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Exergy analysis of a lunar based solar thermal power system with finite-time thermodynamics

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Abstract

The exploration of the moon and the construction of the manned lunar outpost are the important parts of the deep space exploration. The continuous supply of thermal energy and power for deep space explorers and scientific equipment is a crucial issue to accomplish manned lunar missions. For most locations on the lunar surface, darkness lasts for periods of about 350 hours, so it is a great challenge for the solar photovoltaic cells and radioisotope thermoelectric generators to launch too much material from Earth. In the mission of manned deep space exploration, it is very necessary to utilize in situ resource effectively and sufficiently to reduce the hardware must be brought from Earth and to meet the requirement of energy and life support system. This paper describes an exergy analysis of a lunar based solar thermal power system using the method of finite-time thermodynamics. The calculations indicate that the system can provide the desired energy for the equipment. The aim of this article is to provide the basis for the design of a solar-powered Stirling engine using thermal energy from the processed lunar regolith.

Keywords: solar thermal power system; exergy analysis; lunar regolith; finite-time thermodynamics

1. Introduction

The exploration of the moon and the construction of the manned lunar outpost are the important parts of the deep space exploration. The manned deep-space exploration becomes a hot topic of the current space activities [1, 2].

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Many nations have expressed interest in temporary outposts and permanent bases on the Moon and the Mars. These outposts would eventually require reliable and continuous power of 10s-100s kWe for many years [3]. The continuous supply of thermal energy and power for deep space explorers and scientific equipment is a crucial issue to accomplish manned lunar missions. However, for most locations on the lunar surface, darkness lasts for periods of about 350 hours, the significant launch mass is required for the energy storage if the traditional photovoltaic-battery power system is adopted. Even if the regenerative fuel cells [4] with high energy density of 500Wh/kg are applied, the weight of the energy storage should be more than 6.7 tons. Another choice is the nuclear reactors which can deliver electric and thermal energy at a constant level during the lunar day and night [3, 5]. However, the nuclear reactors do require additional mass for shielding radiation-sensitive payloads and measures to protect human beings from nuclear radiations during launch, operation and post-utilization.

In-Situ Resource Utilization (ISRU) can have a tremendous beneficial impact on robotic and human exploration of the Moon, Mars and other planets [6, 7]. In the lunar outposts, it is very necessary to utilize in-situ resource effectively and sufficiently to minimize the hardware which must be brought from the Earth and reduce the mission cost significantly. Accordingly, the idea has been proposed to use lunar regolith for thermal energy storage and electrical power generation [8, 9]. To improve the thermal conductivity and energy storage efficiency, some methods such as regolith-helium mixture [10], melting regime [11, 12], and processed regolith [13-15] have been proposed, and the temperature evolution and distribution of the regolith energy storage system are analyzed [15], while detailed system performance is still needed.

The use of exergy analysis or second law analysis is very important in developing a good understanding of the thermodynamic behavior of solar thermal power system. However, in contrast to the studies based on the first law of thermodynamics, very little work has been done based on the second law of thermodynamics.

2. System description and methodology

Fig. 1 presents the schematic of a lunar based solar thermal power system with regolith thermal storage. The system includes a solar concentrator, a regolith thermal reservoir, a high temperature fluid loop, a Stirling generator, a low temperature fluid loop, a thermal radiator with a radiation shield, etc.

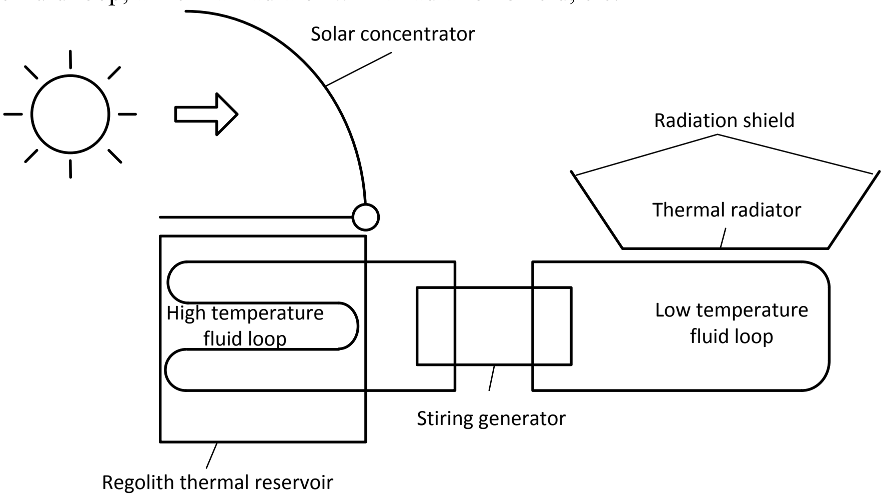

Fig. 1. Schematic of a lunar based solar thermal power system [16]

Fig.2 shows the working principle and the energy flow of the lunar based solar thermal power system. The solar energy is concentrated and reflected by the solar concentrator to the surface of the regolith thermal storage with high solar absorptivity. Accordingly, most of the solar radiation is absorbed and restored in the regolith thermal storage during the period of daytime, and a small part of the absorbed heat is dissipated to the environment by the surface thermal radiation. The restored thermal energy in the regolith thermal storage is transported to the hot end of the thermoelectricity device for power generation by the high temperature fluid loop. The Stirling generator converts the thermal energy into electrical power. The waste heat is transported by the low temperature fluid loop from the cold end of the thermoelectricity device to the thermal radiator and finally dissipated to the space.

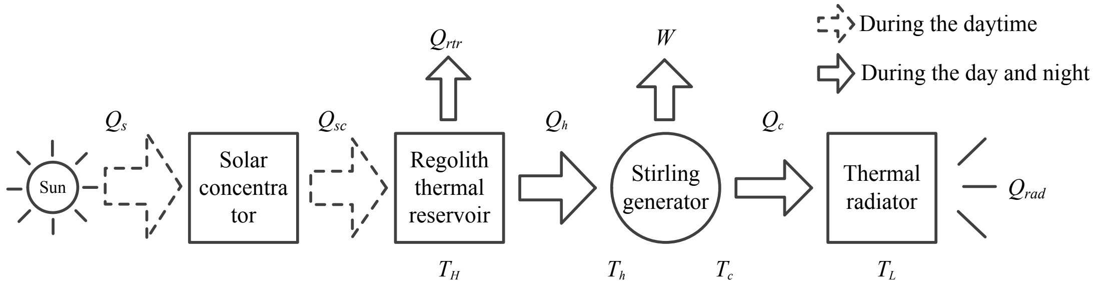

Fig. 2. Principle and energy flow of the lunar based solar thermal power system

3. Theoretical model

The exergy efficient of the solar concentrator is [17],

$$\varepsilon_s = \frac{\left[\eta_0 - \frac{1}{IC}\varepsilon\sigma\left(T_H^4 - T_0^4\right)\right]\left(1 - \frac{T_0}{T_H}\right)}{1 - \frac{T_0}{T_*}} \tag{1}$$

where η_0 is the optical efficient, I is the direct solar flux intensity, C is the concentrating ratio, ε is the emissivity factor, σ is Stefan-Boltzmann constant, T_H is the temperature of the heat source, T_0 is the environmental temperature, T_* is about 3/4 of the solar surface temperature, 4500 K.

Based on the theory of the finite-time thermodynamics, the optimized exergy efficient of the Stirling generator is,

$$\varepsilon_t = \frac{T_H - T_c - \frac{q}{1-B}}{\varepsilon_1 T_H - \varepsilon_2 T_c - \frac{\varepsilon_1 q}{1-B}} \tag{2}$$

where T_H is the temperature of the heat source, T_c is the temperature of the working fluid during isothermal heat rejection process, B is the regenerative time coefficient, $\varepsilon_1 = 1 - T_0 / T_H$, $\varepsilon_2 = 1 - T_0 / T_c$.

The exergy efficient of the solar power system is the product of the exergy efficient of the solar concentrator and the exergy efficient of the Stirling generator, so the equation is,

$$\begin{aligned}\varepsilon &= \varepsilon_s \varepsilon_t \\ &= \frac{\left[\eta_0 - \frac{1}{IC}\varepsilon\sigma\left(T_H^4 - T_0^4\right)\right]\left(1 - \frac{T_0}{T_H}\right)}{1 - \frac{T_0}{T_*}} \times \frac{T_H - T_c - \frac{q}{1-B}}{\varepsilon_1 T_H - \varepsilon_2 T_c - \frac{\varepsilon_1 q}{1-B}}\end{aligned} \tag{3}$$

4. Results and discussion

Fig. 3 shows the exergy efficient of the solar concentrator at different temperature of the heat source, environmental temperature and concentrating ratio. When the environmental temperature is 0 K, the exergy efficient of the solar concentrator decreased with the temperature of the heat source. Except the case of the environmental temperature is 0 K, there exists an optimized temperature of the heat source, and the optimized temperature of the heat source decreases with the increasing of the environmental temperature. The exergy efficient of the solar concentrator increases with the increasing of the concentrating ratio.

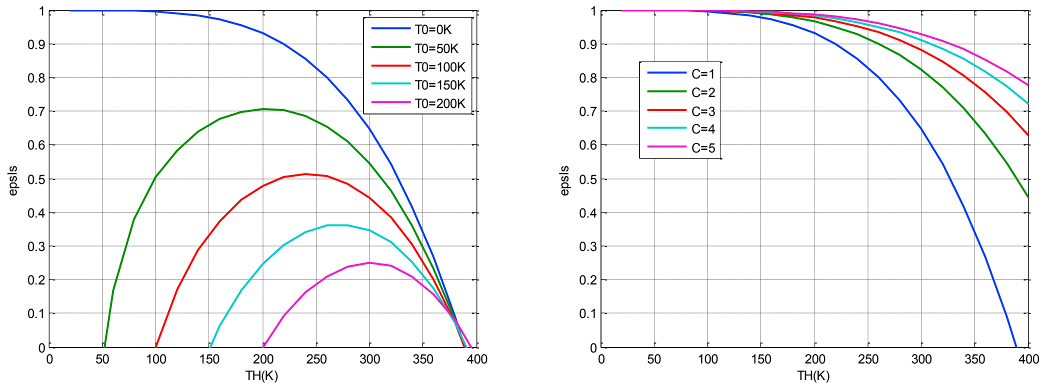

Fig. 3. The exergy efficient of the solar concentrator

Fig. 4 shows the exergy efficient of the Stiring generator at different temperature of the heat source, environmental temperature and concentrating ratio. The exergy efficient of the Stiring generator increases with the increasing of the temperature of the heat source and the concentrating ratio except the case of the environmental temperature is 0 K.

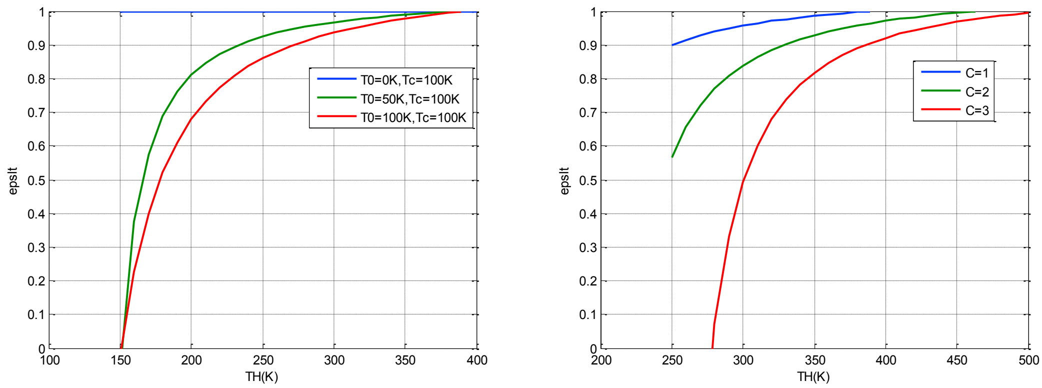

Fig. 4. The exergy efficient of the Stirling generator

Fig. 5 shows the exergy efficient of the solar power system at different temperature of the heat source, environmental temperature and concentrating ratio. When the environmental temperature is 0 K, the exergy efficient of the solar power system decreased with the temperature of the heat source. Except the case of the environmental temperature is 0 K, there exists an optimized temperature of the heat source for different environmental temperature, and the optimized temperature of the heat source decreases with the increasing of the environmental temperature. There also exists an optimized temperature of the heat source for different concentrating ratio.

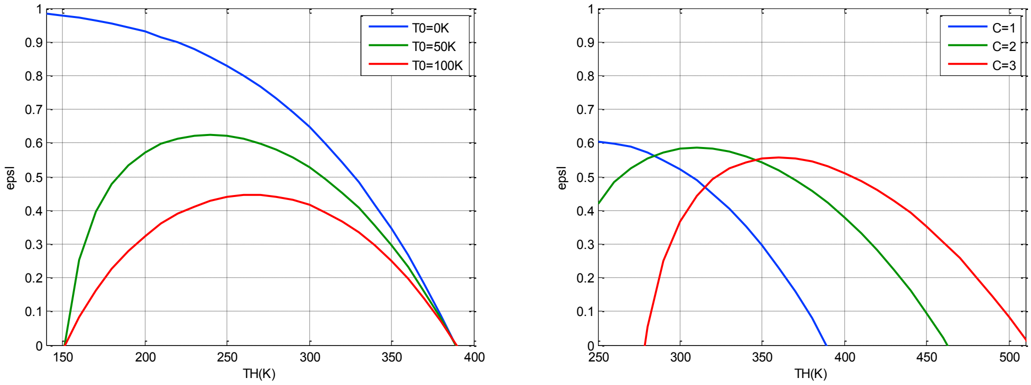

Fig. 5. The exergy efficient of the solar power system

5. Conclusions

The exergy analysis of a lunar based solar thermal power system with regolith thermal storage is presented. For the exergy efficient of the solar power system, except the case of the environmental temperature is 0 K, there exists an optimized temperature of the heat source for different environmental temperature, and the optimized temperature of the heat source decreases with the increasing of the environmental temperature. There also exists an optimized temperature of the heat source for different concentrating ratio.

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