Energy 107 (2016) 227–233

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Performance analysis of a lunar based solar thermal power system with regolith thermal storage

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ARTICLE INFO

Article history:
Received 3 May 2015
Received in revised form
8 February 2016
Accepted 28 March 2016
Available online 27 April 2016

Keywords:
Solar thermal power system
Lunar regolith
Stirling generator
Finite-time thermodynamics

ABSTRACT

The manned deep-space exploration is a hot topic of the current space activities. The continuous supply of thermal and electrical energy for the scientific equipment and human beings is a crucial issue for the lunar outposts. Since the night lasts for periods of about 350 h at most locations on the lunar surface, massive energy storage is required for continuous energy supply during the lengthy lunar night and the in-situ resource utilization is demanded. A lunar based solar thermal power system with regolith thermal storage is presented in this paper. The performance analysis is carried out by the finite-time thermodynamics to take into account major irreversible losses. The influences of some key design parameters are analyzed for system optimization. The analytical results shows that the lunar based solar thermal power system with regolith thermal storage can meet the requirement of the continuous energy supply for lunar outposts.

1. Introduction

After US government proposed the ambitious manned Mars mission [1], the manned deep-space exploration becomes a hot topic of the current space activities [2,3]. 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 [4]. The continuous supply of thermal and electrical energy for the scientific equipment and human beings is a crucial issue for the lunar outposts. Since the Moon night lasts for a period of about 350 h for most locations on the lunar surface, 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 [5] with high energy density of 500 Wh/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 [4,6]. 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.

ISRU (In-Situ Resource Utilization) can have a tremendous beneficial impact on robotic and human exploration of the Moon, Mars and other planets [7,8]. 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 [9,10]. To improve the thermal conductivity and energy storage efficiency, some methods such as regolith–helium mixture [11], melting regime [12,13], and processed regolith [14–16] have been proposed, and the temperature evolution and distribution of the regolith energy storage system are analyzed [16], while detailed system performance is still needed.

Since Stirling engines have principal advantages of high efficiency and suitable for variable external heat sources, solar-powered Stirling engines are paid much attention in recent years on the Earth [17–20] and other planet [21] applications. Since solar energy is not available during two-thirds of the day on the Earth, some methods, such as solar/fuel hybrids [17], thermo-chemical energy storage [22], and phase-change energy storage [23] have been proposed.

A lunar based solar thermal power system with regolith thermal storage is presented and analyzed in this paper. In order to take into account important irreversible losses such as finite-rate heat transfer, regenerative heat losses, conductive thermal bridging

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http://dx.doi.org/10.1016/j.energy.2016.03.132
0360-5442/

Nomenclature

A	area, m^2
a	thermal diffusivity, m^2/s
C	concentrating ratio
C_p	specific heat at constant pressure, J/(kg·K)
C_v	specific heat capacity at constant volume per mole, J/(mol·K)
h	depth, m
k	thermal conductivity, W/(m·K)
k_0	heat leak coefficient, W/K
M	regenerative time constant, K/s
n	mole numbers of the working fluid, mol
P	power, W
Q	heat energy, J
$\dot{Q}$	heat transfer rate, W
$\dot{q}$	heat flux, W/m^2
R	ideal gas constant, J/(mol·K)
T	temperature, K
T_a	ambient temperature, K
T_c	temperature of the working fluid during isothermal heat rejection process, K
T_H	temperature of the heat source, K
T_h	temperature of the working fluid during isothermal heat absorption process, K
T_i	initial temperature, K
T_L	temperature of the heat sink, K
t	time, s
U	overall heat transfer coefficient, W/(m^2·K)
W	Work, J
z	coordinate in the vertical direction, m

Greek symbols

α	solar absorptivity
ε	infrared emissivity
ε_R	effectiveness of the regenerator
η_m	thermal efficiency at maximum power output
η_t	thermal efficiency
λ	ratio of volume during the regenerative processes
ρ	density, kg/m^3
σ	Stefan–Boltzmann constant, 5.67×10^{-8} W/(m^2·K^4)
τ	cyclic period, s

Subscripts and superscripts

max	maximum
R	regenerator
rad	radiator
rtr	regolith thermal reservoir
s	sun
sc	solar concentrator

losses and finite regeneration processes time, the finite-time thermodynamics [18,24–26] is applied to analyze the lunar based solar thermal power system.

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. The processed regolith with thermal diffusivity which is several orders higher than that of the native regolith [11] is adopted in the regolith thermal storage.

Fig. 2 shows the working principle and the energy flow of the lunar based solar thermal power system. During the daytime, 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 Stirling generator for power generation by the high temperature fluid loop during all the day–night cycle. The Stirling generator converts the thermal energy into mechanical energy and finally to electrical power. The waste heat is transported by the low temperature fluid loop from the cold end of the Stirling generator to the thermal radiator and finally dissipated to the space.

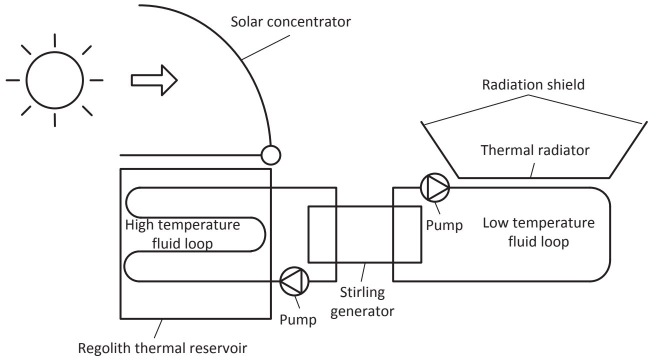

Fig. 1. Schematic of a lunar based solar thermal power system.

3. Theoretical model

3.1. Solar radiation

The solar radiation has significant difference at various places on the moon. For example, the equatorial solar flux on a unit horizontal surface varies sinusoidal during the daytime and vanishes during the lunar night with the peak heat flux about 1300 W/m^2. The time period of the solar flux is the synodic period, which is approximately 708 h [15]. While for the lunar north and south poles, the solar elevation angle would vary in a sinusoidal fashion from $-1.53°$ to $+1.53°$, and the longest lunar night is approximately 52 h [14]. For simplicity, the equatorial position with the longest lunar night is analyzed in this paper.

The solar heating of the regolith thermal storage can be enhanced by a concentrator that tracks the sun to direct the full solar flux to the regolith surface throughout the lunar day [16]. The solar flux on the surface of the regolith thermal storage becomes a square wave in this case, which can be written as,

$$\begin{aligned} &\dot{q}_{sc}(t) = C\dot{q}_{s,\max}, \quad nt_c \le t \le nt_c + t_d \\ &\dot{q}_{sc}(t) = 0, \quad nt_c + t_d \le t \le (n+1)t_c \end{aligned} \tag{1}$$