistojet contains a resistive element over which a propellant flows, and it can achieve an efficiency of up to 95%. The advantage of the microwave system is the higher reaction chamber temperature (T) that can be achieved and hence higher power and performance. In line with our previous assumption, we take $T = \Delta T$ and from eq. 6 get

$$\Delta T = m\mathrm{C_p}\epsilon\Delta E = \frac{P}{\epsilon\dot{m}\mathrm{C_p}} \quad (7)$$

A resistive element cannot withstand temperatures much higher than 2000K [2], but a magnetron can generate as much heat as the chamber can be built to withstand. Crucially, the walls of the chamber can be easily cooled, but cooling a resistojet element rather defeats the point.

The rate at which heat energy is transferred to the chamber walls is dependent on chamber gas density – for high mass flow rate applications (such as launchers) the chamber will absorb a lot more heat and be harder to keep cool. Eq. (9) can be used to find the exhaust velocity with water as a propellant; with a 3500K chamber temperature (that of the space shuttle), the limiting exhaust velocity is 3700m/s - comparable to chemical rockets.

$$F = \sqrt{\frac{2P^2}{\epsilon\Delta T\mathrm{C_p}}} \quad (8)$$

$$v_{ex} = \sqrt{2\Delta T\mathrm{C_p}} \quad (9)$$

To launch a 10,000kg rocket from the earth's surface, we would need an initial thrust of at least 100kN (greater than 10^5 g). From Eq. (8), this would require a power plant that can give out 235MW. This is enormous for a spacecraft; comparable to the output of a commercial nuclear power station. This, combined with the comparable exhaust velocity of chemical rockets, makes the microwave engine unsuitable for launch vehicle applications.

Chamber temperature is not a constraint for low mass flow rates, when chamber gas density would be low. For manoeuvres where long range is more important than thrust (such as interplanetary course adjustments) we compare the microwave rocket to the SMART-1 hall-effect thrusters [3]. This ran off a 1.2kW power supply and had a specific impulse of 15km/s, producing 68mN of thrust. The microwave thermal rocket running off the same power supply and producing the same thrust would give an exhaust velocity of 35km/s, theoretically resulting in improved performance.

Conclusions

The microwave thermal rocket engine's simple design and capability as an orbital manoeuvring engine show promise, with it theoretically outperforming the engine on SMART-1. That the engine's tradeoff between thrust and efficiency can be altered by changing the propellant flow rate is also a potentially very useful feature.

References

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[2] Rocket and spacecraft propulsion (p154) – M J L Turner 2006

[3] Accommodating electric propulsion on SMART-1 - Kugelberg J., Bodin P., Persson S., Rathsman P. (2004)