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Preliminary Thermo-hydraulic Core Design Analysis of Korea Advanced Nuclear Thermal Engine Rocket for Space Application

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1. Introduction

Space exploration or exploitation is a realistic and reasonable goal for long-term humanity survival, even though the extremely harsh space environment imposes lots of severe challenges to space pioneers. Until now, almost all space programs have relied upon Chemical Rockets (CRs) rating superior thrust level to transit from Earth's surface to orbit. Unfortunately, CRs inherently confront with insurmountable barrier to carry out deep space missions beyond Earth orbit because of its low propellant efficiency and resultant enormous propellant requirement and launch costs. Meanwhile, nuclear rockets improve the propellant efficiency more than twice compared to CRs and thus significantly reduce the propellant requirement. The superior efficiency of nuclear rockets is due to the combination of the huge energy density and a single low molecular weight propellant utilization. Nuclear Thermal Rockets (NTRs) are particularly suitable for manned missions to Mars because it satisfies a relatively high thrust as well as a high propellant efficiency [1]. NTRs use thermal energy released from a nuclear fission reactor to heat a single low molecular weight propellant, i.e., Hydrogen (H_2) and then exhausted the extremely heated propellant through a thermodynamic nozzle to produce thrust. A propellant efficiency parameter of rocket engines is specific impulse (I_{sp}) which represents the ratio of the thrust over the rate of propellant consumption. If the maximum exhaust temperature of a NTR is around 3,000 K, the I_{sp} can be achieved as high as 1,000 s as compared to only 450 ~ 500 s of the best CRs. The difference of I_{sp} makes over three times propellant savings of NTRs for a manned Mars mission compared to CRs [1,2]. NTRs can also be configured to operate bimodally by converting the surplus nuclear energy to auxiliary electric power required for the operation of a spacecraft [3]. Moreover, the concept and technology of NTRs are very simple, already proven, and safe [4,5]. Thus, NTRs can be applied to various space missions such as solar system exploration [6,7], International Space Station (ISS) transport support [8], Near Earth Objects (NEOs) interception [9], etc .

Up to date, the NTR has been researched and developed mainly in two countries: the United States of America (USA) and the Russian Federation (also former Soviet Union). Space development, however, is not duty of just the advanced nations in space technology. The Republic of Korea (ROK), who successfully launched a two-stage NARO rocket on January, 2013, is also a volunteer in the international space race. This is particularly important given that the ROK promises great potential in terms of developing prominent space nuclear systems since it already develops advanced nuclear technology as an established major nuclear energy country, even exporting it to other countries. In fact, the ROK has already begun the research for space nuclear systems. The Korea Advanced NUclear Thermal Engine Rocket (KANUTER) is one of the advanced nuclear thermal rocket engines currently under development at Korea Advanced Institute of Science and Technology (KAIST) for space application [10]. This paper briefly presents the preliminary thermal-hydraulic core design analysis of KANUTER, which focuses on coolant channel geometry effects to lessen severe thermal attack in the core and thus to produce great rocket performance.

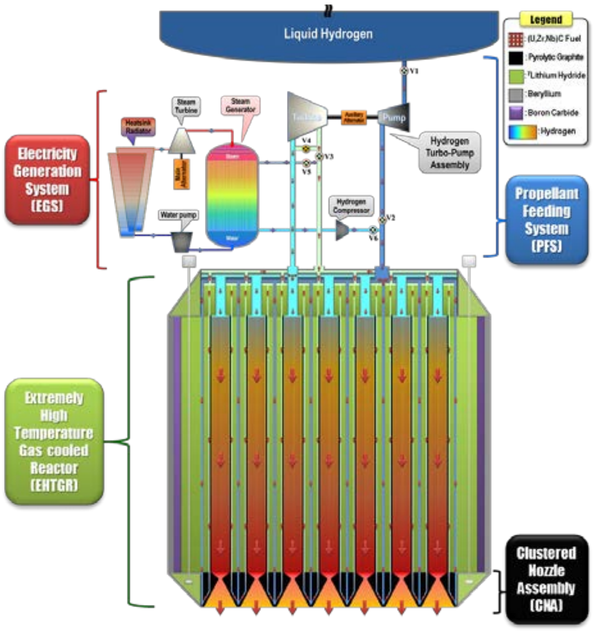


Fig. 1. Schematic view of KANUTER.

2. System Description of KANUTER

As depicted in Fig. 1, KANUTER mainly consists of a 100 MW_{th} Extremely High Temperature Gas cooled Reactor (EHTGR) utilizing H_2 propellant, a propulsion system housing a Propellant Feeding System (PFS), a

Clustered Nozzle Assembly (CNA), etc., and an Electricity Generation System (EGS) as a bimodal engine. KANUTER has the design characteristics: high efficiency, a compact and lightweight system, auxiliary electricity generation (bimodal), and mission versatility.

2.1 Extremely High Temperature Gas cooled Reactor

The fission reactor type of KANUTER is an EHTGR utilizing H_2 coolant (also propellant), whose maximum core temperature exceeds 3,000 K. The H_2 is the best option of the NTRs' propellant candidates because of its low molecular weight, good thermal properties, and thus high propellant efficiency. As shown in Fig. 2, the heterogeneous core of the EHTGR consists of 37 fuel elements and Beryllium (Be) spacers arranged in a hexagonal prism pattern.

The nuclear fuel is (U, Zr, Nb)C solid solution (93 w/o ^{235}Uranium), which is one of the ternary carbide fuels under consideration for next generation NTRs, as a reasonable choice to increase safety margins and resultant rocket performance due to its high melting point (about 3,800 K), high thermal conductivity (about 50 W/m·K), improved H_2 corrosion resistance (within 2 hours operation around 3,000 K), and good fission product retention among other features [11,12]. The fuel assembly has the peculiar design of the Square Lattice HoneyComb (SLHC) geometry proposed by the Innovative Nuclear Space power & Propulsion Institute (INSPI) to reduce the fabrication difficulties and thus costs of the ultra-heat resistant ternary carbide fuel [11]. In this SLHC design, the fuel wafers manufactured in thickness from 0.75 mm to 1.50 mm are interlocked with each other to form the SLHC geometry creating numerous Square Flow Channels (SFCs) as shown in Fig. 3. The SFCs occupy 30% cross-sectional voided flow area of the fuel assembly to maintain enough protective coolant passages. This SLHC fuel design satisfies the required critical fuel mass (Uranium density: 0.4 ~ 0.9 g/cm^3) and the power density as well as better durability and fabricability at lower costs [11]. Each fuel element comprises the ultra-heat resistant fuel assembly surrounded by three layers of moderator and pressure tubes (1st: Zirconium Carbide (ZrC) coated Pyrolytic Graphite (PG), 2nd: ^{7}Lithium Hydride (^{7}LiH), and 3rd: Be), a top reflector cover (^{7}LiH - Be) and a bottom small nozzle (ZrC coated PG) as a compact and modular design [13] as shown in Fig. 3. The three moderator tubes, which are arranged according to the structural and thermal considerations, contains a protective ring-type coolant channel between the first and the second tubes to protect the moderator from the thermal attack of the fuel assembly.

The core comprising 37 fuel elements is surrounded by the reflector composed of ^{7}LiH - Be layers except for the bottom to reduce neutron leakage. The bottom reflector is replaced by the CNA consisting of the 37 PG nozzles of the fuel elements. The combination of the outer Be reflector, and the individual Be pressure tubes and small nozzles of the fuel elements could eliminate the needs for a heavy pressure vessel and a large single nozzle which are typically mounted on other NTR reactors [13]. In order to control the reactivity and in turn the power, the cylindrical rotating control drums, each of which partially comprises a Boron Carbide (B_4C) neutron absorber, are symmetrically placed in the radial reflector.

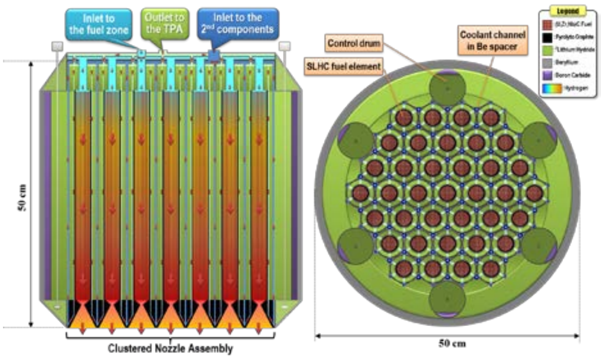


Fig. 2. Configuration of EHTGR.

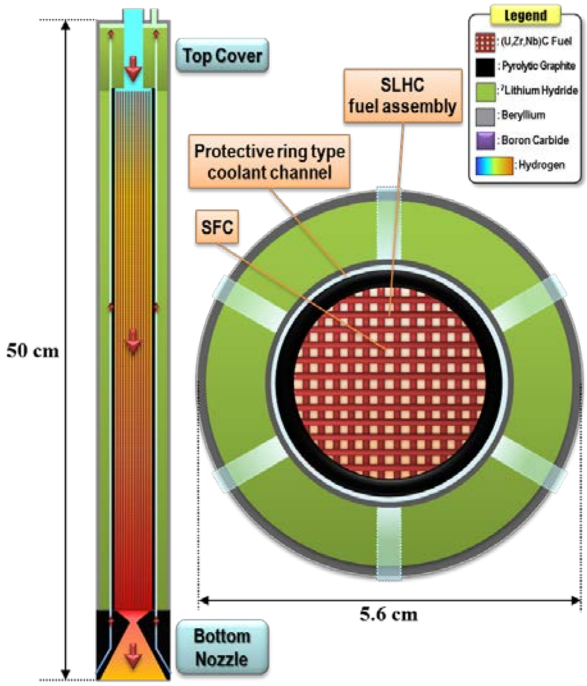


Fig. 3. Configuration of SLHC fuel element.

The EHTGR particularly has a fully thermalized neutron energy spectrum compared to the fast spectrum of the typical other NTRs to achieve a critical state with even a small amount of fuel, and thereby a lightweight and small size reactor. The thermal spectrum and lightweight characteristics are mainly attributed to the ^{7}LiH moderator having not only a high neutron scattering cross-section in the thermal energy range, but also a low density (0.77 g/cm^3) [14,15]. In the preliminary neutronics study utilizing MCNP5 computer code [16], the EHTGR achieves an effective neutron multiplication factor (K_{eff}) of 1.0351 (standard deviation: 0.00013) despite the ultra-small size and mass: 50 cm of equal diameter and height (2.0 of pitch to diameter ratio), and 138 kg of reactor mass containing only 4.1 kg of ^{235}U.

The EHTGR is operated in two modes of propulsion and electricity generation by adjusting the control drums and propellant valves for the bimodal capability. In the propulsion mode, the reactor power is 100 MW_{th} for both propulsion and electricity generation. In case of the electricity generation mode, the reactor is operated at 100 kW_{th} power for the EGS. This moderated EHTGR has the characteristics of a compact and lightweight system, a high power density of fuel (16 MW_{th}/liter), and the protective cooling structures to prevent melting of the solid fuel and moderators. Table Ⅰ summarizes the reference design parameters of the EHTGR.

Table Ⅰ: Reference design parameters of EHTGR

Reactor power (electric power mode)	100 MW_{th} (100 kW_{th})
Average power density in fuel region	16 MW_{th}/liter
Number of fuel elements	37
Fuel element pitch/diameter ratio	2
Fuel type and mass (93% enriched U mass)	(U, Zr, Nb)C & 46.3 kg (4 ~ 5 kg)
Moderator type and mass	PG, ^{7}LiH, Be & 41.5 kg
Reflector type and mass (comprising control drums)	^{7}LiH, Be, B_4C & 50 kg
Total reactor mass	137.8 kg
Reactor diameter and height (core diameter and height)	50 & 50 cm (39.2 & 39.2 cm)

2.2 Bimodal Engine System

The bimodal engine mainly consists of the EHTGR, the propulsion system, and the EGS as shown in Fig. 1 to execute the dual functions of propulsion and electricity generation to reduce the mass and size of a spacecraft.

The propulsion system is mainly made up of the PFS comprising a Turbo Pump Assembly (TPA) and a propellant management unit, the CNA, a thrust vector control, and an instrumentation package. The key element of the propulsion system is the TPA to feed the propellant to the EHTGR and in turn to the CNA. The TPA utilizing the H_2 working fluid converts a small portion of thermal energy of the EHTGR into dynamic power to make the flow continue for the self-sustaining system. Uniquely, the TPA of KANUTER is equipped with an auxiliary alternator to generate electricity in the propulsion mode or emergency of the EGS malfunctions. The CNA consists of 37 individual small nozzles connected with the fuel elements. This CNA may slightly reduce the thrust compared with a massive single nozzle, but the small penalty is outweighed by the compact and modular fuel element design, the shortened nozzle length, and resultant reduction of the engine mass [17]. The mass of the propulsion system is estimated to be 162 kg containing 60% contingency of the total engine mass to cover design uncertainties and shadow shield mass. As a preliminary study, the expander cycle is selected for the propulsion system since the protective cooling structures in the EHTGR could ensure plentiful heat transfer to the PFS and the pressure loss is also sufficiently low. In the expander cycle, the cold H_2 in propellant tanks pumped through the Turbo Pump Assembly (TPA) of the PFS first cools the secondary reactor components (moderator, reflector, nozzle, etc.) in passing through the Be spacers and the ring-type coolant channels in the core, and then transfers the propellant feeding power to the TPA uniquely equipped with an auxiliary alternator for electricity generation. After the power conversion in the PFS, the H_2 flows into the SLHC fuel assemblies in the core again to be heated to around 3,000 K, and then it expands out through the CNA to produce the desired thrust. Fig. 4 shows the reference component-level operating conditions of the propulsion mode using the expander cycle. The H_2 flows through the open expander cycle in the order of (A) ~ (G) components both to cool the EHTGR and to convert the EHTRG's thermal energy to the thrust, propellant feeding power, and electricity. Most of the reactor power is used to produce the thrust through the CNA, and only 18 kW_{th} power is converted to 16.2 kW_e of electric power. The maximum rocket performance, whose calculation assumed an ideal nozzle with a Nozzle Expansion Ratio (NER) of 200, is ideally estimated at 20,764 N thrust, 7.1 T/W ratio, and 1,008 s I_{sp} in the chamber conditions of 3,058 K and 4.20 MPa.

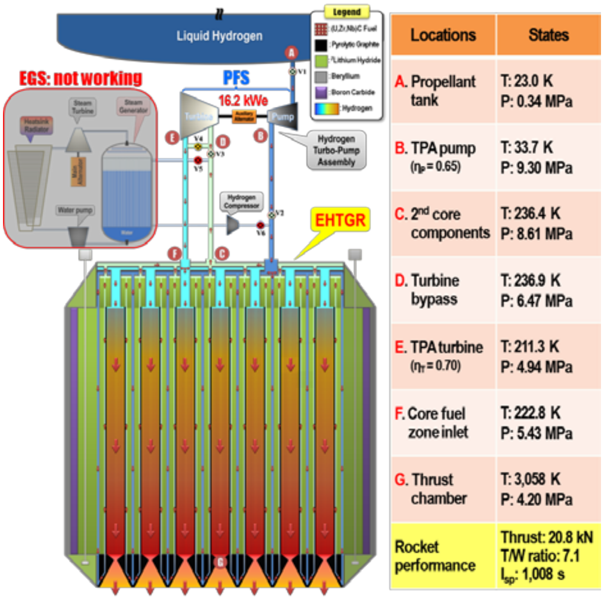


Fig. 4. Reference component-level operating conditions of propulsion mode.

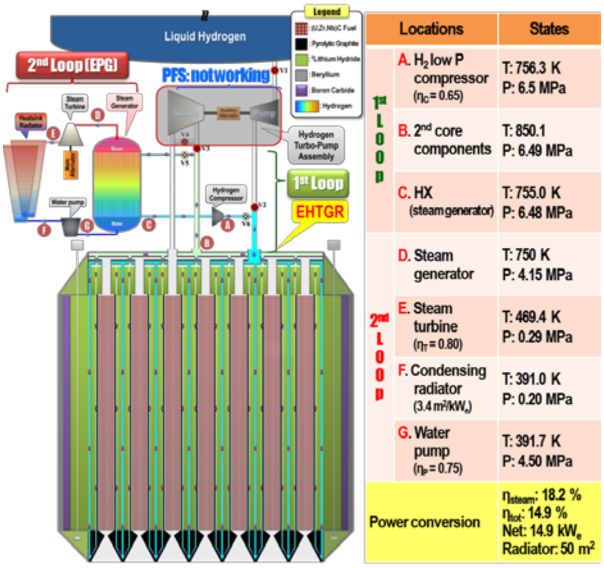


Fig. 5. Reference component-level operating conditions of electric power mode.

In the case of electric power mode, the EHTGR is operated at just 100 kW_{th} idle power, and both Brayton and steam Rankine cycles are main power conversion options for the EGS to yield high power and efficiency on the basis of proven technology [18]. In the particular case of KANUTER, however, the relatively low temperature of the working fluid at the moderated EHTGR's outlet (the turbine's inlet) restricts the power conversion efficiency of these power cycles, because the maximum temperature at the turbine's inlet is limited by the moderator's melting point (962 K of ^7LiH). The steam Rankine cycle has a better potential in the viewpoint of cycle efficiency in the limited conditions, although the Rankine cycle must overcome the handling and separation issues of two-phase flow, which are problematic in zero-gravity. As a preliminary study, the steam Rankine cycle is selected for the EGS because it could not only yield higher thermal efficiency, but also overcome the two-phase issues by utilizing the unique condensing radiator even operating in zero-gravity [19] or the artificial gravity mode of a crewed space transfer vehicle [6]. The EGS consists of two closed loops: the first loop for heat transfer and the second loop for power conversion. In the first loop, the H_2, forced from a low pressure compressor, flows into the existing coolant channels in the reactor's secondary components. However, the coolant does not flow out to the PFS for propulsion, but runs to a heat exchanger (HX) connected with the second power conversion loop, and flows back to circulate the closed loop. The second loop, as a steam Rankine power cycle, mainly consists of a steam/water working fluid, a steam generator connected with the first loop, a steam turbine with a main alternator, a condensing radiator, and a water pump. As presented in Fig. 5, the working fluids are circulated in the two closed loops in the order of the first loop's components (A) ~ (C) and the second loop's components (D) ~ (G) for electricity generation. The thermal efficiency of the steam power cycle is rated at 18.2% due to the low back work of the water pump, and thus the electric power output is estimated to be 16.4 kW_e with a radiator area of 50 m^2. When the H_2 compressor work of 1.5 kW_e is considered in the first loop, the net power output of the system is estimated at 14.9 kW_e, so that the radiator area is 3.4 m^2 per kW_e.

The reference design parameters presented in Table Ⅱ indicate the characteristics of KANUTER as being a compact and lightweight system, having excellent propellant efficiency, and providing auxiliary electricity. In addition, this compact and modular KANUTER, yielding relatively low power and thrust, can be utilized for multi-applications requiring various thrust levels by the multiple engine arrangement (mission versatility).

Table Ⅱ: Reference design parameters of KANUTER

Categories			Estimation
Engine mass budgets	EHTGR		137.8 kg
	Propulsion system		162.4 kg
	- *Turbo-pump assembly*		*8.0 kg*
	- *Propellant management*		*10.4 kg*
	- *Thrust vector control*		*7.2 kg*
	- *Instrumentation*		*8.0 kg*
	- *Clustered nozzle assembly*		*16.2 kg*
	- *Contingency (60%)*		*112.6 kg*
	Total		300.2 kg
Rocket performance (100 MW_{th})	Thrust chamber's temperature & pressure		3,058 K & 4.20MPa
	Nozzle expansion ratio		200
	Ideal	Thrust	20,764 N
		T/W ratio	7.1
		I_{sp}	1,008 s
	3% losses	Thrust	20,141 N
		T/W ratio	6.8
		I_{sp}	978 s
Electric power generation (100 kW_{th})	Power cycle		Steam/water
	Net power output		14 ~ 16 kW_e
	Radiator size		50 m^2 (3.4 m^2 / kW_e)

3. Preliminary Thermo-hydraulic Analysis of Core

The tremendous rocket performance of a NTR is mainly due to the low molecular weight propellant and high exhaust temperature of the EHTGR. Ultimately, the maximization of the core temperature is the most important factor to create better rocket performance, if it is assumed that the NTR utilizes the lowest molecular weight H_2 propellant. Thus, the key design issue of NTR engines in the viewpoint of thermo-hydraulics comes down to heat resistance of a fuel and coolant channel geometry to maximize the heat transfer area in their cores. In the case of KANUTER, the 93% enriched (U, Zr, Nb)C solid solution is adopted as its fuel material, which has the ultra heat resistant properties. In addition, the fuel assemblies are fabricated from the ternary carbide fuel wafers in the SLHC geometry formulating the numerous SFCs occupying 30% cross-sectional voided propellant flow area. [11]. Particularly, in the SLHC design, the Fuel Wafer Thickness (FWT) is directly correlated with the size and number of SFCs, and thus it affects the mechanical strength as well as the thermo-hydraulic capability mainly depending on the heat transfer area of the fuel assemblies as depicted in Fig. 6. As the fuel wafers get thicker, the mechanical strength against both thermal and shear stresses is better, but the heat flux and resultant fuel temperature are increased because the heat transfer area is reduced, and vice versa. Therefore, thicker fuel wafers are mechanically strong with low pressure drop, while thinner fuel wafers are thermally robust with less mechanical strength and higher shear stress in the core. The optimum FWT will balance both thermal and mechanical resistances of the fuel assembly [20]. Accordingly, the objective of this preliminary analysis is to estimate the optimum FWT improving the rocket performance in consideration of only thermal design criterions of the ternary carbide fuel.

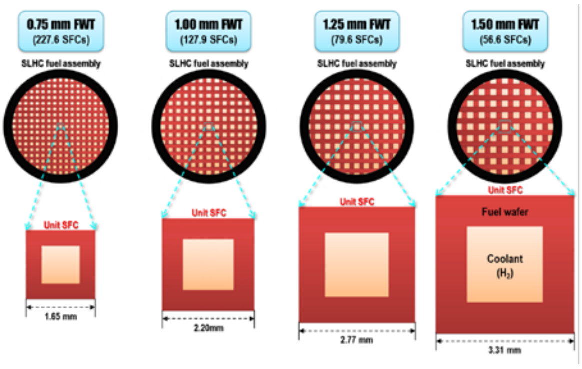


Fig. 6. Thermo-hydraulic analysis models (Unit SFCs) of core.

3.1 Methodology

In order to estimate the optimum FWT of the unique SLHC fuel assembly design and thereby the best rocket performance of KANUTER, a preliminary thermo-hydraulics design study was carried out using ANSYS CFX, the three-dimensional (3D) Computational Fluid Dynamics (CFD) code [21] to simulate the detailed steady state heat and mass transfer in the unit SFC. The thrust was estimated by one-dimensional ideal nozzle calculation having the NERs of 100 and 200. The calculated performance of an ideal nozzle is generally 1 ~ 6% higher than that of an actual nozzle [22]. As a preliminary study, only two thermal design criterions were considered to estimate the best rocket performance. The first design criterion was that the maximum temperature of fuel's center line must be below its melting point. To preclude the center melting, the maximum fuel temperature limit was determined at about 3,420 K which provides a 10% design margin of the (U, Zr, Nb)C fuel's melting point (3,800 K) for uncertainties. Additionally, to ensure at least two hours engine operating time against hot H_2 corrosion in the core, the H_2 exhaust temperature was limited to around 3,000 K, but it should be lower than 3,100 K as the second design criterion [23,24]. The unit SFC containing two domains of the fuel and propellant channel was adopted as a simplified 3D analysis model [25]. The boundary conditions included symmetric outer walls (cut surfaces) of the unit SFC, volumetric fuel energy deposition rates coupled with the axial and radial power distributions in the propulsion mode, 2.10 kg/s of the system mass flow rate, 222.8 K and 5.43 MPa of the H_2 core inlet states, etc. The volumetric fuel energy deposition rates and H_2 inlet states were taken from the preliminary neutronics and engine cycle studies, respectively. Fig. 7 shows the axial and radial power distributions of the core applied to this analysis. Non-uniform local mass flow rates in the core were employed according to the radial locations of the fuel elements to consider the non-optimized radial power profile, thereby mitigating severe local heat concentration. The non-uniform local mass flow rates were calculated based on the radial power profile and the mass flow rate per fuel element in each fuel element ring as described in Fig. 8. The NASA chemical equilibrium [26] was applied to evaluate the thermodynamic properties of H_2, and the thermal conductivity of the fuel was assumed to be a constant 50 W/(m·K) [11]. The major variables for this study were the FWTs of 0.75, 1.00, 1.25, and 1.50 mm as the four unit SFC samples. Each unit SFC sample represented both the hottest channel in the central fuel element rating the highest radial power peaking factor of 1.48 to examine the maximum fuel center line temperature, and a neutral temperature channel in a standard fuel element having the mean radial power peaking factor of 1.00 to estimate the average thrust.

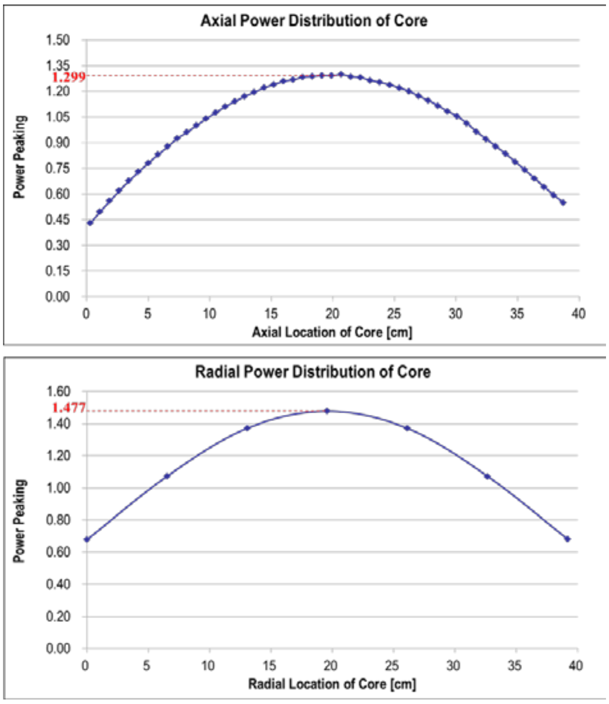
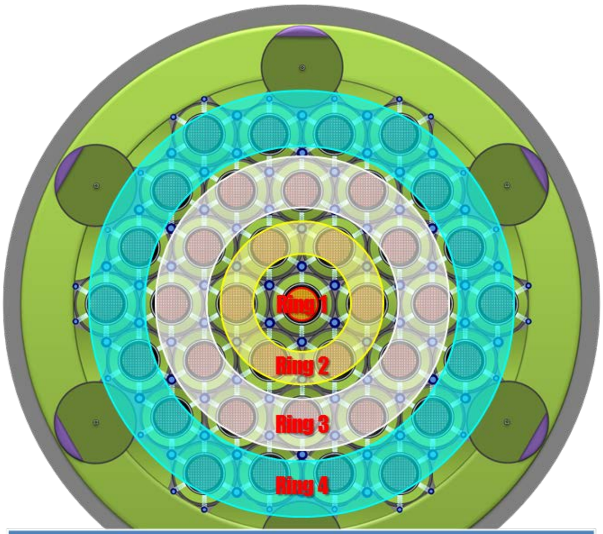


Fig. 7. Axial and radial power distributions of EHTGR.



Non-uniform Local Mass Flow Rates in the Core		
Locations	*Number of FEs*	*MFR per one FE*
Ring 1	1	7.931E-02 kg/s
Ring 2	6	7.500E-02 kg/s
Ring 3	12	6.556E-02 kg/s
Ring 4	18	4.356E-02 kg/s

Fig. 8. Non-uniform local mass flow rates in EHTGR.

3.2 Result and Discussion

Table Ⅲ summarizes the results of this study as a function of the FWT. The increasing of the FWT causes a significant rise in the temperature at the fuel wafer's center line, and a slight decrease in the H_2 exhaust temperature, which in turn slightly reduces the rocket performance as shown in Fig. 9. That is because the thicker FWT of fuel assembly decreases the heat transfer area available to remove the heat of fuel and thus increases the heat flux. In order to meet both the maximum fuel centerline temperature and the H_2 exhaust temperature limits, the relevant FWT should be more than 0.75 mm and less than 1.25 mm as presented in Fig. 10. In this study KANUTER, having the thinnest FWT of 0.75 mm in the core and a NER of 200, ideally yields the best rocket performance of 20,764 N thrust, 7.1 T/W ratio, and 1,008 I_{sp}. The more conservative performance is estimated at 1.00 mm FWT and a NER of 100 as 20,350 N thrust, 6.9 T/W ratio, and 988 s I_{sp} as shown in Figs. 11 and 12. However, the thinner FWT results in the less mechanical strength and higher shear stress induced by the larger pressure drop. Thus, a more detailed thermal-mechanical analysis is still required in a future study to accurately evaluate the optimum FWT of the SLHC design and the best rocket performance. Besides, the detailed and verified information about H_2 corrosion and mechanical properties on the carbide fuels is required to define more robust design criterions.

In this analysis, although the rocket performance was ideally estimated, the system design was not optimized. Thus, the actual performance may be slightly better or worse than the reference values. If KANUTER achieves an I_{sp} of 1,000 s, then it can significantly reduce the propellant requirement compared to other existing NTRs and CRs to achieve a same manned Mars mission. For example, Table Ⅳ shows the mission performance comparison among various rocket engines based on the NASA 2033 Mars orbital mission requirements: 600 days for the mission period and 8.42 km/s of ΔV [27]. KANUTER uses a total of 13 engines: 5 for bimodal and 8 for propulsion only to produce 268 kN of thrust and 50 kW_e of electric power. The mass of the total engines, propellant, and IMLEO are estimated at 3.9 metric tons, 169 metric tons, and 316 metric tons, respectively. These results show the large mass savings

Table Ⅲ: Summary of rocket performance as a function of FWT of KANUTER.

Core conditions	Fuel wafer thickness [mm]		0.75	1.00	1.25	1.50
	Number of square flow channels in core		8,421	4,735	2,947	2,094
	Heat transfer area of fuel assemblies [cm^2]		118,948	89,196	70,367	59,307
	Fuel temperature limit [K]		around 3,420			
	H_2 exhaust temperature limit [K]		around 3,000 K, but less than 3,100 K			
	Max. fuel temperature in the center line		3,181	3,311	3,435	3,557
	Margin to fuel melting [K]		619	489	365	243
	H_2 exhaust temperature [K]		3,058	3,034	3,007	2,980
	H_2 exhaust pressure [MPa]		4.20	4.57	4.77	4.96
	H_2 pressure drop [MPa]		1.22	0.85	0.65	0.46
Rocket performance	Nozzle expansion ratio = 100	Thrust [N]	20,448	20,350	20,254	20,161
		T/W ratio	6.95	6.92	6.88	6.85
		I_{sp} [s]	993	988	983	979
	Nozzle expansion ratio = 200	Thrust [N]	20,764	20,657	20,554	20,457
		T/W ratio	7.06	7.02	6.99	6.95
		I_{sp} [s]	1,008	1,003	998	993

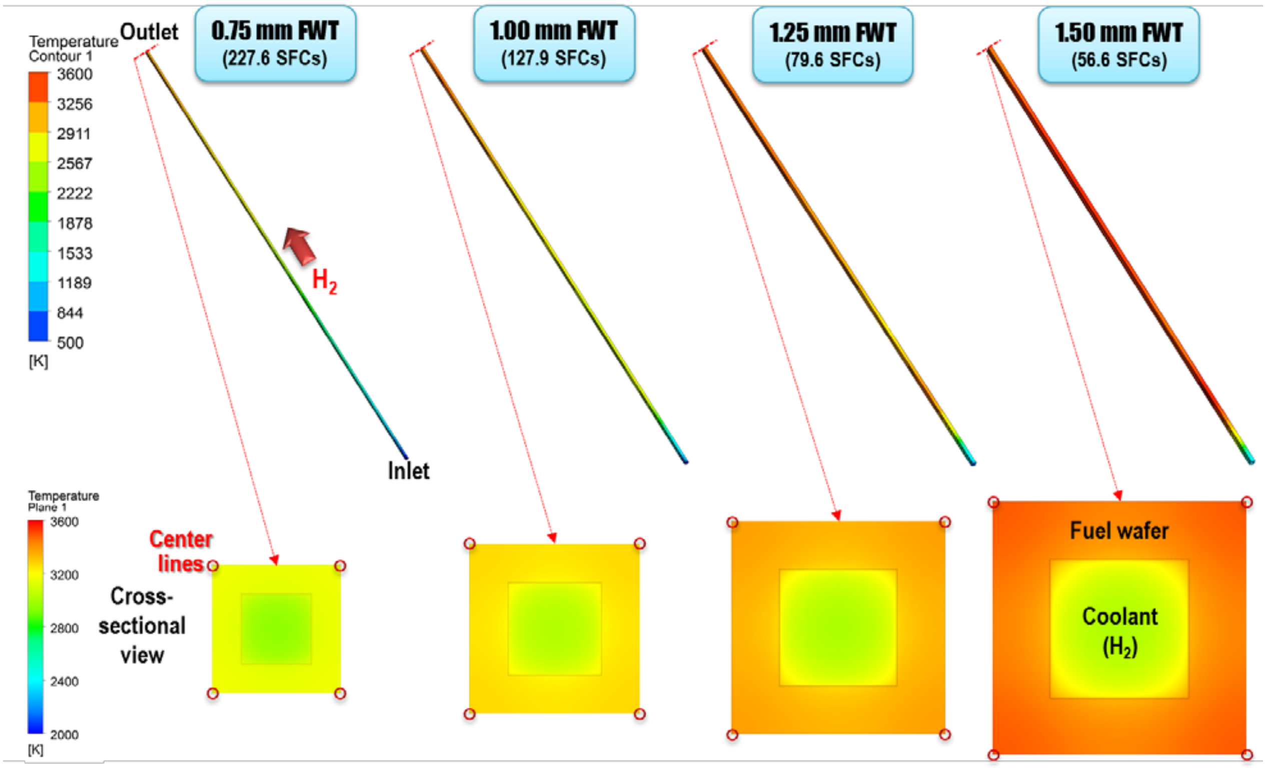


Fig. 9. Temperature distributions of unit SFCs in core.

of KANUTER compared with those of the enhanced Pewee engine [27], which produces 335 kN of thrust for the same ΔV and electric power with KANUTER. The mass of total engines, propellant, and IMLEO of the enhanced Pewee are estimated at 9.8 metric tons, 232 metric tons, and 413 metric tons, respectively. Thereupon, KANUTER can reduce the amount of propellant mass by 27 ~ 36% compared with that of the other NTR engines despite the larger number of engines. Additionally, the best CR demands at least 3.65 times as much propellant mass compared to that of KANUTER. These differences of propellant mass enables substantial launch cost saving or larger payloads of KANUTER.

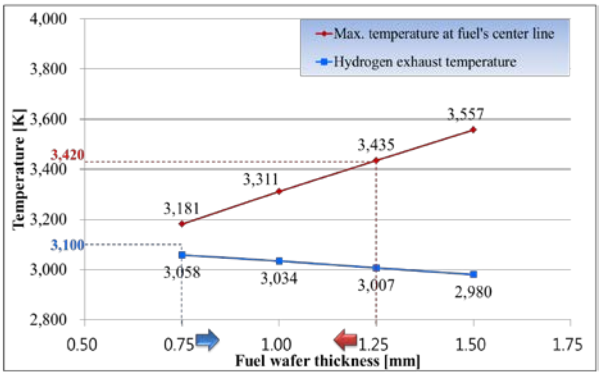


Fig. 10. Temperature states as a function of FWT in core.

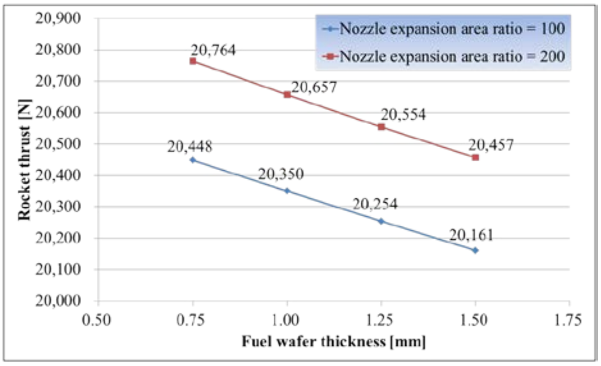


Fig. 11. Thrust estimation as a function of FWT of KANUTER.

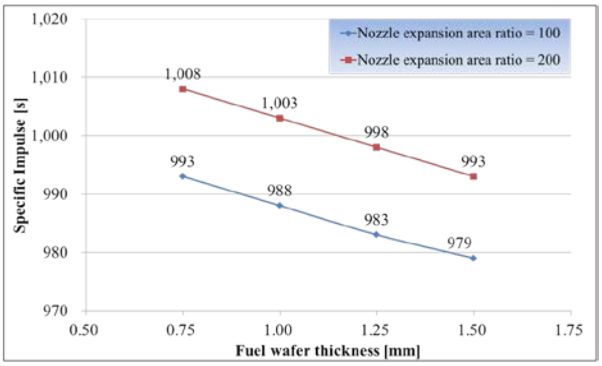


Fig. 12. Specific impulse estimation as a function of FWT of KANUTER.

Table Ⅳ: Reference mission performance comparison among various rocket engines.

	Engine type	Best Chemical (assumed)	NERVA	NERVA-derived		KANUTER
			Pewee	SNRE	Enhanced Pewee (DRA 5.0)	
Boundary conditions	Propellant type	$H_2 + O_2$	H_2			
	Payload [t] (6 ~ 8 crews)	71				
	Propellant tanks mass [t] (tankage fraction)	92 (0.130)	111 (0.301)	114 (0.301)	100 (0.301)	73 (0.301)
	Number of engines	13	3	5	3	13
	Total engine mass [t] (single mass [kg])	2.6 (200)	7.7 (2,570)	12.7 (2,545)	9.7 (3,250)	3.9 (300)
	Total reactor power [MW_{th}] (single power)	-	1,500 (500)	1,835 (367)	1,575 (525)	1,300 (100)
	Nuclear fuel type	-	Graphite matrix or composite		Composite or carbide	Ternary carbide
	Core neutron spectrum	-	Fast	Fast	Fast	Thermal
	Core diameter & height [cm]	-	50.8 & 132.1	59.0 & 89	59.0 & 132	39.2 & 39.2
	Total thrust [kN] (single thrust)	2,340 (180.0)	334 (111.2)	365 (72.9)	335 (111.7)	268 (20.6)
	T/W Ratio	91.8	4.4	2.9	3.5	7.0
	I_{sp} [s]	500	865	875	906	1,000
	Mission ΔV [km/s]	8.42				
	Mission period [days]	600 (round trip time: 540 + stay time: 60)				
Results	Operating time [minutes] (within 2 hours)	21.3	107.7	102.7	101.6	102.0
	Propellant mass [t] (+ 1 % margin)	615	257	264	232	169
	IMLEO [t]	780	446	462	413	316
	Final dry mass [t] (one tank jettisoned)	123	142	150	139	118

4. Conclusions

Nuclear propulsion is the most promising and viable option to achieve challenging deep space missions. Particularly, the attractions of a NTR include excellent thrust and propellant efficiency, bimodal capability, proven technology, and safe and reliable performance. The ROK has also begun the research for space nuclear systems as a volunteer of the international space race and a major world nuclear energy country. KANUTER is one of the advanced NTR engines currently under development at KAIST. KANUTER mainly consists of the 100 MW_{th} power EHTGR utilizing H_2 propellant, the propulsion system, and the EGS. To achieve the leading rocket performance, KANUTER adopts the ultra heat-resistant ternary carbide fuel, protective cooling structures, a thermalized neutron spectrum core, a modular fuel element design having the individual pressure tube and nozzle, and an EGS based on a dynamic power cycle. This bimodal engine is operated in two modes of propulsion with 100 MW_{th} power and electricity generation with 100 kW_{th} idle power. Consequently, KANUTER has the characteristics of a compact and lightweight system, excellent propellant efficiency, bimodal capability, and mission versatility as indicated in the reference design parameters.

This thermo-hydraulic design analysis was carried out to estimate the optimum FWT of the unique SLHC fuel design in the core and thereby the maximum rocket performance. The FWT affects the mechanical strength of the SLHC fuel assembly as well as the thermo-hydraulic capability mainly depending on the heat transfer area of fuel. The thicker fuel wafer is mechanically strong with low pressure drop, while the thinner fuel wafer is thermally robust with less mechanical strength and higher shear stress in the core. To satisfy the design criterions preventing fuel failures by both melting and H_2 corrosion, the FWT should be between 0.75 mm and 1.25 mm. In these FWTs, the rocket performance is theoretically estimated at the thrust range of 20.25 kN ~ 20.76 kN, the T/W ratios of 6.88 ~ 7.06, and the I_{sp} range of 983 s ~ 1,008 s. The excellent rocket performance of KANUTER can save enormous propellant mass and thus launch costs compared to other existing NTRs and CRs.

However, to actually develop KANUTER in the ROK, the security issue utilizing High Enriched Uranium (HEU) must be resolved because it is almost impossible for the ROK, as a non-nuclear weapon state. If the ROK never uses HEU for the NTR, then the only alternative is to utilize Low Enriched Uranium (LEU) to develop a new type NTR, though the mass and size of the new type may increase [28]. Therefore, in future work, this research will focus on designing the high performance KANUTER utilizing LEU to enhance the nuclear non-proliferation for space application.

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