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CFD Analysis of Square Flow Channel in Thermal Engine Rocket Adventurer for Space Nuclear Application

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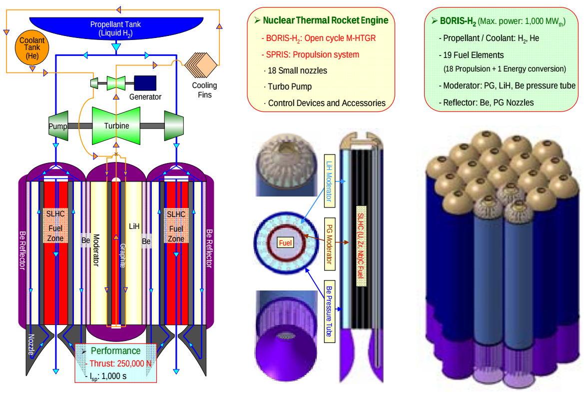
1. Introduction

Solar system exploration relying on chemical rockets suffers from long trip time and high cost. In this regard nuclear propulsion is an attractive option for space exploration. The performance of Nuclear Thermal Rocket (NTR) is more than twice that of the best chemical rocket. Resorting to the pure hydrogen (H_2) propellant the NTRs can possibly achieve as high as 1,000 s of specific impulse (I_{sp}) representing the ratio of the thrust over the fuel consumption rate, as compared to only 425 s of H_2/O_2 rockets. If we reflect on the mission to Mars, NTRs would reduce the round trip time to less than 300 days, instead of over 600 days with chemical rockets.

This work presents CFD analysis of one Fuel Element (FE) of Thermal Engine Rocket Adventurer (TERA). In particular, one Square Flow Channel (SFC) is analyzed in Square Lattice Honeycomb (SLHC) fuel to examine the effects of mass flow rate on rocket performance.

2. Design Concepts

TERA shown in Fig. 1 is one of the NTRs utilizing nuclear energy and H_2 propellant. The objective performance of TERA for these applications are the reactor power of 1,000 MW_{th}, the thrust of 250,000 N, the I_{sp} of 1,000 s, and the total mass of 600 kg including the reactor, turbo pump and auxiliaries within its safety design limits. TERA comprises the Battery Omnibus Reactor Integral System (BORIS) as the heat resource and the Space Propulsion Reactor Integral System (SPRIS) as the propulsion system. BORIS-H_2 is an open cycle, very high temperature gas cooled reactor that has eighteen fuel elements for propulsion and one fuel element for such utility as electricity generation and propellant pumping. Each fuel element for propulsion has its own small nozzle. [1, 2] There are two independent working fluid loops in BORIS-H_2: an open cycle H_2 loop going through the 18 fuel elements for propulsion, and a closed cycle helium (He) loop going through one fuel element for utility as presented in Fig 1A. The nineteen fuel elements are arranged in hexagonal prisms in the core and surrounded by outer beryllium (Be) reflector. Each fuel element comprises fuel assembly, pressure moderator tubes and a small nozzle as shown in Fig 1B [1, 2, 3]. The fuel assembly is fabricated of 93% enriched 1.5 mm (U, Zr, Nb)C wafers in 30% voided SLHC geometry being developed at Innovative Nuclear Space Power and Propulsion Institute (INSPI) of the University of Florida [4]. The H_2 propellant passes through these voided SFCs in the fuel assembly. The moderator tubes surround the fuel assembly directly as the first pyrolytic graphite (PG) layer tube and then the second LiH layer tube that contains the beryllium (Be) pressure piping for cooling the fuel element. These moderator tubes are enclosed by the Be moderator tube that also works as a pressure tube. Each fuel element has its own small nozzle. The control device is a kind of small electric pump emitting highly neutron absorbing powder into the vacuum spaces between fuel elements [1, 2].



A. Schematic View of TERA **B. 3D Design of Fuel Element** **C. 3D Design of BORIS Core**

Fig. 1. Schematic view of TERA

3. CFD analysis of Fuel Element

3.1 Problem Statement

Analysis is made to examine propulsion performance of a fuel element in the BORIS core. The analysis model is a SFC of the fuel element having 30% void SLHC fuel assembly geometry. The calculations need to recognize that the heat of the fuel must be removed properly and the thermal and mechanical stresses must not exceed their design limits. Only the safety temperature limit is considered in this simplified analysis. High temperatures approach 95 % locally and 80 % on the average of the fuel's melting point, respectively [2]. ANSYS CFX is used to solve the Reynolds averaged Navier-Stokes equations, using the shear stress transport (SST) turbulence model and to simulate the compressible flow and heat transfer with characteristics of choking, wherein the SFC flow is sharply limited by the sonic condition [5].

3.2 Boundary Conditions

This analysis simulates the behaviour of H_2 from a SFC inlet to a SFC outlet at the four different mass flow rates from 0.993 to 1.417 kg/s and the seven reactor powers from 400 to 1,000 MW_{th} coupled with the M-SLHC power distribution [4]. The static pressures are the same as 11.1 MPa and the static temperature are 151.0 ~ 196.4 K as initial values, respectively. Symmetry conditions are applied outer walls of the SFC.

3.3 Materials Thermophysical Properties

The H_2 state is treated as an ideal gas by default in ANSYS CFX [5]. The specific heat capacity, enthalpy and entropy are specified using the NASA SP-273 format. Others properties are taken as functions of temperature and pressure. The H_2 behaves ideally within 10% error in the range of 400 ~ 3,300 K and 1 Pa ~ 22 MPa according to its compressibility factor. In the range of 50 ~ 400 K and under 15 ~ 18 MPa the H_2 compressibility factor is less than 1.2. In case of (U, Zr, Nb)C fuel material, the fixed thermal conductivity of 50 W/(m•K) is applied for calculation [4]. Its melting point is 3,800 K.

3.4 Results

First of all, the design limits of the structures must be considered before checking on the states of H_2 in each case of the mass flow rates. The temperature limits of the fuel surface are 3,610 K locally, and 3,040 K on the average. At the 0.993 ~ 1.417 kg/s of mass flow rates, the safety temperature limits are satisfied in the vicinity of 450, 500, 550 and 600 MW_{th} as maximum applicable powers, respectively. Then the local peak temperatures on the fuel surfaces are 3,617, 3,524, 3,587 and 3,626 K for each mass flow rate approaching the safety temperature limit 3,610 K. The average temperatures are also 2,088 K, 2,094 K and 2,099 K below the safety temperature limit 3,040 K.

Table 1 shows the H_2 states and rocket performances in each case of the mass flow rates at their maximum powers, respectively. The rocket performances are calculated through ideal nozzle assumption and the nozzle area ratio of 200.

4. Conclusions

The increment of mass flow rate leads to higher power and thrust coupled with rising pressure and density, but I_{sp} goes down on the contrary in TERA design. I_{sp} of each case is still lower than 1,000 s of the objective design value. Therefore, in order to enhance the thrust and I_{sp} simultaneously, the power peaking has to be flatter than that of the M-SLHC and the contact surface area between the fuel and propellant wider.

Further thermohydrodynamic analysis will be made to optimize the TERA design and examine its maximum performance at the reformed fuel element geometries by applying the real H_2 thermophysical properties as functions of pressure and temperature for more realistic calculations.

Table 1. Summary of SFC Analysis Results

Mass Flow Rate [kg/s]	0.993	1.134	1.276	1.417
Max. Power [MW_{th}]	450	500	550	600
H_2 Outlet Temp. [K]	1,734	1,669	1,655	1,631
H_2 Inlet Pressure [MPa]	11.45	12.69	14.13	15.50
Pressure Drop [MPa]	7.927	8.788	9.780	10.72
H_2 Outlet Velocity [m/s]	3,120	3,059	3,015	2,998
Thrust [N] (1 FE / 18 FEs)	7,742 / 139,400	8,662 / 155,900	9,684 / 174,300	10,670 / 192,100
T/W Ratio	23.7	26.5	29.6	32.6
I_{sp} [s]	795	779	773	767

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