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Conceptual design and analysis of a multipurpose micro nuclear reactor power source

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ABSTRACT

Micro Heat Pipe-cooled Reactor (HPR) power source is featured with lower noise level, higher power output, longer lifetime than conventional power sources. It could be applied for the energy system of space or underwater vehicles. The HPR power source is considered as an ideal candidate for the space and underwater reactor concept. In this paper, a 120 kWe lithium HPR power source applied for multiple use is neutronics designed. Uranium nitride fuel with 70% enrichment and lithium heat pipe are adopted in the reactor core. Tungsten and water are used as shields on both sides of the core. The reactivity is controlled by 6 control drums with B_4C neutron absorbers. Monte Carlo code MCNP is used to obtain kinetics parameters, the power distribution, shield analysis, reactivity coefficient and core criticality safety. A code MCORE coupling MCNP and ORIGEN is used to analysis the fuel depletion characteristics of the designed reactor core. A 14-year once-through fuel cycle is adopted according to optimization analysis. Overall, the designed core parameters preliminary satisfy the safety requirements and the rector is neutronics safe. This work provides reference to the design and application of the micro nuclear power source.

1. Introduction

Micro nuclear power source could be applied to the energy systems of space station and underwater vehicles. The future demands of multipurpose micro nuclear reactor power source are as follows: more compact structure; higher energy density; longer lifetime; higher power output and higher reliability. Compared with the conventional energy systems such as storage battery, fuel cell and Stirling engine, micro nuclear power source featured with high energy capacity, high power output, core lifetime of more than 10 years and strong adaptability to environment is much better meet the future demands of energy systems for multiple use.

There are two types of micro nuclear power source (Bennett, 2006): 1) isotope generator which convert decay heat into electricity; 2) nuclear reactor power source which convert fission heat into electricity. According to the neutron energy spectrum, micro nuclear reactor can be divided into thermal reactor, epithermal reactor and fast reactor; according to the coolant, micro nuclear reactor can be divided into heat pipe cooled reactor (HPR), liquid metal cooled reactor and gas cooled reactor etc. Nuclear reactor is widely used in submarines. After the World War II, the USA and the USSR started to conduct researches relevant to nuclear submarine equipped with liquid metal fast reactor. The USSR focused lead-bismuth cooled fast reactor and put it into application. Up to now, many theoretical and experimental researches about lead or lead-bismuth cooled reactor have been conducted (Wang et al., 2013).

Compared to other types of reactors, heat pipe cooled reactor is featured with significant advantages as follows:

1) High pressures are undesirable for underwater power source, because it makes the system more heavy and complex. Heat pipe cooled reactor creates a much lower-pressure gradient than LWR or gas cooled reactor, which have to operate at high pressure to attain better thermal properties.
2) For reactors with liquid or gas coolant, a break of coolant pipes could lead to severe accidents to the nuclear reactor, such as LOCA (Wang et al., 2014). Such severe accidents do not occur in a HPR system.
3) Water or liquid metal cooled reactor need active components such as pumps. Heat pipe cooled reactor with fewer movable parts produces lower noise level.
4) In HPR, each heat pipe works independently. When a single heat pipe fails, heat would be transferred out of the reactor

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Nomenclature

HPR	heat pipe cooled reactor	LANL	Los alamos national laboratory
LWR	light water reactor	PWR	pressurized water reactor
LOCA	loss of coolant accident	BOL	begin of life
MSR	martian surface reactor	EOL	end of life
TEG	thermoelectric generator	FSP	Fission Surface Power
AMTEC	alkali metal thermoelectric converter		

core by other adjacent heat pipes, instead of causing severe damage to the reactor core (Zhang et al., 2017).

5) Moreover, HPR is featured with high reliability, minimum maintenance requirements, and well property of thermal transient feedback.

Comprehensively considering the reactor mass and volume, criticality safety, reliability and maneuverability, heat pipe cooled fast reactor power source featured with compact structure, less movable parts, and low noise level could be widely adopted in the energy systems of underwater vehicles.

HPR has already been widely researched, as shown in Table 1. Various micro heat pipe cooled reactor power sources for space missions have been designed in the United States. For instance, HOMER (Poston, 2000) is a series of heat pipe cooled reactors applied for the moon and mars missions, featured with UN or UO_2 fission fuel, and the uranium enrichment is more than 90%. Potassium or sodium heat pipes are adopted as cooling method. Stirling engine is used to generate electricity of 3 kWe for HOMER-15 and 25 kWe for HOMER-25. The thermoelectric conversion efficiency of the HOMER power sources is more than 20%. Martian surface reactor (Bushman et al., 2004) (MSR) is another micro heat pipe cooled reactor power source designed by USA, featured with electrical power of the scale of hundred kilowatts. Lithium heat pipes and thermoelectric generator (TEG) are adopted in the reactor power source with thermal power of 1.2 MWt and efficiency of more than 10%. SAIRS (El-Genk, 2008) is a kind of sodium heat pipe cooled fast reactor controlled by drums and featured with electrical power of 100 kWe. And alkali metal thermoelectric converter (AMTEC) with thermoelectric conversion efficiency reaches more than 30% is adopted. LEGO-LRCs (Bess, 2008), controlled by control rods, is a sodium heat pipe cooled fast reactor with Stirling engine, producing a 30 kWe electricity. SAFE-400 (Poston et al., 2002) is a HPR system featured with Brayton cycle, producing 400kWt thermal power. China institute of atomic energy has proposed a series heat pipe cooled reactors for space missions, such as the mars surface power plant (Yao et al., 2016), and the lunar surface power plant HPCMR (Chengzhi et al., 2015), etc. KRUSTY, designed by NASA, is a kilowatt-class HPR with Stirling engine for space missions (Gibson et al., 2013), and the ground testing was conducted in 2017 (Briggs et al., 2017). Micro nuclear reactor power source for underwater working condition has already been researched theoretically and experimentally.

Based on a literature review about the design and application of HPRs, a micro nuclear reactor power source applied featured with 120 kWe electrical power output and a lifetime of more than 10 years is conceptual designed, as the Fig. 1 shows. Lithium heat pipes cooled core, 6 control drums, tungsten and water radiation shields are adopted in this power source. Monte Carlo code MCNP and a code MCORE coupling MCNP with depletion code ORIGEN are used to preliminarily calculate the design parameters, and analyze the criticality safety features as well as depletion features of the design scheme.

2. System design

The HPR power source consists of the following parts: active zone, control mechanism, shield, heat pipes and thermoelectric generator (TEG). The core of HPR power source is a fast reactor with thermal power of 2.4MWt, and its structure is shown in Fig. 2. In this core, UN cermet fission fuel is adopted. Due to the

Table 1
Several heat pipes cooled reactor power sources.

Name	Cooling method	Thermoelectric conversion	Waste heat discharge	Control method	Power (kWe)	Efficiency (%)	Specific power (We/kg)
SAIRS	Sodium heat pipes	AMTEC	Heat pipe radiator	Control drums	100	18.5–22.1	29.7–34.8
HP-STMCs	Lithium heat pipes	Multistage thermocouples		Control drums	110	6.7	25.8
MSR	Lithium heat pipes	Thermionic conversion		Control drums	100	>10	15.4
LEGO-LRCS	Sodium heat pipes	Stirling engine		Control rods	30	25	11.2
HOMER-15	Sodium heat pipes	Stirling engine		Control drums	3	20	3.9
HOMER-25	Potassium heat pipes	Stirling engine		Control drums	25	26.5	11.7
KRUSTY	Sodium heat pipes	Stirling engine		Control rod	1–10	23	2.5–6.5

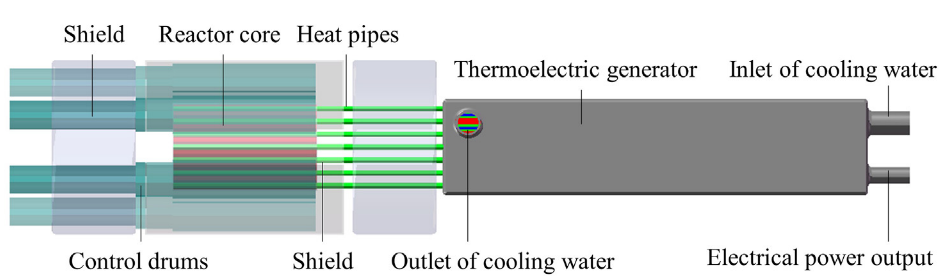

Fig. 1. Structure of micro nuclear reactor power source.