Proposal of Space Reactor for Nuclear Electric Propulsion System

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Currently, the solar battery, the chemical cell, and the RI battery are used for the energy source in space. However, it is difficult for them to satisfy requirements for deep space explorations. Therefore, other electric power sources which can stably produce high electric energy output, regardless of distance from the sun, are necessary to execute such missions. Then, we here propose small nuclear reactors as power sources for deep space exploration, and consider a conceptual design of a small nuclear reactor for Nuclear Electric Propulsion System. It is found from nuclear analyses that the Gas-Cooled reactor could not meet the design requirement imposed on the core mass. On the other hand, a light water reactor is found to be a promising alternative to the Gas-Cooled reactor.

Key Words: Space Nuclear Reactor, MHD Energy Conversion, Ion Thruster

Nomenclature

\[ \begin{align*}
R & : \text{core radius of nuclear reactor} \\
D & : \text{core diameter} \\
L & : \text{core height}
\end{align*} \]

1. Introduction

Currently, solar cells and nuclear batteries are used as space power supply. A nuclear battery provides electric energy from decay heat of radioactive nuclides such as \(^{238}\text{Pu}\), and is used in deep space mission. In 2005, Hayabusa, a spacecraft developed at JAXA in Japan, arrived at an asteroid ‘Iokawa’. Hayabusa has four 350W Microwave Discharge Ion Engines as main thrusters. The source power of the engines is provided by solar cells. A next targeted mission is exploration of the planet Jupiter and its moons, but the solar cells cannot generate enough energy in such a mission, because Jupiter is far away from the sun. On the other hand, the nuclear battery also cannot provide enough energy, because of low power density in principle. So other electric power sources, which can produce large electric energy stably, regardless of distance from the sun, are necessary to execute such a mission. With a background mentioned above, nuclear propulsion systems have been studied in United States and Russia since 1950’s. In Japan, only a small number of studies for the space nuclear reactor has been conducted. Therefore, we here propose a Nuclear Electric Propulsion System (NEPS) for deep space exploration, and consider a conceptual design of a small nuclear reactor for the NEPS.

2. System Design

A NEPS is composed mainly of a nuclear reactor, an energy converter, waste heat radiators and electric propulsion engines. The NEPS generates electric energy from thermal energy produced in the nuclear reactor, and provides propulsion force by the electric propulsion system. Fig. 1 is a conceptual diagram of NEPS considered here. This system has a small nuclear reactor, a Magneto Hydro Dynamic (MHD) energy converter and ion thrusters. A MHD energy conversion system can generate electric energy with high efficiency at high temperatures. Thrust force is produced by microwave discharge ion thrusters. If MHD energy converter is adopted, it is necessary to convert working fluid into plasma state. So a Gas-Cooled Nuclear Reactor suits this purpose. Fig. 2 is a power flow in the NEPS. The reactor thermal power output is 100kW, the energy conversion efficiency is 40%, and the electric energy – microwave energy conversion efficiency is 60%. Eventually, the ion thrusters can use 24kW electric energy.

Fig. 1. Conceptual Diagram of a NEPS Probe

Fig. 2. Power Flow
3. Nuclear Reactor Core Design

The Gas-cooled reactor has a graphite core filled with coated fuel particles (as shown in Fig.3), and cooled by He-Xe, and the reactor provides 100kW thermal energy for 7 years. Inlet-outlet coolant temperature is 1,100-1,800K, to convert the coolant into plasma state. Fuel is uranium dioxide whose enrichment is 20 weight percent. The target of the core mass is less than 500kg. The reference design adopted here for this core is GTHTR300 (High Temperature Engineering Test Reactor) studied at JAEA (The Japan Atomic Energy Agency) in Japan. On this specification, we have studied a thermal design and a nuclear design of the core.

3.1. Thermal Design

There is an upper temperature limit of 2,000K for the coated fuel particles, so we initially estimated a core dimension which matches this limit for the coolant temperature of 1,100-1,800K. Fig. 5 is the relation between core radius and core height when the fuel temperature is lower than 1,900K and the core power output is 100kW. Calculation model is shown in Fig. 4. We assumed that the power output density is uniform in r-direction, while in z-direction the power output density follows the distribution which decreases exponentially with z. In this case, the fuel region temperature is uniform in all directions, and we can estimate the axial temperature distributions for fuel and coolant, the distributions being the same for all coolant channels. In this result, we take up the point (R=18cm, L=42cm), where the ratio of D to L is about 1, as a reference dimension. This is because the number of neutrons which escape from the core takes the minimum value at D/L=1, and it is easier to get criticality of the nuclear reactor.

3.2. Criticality Assessment

We got a reference size of core as R=18cm and L=42cm, with thermal design. Then we conducted nuclear design of the core. Distribution with nuclear calculations by using SRAC (a Comprehensive Neutronics Calculation Code System) developed at JAEA. Fig. 6 is the computational model of criticality assessment. The graphite core radius is 18cm, and its height is 42 cm. The thickness of beryllium oxide neutron reflector around the core is 10cm. Mass of this core including the reflector is 460kg, and meet the target mass of less than 500kg. However, as a result of criticality assessment of this core, the effective neutron multiplication factor $k_{eff}$ is only 0.420. It is very small compared with the critical value $k_{eff}=1.0$. So we have changed and optimized the core size and configuration to increase $k_{eff}$, but when $k_{eff}$ was larger than 1.0, the mass of core was estimated to be larger than 4000kg. Therefore a graphite core reactor does not suit a space reactor. This is because the moderating power of graphite is not high, and that the number density of uranium is small since fuels are filled as coated fuel particles. For the reasons mentioned above, it seems very difficult to design a graphite core whose mass is less than 500kg.
4. Light-Water Nuclear Reactor

Accordingly a gas-cooled reactor cannot be put on the NEPS, and then we have also studied a light-water nuclear reactor for reference. Light-water has the high moderating power for neutrons, so the reactor can be small and light.

4.1. Specification of Core

The core design is shown in Fig. 7. This core design is determined by reference to SUSEE1,2. The core has about 300 fuel rods which have uranium dioxide (enrichment of 20%) inside Molybdenum tubes, and is filled with light-water. The inner diameter of Molybdenum tubes is 6mm, and the thickness of them is 1mm. The core diameter and height are the same value of 36cm. The reflector is beryllium oxide, being set around the core, and the thickness of it is 5cm. For this dimension, the mass of the core including the reflector is 380kg. We have conducted criticality and burn up calculations for 2700days (about 7years), to obtain \( k_{\text{eff}} \) value and a variation of \( k_{\text{eff}} \) for this core. Then we found that the initial \( k_{\text{eff}} \) is 1.10. Fig. 8 shows the variation of \( k_{\text{eff}} \) for these days. \( k_{\text{eff}} \) decrease linearly, the variation of \( k_{\text{eff}} \) is small and \( k_{\text{eff}} \) is always larger than 1.0. In addition, when the burn up calculation was conducted, we consider the core output power as 1MW. With these results, it seems possible to set the light-water nuclear reactor on a deep space probe.

4.2. Mass of Radiators

If NEPS adopts a light-water reactor, it is expected that large radiators are necessary for waste heat, because the coolant temperature is low. If the mass of the radiators is very large, the advantage that core mass is low will be negated. Then we have estimated the mass of the two-sided radiators which can radiate in both sides. The result is shown in Fig. 9 where the left vertical axis shows temperature of fuels in rod, while the right vertical axis shows the radiator mass. The horizontal axis shows the core coolant outlet temperature. The radiator temperature is assumed to be equal to the core outlet temperature. The radiator area \( A \) is calculated by Eq. (1).

\[
\sigma \varepsilon A (T_{\text{rad}}^4 - T_{\text{s}}^4) = (1 - \eta)W_{\text{th}}
\]

(1)

\( T_{\text{rad}} \) is the radiator, and \( T_{\text{out}} \) the coolant outlet temperature, respectively. \( \eta \) is the thermal-electric energy conversion efficiency. \( \sigma \) is a Stefan-Boltzmann constant, \( \varepsilon \) is the radiator emissivity, and \( W_{\text{th}} \) is the core output thermal energy. The radiator area \( A \) is the total area in both directions, so we used half value of \( A \) when we calculated the radiator mass. In Fig. 9, \( W_{\text{th}} \) is assumed as 100kW, \( T_{\text{s}} \) 360K, \( \eta \) 10% with a thermoelectric converter, and \( \varepsilon \) 0.9. \( T_{\text{s}} \) is the temperature of space 4K. The mass density of the radiator is tentatively assumed as 4.0kg/m\(^2\). When the fuel temperature is calculated, we assumed that the coolant water remains liquid state, and neglected the effects of boiling. The fuel temperature decreases and the radiator mass increases with the coolant outlet temperature. The value of radiator mass is not small, but the value is allowable for the 500kg mass limit. Thus, the radiator mass is not a critical issue even when the coolant outlet temperature is not so high.
5. Summary and Conclusions

We considered a small nuclear reactor for the NEPS. First, we studied the graphite core which has inherent safety. However, it is found that a large and heavy core is necessary to obtain the effective neutron multiplication factor $k_{\text{eff}}$ of the critical value 1.0. Thus, the graphite core does not suit to space probe. Then, we have change the focus from the graphite core reactor to the light-water reactor. Light water can moderate effectively fission neutrons, so it is possible to make a small core with light mass of 460kg. If a light-water reactor is used in space, it is expected that the mass and area of radiators will be larger, but the fact is that the radiator mass is not a critical issue because the radiator mass is much smaller than the core mass. On a deep space probe with NEPS, it is requested that the reactor can operate for long term. We assumed the term as 7 years, and estimated whether the core can keep critical for all times with burn up calculation. As a result, $k_{\text{eff}}$ is over 1.0 for 2,700 days and the decrease of $k_{\text{eff}}$ is small. In conclusion, a light-water reactor meets NEPS as compared with a graphite core in terms of the mass, and the size. However, if $W_{\text{th}}$ is larger (ex. 1MW), the conclusion above will be not true because the radiator mass also increases with thermal energy which has to be wasted. Then the graphite core reactor may be suitable for high core power output range. For the time being, several tens of electric energy is enough to operate several ion thrusters, and then the value of $W_{\text{th}}$ needed by NEPS is 100kW at most. For that reason, the light-water nuclear reactor is likely as a first-generation space nuclear reactor for a deep space probe.

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References