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Design and analysis of nuclear battery driven by the external neutron source

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ABSTRACT

Based on the theory of ADS (Accelerator Driven Subcritical reactor), a new type of nuclear battery was investigated, which was composed of a subcritical fission module and an isotope neutron source, called NBDEx (Nuclear Battery Driven by External neutron source). According to the structure of GPHS-RTG (General Purpose Heat Source Radioisotope Thermoelectric Generator), the fuel cell model and fuel assembly model of NBDEx were set up, and then their performances were analyzed with MCNP code. From these results, it was found that the power and power density of NBDEx were almost six times higher than the RTG's. For fully demonstrating the advantage of NBDEx, the analysis of its impact factors was performed with MCNP code, and its lifetime was also calculated using the Origen code. These results verified that NBDEx was more suitable for the space missions than RTG.

1. Introduction

Compared with solar and fossil power systems, space nuclear power system has many advantages, such as better environmental adaptability, longer service life and higher power density. Therefore, space nuclear power system is considered as the key technology of deep space exploration mission in future (Christopher, 2002; Hou and Wang, 2007; Summerer and Stephenson, 2011).

At present, space nuclear power, which are really applied to deep space exploration mission, mainly contain RTG (Radioisotope Thermoelectric Generator) and SNRs (Space Nuclear Reactor system). Among them, RTG has advantages of modularization, small size, long service life and environmental adaptability, but the maximum thermal power output of present RTG is much less than 10 kW. Meanwhile, SNRs has many shortcomings, such as critical security, complex control strategy, huge mass and so on, which needs strict design to meet the requirement of safety and carrying capacity of spacecraft.

Inspired by the theory of ADS (Accelerator Driven Subcritical reactor) (Nifenecker et al., 2001), a new type of nuclear power system was investigated, called NBDEx (Nuclear Battery Driven by External neutron source system). NBDEx is composed of several subcritical fuel modules driven by an isotope neutron source. Compared with RTG, NBDEx has advantages of higher power density; compared with SNRs, it is more safer and has simpler structure. So it can be used as one of the candidate power for space exploration mission in future.

2. Models of NBDEx and GPHS-RTG

At present, the mature technology of space nuclear power is RTG, especially GPHS-RTG (General Purpose Heat Source-RTG), which has been applied to the Cassini mission and the New Horizons mission (Bennett et al., 2006; Lange and Carroll, 2008). As shown in Fig. 1 (Bennett et al., 2006), the structure of GPHS-RTG is very simple and tight. GPHS-RTG is composed of 18 GPHS modules, and every module is 9.718 cm × 9.317 cm × 5.308 cm, which contains 4 fuel pellets producing 0.25 kW thermal power as shown in Fig. 1(right). Thus, GPHS-RTG can generate total 4.5 kW thermal power or 0.306 kW electric power (theoretically) with 6.8% thermo-electric conversion efficiency. Because the range of alpha particle in the pure Pu metal fuel or PuO_2 is very short, almost all the decay energy deposits in the nuclear fuel, which means that the thermal power of GPHS-RTG mostly depends on the mass of Pu or PuO_2 fuel. This brings another advantage that the thermal power of GPHS-RTG would increase with the increment of the number of GPHS module, and vice versa. Meanwhile, its power density remains unchanged.

In order to make NBDEx a better application in the spacecraft based on the present technology and not to redesign the structure of power system, the final geometry design of NBDEx was

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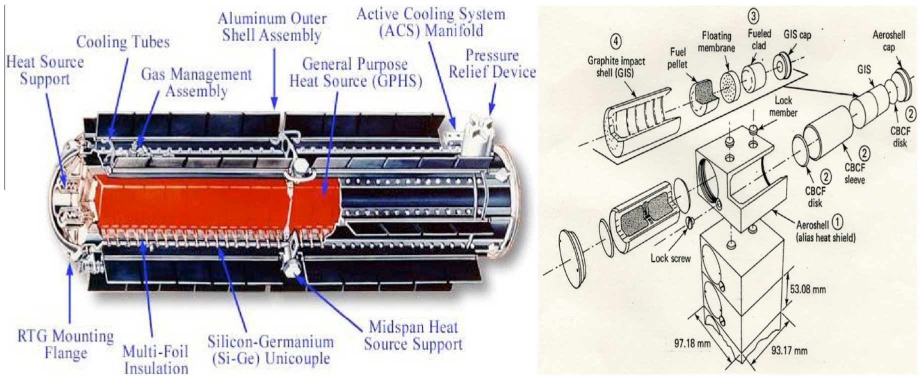

Fig. 1. The schematics of GPHS-RTG: (left) GPHS-RTG; (right) fuel assembly (Bennett et al., 2006).

proposed to be similar with GPHS-RTG. Meanwhile, in order to compare the performance of RTG and NBDEx, two types of NBDEx model were supposed respectively, including fuel cell model and fuel assembly model as following:

(1) Fuel cell model: in order to primarily verify the feasibility of NBDEx, the fuel cell models of both GPHS-RTG and NBDEx are developed as shown in Fig. 2, which are simplified models based on the design of GPHS module. And the density of Pu metal fuel is much higher than PuO_2 fuel, so GPHS-RTG with Pu as fuel can generate more thermal power by research of O'Brien (2008). In order to improve its thermal power, the fuel cell model of GPHS-RTG is composed of Pu metal fuel (with 19.35 g/cm^3 density) and sparse graphite layer as shown in Fig. 2(a). The Pu metal fuel is 3 cm radius and 10 cm height, and the graphite is 5 cm outer radius, 3 cm inner radius and 18 cm height. Based on the structure of GPHS-RTG's fuel cell model, the designed NBDEx system (Fig. 2(b)) is divided into three parts: ^{252}Cf neutron source, UO_2 fuel (with 90% ^{235}U enrichment and 10.8 g/cm^3 density) and sparse graphite. The ^{252}Cf neutron source is located in the center of fuel cell model, which is 0.4472 cm radius and 10 cm height. The UO_2 fuel is 3 cm outer radius, 0.4472 cm inner radius and 10 cm height. And the sparse graphite is 5 cm total radius and 18 cm height.

(2) Fuel assembly model: in order to better analyze the difference between GPHS-RTG and NBDEx, the fuel assembly model of NBDEx system is designed as the same as the real structure of GPHS-RTG as shown in Fig. 1(right). The fuel assembly model of both NBDEx and GPHS-RTG contains 5 GPHS modules. Every module is 9.718 cm × 9.317 cm × 5.308 cm, which contains 4 fuel pellets. But there is only one difference between NBDEx system and GPHS-RTG. The fuel pellet of GPHS-RTG is composed of PuO_2 fuel (with 9.14 g/cm^3 density) with 1.38 cm radius and 2.76 cm height (O'Brien, 2008; Lipinski and Hensen, 2008), while the fuel pellet of NBDEx is composed of ^{252}Cf neutron source and UO_2 fuel (83.88% ^{235}U enrichment and 10.8 g/cm^3). And the ^{252}Cf neutron source is 0.435 cm radius and 2.76 cm height, locating in the center of the UO_2, the UO_2 fuel is 1.38 cm outer radius, 0.435 cm inner radius and 2.76 cm height.

3. MC simulation of the nuclear power system

Through transport calculations of alpha and electron with MCNPX (Denise, 2007), the thermal power output and power density of the GPHS-RTG were calculated. Through transport calculations of neutron and electron with MCNP (Briesmeiter, 2000), the thermal power output and power density of NBDEx system were analyzed as shown in Table 1.

The calculation results showed that NBDEx could generate higher power density than GPHS-RTG with the same volume. In the fuel cell model, the power density and thermal power output of the GPHS-RTG were only 0.51 W/g and 2.79 kW respectively. In real structure design, 5 GPHS modules would produce total 1.25 kW thermal power. The reason why the thermal power of GPHS-RTG in fuel cell model got increment is that PuO_2 fuel is substituted by Pu metal fuel. However, although the volume of

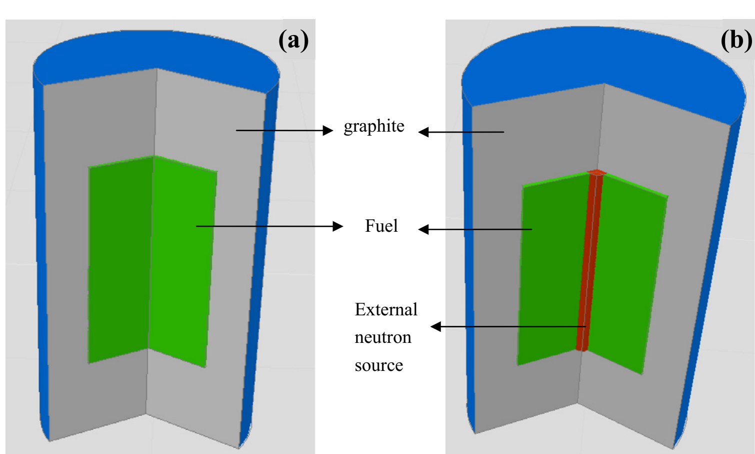

Fig. 2. The detailed schematics of fuel cell model: (a) GPHS (b) nuclear battery fuel cell.