Journal of Special Topics

P2_9 Antimatter Propulsion

J. Anand, A. Buccheri, M. Gorley, I. Weaver

Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH.

13 November, 2009

Abstract
A method of using matter-antimatter annihilation to power a spacecraft via propellant heating is discussed in this paper. Using Tsiolkovsky's rocket equation it is determined that such a spacecraft would require a propellant-to-craft ratio of approximately 3.90, and a comparatively tiny amount of fuel (e.g. 8.77×10^{-9} kg for a LEO mission) which would greatly improve the craft-to-fuel mass carried by current missions.

P2_1 Space Science

Introduction

Conventional spacecraft rely on reaction engines for propulsion; engines that expel a propellant to gain forward momentum in accordance with Newton's Third Law. In addition to this, a considerable amount of energy is required to overcome the gravitational potential of the Earth in order to reach Low Earth Orbit (LEO) and beyond. As a result, this puts a considerable strain on the "dry" mass (i.e. spacecraft, supplies, etc) that can be taken into missions and the propellant required to launch it into space. This poses a significant problem for future missions that may want to carry more mass, such as interstellar or manned missions.

One possible alternative would be to use a fuel to heat an exhaust propellant rather than existing chemical propellants. Potentially, the energy given off from the annihilation of antimatter and matter would be ample to meet the energy required to launch a spacecraft. The energy density of antimatter is 9.00×10^{16} $\mathrm{Jkg^{-1}}$, much larger than any conventional fuel density [1].

Model

The ideal velocity of any spacecraft can be calculated using Tsiolkovsky's rocket equation [2]:

$$v_s = v_e \ln R \qquad (1)$$

where v_s is the spacecraft velocity (the required change in velocity required for a particular mission profile), v_e is the exhaust velocity of the propellant and R is the ratio between the final and initial masses of the system after the propellant is exhausted. For convenience, the ratio between v_s and v_e will be called x for later use.

The initial mass is defined as the mass of the spacecraft M_s and propellant M_p, whilst the final mass is that of the spacecraft. Due to the comparatively large size of the spacecraft it can be assumed that the mass of the antimatter fuel required M_a will not contribute much to R, and so will be ignored at this stage.

$$R = \frac{M_S + M_p}{M_S} \quad (2)$$

As previously stated, the kinetic energy of the propellant would come from the energy released from the annihilation reaction. That is, assuming 100% efficiency:

$$M_a c^2 = {}^1/_2\, M_p {v_e}^2 \quad (3)$$

Therefore, by combining equations 1, 2 and 3 the mass of antimatter required to propel such a spacecraft can be derived.

$$M_a = M_S \frac{{v_s}^2}{2c^2} \frac{(e^x - 1)}{x^2} \quad (4)$$

Differentiating equation (4) with respect to x and equating to zero gives

$$x(e^x - 2) + 2 = 0 \quad (5)$$

The resulting expression is then solved numerically in order to give an *x* value of: 1.59 (3 s.f). That is, the spacecraft would have to be travelling 1.59 times faster than its exhaust velocity for the antimatter mass to be minimised.

This value can therefore be substituted into equation (1) to give a value of R as 4.90 (3 s.f). From equation (2) this means that the propellant required for this design would have to be approximately 3.90 times the payload mass.

Discussion

The propellant-to-spacecraft ratio is an interesting result, as it is much smaller than conventional launch systems used. For instance, by using data for launch and landing masses [3] the Space Shuttle has an equivalent ratio of approximately 20- far more propellant compared to its vehicle mass.

Another comparison to be made with the Shuttle would be the amount of fuel required to reach LEO. The change in velocity required to reach LEO is 9.8kms^{-1} (including losses due to air resistance, etc) [4]. Substituting this into equation (4) as v_s with the minimum value of x and the mass of the Shuttle therefore gives a required antimatter mass of: 8.77 x 10^{-9} kg (3 s.f). This is vastly less than the conventional rocket fuel required by missions such as the Space Shuttle.

Another good reference for the efficiency of a rocket engine is its specific impulse, I_{sp} (the change in momentum per unit of propellant). This is given by [2]:

$$I_{sp} = \frac{v_e}{g_0} \quad (6)$$

where v_e is the propellant exhaust velocity of the engine (ms^{-1}), and g_0 is the local gravitational acceleration, usually taken as 9.81 ms^{-2}. For instance, the main engine of the Space Shuttle has a specific impulse of 453 s [3]. Referring back to the previous case of reaching LEO, the specific impulse of the antimatter engine can be calculated as: 628 s (3 s.f). Again, this demonstrates that the concept would offer a more efficient method of at least launching into a Low Earth Orbit, as the higher value of I_{sp} means that less propellant needs to be expended to gain the same momentum.

However, there are issues in the implementation of this concept. A major issue is the containment of the fuel before use, as the antimatter would annihilate with any surrounding matter. One possible solution would be using magnetic fields to contain the fuel, as currently antimatter is produced as charged subatomic particles such as antiprotons that are affected by magnetic fields. One such method currently employed is the Penning Trap [5] at CERN.

Another issue is the mechanism required to convert the liberated energy into the kinetic energy of the propellant is currently unknown, as is the optimum propellant used for this method. The propellant used would need to be chemically inert to prevent reactions with the spacecraft occurring in the high-temperature environment of the engine, and also have a high specific heat capacity to ensure efficient energy transfer.

Another issue is that this process would be less than 100% efficient as assumed by the derivation; equation (4) would need to have an extra variable to reflect this, though the exact value is currently unknown.

Conclusions

From elementary analysis using the rocket equation, it is estimated that a spacecraft using antimatter annihilation as a means of heating its propellant would in theory be much more efficient than current methods, offering a fuel-to-craft ratio of ~3.9 as it would offer a much greater engine efficiency as well as the opportunity to carry more mass onto missions, for a lot less fuel and propellant mass. However, due to existing issues with containment and fuel production, this remains a theoretical concept only.

References

[1] Comparison of Fusion/Antiproton Propulsion Systems for Interplanetary Travel, *http://gltrs.grc.nasa.gov/reports/1996/TM-107030.pdf*

[2] The Ideal Rocket Equation, *http://exploration.grc.nasa.gov/education/rocket/rktpow.html*

[3] Space Shuttle Data, *http://www.braeunig.us/space/specs/shuttle.htm*

[4] R. Warwick, "Spaceflight Dynamics", (Lecture notes), pg 9

[5] Antimatter in a Trap, *http://www.npl.washington.edu/av/altvw10.html*