A Liquid Sheet Radiator for a Lunar Stirling Power System

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This paper will propose a new lunar based power system consisting of a concentrated sunlight heat source (without detail), a Stirling convertor, and a liquid sheet radiator. Radiative effects are calculated and presented for both a spherical and a planar liquid sheet radiator using the waste heat rejection demands of the 25 kW Stirling convertor. The design of the liquid sheet radiator is evaluated on the effects of dust propagation, system cost, specific power, overall weight, and efficiency.

I. Introduction

In NASA's new vision for space exploration program, extended human presence on the moon is a primary focus. Lightweight, highly efficient, nighttime capable, and survivability to broad temperature swings are the necessary parameters for a lunar power supply. NASA exploration missions envision a nuclear reactor power system placed on the lunar surface.

In the 1990's, NASA successfully developed and tested a 25 kW free piston Stirling convertor under the SP-100 space nuclear power program. This program demonstrated the feasibility of the free piston Stirling convertor system for space power systems. Mass estimates based on known technology advances at that time projected a convertor specific mass of 4.9 kg/kWe. Since that time, new developments in free piston Stirling convertors have produced smaller and lighter versions.


Figure 1: Artists concept of a LSR on lunar surface.

Lunar power system designers face the challenge of how to dissipate large amounts of heat in an environment that experiences both temperature extremes in a single lunar cycle without adding massive weight to the system. Traditional heat pipe radiators can make up 50% of the weight on a power system and have been the key limitation for high power reactor power systems coupled to dynamic conversion subsystems. A lightweight alternative to traditional heat pipe radiators is a modified Liquid Sheet Radiator (LSR) as shown conceptually in figure 1. The liquid sheet radiator was extensively explored by NASA-Lewis researchers and the basic characteristics defined and confirmed experimentally in the 1990 time frame. This new design of the liquid sheet radiator has been adapted for planetary surfaces by enclosing the radiating liquid within a transparent envelope. The liquid that flows down the inside of this envelope is only 300 µm thick and has an optical emissivity of 0.85 at a temperature of 373 K. Initial calculations to determine the radiator size needed to dissipate waste heat indicate an envelope diameter of approximately 5 m at a specific mass of 1.5 kg/m^2 would be suitable for a 25 kW Stirling-based power system.

This paper will propose a new lunar based power system consisting of a nominal concentrated sunlight heat source (without detail), a Stirling convertor, and a liquid sheet radiator. Radiative effects will be calculated and presented for both a spherical and a planar liquid sheet radiator using the waste heat rejection demands of the 25 kW Stirling convertor. The design of the liquid sheet radiator is evaluated for the effects of dust propagation, system cost, specific power, overall weight, and efficiency. The enclosed liquid sheet radiator when combined with a free piston Stirling convertor may lead to a new lunar power system and can be extensible to other high power space thermal systems.

II. System Overview

The purpose of this paper is to describe a lunar power system concept using a heat source based on concentrated sunlight with an updated 25 kW free piston Stirling convertor and a newly designed liquid sheet radiator. Each component has been selected due to its operating performance, efficiency, durability, and weight, which coincide with payload delivery costs. Limiting characteristics of this system are described along with potential solutions and areas of future research.

The SP-100 effort projected a specific mass for a 25 kW free piston Stirling engine at 4.9 kg/kWe. Free piston Stirling systems have exceptionally long lifetimes, in excess of the 60,000-hour life requirement, due to the absence of wearing mechanisms. In addition, Stirling engine systems demonstrate high efficiency at temperature ratios of 2 to 2.5 and can operate on any source of heat. Other advantages of the Stirling system include an alternating current output, which can simplify power management systems, and the waste heat can also be used for process heating.

This new version of the liquid sheet radiator, adapted for planetary surfaces, is essentially a fountain enclosed in a transparent envelope. The liquid that flows down the inside of this envelope is thick enough to have high optical emissivity for the system. One additional characteristic of the liquid sheet radiator concept is that it is exceptionally stable and does not require special machining of the orifice to achieve its performance. Based on existing data, this system could achieve a specific power equivalent to or better than the conventional solar arrays in use today.

III. Lunar Design Considerations

This study's primary focus is to describe a 25 kW lunar Stirling power system concept for the lunar surface. Lunar base power system design considerations include: extreme temperature cycling, limited heat transfer modes, gravity, reflectivity of solar energy, radiation, micrometeoroid bombardment, soil abrasiveness, atmospheric contamination, electrostatic charging of dust, opacity, and extended night.

The maximum temperature at the lunar equator at noon has been calculated at 387 K.[1] Temperatures drop below 100 K during the lunar night. Thus materials used on the lunar surface would need to withstand the severe stress of this temperature cycling. Figure 2 shows a typical lunar temperature profiles as well as a comparison to Mars.

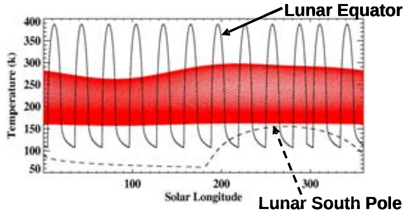

Figure 2: Lunar temperature profiles compared to Mars (red)

High daytime temperatures cause difficulty in cooling the system. The three heat loss mechanisms are convection, conduction and radiation. The lack of atmosphere eliminates convection. Conduction is limited due to the poor thermal conductivity of the regolith. The surface can heat to 380 K but at a depth of 1 meter the temperature stays at 238 K. Thus radiation is the only practical method to reject unwanted heat. Waste heat from a power system will be rejected through radiation to the surroundings. The high lunar temperature during the day lowers the ability of a radiator to dissipate waste heat efficiently.

The gravity on the moon's surface is 1.623 m/s^2, approximately 1/6th of the gravity on earth. This low gravity will assist in the design of the liquid sheet radiator allowing for a natural gravity induced fountain to be used with minimal pumping power. The intensity of solar energy falling on the lunar surface is about 1370 W/m^2. Radiation is also experienced in the form of cosmic rays, the solar wind, and solar flares. With no atmosphere, micrometeoroid damage is prevalent on the moon. Meteoroids range from 10 g to 100 kg with velocities ranging from 2.4 to 72 km/s.[2] A lunar base system must be designed to withstand the impact of some of these particles.

The consistency of the regolith ranges from dust to silt to fine sand. Electrostatic charging of lunar dust will be a problem for any surface system. Dust will cause thermal control problems by reducing the emissivity of surface thus lowering its radiative properties. Dust also does damage by abrading materials leading to seal failures.[3]

IV. The Concept

The concept consists of a new lunar based power system consisting of a nominal concentrated sunlight heat source (without detail), a Stirling convertor, and a liquid sheet radiator. The low temperature side of the Stirling convertor is connected to a new liquid sheet radiator enclosed in a polymeric envelope. The following sections describe each of these two subsystem elements.

Stirling Convertors

The Stirling convertor has been demonstrated in various applications around the world. However, nearly all used kinematic engines. Kinematic engines have wear mechanisms that limit their lifetime and require maintenance, thus they are not suitable for space use. The free piston Stirling convertor on the other hand is an optimal candidate for space use due to the absence of wear mechanisms. The Stirling engine system demonstrates high efficiency at a (T_H/T_C) ratio of 2 to 2.5 whereas Brayton or Rankine systems require a ratio of 3 to achieve a similar efficiency.[4]

In the 1990's, NASA developed a 25 kW free piston Stirling convertor for testing under the SP-100 space nuclear power program. The 25 kW convertor shown in figure 3 consisted of two 12.5 kW convertors connected through the central heat source.

Figure 3: 25 kW Stirling SPDE (1992)

Later the system was disassembled into two separate convertor units. The system goal was a T_H of 1050 K and T_C of 525 K and a ratio of 2. In order to save time and costs, the convertor was made from Inconel 718 and operated at a hot end temperature of 650 K and a cold end of 325 K. It operated for 1500 hrs of virtually unattended operation at 25% efficiency.[5]

This program laid a solid foundation by demonstrating the feasibility of free piston Stirling convertor systems for space power systems. Mass estimates based on known technology advances projected a convertor mass over 200 W/kg (4.9 kg/kW).[5] Since that time, new developments in free piston Stirling convertors have produced smaller and lighter versions. These convertors operate as high as T_H of 925 K and T_C as low as 325 K for a ratio of 2.8 and efficiencies above 30%. Advanced developments incorporating ceramic materials have the potential to support a hot end temperature of 1275 K.[6]

Recently, significant progress has taken place in increasing the specific power of free piston Stirling convertor systems.[7] Figure 4 shows the specific power of the Space Power Demonstrator Engine (SPDE) of 1992 as well as various expert opinions and a projection over a range of sizes. It appears that the use of a free piston Stirling convertor system for a lunar power system is feasible.[8,4] The free-piston Stirling convertor can meet the 60,000 hour life requirement for a lunar thermal system because it can be hermetically sealed and has no rubbing parts. The Stirling convertor will be actively controlled to regulate the power output under varying loads. The Stirling convertor output is alternating current, which may have an advantage for the lunar surface base.

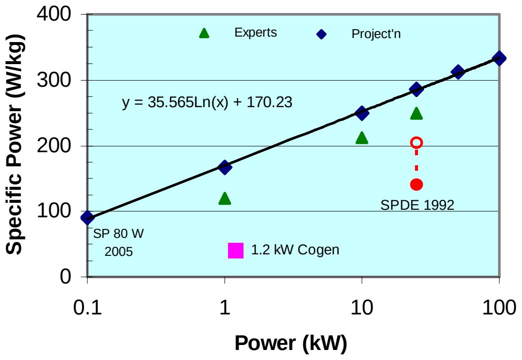

Figure 4: Specific power projections for modern free piston Stirling convertors

Liquid Sheet Radiator (LSR)

In space, radiation is the primary form of heat transfer. The amount of heat that can be radiated to space by a given surface area is proportional to the difference in the forth power of the radiating surface temperature and the fourth power of the surrounding temperature or temperature sink. The lower the heat rejection temperature, the higher the efficiency of the radiator, but the higher the heat rejection temperature, the smaller and lighter the radiator. This leads to a tradeoff between efficiency and weight for the entire system. High launch costs and limited volume require low total mass even at the cost of lowering the efficiency of the entire system.

When designing a radiator for a Stirling convertor, the ratio between the hot end temperature and the cold end temperature (T_H/T_C) determines most of the radiator properties. If the Stirling engine has a hot end temperature of 925 K with a ratio of 2, the cold end (rejection) temperature will be approximately 460 K. Likewise for a T_H/T_C ratio of 2.3 the rejection temperature drops to 400 K. Liquid sheet radiators are suitable for moderate rejection temperatures around 400 K and when small differences in temperature are available to reject the required heat flux.[9]

The rejection temperature also affects the overall weight of the system. If the thermal load is compatible with the working fluid, a heat exchanger is not needed. The working fluid can be used throughout the entire system saving weight and complexity. The liquid sheet radiator would behave like a constant temperature radiator because the temperature drop between the rejection and collection is very small.[8] Figure 5 shows the sheet area required to dissipate 75 kW of heat flux based on the rejection and sink temperature.

For radiator applications in areas with gravity, a new design of an encapsulated liquid sheet is proposed. The liquid sheet would be sprayed upward through a rectangular slot. Due to fluid surface tension conditions in a vacuum, the sheet will form a triangular configuration that coalesces to a single point. This point would contact the uppermost part of a thin film sphere and the fluid would flow down the sides of the sphere giving the appearance of a decorative fountain (Figure 1). The working fluid would be collected by a simple pool at the bottom of the sphere and be returned to the system. A variation on this design would be a planar liquid sheet radiator (LSR) arranged vertically and enclosed within an envelope.

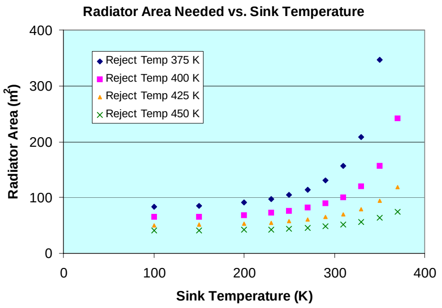

Figure 5: Radiator area needed to dissipate 75 kW waste heat for four different Stirling convertor rejection temperatures verses the Lunar heat sink temperature.

Different working fluids can be used based on the heat rejection temperature. Silicone oils, which have a high emissivity, work well in the range of 300 – 400 K. The rejection temperature affects the evaporative loss, however, because this system operates in an envelope, these losses have been ignored. Dow Corning 705 and Dow Corning ME_2 are the two working fluids that have been considered. For reject temperatures lower than 350 K, Dow Corning 705 is the better choice due to its higher emissivity. At higher reject temperatures, ME_2 is a better choice due to lower evaporative rate.[10]

Other design constraints for the radiator include its low mass and compactness for transportation, be easy to install once on the moon, and work reliably for extended times without maintenance. Mass is an issue because the mass of the radiator can make up about 50% of the total mass of a space power sytem.[9] The liquid sheet radiator has an estimated mass of 1.5 kg/m^2.[8]

V. LSR Theory

The overall heat transfer rate is given by the following equation:

$$Q = \sigma_{SB} \int \varepsilon(T,d)(T_f^4 - T_s^4)\,dA \qquad (1)$$

where σ_{SB} is the Stefan-Boltzmann constant, ε is the fluid emissivity, T_f is the fluid temperature, and T_s is the sink temperature. This equation quantifies the relationship between radiator area and heat flux to be dissipated.

The greater the temperature difference between the rejection temperature and the heat sink temperature, the easier it is to dissipate waste heat with a smaller radiator. In deep space, this is easily attained since the heat sink is near absolute zero. When on a planetary surface, the amount of heat radiated from the planets surface and reflected energy from the sun must be considered. A thermal equilibrium must be calculated. The maximum temperature at the lunar equator at noon has been calculated to be 387 K.[2] For power system heat rejection calculations a mean effective daytime lunar sink temperature of 360 K was determined by radiatively coupling the lunar sky temperature with the lunar surface temperature profile.[11] For lunar applications waste heat elimination is limited due to the small difference between the rejection temperature and heat sink temperature. The sink temperature can be lowered to approximately 340 K if the radiator is in a horizontal configuration.[11] In order to reduce the heat sink even further; the area around the radiator could be covered with a highly reflective aluminized blanket. This would decrease the sink temperature to 230 K and would only increase the mass of the radiator system by less than 0.1 kg/m^2.[11] Another option would be to place the radiator in a crater where it is not illuminated by sunlight.

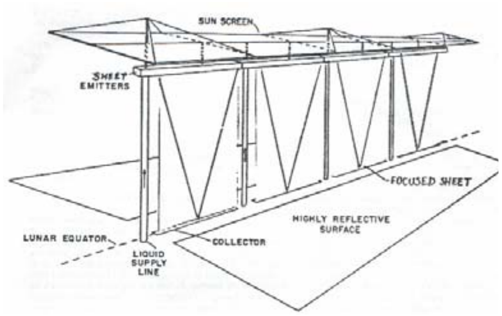

Figure 6: Conceptual LSR configuration for lunar power system by A. P. Bruckner

In previous liquid sheet radiator designs as seen in figure 6, multiple sheets were needed to create large radiating surface areas to dissipate the heat flux. This was due to the fluid dynamics that control spread of the liquid sheet. Sheet width does not seem to be stable above one meter. Experimental testing has only been done on sheets with a maximum width of 23.5 cm due to lack of testing facilities. The multiple sheet design works well for power conversion systems on the scale of 1 to 5 kW. However, as the convertor increases in size so does the radiator to control waste heat. For a 25 kW converter, a liquid sheet radiator would need to be made up of over 30 sheets; each with a 0.5 m width. The fountain design for the basic liquid sheet radiator significantly increases the radiative surface area without increasing the geographical area. Figure 7 shows the amount of sheets needed in a liquid sheet radiator to dissipate 75 kW of waste heat at various temperatures. Each sheet is 0.5 m in width and 5 m long. The sheet area is divided by half due to the triangular sheet configuration but is then doubled due both sides radiating heat to the surroundings. Figure 8 shows the sphere diameter needed to dissipate the same amount of heat flux over the same temperature ranges. The overall area needed to dissipate the waste heat does not change between the two designs but the configuration of the LSR does change.

The enclosed liquid sheet configuration combines two different radiative shapes. The surface area of the sphere would radiate excess heat to the surroundings in addition to the triangular sheet inside the sphere. This study lessens the complexity of the radiative properties of the system by primarily focusing on the radiative affects of the sphere. It is important to note that the length of the liquid stream must be approximately the same length as the diameter of the sphere and the sphere must be completely coated for maximum radiative effect. Adhesion of the fluid sheet to the inside of the sphere and flow down the sides is a design feature and is strictly related to the surface tension of the fluid, the upward velocity of the sheet, and the force of gravity. The sphere will be made of a thin film from a polymer such as Teflon or polyethylene terephthalate (PET). Thickness would be about 6 to 12 μm thick. The sphere must also have a conductive layer to help prevent dust accumulation and for UV protection. Internal charging of the stream would also be mitigated by a proper coating. The radiator may also have a shield to block the direct solar radiation on the streams.

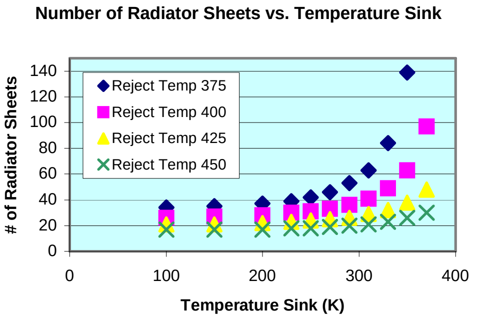

Figure 7: Stirling convertor rejection temperature shown on a plot of the number of liquid sheets needed to dissipate 75 kW waste heat to the lunar temperature sink. Each sheet is 0.5m wide and 5m long.

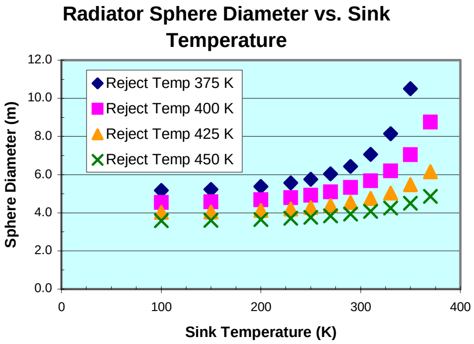

Figure 8: Stirling convertor rejection temperature shown on a plot of the radiator sphere diameter needed to dissipate 75 kW waste heat versus the lunar sink temp.

A liquid sheet radiator has several design constraints affecting the stability of the sheet, which include the surrounding environment, gravity, sheet surface tension, sheet velocity, and sheet geometry. The liquid sheet needs to be in a near vacuum or the liquid to gas interaction will cause the sheet to break up. Gravity also affects the liquid sheet. The Froude number, which is the ratio of the kinetic energy to the gravitational energy, can be calculated by the following equation.

$$Fr = \frac{w_0^2}{gW} \qquad (2)$$

where w_0 is the sheet velocity, g is the lunar gravity, and W is the width of the slit where the sheet is being ejected. The Froude number depends primarily on the velocity of the sheet flow. When the Froude number is greater than 50, gravity can be neglected.[12] This allows for the sheet length to width ratio to be equated to the Weber number by the simplified equation shown below.

$$\frac{L}{W} = \sqrt{\frac{We}{8}} \qquad (3)$$

The sheet length to sheet width ratio needs to be greater than 3.5 for stability and seems to be optimal around 10.[13]

The Weber number (We) is the ratio of the dynamic pressure to the surface tension pressure. It is calculated using the following equation.

$$We = \frac{\rho \tau w_0^2}{\sigma} \qquad (4)$$

where ρ is fluid density, τ is the sheet thickness, and σ is the surface tension. The liquid surface remains stable for Weber numbers up to at least 3000.[9] Another dimensional constraint is the slit width to sheet thickness must remain in 200-4000 range for stability.[9]

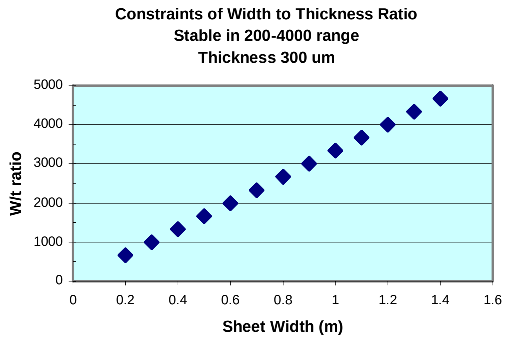

Figure 9: Stable sheet flow requires the width to thickness ratio to be in the 200-4000 range. Widths more than 1.2 m appear to be unstable

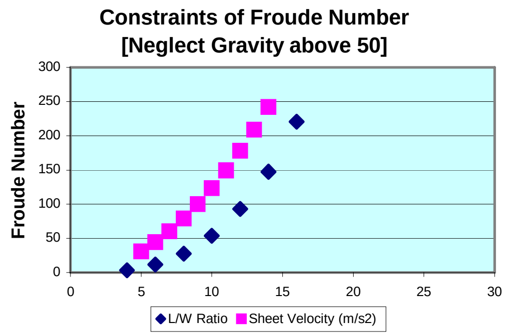

Figure 10: Constraints for L/W ratio and sheet velocity

Once the heat flux, rejection temperature, and sink temperature are determined, the exact dimensions of the liquid sheet and sphere diameter can be devised using the constraints of the Froude number, Weber number, and ratio of width to thickness. Figures 9 and 10 show the constraints of the Weber and Froude numbers on sheet length and velocity for a heat flux of 75 kW, a 400 K rejection temperature, and a 230 K sink temperature. The optimal parameters for this 25 kW power system with a T_H/T_C ratio of 2.3 are a sheet width between 0.3-0.6m, a sheet length between 4-6 m, and a sheet velocity between 6-10 m/s. The sheet thickness is constant at 300 μm allowing for a minimum emissivity of 0.8. By combining all of the above constraints, a workable radiator system to remove the excess heat from a Stirling engine used on the lunar surface can be designed.

VI. System Summary

This study is a first order system design of a new radiator system for the lunar surface. Further research needs to be done on key elements of the system – especially the liquid sheet radiator. Radiative effects have been calculated and presented for both a spherical and a planar liquid sheet radiator. Both configurations meet the waste heat rejection demands of a 25 kW Stirling convertor. One advantage of a spherical system over an elongate system is the effect of dust. The spherical system would be higher off the ground lowering the dust cover and reflected heat. The spherical design would also lower the amount of polymer film needed to encapsulate the liquid sheet.

Specific power calculations for future free piston Stirling convertors were shown in figure 4 and reach over 200 W/kg at the 25 kW size. This was based on a minimal projected specific mass for a Stirling engine being 4.9

kg/kWe. The specific mass of the LSR with fluid was shown to be 1.5 kg/m^2. Combining these values into an overall radiator system yields a system specific power comparable to lightweight designs of today. This design is lightweight, efficient, and affordable. With further study is has the ability to become a new lunar radiator system.

VII. Conclusions

This simplified analysis indicates that a free piston Stirling convertor combined with a liquid sheet radiator makes a feasible radiator system concept. Future studies must include the effects of lunar dust and micrometeoroid impact on the thin film sphere and liquid sheets, temperature cycling under the harsh lunar environment, fluid flow dynamics, and the interface of the liquid sheet and sphere. In addition, more exact weight estimates for the entire system, with a breakdown of all components and accessory parts is needed. The impact of the lunar habitat and long term effects on all equipment deserves additional study.

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