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Invited Paper

Heat storage and electricity generation in the Moon during the lunar night

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ABSTRACT

One of the biggest challenges of the exploration of the Moon is the survival of the crew and the lunar assets during the lunar night. The environmental conditions on the lunar surface and its cycle, with long periods of darkness, make any long mission in need of specific amounts of heat and electricity to be successful. We have analyzed two different systems to produce heat and electricity on the Moon's surface. The first system consists of Thermal Wadis, sources of thermal power that can be used to supply heat to protect the exploration systems from the extreme cold during periods of darkness. Previous results showed that Wadis can supply enough heat to keep lunar devices such as rovers above their minimum operating temperature (approximately 243 K). The second system studied here is the Thermal Energy Storage (TES), which is able to run a heat engine during the lunar night to produce electricity. When the Sun is shining on the Moon's surface, the system can run the engine directly using the solar power and simultaneously heat a thermal mass. This thermal mass is used as a high temperature source to run the heat engine during the night. We present analytical and numerical calculations for the determination of an appropriate thermal mass for the TES system.

1. Introduction

Long term exploration of space requires a systematic, milestone driven approach whereby critical technologies of increasing complexity are rigorously tested and verified thereby increasing our confidence level to embark on more ambitious missions. The US space flight program has shown that this approach works. There can however be a trade off as to whether this approach should be based on standalone technologies or more of a systems-type approach (comprising of several technologies all tested together like was done for the Apollo program). The latter approach allows for a more ambitious schedule but tends to be more complex and as a result carries more risk and is more cost intensive than the former approach. Designating achievable intermediate milestones for extended duration space exploration with which to quantify progress in this arena is not only prudent but also a requirement of sound engineering practice. Returning to the Moon offers the most logical way to move this quest forward. Moon-Base 2025 should be an engineering test bed for technologies applicable to long-term exploration missions. Without these technologies, long-term exploration goals will be elusive [1]. Key technologies that have to be developed and tested have been prioritized by a recent NRC study [2].

The lunar environment presents unique challenges for human exploration. It is a harsh, alien environment in the

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true sense of the word and requires technological solutions to problems that must be surmounted or mitigated if long term exploration is the ultimate goal. Short term sojourns ranging from a few days, like the Apollo missions, to a week or so can be accomplished without expending major effort into finding technological solutions. However, near-permanent presence on a human lunar outpost requires careful attention to detail and systematically worked out requirements and the means to achieve them.

We know a great deal about the Moon. It features a hard vacuum, $\sim 10^{-11}$ torr, a 14 Earth-day diurnal cycle, severe temperature day–night cycling from 150 °C to −150 °C (approximate values), no atmospheric protection from meteor impacts, a hard radiation environment, and very little water. Of course, the recent findings from the LCROSS mission [3] seem to suggest the presence of frozen water, up to ~5% by weight of the ejecta, in the permanently shadowed polar craters. Another significant challenge is dealing with the lunar regolith and associated dust (fines). Approximately 10–20% of the near-surface lunar regolith (as sampled during the Apollo moon missions) by mass is composed of particles that are smaller than 20 microns, and 90% of this regolith is typically less 1 mm in size. During the Apollo missions, there were several findings, related to the regolith, that were unexpected, some with dramatic direct impact on lunar surface operations such as EVAs that had to be curtailed because of bigger than expected space suit leaks caused, at least in part, by dust particles on the seals. Apollo experiments have provided us a wealth of data on the composition of mare regolith that are in the equatorial regions of the Moon [4]. Heat measurement experiments on the moon show that below 0.5 m, the temperature remains nearly constant at approximately −25 °C – the cave temperature of the Moon (compare this to cave temperature on Earth which is ~14.5 °C). This means that a few feet of lunar regolith can effectively shield against a fairly large surface temperature variation of ~300 °C. Order of magnitude calculations shows that habitat protection from meteors can be achieved by ~1 m of regolith shield. Detailed radiation code calculations show that a regolith shield of 1–3 m of lunar regolith can ameliorate the major impacts of space radiation, consisting of galactic cosmic rays and solar energetic particle events. This does not preclude effects from cascading lower energy radiation that will require more sophisticated and customized solutions [5,6].

So in some respect we are destined to be cave dwellers on the Moon if we plan on long duration stays. Near continuous presence using a rotating crew approach can help alleviate this requirement and allow above surface presence with carefully engineered habitats while maximizing solutions derived from in situ resources and adaptations. Spending a night on the moon presents a logical, formidable but achievable first challenge that we must confront and surmount.

In this paper we consider different alternatives for the energy storage and electricity production on the Moon for a mission during the lunar night.

2. Thermal Wadis and thermal energy storage system

Thermal Wadis [7,8] are engineered sources of stored solar energy which use modified lunar regolith as a thermal storage mass (Fig. 1). Wadis can supply heat during the lunar night

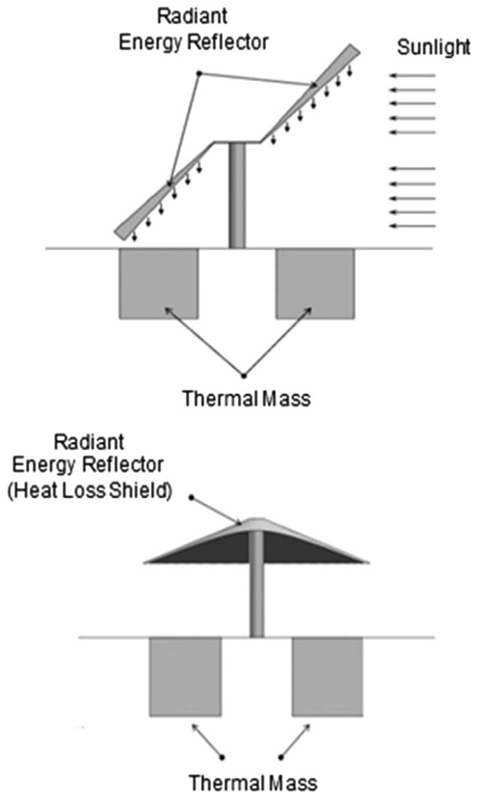

Fig. 1. Lunar thermal Wadi concept [7,8].

and enable the operation of lightweight robotic rovers or other assets in cold, dark environments without incurring potential mass, cost, and risk penalties associated with various on board sources of thermal energy.

The best terrestrial batteries utilizing liquid electrolytes freeze at approximately −50 °C rendering electrical machinery dependent on this power in operational. For example, the Mars exploration rovers operate within a ±40 °C envelope. During a typical night on Mars the temperature can reach −96 °C and special heating/insulation strategies are adopted to maintain the operational limits. The basic concept of a thermal Wadi consists of a thermal mass plus one or more energy reflectors for reflecting solar energy onto the thermal mass during periods of sunlight and reflecting radiant energy back to the thermal mass during periods of darkness. During periods of sunlight, thermal energy is absorbed and stored within the thermal mass. During periods of darkness the stored energy is used to provide temperature control for rovers and other exploration assets.

The Wadi system can be useful to provide heat directly to the rovers. Alternatively, in order to produce electricity to use during the lunar night, a system like the Thermal Energy Storage [9] (TES) system can be considered (Fig. 2).

The TES concept is based on the concentration of the sunlight to heat a thermal mass or High Temperature Thermal Energy Reservoir (HTTER) through a reflector/concentrator/collector (RCC) system during the lunar day. The HTTER, made of modified regolith, stores heat during the day and runs a heat engine (Stirling) during the lunar

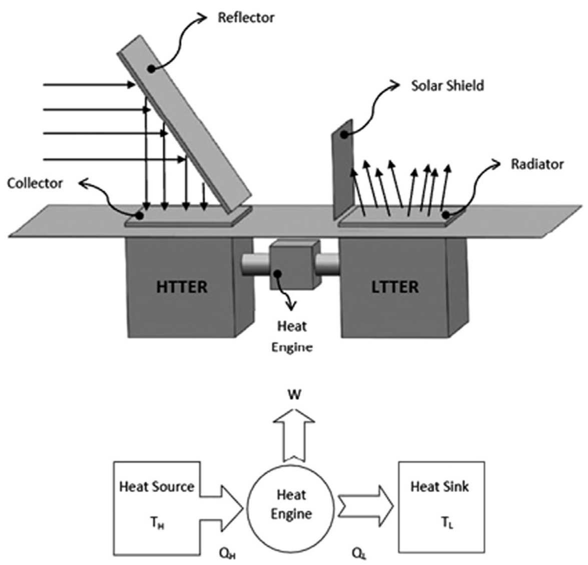

Fig. 2. Thermal Energy Storage (TES) concept [9].

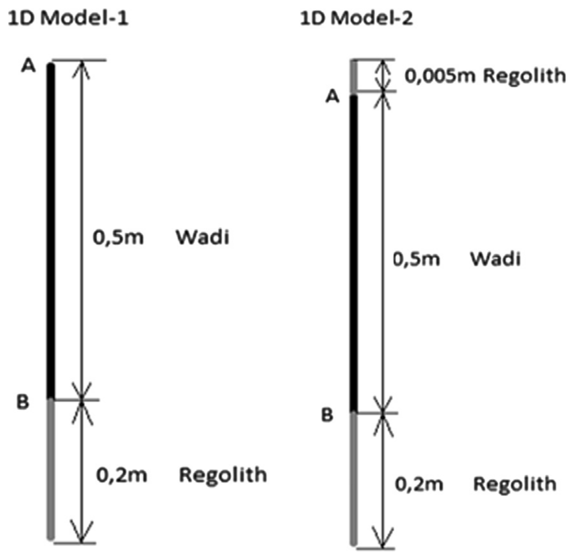

Fig. 3. Model-1 (left) and Model-2 (right).

night to produce electricity. The system can also produce electricity during the whole lunar cycle. The Low Temperature Thermal Energy Storage system (LTTER), the Solar shield and the Radiator are used to keep the low temperature source of the heat engine cold.

The choice of appropriate HTTER and RCC systems is essential to obtain the required high temperature to heat the HTTER and to run the heat engine.

3. Heat reservoir and collector systems

We consider the Wadi concept as an initial option to build the HTTER. The aim is to determine whether the temperatures reached by the Wadi are high enough to be able to run a heat engine at night. We assume that the engine has to be kept at a minimum temperature of 700 K [9].

The variation of temperature at different points of the Wadi has been studied by means of the computational fluid dynamics tool COMSOL [10], considering the assumptions presented by Balasubramaniam et al. [7,8] for the equatorial region. The ambient temperature T_{amb} dependence on the solar flux can be expressed as

$$T_{amb} = 60 \times \frac{solarflux(t)}{1300} + 110 \tag{1}$$

Two expressions of the solar flux have been taken into account. On one hand, *solarflux*(*t*) corresponds to the solar flux in the Wadi without any reflector. On the other hand, *solarfluxtrack*(*t*) corresponds to the solar flux with a Sun-tracking reflector.

For $[n \times 1\,274\,400 < t < 1\,274\,400 \times (n+1)]$

$$solarflux(t) = 1300 \times \sin\left(\frac{\pi \times t}{1\,274\,400}\right), \quad solarfluxtrack(t) = 1300 \tag{2}$$

For $[1\,274\,400 \times (n+1) < t < 1\,274\,400 \times (n+2)]$

$$solarflux(t) = 0, \quad solarfluxtrack(t) = 0 \tag{3}$$

where $n = 0$, 2, 4, 6 and 1 274 400 s (354 h) correspond to the semi-sinodic period of the Moon. The solar flux incident on the surface is assumed spatially uniform. The absorptivity and native emissivity of the Wadi surface are considered constant and equal to 0.9.

The maximum and minimum surface temperatures depend on the incident solar flux, the depth of the Wadi and its thermal properties. The thermal properties of basalt rock (modified regolith) have been considered. Lateral heat losses to the regolith surrounding the Wadi are assumed negligible.

Balasubramaniam et al. [7] showed that 1D models are sufficiently accurate to simulate the Wadi concept. The effect of dust covering the Wadi was studied considering two 1D models (Fig. 3). In Model-1 the surface of the Wadi is directly heated by the reflector, while in Model-2 the Wadi is covered by a dust layer of 5 mm. Points A and B in Fig. 3 correspond to the Wadi surface and the deepest point underground, respectively. Thus, the maximum temperature of the system will be reached at A, while B will be at the minimum temperature.

Similar to Ref. [8], we obtained the temperature at A and B for both models with a tracking reflector and with or without a heat-loss limiting shield protection during darkness. The most favourable situation for the Wadi heating in both models corresponds to the case with heat-loss limiting protection. Fig. 4 shows the time evolution of the temperature in points A and B of Model-1 with tracking reflection and heat-loss protection. Maximum and minimum temperatures values are $T_{Amax} = 390.3$ K, $T_{Amin} = 251.9$ K, $T_{Bmax} = 388.6$ K, $T_{Bmin} = 256.9$ K.

The Wadi performance in an equatorial location illuminated by a tracking reflector and protected during darkness by a heat-loss limiting shield for the 1D Model-2 is shown in Fig. 5. Maximum and minimum temperature values are $T_{Amax} = 366.8$ K, $T_{Amin} = 285.2$ K, $T_{Bmax} = 360.9$ K, $T_{Bmin} = 293.1$ K.

As observed in Ref. [8], simulations show that the temperature does not change significantly between the extreme points in the Wadi. Moreover, when a dust layer is considered, the highest temperature is reduced and the lowest temperature is increased. In any case, thermal Wadis can provide the desired thermal energy for the survival of rovers and other equipment during periods of darkness [8]. However, in order to analyze the feasibility of thermal Wadis to perform the role of the HTTER in a TES system, one has to compare temperatures in points A and B with the required temperature for the heat engine. Considering that the engine has to be kept at a minimum temperature of 700 K, the temperatures reached in the Wadi with the reflector and the heat-loss protection are not high enough to run a heat engine efficiently during the lunar night. Thus, the alternative system consisting of an RCC connected to the HTTER has to be considered.

Among the different RCC concepts currently used on Earth (e.g. Stirling dish, solar power tower, etc.), we consider parabolic troughs and Fresnel reflectors as the most appropriate systems to use in the Moon.

Parabolic troughs consist of a long parabolic mirror (usually coated silver or polished aluminium) with a Dewar tube along the mirror's length at the focal point. Sunlight is reflected by the mirror and concentrated into the Dewar tube. The trough is usually aligned on a north–south axis, and rotated to track the Sun as it moves across the sky during the day. The temperature of the fluid running inside the tube reaches about 400 °C. The heat transfer fluid is used to heat steam in a standard turbine generator. The overall efficiency from collector to grid, i.e. (Electrical Output Power)/(Total Impinging Solar Power), is about 15%.

Fresnel reflectors use a series of long, narrow, shallow-curvature (or even flat) mirrors to focus light into one or more linear receivers positioned above the mirrors. A small parabolic mirror can be attached above the receiver for further focusing the light. The receiver is stationary and so fluid couplings are not required (as in troughs and dishes). Mirrors do not need to support the receiver, so they are structurally simpler. The overall efficiency from collector to grid is slightly lower than the efficiency of the parabolic trough. However, Fresnel reflectors present several advantages for our application compared to the parabolic troughs. They are structurally simpler and lighter, and use inexpensive planar mirrors and a simple tracking system. Moreover, the Fresnel reflectors use only one absorber tube through which the fluid used to heat the HTTER flows. This tube is fixed and does not need any flexible high pressure joints. In the case of the equatorial regions in the Moon, RCC can be composed of Fresnel reflectors since the trajectory of the Sun is nearly the same as on the Earth.

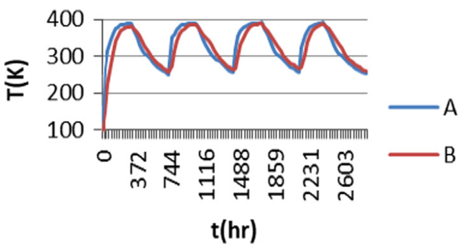

Fig. 4. Temperature evolution in points A and B for a 50 cm deep Wadi with the thermal properties of basalt rock illuminated by a tracking reflector, and with a heat-loss limiting shield (Model-1).

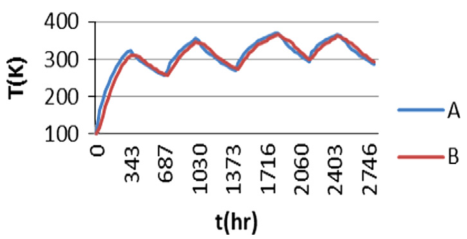

Fig. 5. Temperature evolution in time in points A and B for a 50 cm deep Wadi with the thermal properties of basalt rock, covered by a 5 mm dust layer, illuminated by a tracking reflector, and with a heat-loss limiting shield (Model-2).

Fig. 6 shows the TES system, in which a set of Fresnel reflectors has been considered for the RCC system. The heat transport between the RCC to the HTTER is carried out by means of loop heat pipes [11]. The Fresnel collector is used as the evaporator of the working fluid and the thermal mass as the condenser. Once the fluid is evaporated in the Fresnel collector, the gas flows to the HTTER warming it up. The gas is condensed while passing through the thermal mass and the cycle starts again. This process is repeated during the whole lunar day to heat the HTTER to the highest possible temperature as well as to keep the heat engine at a sufficiently high temperature. Once the lunar day is over, the thermal mass is hot and ready to provide heat to the high temperature side of the Stirling engine to run it. Now the HTTER will take the role of the evaporator and the high temperature side of the Stirling engine will be the condenser.

While the HTTER is heating the high temperature side of the Stirling engine, the low temperature side of it must be constantly refrigerated to obtain the highest efficiency $\eta_{Ss} \approx 0.6 \times \eta_C = 0.6 \times (1-T_{LH})$, T_{LH} being the ratio between the low and high temperatures at the engine. A pumped-loop heat transport system coupled to a heat pipe radiator can be used to remove the heat from the low temperature side of the Stirling cycle rejecting it to the environment through a radiator [12]. A system using only heat pipes can

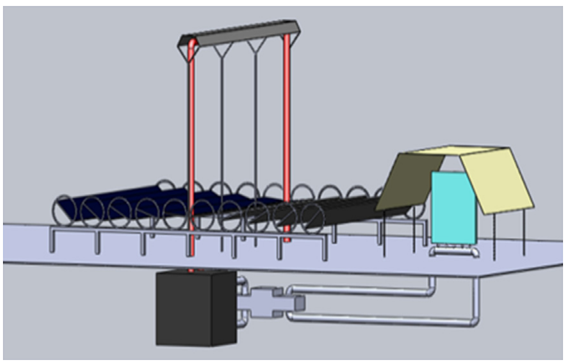

Fig. 6. TES with Fresnel reflectors as RCC. Fresnel reflectors (blue), HTTER (dark grey), Stirling engine (grey) and radiator as a part of the LTTER with its shield (turquoise and beige, respectively). (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

also be developed. In this case, the low temperature side of the engine will work as the evaporator and the radiator (LTTER) as the condenser.

In order to be able to carry out a practical demonstration of the TES system, geometry, dimensions and distribution of the components have to be defined. To do so, analytical and numerical work based on an optimization of the weight and the efficiency of the system is required.

4. Heat Storage in the TES

4.1. Heat requirements

The number of reflectors (NR) in the RCC system is determined by the amount of heat required to run the Stirling engine. In order to determine NR, we have considered a HTTER made of modified regolith (basalt rock) with the dimensions shown in Fig. 7.

The analysis to determine the required NR has been carried out under the following assumptions:

- All the calculated flux is used to heat the fluid through convection.
- Forced convection is considered since the fluid flows by the effect of external forces.
- The steady temperature at the HTTER is $T_H = 1000$ K.
- Heat losses in the pipes are 20%.
- The temperature of the high temperature side of the heat engine must be 700 K to properly run the engine.
- The forced convection heat transfer coefficient for water is $h = 50$ W/m^{2}K.

Heat is transmitted in the HTTER by conduction. In order to determine the heat flux q in the HTTER, we can simplify the calculations by considering that the heat flux is the same and symmetric in all three axes. Hence, we can perform the analysis in only one dimension (x), assuming the pipe that heats the HTTER as a thin wall (see Fig. 8).

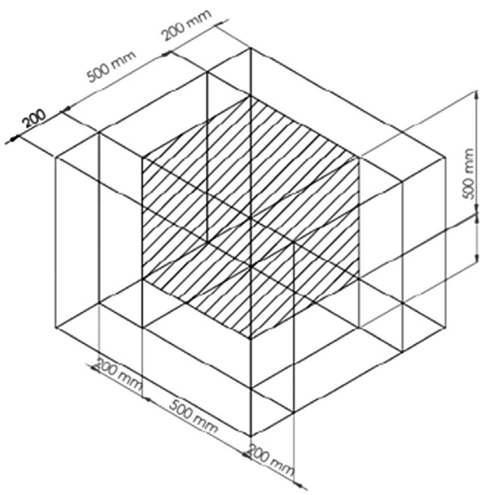

Fig. 7. HTTER surrounded by lunar regolith.

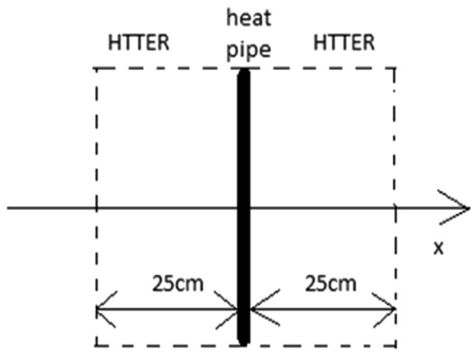

Fig. 8. HTTER for the calculations in the x-axis.

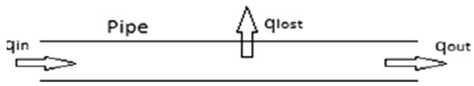

Fig. 9. Heat transfer in the heat pipe.

The conservation of energy is given by

$$\rho c \frac{\partial T}{\partial t} = k_x \left(\frac{\partial^2 T}{\partial x^2} \right) + S \tag{4}$$

where ρ is density, c is the specific heat, k_x is the thermal conductivity, T is temperature, t is time, and S is the heat source. During the lunar day, the Sun is constantly heating the HTTER, which reaches a steady state after a few hours. Temperature in the steady state is given by

$$T = -\left(\frac{S}{2K_x} \right) x^2 \tag{5}$$

The heat flux can be determined by means of the Fourier law

$$q_x = -k_x \frac{\partial T}{\partial x} = S_x \tag{6}$$

Similarly, $q_y = S_y$ and $q_z = S_z$.

The HTTER heats (q_{in}) by means of convection the fluid in the pipes that flows to the Stirling engine and heats (q_{out}) it. The process is illustrated in Fig. 9.

The heat transferred by convection from the edge ($x = 0.25$ m) of the HTTER to the fluid at temperature T_f is given by

$$q_{in} = q_x = h \cdot (T_H - T_f), \tag{7}$$

which, combined with Eq. (6), yields to

$$S \cdot 0.25 = 50 \cdot (1000 - T_f) \tag{8}$$

The heat transfer equation in the heat pipe is given by

$$q_{in} = q_{lost} + q_{out}, \tag{9}$$

which can be expressed by

$$50 \cdot (1000 - T_f) = 0.2h \cdot (1000 - T_f) + h \cdot (T_f - 700) \tag{10}$$

Solution of Eq. (10) yields to $T_f = 833$ K, which, substituted into Eq. (8) gives a required amount of heat of $S = 33\,333$ W/m^3 and $q_x = 8335$ W/m^2. Thus, the RCC should supply 33 333 W/m^3 to the HTTER through the heat transfer system in order to keep it at 1000 K and the heat engine at 700 K.

The required number of reflectors NR can be determined from q_x and the following expression:

$$NR = \frac{Solarflux}{Solarconstant \cdot \alpha_1 \cdot \alpha_2 \cdot A_{reflector}} \tag{11}$$

where $Solar\ flux = q_x\ A_{pipe}$, A_{pipe} being the area of the pipe illuminated by the reflectors, $\alpha 1$ and $\alpha 2$ are the reflectance of the primary and secondary reflectors, respectively, and $A_{reflector}$ is the area of a reflector. Considering a 5 m long pipe with an 8 cm diameter, $\alpha 1 = 0.92$, $\alpha 2 = 0.95$ [14], $A_{reflector} = 2\ m^2$, and assuming a solar constant of 1300 W/m^2, the minimum required number of reflectors is 5 ($NR = 4.6$). If additional pipe transmission losses are taken into account, NR will increase.

4.2. Thermal mass heating

Analytical calculations presented in Section 4.1 are limited by the considered assumptions. In particular, the transfer of heat in different pipe geometries presents some difficulties to study analytically. We have used the computational fluid dynamics tool ANSYS/FLUENT [13] to perform a preliminary study of two pipe geometries. Our goal is to analyze the HTTER heating and to obtain the time evolution of the temperature inside the HTTER for the pipe geometries shown in Figs. 10 and 11. The main difference between them lies in the pipes inside the HTTER. In Geometry 1, heat is transferred from a single pipe to the thermal mass. In Geometry 2, flow is diverted into two pipes when crossing the HTTER.

The HTTER and the heat engine are made of modified regolith with a 5 mm layer of dust above them. Native lunar regolith properties have been considered for material surrounding the HTTER and the engine. In order to be able to work with a high range of temperatures, incompressible liquid water has been considered as the fluid in the pipes. Temperature at the collector is taken constant and equal to 1000 K. The initial temperature at the rest of

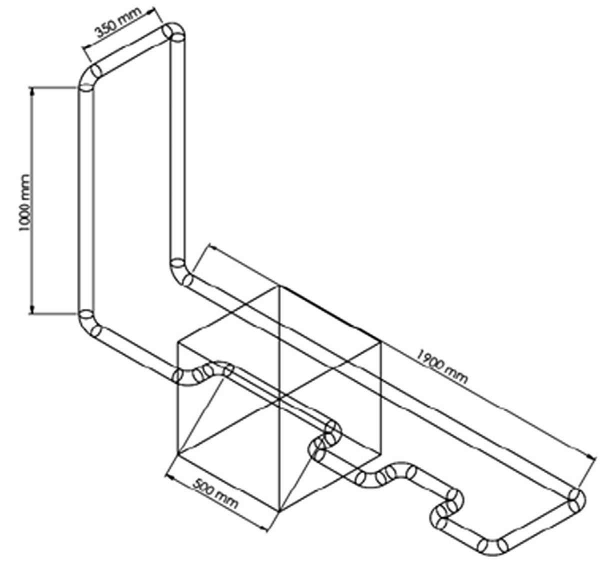

Fig. 10. Geometry 1.

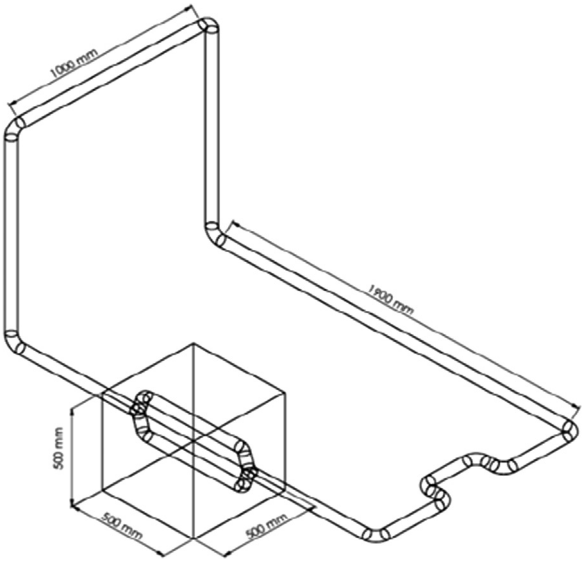

Fig. 11. Geometry 2.

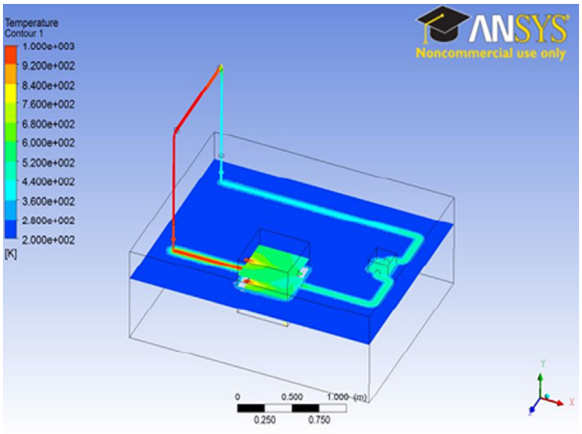

Fig. 12. Temperature distribution in the TES.

the system has been obtained from Fig. 5. According to this figure, the temperature at the beginning of the lunar day of the underground regolith illuminated by a tracking reflector and with a heat-loss limiting shield is approximately 250 K. The same initial temperature has been considered in the fluid.

Fig. 12 shows the temperature distribution in the TES system in the case of Geometry 2 at a time in the transient state before the maximum temperature is reached.

Figs. 13 shows the time evolution during the lunar day of the temperature at the most remote point from the pipe in the HTTER at a fixed fluid speed of 10 m/s for Geometries 1 and 2. Although in both cases a steady state is reached, the temperature obtained in Geometry 2 is significantly higher than the one obtained in Geometry 1.

During the lunar day, the heat collected by the RCC is used to heat both the HTTER and the Stirling engine. Fig. 14 shows the evolution of the temperature in the heat engine for each geometry. The temperature at the steady state in both geometries is higher than the required 700 K.

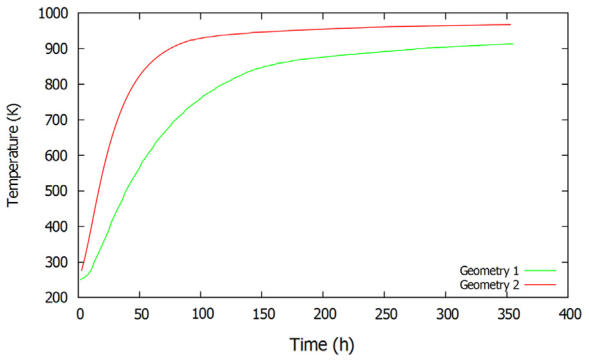

Fig. 13. Temperature evolution during the lunar day in the HTTER for Geometries 1 and 2.

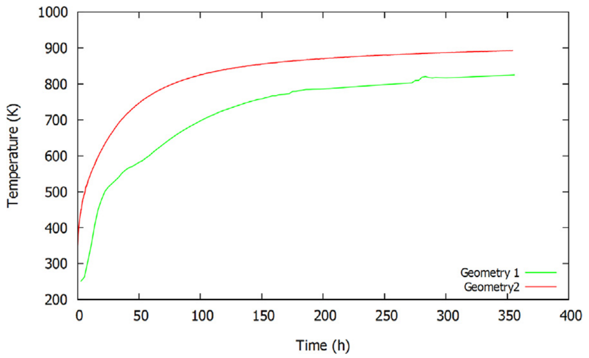

Fig. 14. Temperature evolution during the lunar day in the heat engine for Geometries 1 and 2.

However, the Stirling engine reaches a higher temperature in Geometry 2 than in 1. Thus, we can conclude from Figs. 13 and 14 that the geometry with the largest contact area with the thermal mass (Geometry 2) is the most appropriate one to heat the HTTER and the heat engine.

Temperatures in the HTTER and the Stirling engine can be increased if the heat source provides a higher temperature to the fluid, which can be achieved by optimising the design of the RCC. Fig. 15 shows the evolution during the lunar day of the temperature in the heat engine in the case of Geometry 2 when two different heat fluxes are considered in the RCC. Increasing the heat collection at the RCC induces higher temperatures at the heat engine which in turn results on a larger electricity production.

5. Conclusions

We have presented a study on two concepts for the thermal energy storage and electricity production in the Moon. Thermal Wadis are good candidates to provide the required thermal energy for the survival of rovers and other equipment during periods of darkness. However, temperatures reached in a Wadi heated with a reflector and with a heat-loss protection are not high enough to run a heat engine efficiently during the lunar night. We have considered an alternative concept consisting of a reflector/concentrator/collector system connected to a thermal mass. An analytical estimation on the required number of reflectors as well as

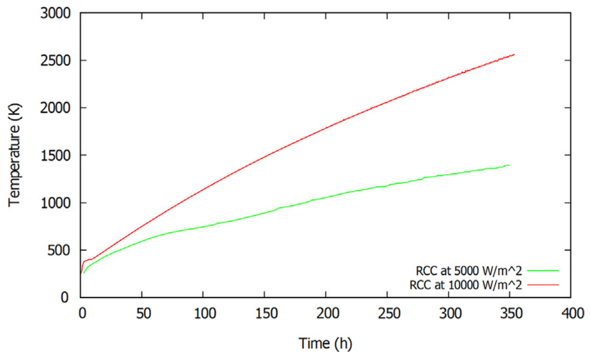

Fig. 15. Temperature evolution during the lunar day in the heat engine for Geometry 2 at different heat fluxes in the RCC.

numerical simulations on the temperature behavior for two different pipe geometries has been carried out. The geometry with a largest contact area with the thermal mass showed a more appropriate performance.

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