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Research Paper

Thermodynamic analysis and optimization of a Stirling cycle for lunar surface nuclear power system

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HIGHLIGHTS

- Lunar surface nuclear power system with Stirling cycle for energy conversion.
- A model with finite time thermodynamics to describe the system thermal efficiency.
- Higher hot side temperature not exceeds 1050 K increased thermal efficiency.
- Higher cold side temperature decreased thermal efficiency but improved heat rejection.
- Higher convection heat transfer coefficient improved the thermal efficiency.

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ABSTRACT

A model for the description of the thermal efficiency of a lunar surface nuclear reactor power system with eight free piston Stirling engines to generate nominal electrical power of 100 kWe was developed. The heat loss of the hot heat pipes, finite rate heat transfer, regenerative heat loss, finite regeneration process time and conductive thermal bridging losses were considered. The results showed that the thermal efficiency increased and then decreased with the hot side temperature increase. The highest thermal efficiency was about 0.29 under the condition of the effectiveness of the regenerator being 0.9 and compression ratio being 2. Higher cold side temperature had bad effect on the thermal efficiency but could reduce the size of the heat rejection system. When the cold side temperature was designed as 500 K, the lowest power system mass of 6.6 ton could be obtained. Enhanced heat transfer of the heat exchangers would increase the thermal efficiency but higher values of the nominal convection heat transfer coefficient of the heat exchangers would lead to a negligible thermal efficiency increase. The results obtained here may provide a new ideal to design lunar surface nuclear powered Stirling cycle.

1. Introduction

The earth's moon is a potential destination for future human space exploration and a wide range of activities including geological exploration, astronomical experiments, manufacturing and utilization of natural resources would be realized [1–4]. Many nations have expressed interest in sending crewed missions to the moon within the past few decades, with an eventual goal of establishing permanent outposts, requiring reliable and expandable electrical power of 10–100 s of kWe for many years and independent of the sun. The long lunar rotational period of about 28 days results in up to 2 weeks of darkness, depending on the selected site for the outpost on the lunar surface. Under this condition, the electrical power can be hardly met using the photovoltaic solar power system with nighttime energy storage or using the isotopic power. Nuclear fission reactor power system offers a low mass and compact alternative for mature lunar outpost and would generate steady electrical power continuously irrespective of the latitude of the outpost on the lunar surface and independent of the sun [5–7]. The essential components of the lunar surface nuclear power system are the reactor, the power conversion system and the heat rejection system [8–11].

The power conversion technologies for space nuclear power system are usually classified as the static and dynamic methods. Static conversion technologies of thermoelectric (TE), alkali-metal thermal-to-electric conversion (AMTEC) units and thermionic (TI), were inherently modular and load following, in addition to the absence of moving parts [8,12]. Despite the merits, the conversion efficiency was generally lower than 10% and therefore the

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Nomenclature

Q	heat (W or kW)
T	temperature (K)
h	heat transfer coefficient ($W\,K^{-1}$ or $W\,m^{-2}\,K^{-1}$)
k_0	heat leak coefficient ($W\,K^{-1}$)
A	heat transfer area (m^2)
W	work (J)
P	power (W)
M	regenerative time constant ($K\,s^{-1}$)
R	universal gas constant ($J\,mol^{-1}\,K^{-1}$)

Greek symbols

Δ	regenerator loss
η	thermal efficiency
ξ	emissivity factor
ε	effectiveness
δ	Stefan-Boltzmann constant ($W\,m^{-2}\,K^{-4}$)
λ	compression ratio

Subscripts

H	hot side
C	cold side
R	regenerator
L	loss
I	reactor
IN	fission heat
HP	heat pipes
HC	convective heat transfer at cold side
CC	convective heat transfer at cold side
s	nuclear power system
t	Stirling engine
0	ambient condition
1–4	process state

specific power of the system could hardly exceed 10 We/kg [3,8]. Dynamic energy conversion technologies of closed Brayton cycle (CBC) and Rankine cycle, typically generated high conversion efficiencies of between 20% and 30% [9,13]. Stirling engine is one of the most promising energy conversion technologies for space power system, since it results in high thermal efficiency and good reliability [14–16]. The Stirling engine can combines high energy conversion efficiency with high power output to system mass. In this study, the free-piston Stirling engines (FPSE) were used as the energy conversion units. The proposed lunar space nuclear power system with Stirling cycle for energy conversion is schematically described in Fig. 1. The nuclear fission heat generated in the reactor core with the temperature of about 1200 K is considered as the heat resource of the Stirling engine. Some of the heat would be lost through radiation during the heat transfer by the heat pipes owing to the high temperature. Part of the heat absorbed by the hot side heat exchanger of the Stirling engine is converted into electrical power and the exhaust heat is rejected from the cold side heat exchanger. A cooling loop can transport the exhaust heat to the heat rejection system and at last the exhaust heat is rejected to the outer space by the radiative heat transfer through the radiators.

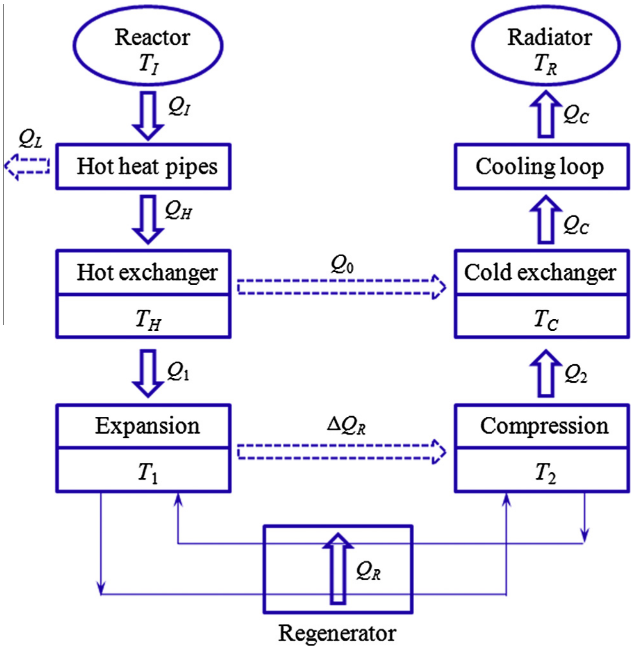

Fig. 1. Linear diagram of the lunar surface nuclear power system with Stirling cycle.

The radial cross-section view of the reactor is illustrated in Fig. 2. The reactor comprises 127 heat pipes and 342 fuel pins with UO_2. The reactor uses neutron Spectral Shift Absorber (SSA) additives in the fuel to satisfy the requirement of remaining the sufficiently subcritical in the unlikely event of a launch abort accident [6]. The ODS-MA956 steel encasement is made for the fuel pins frits, the core frits and the reactor vessel, owing to the high nominal exit temperature of the core [17]. The reactor core vessel is surrounded by a BeO radial reflector and the reflector is clad in thin stainless steel to protect from meteorites impact and prevent sublimation of BeO into space. The control of the reactor starting up, shutting down and operation through the end of life is accomplished using a total of six BeO/B_4C rotating drums in the radial reflector. The control drums are also clad in stainless steel and faces with B_4C segment (4 mm thick and 120 °C sectors) enriched in ^{10}B. The control drums in the BeO radial reflector would be rotated with the B_4C segments facing the core during launch before the reactor startup on the lunar surface.

The energy conversion is achieved in the Stirling engine, with the helium as the working fluid circulating in a closed system. Eight Stirling engines are use as the energy conversion units for the lunar surface unclear power system with nominal electrical power of 100 kWe. The schematic diagram of the Stirling engine is illustrated in Fig. 3. The diameter and length (including no electrical motor) of one Stirling engine are 500 mm and 1000 mm, respectively. A Stirling engine configuration consists of a cylinder (contained with hot space and cold space), the hot side heat exchanger, the cold side heat exchanger, the regenerator, the power piston and the displacer piston. A Stirling cycle consists of four steps, including two isothermal and two isochoric steps [14,18–20]. The compression and expansion steps of the cycle takes place in the cylinder with the power piston at constant temperature [21]. The displacer piston shuttles the helium back and forth through the hot side heat exchanger, regenerator and cold side heat exchanger at a constant volume [22]. If the regenerator is ideal, the heat absorbed by the regenerator when the helium flows from the hot space to the cold space should be equal to the heat rejected from the regenerator when the helium flows from the cold space to the hot space [19]. However, the ideal regenerator requires an infinite area or infinite regeneration time to transfer