2021 International Nuclear Atlantic Conference – INAC 2021
Virtual meeting, Brazil, November 29 – December 2, 2021

ISBN: 978-65-594-1256-3

Hydrogen as a Nuclear Thermal Rocket Propellant

Pedro A. Rezende[1], João G. O. Marques[1],
Antonella L. Costa[1], Claubia Pereira[1]

[1]parufmg@ufmg.br, jgabrieloliveira2010@bol.com.br,
antonella@nuclear.ufmg.br, claubia@nuclear.ufmg.br,
Universidade Federal de Minas Gerais
Departamento de Engenharia Nuclear
Belo Horizonte, Brazil

1. Introduction

Nuclear Thermal Propulsion (NTP) is a promising technology that is expected to be one of the best propulsion alternatives for the near futures regarding long range space missions. The main reason for that is the high performance on propellant consumption. This characteristic allows the spacecraft to reach higher speeds which can dramatically reduce the mission duration, when compared with combustion propelled rockets. Hence, the propellant choice clearly plays an important role in NTP efficiency. Hydrogen is a strong candidate as a propellant due, mainly, to its low molecular mass [2]. The purpose of this paper is to demonstrate why that is the case and how that conclusion is reached. The work was performed through the expression that relates molecular mass to efficiency while explaining the assumptions made to do so, and the CFD simulation of the Kiwi A reactor, the first reactor built in the Rover program [1,3], which gives quantitative answers to how hydrogen performs compared to other fluids, like water vapor and air.

2. Methodology

In this Section, Eq. 1, which makes explicit the relation between exhaust velocity and the ratio between nozzle inlet temperature and propellant molecular mass, is deduced from isentropic and control volume thermodynamics and from ideal gases relations [4,5,6].

$$V_e = \sqrt{\frac{T_i}{M}}\sqrt{2\frac{kR}{k-1}[1-\left(\frac{p_e}{p_i}\right)^{\frac{k-1}{k}}] + V_i^2} \tag{1}$$

Where V_e is the exhaust velocity (m/s), T_i is the inlet temperature (K), M is the propellant molecular mass (g/mol), k is the propellant specific heat ratio, R is the universal gas constant (J/K.mol), p_e is the exit pressure (Pa), p_i is the inlet pressure (Pa) and V_i is the inlet velocity (m/s). To feed Equation 1, data on the Kiwi A reactor tests was collected from [1]. The reactor dimensions were used to draw the 3D model, illustrated in Fig. 1, used in the CFD simulation. Moreover, reactor power and mass flow data were used to estimate the test boundary conditions. In that sense, it was assumed that the reactor operated in steady state conditions, and, therefore, the reactor internal walls were supposed to heat the propellant with a constant heat flux throughout the reactor. The Kiwi A reactor consisted of a sequence of 3 "whims" (the structure illustrated in Fig. 1) loaded with uranium, followed by one unloaded whim [1,3]. For the sake of simplicity and due to symmetry, only 1/12 of a whim was simulated. It is enough to make the intended point. It is important to note that the reactor was simulated in test conditions, which are very different from operation conditions on potential missions. Mesh and other simulation details will be discussed in the complete paper. The same problem was simulated using 3 different propellants: air, water vapor and hydrogen.

The most important result from the simulation is the average temperature in the reactor outlet, which would be the nozzle inlet if one was attached, since molecular mass is already known. These 2 variables define the first factor in Eq. 1. This factor is responsible for most of the impact on the exhaust velocity due to change in the propellant. Hence, this factor is calculated for each propellant using the results from the simulations and then compared with one another. Moreover, the simulations allow for an analysis of the propellant mechanical behavior inside the reactor, and for detection of heat concentration points.

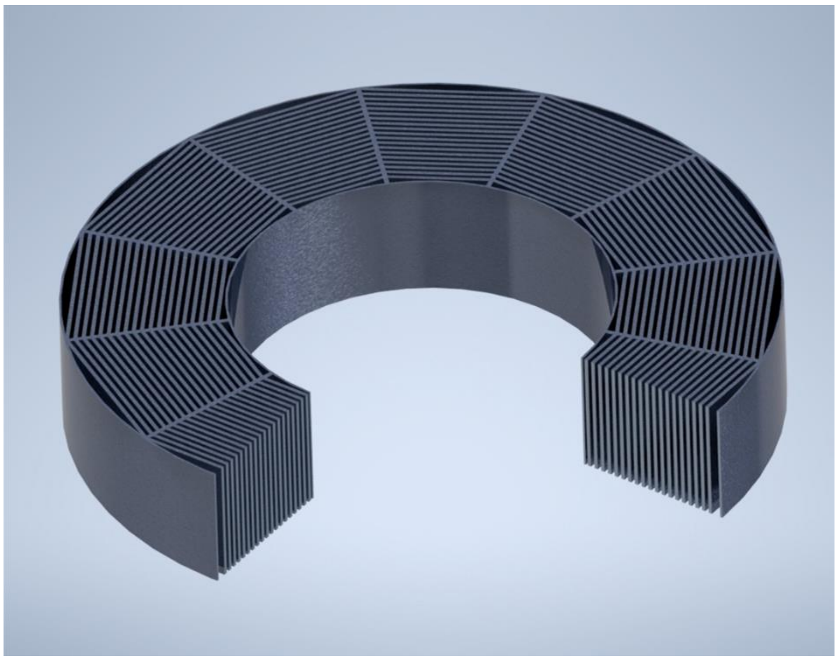

Figure 1: A sectional view of the 3D drawing of the KIWI A 84 cm diameter whim.

3. Results and Discussion

As expected, the results show hydrogen has a higher ratio between average reactor outlet temperature and molecular mass. The ratio for each propellant is shown in Table I.

Table I: the simulated propellants, their molecular masses, the reactor outlet temperature and the square root of their ratio.

Propellant	Molecular Mass [7] (g/mol)	Simulated Reactor Outlet Average Temperature (K)	$\sqrt{\frac{T_i}{M}}$ (K.mol/g)$^{1/2}$
Air	28.97	2605	9.48
Water Vapor	18.02	2328	11.37
Hydrogen	2.016	2363	34.27

The intent of the average temperature values calculated is not to match the reported temperature values, since this reactor test was terminated due to fuel overheating [1]. Moreover, the boundary conditions, like the propellant inlet temperature, are mostly unknown. Despite all of that, since the propellants were simulated under the same conditions, it is enough to show that exhaust velocity would be more than 3 times higher for hydrogen when compared to water vapor and air. That means a hydrogen propelled nuclear rocket needs less than 1/3 the propellant mass a water vapor or air-cooled nuclear would need to generate the same thrust.

The temperature contour plot at the reactor outlet for hydrogen is illustrated in Fig. 2. It shows that, despite the plenum following the reactor exit, heat is not well distributed yet. Moreover, it shows that there is a strong heat concentration at the narrow passage between the last fuel plate and the reactor wall and a considerable amount of propellant passing by without receiving much heat at points further away from the fuel plates.

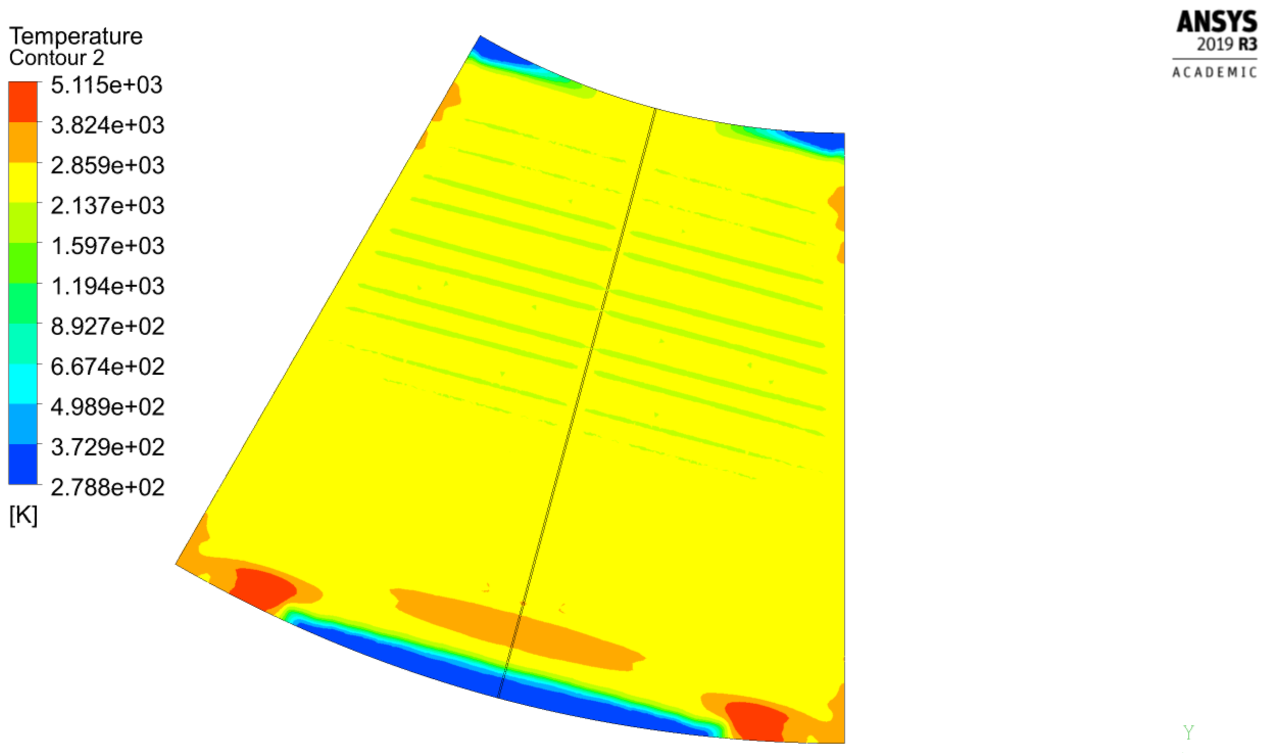

Figure 2: Outlet temperature contour plot for the KIWI A reactor using hydrogen.

4. Conclusions

The results confirmed the expected relation between hydrogen and other propellants: it is a lot more efficient. The results are specifically interesting because they match very closely the comparison made by Corliss and Scwenk [2], between a combustion rocket that burns hydrogen with oxygen, expelling water through the nozzle, and a nuclear rocket using hydrogen. It was estimated that hydrogen would be 3 times more efficient than water. Moreover, the results show that indeed, the KIWI A reactor would probably suffer from overheating, which was the reason its real tests were terminated [1]. Hence, even without accurate boundary conditions data, it is possible to detect potential problems in the reactor design.

Acknowledgements

The authors are greateful to the *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* (CAPES), to *Fundação de Amparo à Pesquisa do Estado de Minas Gerais* (FAPEMIG), to *Conselho Nacional de Desenvolvimento Científico e Tecnológico* (CNPq) and to *Comissão Nacional de Energia Nuclear* (CNEN) for the support to the several research projects of the Nuclear Engineering Department of UFMG.

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