Comparative Investigation of Fusion Reactions for Space Propulsion Applications

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A space propulsion system based on the acceleration of fusion ash is discussed by use of the energy balance equation and a hypothetic ash extraction and acceleration system. The fusion reactions D-T, D-³He, p-¹¹B and ³He-³He are investigated under the condition of thermal generation of high energy ions and equal plasma system conditions in terms of T_i/T_e relation and plasma beta. External plasma heating is defined by an equal efficiency concerning thermal energy conversion and energy transfer back into the plasma. There is no additional external heating applied to the fusion system. Power losses are based on neutrons, bremsstrahlung, synchrotron radiation and convection. We compare the plasma pressures, volumetric power densities, magnetic field strengths, heat waste, exhaust velocities and thrust density levels depending on the temperature and the hot ion mode. We show that, based on the fusion products, the exhaust velocity may reach several percent of speed of light in the case of ³He-³He. The temperature driven radiation losses of the ³He-³He reaction puts the purely aneutronic property into perspective. The mass flow rate densities of the considered fusion products are very low leading to very low thrust power densities. Considering the supposed system masses of a fusion based space vessel the thrust density levels are negligible and reach the order of 1 N/m³ near the optimum in the case of ³He-³He. We conclude that a propulsion system based on the acceleration of fusion products or ash is unfeasible for typical manned missions e.g. to Mars.

Key Words: Space Propulsion, Fusion, Aneutronic, Plasma

Nomenclature

D	:deuterium (-)
T	:tritium (-)
p	:proton (-)
^{11}B	:boron-11 (-)
3He	:helium-3 (-)
P	:power density (W/m ³)
p	:pressure (Pa)
E	:energy (J)
σ	:cross section (barn, m ²)
T	:temperature (keV)
T_i	:ion temperature (keV)
v	:velocity (m/s)
k_B	:Boltzmann constant (J/K)
M_{eff}	: effective mole mass (kg/mol)
n	:particle density (m ⁻³)
N_A	:Avogadro constant (mol ⁻¹)
Q	:power factor (-)
S	:constant (~)
Z	:charge number (-)
B	:magnetic field (T)
c^*	:constant (1/keV)
η	:energy absorption coefficient for reactor wall(-)
ζ	:relation of product ion energy to total fusion energy release (-)
φ	:hot ion mode temperature relation (-)
δ_{ik}	:Kronecker symbol (-)
μ_0	:vacuum permeability (Vs/Am)

Subscripts

F	:fusion
m	:magnetic
th	:thermal
Br	:bremsstrahlung
Sy	:synchrotron radiation
N	:neutron
e	:electron
i	:ion species
j	:species counter
k	:power source

Superscripts

'	:temperature in K
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1. Introduction

Nuclear fusion is investigated as a future option for commercial energy production¹⁻³⁾ and discussed as a future option for space propulsion purposes⁴⁻⁶⁾. The difficulties in realizing a fusion based propulsion system are fundamental as they are in case of terrestrial fusion reactors: fusion plasmas burn at extremely high temperatures and one of the core problems is to achieve these temperatures. Other problems concern e.g. the high temperature resistivity of the reactor material and the generation of very high magnetic field strength for the plasma confinement.

Besides that, fusion based energy production on Earth demands technologies which are quite different from those for space applications in terms of complexity, reliability, redundancy, accessibility, mass, heat and cost aspects⁷⁾. The first three aspects are strongly connected to each other leading to the statement that the space propul-

sion system has to be as simple as possible. The D-T reaction is usually disregarded due to the intense production of neutrons which heat up the reactor wall. Since moving parts e.g. for calorimetric energy conversion are to be avoided as far as possible and heat waste can be removed only by large and heavy radiators, heat losses to the wall have to be minimized. Correspondingly, this leads to the common conclusion that aneutronic fusion reactions are the most promising candidates. However, it is well known that the aneutronic ${}^3\text{He}$ - ${}^3\text{He}$ reaction needs extremely high temperatures for ignition and operation which is accompanied by strong radiation losses of just another type (bremsstrahlung) but with the same wall heating effect. As a consequence, it is unknown which fusion propellant is more feasible for space propulsion. It is the objective of this work to compare of the four most popular fusion propellants which are usually discussed separately and not on a system level.

The structure and proceeding of this study is as follows: In section 2 the theoretical basics are briefly introduced. After introducing system based model, the power loss and gain terms are briefly introduced and balanced by applying system parameters (efficiencies) which are equal for all propellants. The balance equation leads to an extended burn criterion expressed by the product of ion particle density n_i times the energy confinement time τ_E . Results like volumetric power densities, mass flow rate densities, exhaust velocities and thrust density levels for different fuel ashes are discussed in section 3. The key aspects of this investigation are summarized and conclusions are made in section 4.

2. Theoretical Considerations

Generally, a space vessel consists of many systems, subsystems etc. Within the scope of this work we consider fusion plasma, reactor wall, energy conversion, heat transport, radiator and energy recirculation as separate subsystems or system properties which are connected by power fluxes. The simplified model is depicted in Fig. 1.

Fig. 1. Simplified model of the fusion propulsion system

The subsystem fusion plasma gains power from the fusion reactions and from recirculated power but loses power to the wall. Outside the reactor wall energy conversion devices are assumed converting heat to electric power. Unconvertible heat waste is transported to the radiators.

The fusion reactor in this study is based on a closed magnetic plasma confinement and has no defined shape or

size. It is assumed that a hypothetical mechanism exists which perfectly extracts and accelerates the fusion ash after its thermalization. Wall erosion effects are neglected.

2.1. Propellant data

We discuss the four most popular (neutronic as well as aneutronic) fusion propellants:

1. $\text{D} + \text{T} \rightarrow {}^4\text{He} + \text{n} + 17.6\text{MeV}$
2. $\text{D} + {}^3\text{He} \rightarrow {}^4\text{He} + \text{p} + 18.3\text{MeV}$
3. $\text{p} + {}^{11}\text{B} \rightarrow 3{}^4\text{He} + 8.7\text{MeV}$
4. ${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + 2\text{p} + 12.9\text{MeV}$

For the sake of simplicity, side reactions as e.g. the D-D reactions are neglected and the fusion plasma is considered as homogeneous. The fusion rates base on the reaction rate coefficients $\langle\sigma v\rangle$ which are generally obtained by averaging the fusion cross section over an equilibrium energy distribution.

Fig. 2. Fusion cross section data.^{11, 12)}

Hence, it is important to know the fundamental data – the cross sections, see Fig. 2. The numerically integrated reaction rate constants are depicted in Fig. 3.

Fig. 3. Reaction rate constants.

2.1. Energy balance

In order to make a comparison between the discussed fusion propellants we use the energy balance equation. Radiative losses are given⁸ by:

$$P_{Br} = S_{Br} \sqrt{T_e} n_e \sum_j (n_j Z_j^2) \quad (1)$$

and

$$P_{Sy} = S_{Sy} B^2 n_e T_e (1 + c^* T_e). \quad (2)$$

The neutron power is defined as:

$$P_N = (1 - \zeta)P_F. \quad (3)$$

Thermal losses are described as follows:

$$P_{th} = E_{th} / \tau_E. \quad (4)$$

Neutrons, bremsstrahlung and thermal losses are fully absorbed by the wall as well as 10 % of the synchrotron radiation. It is assumed that 30 % of this heat wall load is converted into electric energy and coupled back into the plasma leading to a sort of external heating P_{ext} . The second gain term is represented by:

$$P_F = \zeta \frac{n_i}{1 + \delta_{ik}} \frac{n_k}{1 + \delta_{ik}} < \sigma v > E_F \quad (5)$$

Due to ζ the neutron losses affect only P_{ext} since they cannot be confined by the magnetic field and are therefore not explicitly treated as a loss in the balance equation. Introducing the hot ion mode one can substitute the electron temperature using the relation $T_i/T_e = \phi$. A hot ion mode is characterized by $\phi > 1$ and reduces the losses via bremsstrahlung which is a well known effect^{15, 16}. It also reduces the plasma pressure and, therefore, the necessary field strength for the magnetic confinement. Although this mode is intrinsic¹⁴ there is an upper limit for ϕ since the effect on a B field strength reduction decreases⁷) and the energy transfer from the hot ions to the cold electrons increases with increasing ϕ .

The electron density can easily be substituted by the ion density. Given that, using Eq. 1-5 by balancing the gain and the loss terms one can derive a fusion burning criterion in terms of the dual product:

$$n_i \tau_E = f(Q, \beta, \phi, T_i, \psi, \eta_{BrS}, \eta_{Sy}, \eta_N, \eta_{th}) \quad (6)$$

with $Q = P_{gain}/P_{ext}$ and ψ describing the mole specific propellant composition. The β parameter is a measure for the magnetic confinement and is introduced in the next section. For the details of the derivation of Eq. 6 please refer to Ref. 13.

3. Results and Discussion

The fusion burning criterion was numerically investigated with MATLAB[®] setting $\psi = 1$, $\tau_E = 0.5 \text{ s}^{1)}$ and $\phi = 1, 2, 5, 10$.

Using the ideal gas relation one easily can estimate the plasma pressure over the temperature for different ϕ , see Fig. 4. Results are plotted for all discussed fusion propellants. The thermal plasma pressure has an optimum pressure for each propellant and each ϕ . Although this point seems to be constant (the same temperature in the case of e. g. D-T) the optimum point increases with decreasing ϕ as can be seen in the $^3\text{He}-^3\text{He}$ case. For the plasma pressure and the confinement needs a high ϕ is advantageous.

The quality of the magnetic confinement is described by the plasma beta which relates the gas dynamic pressure to the magnetic pressure:

$$\beta = \frac{p_{th}}{p_m} = \frac{\sum n k_B T_i}{B^2 / 2\mu_0} < 1 \quad (7)$$

Assuming a constant plasma beta of 0.9 for all fusion propellants one can estimate the necessary magnetic field

strengths for the confinement following Eq. 7. The results are depicted in Fig. 5. The D-T reaction demands the lowest magnetic field strengths (1-10 T) which represents in the area around the optimum point available technology. For $^3\text{He}-^3\text{He}$ the magnetic fields are very advanced and in the range of approximately 300 T.

Figure 6 shows the plasma power density for all propellants and for different hot ion modes. The D-T plasma has the lowest plasma density (1-10 MW/m³). The power density of $^3\text{He}-^3\text{He}$ is four orders of magnitude higher than that (10-100 GW/m³).

Fig. 4. Plasma pressure p_{th} over temperature for different ϕ .

Fig. 5. Magnetic field strength B for $\beta = 0.9$ over temperature for different ϕ .

Fig. 6. Plasma power densities P_{th} over temperature for different ϕ .

Figure 7 depicts the power densities which have to be removed from the system. These values result from the power losses which cannot be converted to electric power, therefore representing heat waste, i.e.

$$P_{ab} = \sum_k (1 - \eta_k) P_{k,loss} \quad (8)$$

They are of the same orders of magnitude as P_{th} and yield enormous radiator masses assuming conventional radiator technology.

Fig. 7. Power waste densities over temperature for different ϕ .

Figure 8 shows the mass flow rate densities:

$$\dot{m}_{ash} = \frac{n_i n_{i+1}}{(1 + \delta)^2} \langle \sigma v \rangle \frac{M_{eff}}{N_A} \quad (9)$$

of the fusion products for all propellants. Obviously, they are extremely small.

Fig. 8. Mass flow rate densities over temperature for different ϕ .

Fig. 9. Exhaust velocity c_e over temperature.

Computing the mole masses M_{eff} of the fusion products allows a general estimation of the adiabatic exhaust velocities $c_e(T)$, see Fig. 9. The values are the same for D-T and p- ^{11}B . For ^3He - ^3He c_e reaches around 35 % of speed of light in case of a non-relativistic calculation due to the high temperature operation.

Given that, one gets the thrust power densities:

$$P_{thrust} = 1/2 \dot{m}_{ash} c_e^2 \quad (10)$$

and the thrust density levels

$$F = \dot{m}_{ash} c_e \quad (11)$$

which can be reached just by the use of the fusion products. The results are depicted in Fig. 10 and 11. P_{thrust} is in the order of 1-10 pW/m³ for D-T and 10-100 nW/m³ for ^3He - ^3He which is reasonable considering Fig. 8. The thrust density is about 10 $\mu\text{N}/\text{m}^3$ in case of D-T and reaches about 1 N/m³ in case of ^3He - ^3He .

Fig. 10. Thrust power densities P_{thrust} over temperature for different ϕ .

Fig. 11. Thrust densities F over temperature for different ϕ .

These results show that using only fusion products as acceleration mass give very high specific impulses but negligible thrust density levels. For the Fig. 4-11 (except Fig. 9) one can state that for increasing hot ion mode the relative change of the physical quantity decreases. This is consistent to the upper limitation of ϕ which is caused by the increasing energy transfer between electron and ions with increasing temperature difference. Moreover, there seems to be a sort of an asymptotic behavior of the high temperature part of the curves independently on the propellant. It is unclear whether this result is of significance for the further investigations.

4. Summary and Conclusions

The main target of the paper was the comparison of typical fusion propellants on a system level for ash based propulsion systems. Therefore, the modelled propulsion system (especially the reactor) has no shape or size. Accordingly, all results are volumetric and for further discussion need to be applied to a specified reactor type, size and shape. The fusion plasma is magnetically confined, thermally heated and only the fusion ash is assumed to be

accelerated. The power balance equation was used in order to compute a stationary mode of operation based on an extended burn criterion which was derived in Ref. 7 and briefly discussed in section 2.

For each propellant, regions of minimum plasma pressure and, therefore, regions of minimum magnetic field strengths were identified, see Fig. 4 and 5. In the D-T case B fields can be generated by available technology.

As can be seen in Fig. 6 plasma power densities are extremely high compared to today's space propulsion technologies which promise a sort of technology breakthrough on the solar system scale. However, one major problem is depicted in Fig. 7. The heat flux seen by the reactor wall is of the same order of magnitude as the plasma power density which is independently on the propellant. Even if these losses can be converted to some degree into electric energy, the need of huge radiator surfaces remains. Therefore, enabling non-fusion related technologies are efficient radiators and, much more important, efficient heat conversion technologies, e.g. thermionic and thermoelectric converters with efficiencies much higher than what is available today. Alternatively, one can assume a transpiration cooled reactor wall. Such a technology would greatly reduce the radiator size but it is different to the herein discussed ash based propulsion concept.

The ash is assumed to be extracted from the plasma core with fusion temperatures yielding very high exhaust velocities, see Fig. 9. However, the advantage of fusion in general becomes a drawback in case of ash based systems: The mass flow rate is extremely low (Fig. 8) leading to very low thrust densities as depicted in Fig. 11. Compared to the commonly discussed mission scenarios like manned mars missions this propulsion concept is therefore no option. In combination with the enabling technologies discussed above we state that only the ^3He - ^3He ash based fusion propulsion concept could be eventually interesting for unmanned or robotic long term missions due to the extremely high specific impulses.

Further investigations will focus on the evaluation of different confinement and fusion ignition schemes concerning their applicability to space propulsion^{9, 10, 17)}. Other activities related to the investigation of such kind of propulsion system are already ongoing at the Institute of Space Systems. At present, experimental investigation of magnetic nozzles in cooperation with the University of

Tokyo is being performed within a scientist exchange program. However, this still requires a set of concept studies such as the extension of the present work towards thruster performance parameters, regenerative wall cooling and related operational environments for the aforementioned technologies.

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