Use of propellants different from hydrogen for space propulsion

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The possibility of hydrogen heating by the fission fragments has been widely discussed in the work "Fission fragment heating for space propulsion" [1], in which an innovative method, developed by C. Rubbia, is presented. In that work the criterions in the choice of the propellant for a spacecraft have been well discussed; for instance, a high enthalpy at an acceptable temperature is an important requirement in order to obtain a high exhaust speed, as shown in the St. Vennant and Wenzel formula,

$$V_{exh} = \sqrt{2(E_c - E_e)},$$

where E_c is the enthalpy for unit mass of the gas in the combustion chamber, and $E_{e,}$ represents the other forms of enthalpy not converted in kinetic beam energy between the chamber and the nozzle exit. As well known, the enthalpy of a gas is a function of the temperature, rising with it, and the pressure. Dissociation energy and ionization also affect the enthalpy of the gas.

The hydrogen is the most light element available, it has a high specific enthalpy, but it is also quite reactive and it may damage the americium layer or other metallic surfaces of the engine, specially taking into account its long-term storage in the form of cryogenic liquid.

The possibility of using different propellants should be investigated on the basis of the kind of mission planned. If a mission to Mars is planned, for example, the possibility of using the Mars's gases as propellants for the return trip should be considered. In fact, one key method to reduce the cost of the mission could be the production of the required supplies, just like the rocket fuel, using Martian resources.

The Mars's atmosphere is composed by 95% of carbon dioxide, 3% of argon, 0.13% of oxygen, 0.01% of water. Xenon, neon, krypton, and very small amounts of ozone and hydrogen complete its composition. Thus, Ar and CO_2 could be, at first glance, two interesting candidates as rocket propellants.

Another interesting possibility could be represented by the Helium, whose atomic weight is small and is an inert gas. This last feature is of particular relevance, if we compare He with H_2, being, with the use of He, completely avoided corrosion problems. Ar is also an inert gas, but while He is 4 times heavier than H, Ar is almost 40 times heavier, and this implies a lower exhaust speed.

The molar fraction of the various components of the hydrogen, helium, argon, and carbon dioxide as a function of the absolute temperature at the pressure of 1 bar is shown in Figure 1, based on data from Ref. [2].

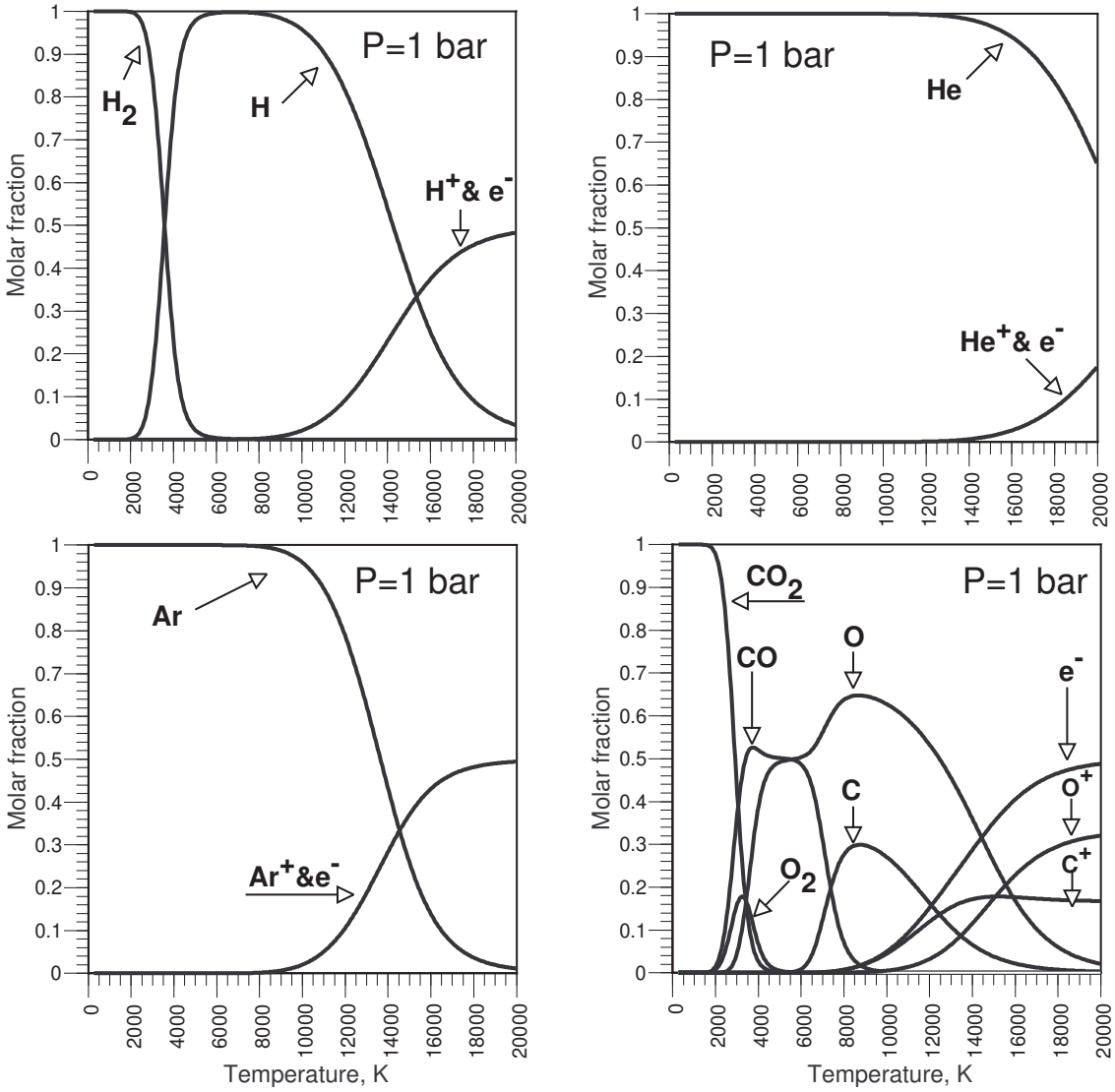

Figure 1. *Composition of hydrogen, helium, argon, and carbon dioxide as a function of the absolute temperature at the pressure of 1 bar.*

We note that, in the case of the CO_2, a relevant fraction of solid carbon is already present at temperatures of about 7000 K (1% C). The presence of carbon powder is obviously a problem because it can damage the mechanical parts of the engine. Thus, if carbon dioxide is supposed to be used as propellant, the temperature of 7000 K cannot be overcome. Furthermore, the presence of molecular oxygen (about 1.8% O_2 at 3000 K), and atomic oxygen (about 1.8% O at 3000 K, but it continues to increase up to 70% at about 9000 K) is also a drawback, because of its oxidant power.

The dependence of the enthalpy from the temperature for the case of hydrogen, helium, argon, and carbon dioxide is displayed in Figure 2, based on data from Ref. [2]. The enthalpy is referred to 1000 K, which is the assumed temperature of the gas injection in the combustion chamber.

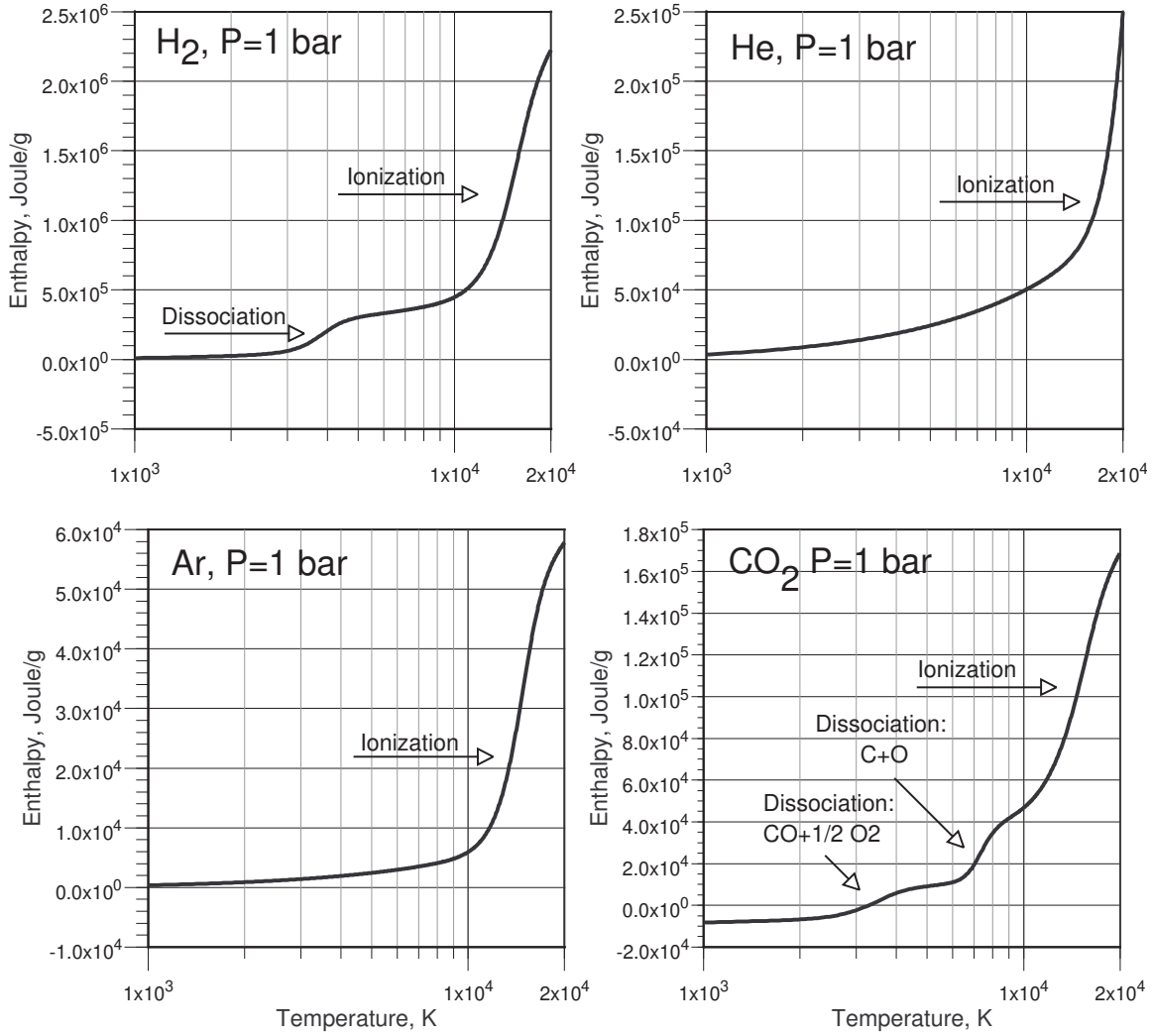

Figure 2. *Enthalpy of Hydrogen, Helium, Argon, and Carbon Dioxide as a function of the absolute temperature at the pressure of 1 bar.*

Helium and argon can only ionize, and the process begins at about 14000 K and 8900 K, respectively. The first ionization potential needs 24.6 eV in the case of He and 15.8 eV in the case of Ar, to compare with the value of 13.6 eV, which is the ionization potential of the H, and to compare also to the average thermal kinetic energy of about 1 eV.

The behavior of the carbon dioxide is more complicate, because of a first dissociation of CO_2 into CO and O_2, an endothermic process with $\Delta H \approx 10^4$

J/g, which starts at about 2000 K and concludes at about 4300K. This value is to compare with the dissociation of H_2, which starts at about 3000 K and whose value is about 0.25×10^6 J/g, that it, 25 times larger. This process is followed by the dissociation of CO into C and O, and O_2 into O, with, globally, $\Delta H \approx 3 \times 10^4$ J/g in the range of temperatures between 5000 K and 9000 K. At about 9000 K the ionization process is already started, with a 2% of charged species present in the mixture of gases.

The calculation of the exhaust speed is based on the following assumption: one-dimensional form of the continuity, energy, and momentum equations; zero velocity in the combustion chamber; complete adiabatic combustion; isentropic expansion; homogeneous mixing; ideal gas law. For equilibrium performance, composition is assumed to attain equilibrium instantaneously during expansion. For frozen performance, composition is assumed to remain fixed at the combustion composition during expansion.

The exhaust speed, and, therefore also the specific impulse ($I = v_{exh} / g$), is inversely proportional to the square root of the molecular weight of the gas. Thus, the hydrogen has the higher specific impulse, and the argon the lower (at 3000 K CO_2 is already dissociated into CO and O_2). These features are shown in Figure 3, where the specific impulse is displayed as a function of the temperature of the stagnation chamber, at a pressure of 1 bar. In this context, the ratio between the area of the throat and the exit of the expansion cone is assumed equal to 150. Both equilibrium and frozen composition during the expansion are assumed in the case of H_2 and CO_2. The ionization threshold is a limiting parameter, because of the plasma formation and its large radiative losses. This was verified in the case of the hydrogen, were an equilibrium temperature of 9800 K is attained and cannot be overcome due to an equilibrium between fission fragments heating and continuum radiative emissions, and the physics of this problem was widely explained in Ref. [1] by C. Rubbia. It was also demonstrated the behavior of the gas as thick at temperatures lower than 9800 K, being most of line radiation reabsorbed in the immediate neighbourhood of the hot gas source. A discussion of the radiative losses in the case of He, Ar, and CO_2 will be the content of a successive work.

From the analysis of these preliminary results, we can observe, that CO_2, and Ar are not ideal candidates as propellants: they have low specific impulses (700 s, and 320 s, respectively, at their ionization temperatures) and, in the case of CO_2, as already pointed out, the formation of solid carbon which starts at about 6500 K, and oxygen with its oxidant power, can seriously compromise the work of the engine . Instead, helium is an interesting candidate to substitute hydrogen for its safety characteristics. Its specific impulse can rise up to 1300 s at 14500 K, which is a value largely greater than that typical of an ordinary chemical rocket (450 s), although, again it is to compare with the value of 2300 s of the hydrogen at 9000 K.

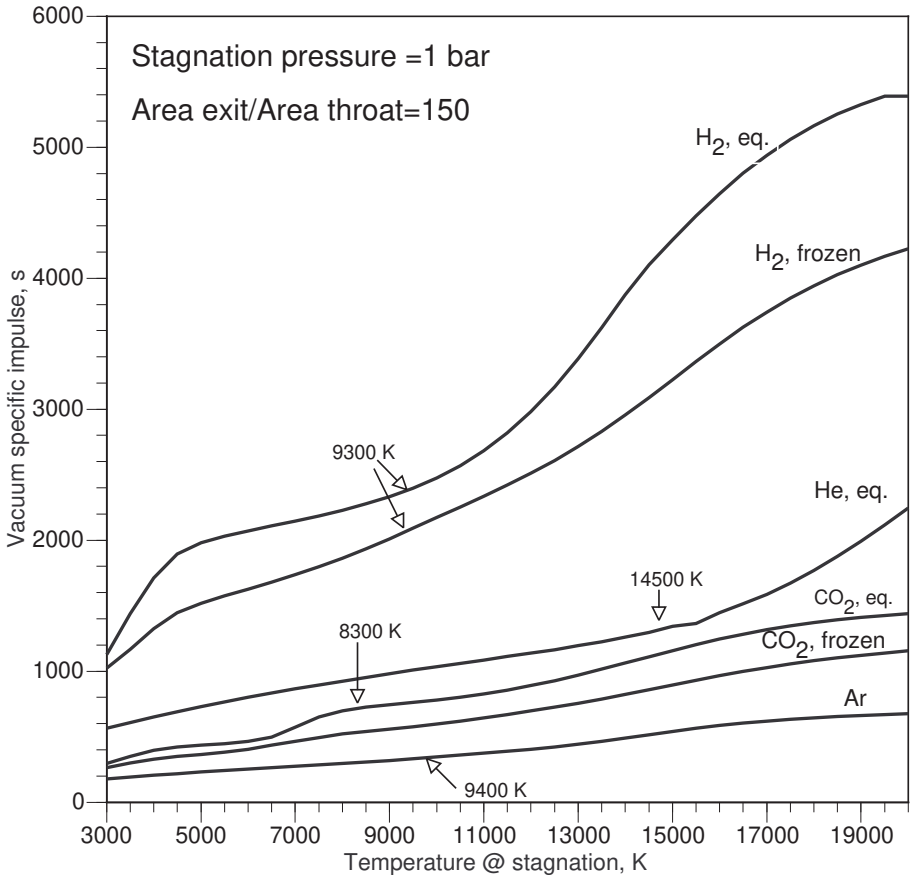

Figure 3. *Specific impulse in the vacuum of Hydrogen (frozen and equilibrium composition), Helium, Argon, and Carbon Dioxide (frozen and equilibrium composition) as a function of the absolute temperature at the pressure of 1 bar. For each species the temperature corresponding 1% of ionization is also indicated.*

References

1. Rubbia C., "Fission fragments heating for space propulsion", CERN/SL-Note- 2000-036 (EET).

2. McBride B. J. and Gordon S. "Computer program for calculation of complex chemical equilibrium compositions and applications", NASA RP 1311 (1996).