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Two generic concepts for space propulsion based on thermal nuclear fusion ☆

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ABSTRACT

In the present work, two different concepts for fusion based space propulsion are compared. While the first concept is based solely on propulsion by hypothetic ejection of fusion products and hence may be called ash drive, the second one uses an additional coolant for thrust enhancement. Since this coolant was initially assumed to be gaseous and since it is doing most of the propulsion work, the name of “working gas drive” has been proposed. Propulsive characteristics for both types are evaluated for four fusion reactant couples (D–T; D–^{3}He; ^{3}He–^{3}He; ^{11}B–p). In working gas drives, only hydrogen is considered as coolant due to its exceptionally good caloric and propulsive properties.

The results of comparative studies show that while ash drives excel working gas drives in terms of specific impulse the latter yield considerably more thrust than ash drives. Another major drawback of the ash drives is relatively small thrust efficiencies. The plasma power has to be disposed of nearly entirely as waste heat leading to prohibitive radiator masses.

1. Introduction

The development of mankind's solar system for human purposes is limited by the technological abilities in space flight, among which the most critical: propulsion. Its decisive role is obvious in the case of launchers in which today's propulsive capabilities restrict the payload to a relatively small fraction of the vehicle's mass. This issue is to a certain extent also a characteristic for space propulsion systems operating on Earth's orbit and beyond, as well as another important matter which is the extremely long mission duration caused by established transfers such as Hohmann's transfer or spirals.

Both the insufficiency in payload mass fraction and voyage duration are of no concern as far as the mission consists in sending unmanned probes or orbiters of a relatively small size to a given destination and as far as there is plenty of time and patience. Yet, if a mission requires moving a considerable payload mass over a vast distance in a conveniently short period of time, which is especially desirable in the case of manned interplanetary space flight, transfer approaches of higher performance are necessary.

Williams [1] proposed an advanced interplanetary transfer consisting of two finite burns along a straight trajectory, extending a field free fly-by estimation already proposed by Shepherd [2]. Williams obtained

$$D = \frac{c_e^2}{F} M_d \left(\frac{1}{\sqrt{\varepsilon}} - 1 \right)^2 \tag{1}$$

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for the voyage distance D and

$$\tau = \frac{c_e}{F} M_d \left(\frac{1}{\varepsilon} - 1 \right) \tag{2}$$

for the voyage duration τ. In these equations, F de-signates the thrust and c_e the exhaust velocity. The spacecraft's dry mass is M_d and $\varepsilon = M_d/M_0$ is the dry mass fraction with respect to the initial mass M_0. These equations show that, in the case of fixed space craft mass composition, the augmentation of c_e by a given factor and of F by this factor's square diminishes the voyage duration by this factor while the voyage distance remains fixed. Thus, both high c_e and high F are to be aspired when developing a propulsion system suitable to perform Williams' transfers.

Present day's propulsion combines high c_e with low F or vice versa: in the case of energy limited propulsion systems like chemical thrusters, c_e is limited by the enthalpy stored in the combustible. A typical approximation often stated is 5.2 km/s [3]. However, energy limited propulsion systems tend to have high thrust compared to power limited propulsors which reach higher c_e. The major advantage of high c_e arises from Tsiolkovski's equation

$$\Delta v = -c_e \ln(\varepsilon) \tag{3}$$

A smaller propellant mass fraction is sufficient to realise the same velocity increment $\Delta \nu$ of the spacecraft. This is the main incentive studying *electric* or *separately powered propulsion*. However, being limited in mass specific power

$$\alpha = \frac{P}{m} = \frac{\frac{1}{2} F c_e}{m} = \frac{1}{2} a c_e \tag{4}$$

the high c_e of electric thrusters is equivalent to a relatively low acceleration forcing long burns to build up a mission's velocity increment. Removing the limitation would consequently allow higher accelerations even at higher c_e. This thought is consistent to the results of an optimisation of separately powered propulsion discussed in references [2,4]: The augmentation of the specific power and of the propulsion system is equivalent to an augmentation of payload *and* a reduction of mission duration.

A considerable augmentation of specific power may be obtained by using *nuclear fusion*. In this process, two light nuclei are brought close enough to form a new larger one – the so called product or ash – while yielding nuclear energy. Nuclear fusion ranks among the most attractive terrestrial power generation processes [5,6] and has already been discussed as a power provider for space propulsion [7–9]. Recently, the identification of a fusion drives' most likely system architecture has become a subject of investigation. Both the physical aspects – such as the applicability of fusion reactant couplings, the practicability of expected fusion plasma properties, and respective confinement [10–12] – and the system engineering aspects – such as key technologies, subsystem requirements and mass estimations [13,14] – have been covered and studied assuming a generic, dimensionless model. Two main system concepts have been made out:

- ***ash drives***, propelling by ejection of fusion products as shown in Fig. 1, and
- ***working gas drives***, using an additional propellant heated by the fusion reactor (Fig. 2).

Note that Figs. 1 and 2 are conceptual, assuming an exemplary toroidal configuration while the investigation has not yet addressed the question of the geometric layout of the fusion plasma confinement.

This contribution aims at presenting these concepts, integrating recent results and giving an update on the state of investigation. Some of the prior uncertainties such as the impact of fusion products on the plasma and its consequences to the propulsive properties and system mass budget are answered.

The propulsion system concepts are described in the next section. The common core of both designs is the generic fusion reactor containing an extremely hot plasma ejecting reactions products and emitting heat. Its physics and basic properties are introduced before describing both propulsion concepts as well as the differences between

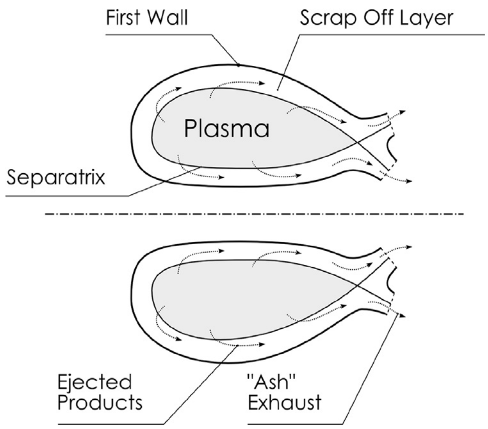

Fig. 1. Concept scheme of a fusion ash drive.

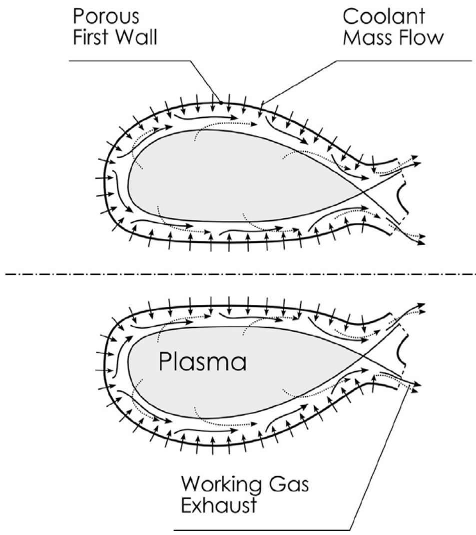

Fig. 2. Concept scheme of a working gas drive.