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Research Paper

Thermodynamic performance of lunar surface nuclear power system with heat sink temperature change in a rotational period

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HIGHLIGHTS

- Models developed based on energy conservation for thermodynamic performance.
- Cold side temperature of FPSE was changing but not following the sine function law.
- Unsteady state with lower thermal efficiency and high exhaust heat during day time.
- A steady state with higher thermal efficiency and less exhaust heat during dark time.
- Larger heat rejection area led to higher thermal efficiency and lightweight.

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ABSTRACT

The thermodynamic performance of the lunar surface nuclear power system with Free-Piston Stirling Engines (FPSE) was analyzed based on the energy conservation of the system. The heat sink temperature was assumed to follow the sine function law. The cold side temperature of the FPSE was changing with time in a rotational period and would be increased with the increase of the heat sink temperature. The thermodynamic performance of the power system was changing with lower thermal efficiency and high amount of exhaust heat rejection, during the day time with heat sink temperature higher than 200 K. During the dark time, the power system could be kept as a steady state with higher thermal efficiency and less amount of exhaust heat rejection. The energy storage option could be required, if the electrical power output was expected to meet the grid. The highest thermal efficiency could be increased from 0.21 to 0.235, if the area of the heat rejection system was increased from 120 m^2 to 180 m^2, since the cold side temperature of the PFSE could be decreased. Larger area of the heat rejection system could increase the specific area but has the advantage of lightweight for the power system.

1. Introduction

The moon is the nearest natural celestial body to earth. The moon exploration can help human search and utilize the natural resources such as ^{3}He and expand the living space. These human activities are conducive to the sustainable development of human society and are of great importance for human's strategic plans [1]. Besides, the manned lunar-landing is technology feasibility and therefore it becomes the focal point in the field of deep space exploration. Power requirements to support a wide range of activities range from 10 s to 1000 s kWe for many years without dependence in solar energy [2]. The long lunar rotational period of about 28 days results up to 2 weeks of darkness, depending on the selected site for the outposts on the lunar surface. Traditional power such as chemical energy, fuel cells and isotopic power are limited under this condition. Only the nuclear power reactor based on fission or fusion can comply with these requirements, since it can operate continuously independent of the solar energy and provide sustainable and reliable electricity for up to 15 years [3]. Compared with the other powers, the nuclear power reactor has compact structure, higher power density and lighter weight [4,5].

The lunar surface nuclear power system is mainly including three sub-systems: the reactor system, the energy conversion system and the heat rejection system [6]. Different from the ground-based Boiling-Water Reactor and Pressured-Water Reactor, the temperature of the lunar surface nuclear reactor is high, in the range of 1000–1500 K, since higher reactor temperature can

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Nomenclature

Q	heat (kWt)
P	electrical power (kWe)
T	temperature (K)
L	length (m)
H	height (m)
A	half of the temperature difference of the heat sink temperature (K)
B	undetermined parameters (K)
k	thermal conductivity (W m^{-1} K^{-1})
h	heat transfer coefficient (W K^{-1} or W m^{-2} K^{-1})
k_0	heat leak coefficient (W K^{-1})
m	number of the radiator plate

Greek symbols

η	thermal efficiency
ξ	emissivity factor
δ	thickness
σ	Stefan-Boltzmann constant (W m^{-2} K^{-4})
ω	rotational frequency of the lunar (rad)

Subscripts

H	hot side
C	cold side
L	loss
I	reactor
IN	fission heat
HP	heat pipes
HC	convective heat transfer at cold side
CC	convective heat transfer at cold side
R	radiator plate
s	nuclear power system
t	stirling engine
0	ambient condition

increase the energy density and exergy efficiency. In this case, the liquid Na such as NaK-78 or inert gas such as He is used as the coolant. In order to avoid the single point failures, the reactor is divided into a number of identical sectors that are thermally and neutronically coupled but hydraulically decoupled [7]. The other approach using the liquid metal heat pipes cooling the reactor can also avoid the single point failures and in this research the Li heat pipes are used to transport the fission heat out of the reactor. The power conversion technologies are clarified as static and dynamic methods [8]. Considering the requirement of the high reliability of the lunar surface nuclear power system, static power conversion technologies are usually the first choices in the early times, since they are absent of the moving parts and inherently modular. The typical static conversion technologies include the thermoelectric (TE), thermionic (TI) and alkali-metal thermal-to-electric conversion (AMTEC) [8,9]. The thermal efficiency of the static conversion technologies are usually lower than 10%, leading to the specific power of the system hardly exceeding 10 We/kg [8]. The dynamic power conversion technologies can generate higher thermal efficiency than 20%. The typical dynamic conversion technologies include the Free-Piston Stirling Engines (FPSE), the Closed Brayton Cycle (CBC) and Rankine Cycle [10–13]. In this research, eight Stirling engines were used to generate electricity. In order to maintain the stable operation of the power system and reasonable temperature distribution, the waste heat must be dissipated by the heat rejection system. The heat rejection system cannot rely on the ground-base heat transfer mechanism such as forced convection by coolants, owing to the absence of the atmosphere in the lunar surface. The waste heat should be rejected to the space environment by radiation [14–16]. Considering the technology feasibility and long heat transfer distance of the heat rejection system, the mechanical pumped cooling loop was applied for the heat rejection in this research [17,18].

Thermodynamic performance is one of the key issues for the lunar surface or other space nuclear power system, since it can provide deep understanding of the energy conversion performance of the power system and a preliminary tool for the power system design. An efficiency of about 6% can be generated by using the SiGe thermoelectric converters operating between 1273 K and 790 K. AMTEC units typically operate at moderate hot-side temperatures (1000–1123 K). It has reported that a net conversion efficiency of 22% to 27% can be generated with potassium and sodium working fluid [8]. Riberro et al has developed a computational model for the thermal prediction of a Closed Regenerative Brayton Cycle for space nuclear power system [11]. It has found that higher heat exchangers thermal conductance improves the system's efficiency and increasing the compressor polytropic efficiency was a useful approach to enhance the system performance, owing to a strong impact of the compressor efficiency on the system efficiency. The FPSE technology combines high energy conversion efficiency with high power output to system mass. Based on these characteristics, energy conversion via FPSE has been glimpsed as a strategic technology for space exploration and several studies of conceptual designs of FPSE for different electrical power were developed [19–21]. In our previous study, we have developed a model with finite time thermodynamics to describe a lunar surface nuclear power system with FPSE for energy conversion [22]. It has found that higher cold side temperature can decrease the thermal efficiency but improve the heat rejection. However, the heat sink temperature is assumed as a constant and this is not realistic. Therefore, the thermal efficiency obtained in previous study can not reflect the energy conversion performance with rotational time changing.

The driven force of the heat rejection is highly related to the heat sink temperature under the lunar surface condition. Higher heat sink temperature can decrease the driven force of the heat rejection and vice versa. The lunar surface temperature is changing with the rotational time, leading to the changing of the heat sink temperature. Therefore, the driven force of the heat rejection is changing with the rotational time. A strong impact of the heat rejection on the energy conversion performance of lunar surface nuclear power system would be seen. In this research, we will study the thermodynamic performance of the lunar surface nuclear power system with heat sink temperature changing in a rotational period. Compared with ground-based nuclear power system, lightweight and small area of the heat rejection are of great importance for lunar surface nuclear power system. Therefore, the effect of the area of the heat rejection system on the thermal efficiency and the total mass of the power system is also studied. The results of the study can provide some new insights for the design of the lunar surface nuclear power system.

2. Mathematical models

The nuclear fission heat generated in the core with the temperature of 1200 K is transported to the hot side of the FPSE by the hot heat pipes. Some of the heat absorbed by the FPSE can converted to