Solid particle radiator systems for heat rejection in space

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Abstract. The radiator for the heat rejected in space proposes a new technological solution which utilizes a stream of solid particle to radiate waste heat. This paper presents the concept of Solid particle radiator (SPR) and highlights the distinctive characteristics of SPR and the Liquid droplet radiator (LDR). The design model of the solid particle radiator system was established and evaluated from the viewpoint of reducing the rate of mass per unit power, avoiding the contamination due to the loss via evaporation and enhancing the efficiency of heat transfer. And the radiating temperature of this system could range to a large extent in the case of without considering evaporation loss. The mass model of system was presented here, and the evaluation parameters were used to analyze the performance of SPR in the different conditions. When compared with the performance of the liquid droplet radiator under the same condition of different mediums and Heat Pipe radiator, the SPR manifests the differences in the variations of thermal load, mission time and other design parameters of the system. Finally, this radiator exhibits the significant potential of substituting for the conventional radiator and the LDR in space according to the calculation results. Thus, the Solid particle radiator could be employed for a wide range of heat rejection applications in space.

1. Introduction

The aim of the space radiator system for the space borne installations was to maintain components within the appropriate temperature under all kinds of operating modes and service lifetime in space. [1-5]. So, the ability to dissipate large amounts of waste heat was a very critical factor to any advanced or high-power space systems, from solar power satellites, space laboratories to planet base.[1,2][4][6] But the space radiator system also exits several problems, including the need of low mass and volume, efficient heat rejection over a wide range of power loads, and the need for thermal control structures to remove heat from thermal loads of systems over wide temperature ranges. Therefore, it was critical to the space radiator design of such systems to provide the maximum heat rejection efficiency for the minimum mass, and find the balance between the device performance and the radiator mass. In addition, the radiator performance also depends on the radiating surface area, the emittance and absorption of the radiator surface and other conditions.

The optimization efforts would primarily focus on the space radiator, because the radiator contributes to around 40% to 50% of the overall mass. As nowadays there is an increasing requirement in high power operations. So, the space radiator system designers must face the new challenge.

In 1978, Hedgepethl proposed the use of a dust radiator to reduce the radiator weight of solar power satellites. A cylindrical column of dust particles was heated by the working fluid of a thermal engine and then sent to a trajectory, ranging from 100 m to 10,000m, to radiate energy into space, and finally was collected, reheated, and redirected. Although this idea could effectively reduce the radiator weight,
it has important practical affects, which includes the difficulty of manipulating, and degradation of the dust itself over time.[1] Later, several new radiator concepts were proposed with the goal of reducing radiator mass/volume and the cost. The most promising ones of these concepts were the Liquid Droplet Radiators (LDR) [2] and the Liquid Sheet Radiators (LSR). [3] The LDR consists of a droplet generator, a droplet collector, a circulating pump, a pressure regulator, an immediate heat exchanger and the reservoir. And the operation process of the LDR could be found in the references. [4-6]. Tagliafico reported that LDR could be as much as 5 to 10 times lighter than advanced heat pipe radiators.[7] Massardo et al. reported that the specific mass of a solar power dynamic system with an LDR was 27% less than that with a conventional heat pipe radiator. [8] Droplet generation experiments and droplet collection experiments on earth have been conducted at the NASA Glenn Research Center and the detail information could be found in the references.[9,10] Tsuyoshi Totani et al. conducted some numerical and experimental studies on the circulation of working flow. The results show that the flow rates of the circulating working flow calculated from the model correspond well to those obtained from the experiments and the flow rate of working flow could be controlled automatically. [11] The performance tests of the droplet generator and the linear droplet collector have been conducted at the Micro-Gravity Laboratory of Japan.[12,13]

Although the LDR could improve the reject waste heat per unit mass, there emerges an important influence factor in design of the LDR, which was the mass loss via evaporation from the droplets. Hence, the mass of fluid reservoir should be included in the whole mass and the mass of reservoir might as much as double when considering an operating temperature of around 1000K. In addition, as the LDR and LSR were operating in an open system essentially, the evaporation of the droplet would contaminate the space installations, the atmosphere and the soil of Moon or MSR. [14]

In addition, in 2017, M.M. Sarafraz investigate the thermal performance of a cooling liquid block working with gallium, CuO/water nanofluid and water. [15] The results proved that the gallium would have more efficiently. In 2018, M.M. Sarafraz investigates the potential application of a liquid metal enriched with aluminum oxide nanoparticles in a microchannel in many experiences, He found that gallium nano-suspension offers a great potential for cooling the surface of the microchannel at high heat flux condition. [16-19]

In this study, in order to overcome those above defects and we propose the use of a stream of solid particle as a lightweight radiate medium for space. This design mode of space radiator was based on the merits of the LDR, which could be used to improve its multiple abilities including the higher ability of rejecting heat, the lighter weight, the smaller volume, no evaporation losses, easy operation and no contaminate of evaporation to the space installations and planet. Its performance and the evaluate parameters will be compared with those of the traditional radiator and the LDR through some calculation examples, and finally we propose a new space radiator, and validate its feasibility and effectiveness in terms of the calculation results, which lays the foundation for the future experiment research. Detailed information of the new design, along with theoretical knowledge of the SPR and the mass model will be addressed in the third and fourth sections of this paper.

2. Requirements of space radiator

With respect to the design standard and evaluation parameters of space radiator, in general, the efficient heat rejection in space requires that the radiators should have high infrared emissivity, high thermal conductance throughout and low solar absorptive. Additionally, the space radiator must exhibit highly reliability, have a lower volume for launch, and meet platform requirements.

To survive the hostile threats as well as the natural space environments, the space radiator should be designed in chosen combinations of materials again. Another consideration in design of a radiator system focuses on its vulnerability, due to the ambient environment consisting of atomic oxygen, and various forms of atomic oxygen, and various forms of naturally occurring radiation. And the space radiator system also needs to provide both high survivability potential and enhanced thermal performance with the use of a fibrous geometry.

In terms of the concrete evaluation parameters, the space radiator had to meet some requirements: it should be of a small mass, capable to handle a lot of heat, easy to transmit in limited spaces, easy to
The solid particle was directly sent to a solid particle collector. After the liquid mixture flow through the separator, the working fluid was recycled to the heat exchanger by the convection heat transfer. The solid particle will be heated by the waste heat generated in a large space structure. Meanwhile, it still should run a long time without maintenance, and using as little energy as possible. Many features could be summarized by the following: [20]

1. Transfer rate of mass per unit power;
2. Radiative heat surface area per unit mass;
3. Rejected heat flux (W/m²) defined as a function of the difference between the maximum temperature of the fluid at the inlet of the intermediate heat exchanger, and the apparent radiative temperature of space;
4. Electrical power absorbed (by the pumping system for the fluid circulation in the radiator) per unit of heat transfer rate rejected;
5. Heat transfer rate per unit mass and per unit temperature difference of the system.

For the purpose of comparison, some typical values of the above-mentioned parameters were discussed in Table 1 for a few traditional space radiators and the innovative space radiators with respect to the disposal of the waste heat in space.

Table 1. Typical of the parameters describing the performance of radiators for space applications [20].

| Type of radiator                  | \( \phi \) (kg/w) | \( \alpha \) (m²/kg) | \( U \) (W/m2K) | \( \pi_\alpha \) (Wel/Wth) | \( \phi / \Delta T \) (Wth/kgK) |
|----------------------------------|-------------------|----------------------|-----------------|--------------------------|-------------------------------|
| Finned piped with fluid circulation | 0.035             | 0.265                | 0.48            | 0.052                     | 0.13                          |
| Heat pipes                       | 0.022             | 0.124                | 2.24            | 0.062                     | 0.28                          |
| Advanced heat pipes              | 0.0153            | 0.224                | 2.33            | ——                        | 0.52                          |
| Liquid droplet radiator(LDR)     | 0.004             | 0.31                 | 3.22            | 0.006                     | 1                             |
| Liquid sheet radiator(LSR)       | 0.0132            | 0.26                 | 1.61            | ——                        | 0.42                          |

*No intermediate heat exchanger

3. The concept of space particle radiator

This new design model which was based on the merits of LDR proposes to use the solid particle instead of the droplet to achieve the heat rejected in space. However, it could overcome the defects which includes the liquid evaporation loss, the bigger mass of fluid reservoir and the contamination of the system and space installations due to the evaporation losses from the droplet, and expands the application region.

The SPR system consists of six main components: pipes, pumps, immediate heat exchanger, solid particle generator, solid particle collector and the segregator (Figure 1). Firstly, the liquid working fluid is heated by the waste heat generated in a large space structure. Then, the solid particles will be mixed with the liquid working fluid in the outlet of the collector, and go through into the static solid-liquid mixed immediate heat exchanger for heat transfer. The solid particle will be heated by the convective in the immediate heat exchanger. Later, the solid-liquid mixture flow was subjected to a segregator to achieve the effect of solid-liquid separate. Finally, the solid particle was direct sent into the space through nozzles effect on the solid particle generator toward a solid particle collector. After the liquid working flow was separated by the segregator, the working flow was recycled to the space structure. During the transport process in space from the solid particle generator to the solid particle collector, the solid particles dissipate heat via radiative heat transfer. After the cooled solid particles were captured by the solid particle collector, the solid particle flow was recycled to the heat exchanger by the heated working flow. See Figure 1 for a schematic layout of the SPR.

The SPR have several distinctive advantages compared with the LDR and LSR in this context:

1. The radiating medium was solid particle, and its radius has uniformity and homogeneity, so the movement track could well predict accurately. Meanwhile it could improve the rate of heat rejected in space compared with another traditional radiator by means of expanding the radiating surface.

2. The immediate heat exchanger was the solid-fluid mix heat transfer, and this kind of heat transfer goes through direct contact between the mediums. Therefore, it could achieve the best effect in heat transfer.
transfer of thermal conductivity and convection heat transfer. Meanwhile the implement and operation were easy to handle.

3 There were no evaporation losses in that the radiating medium was the solid particle, thus the overall mass of system would get smaller relatively. And the space environment and space installations would not be contaminated.

4 They could operate in a wide range of temperature for a long time without considering the evaporation heat loss and the property value of the radiating medium.

![Figure 1. Schematic diagram of solid particle radiator.](image)

The SPR was still in the conceptual stage of development. Preliminary system analysis of the SPR has accompanied by these investigations, and it will lead to guide the experimental endeavors and to model the performance of various configurations. And the detailed description of the system mass model and theory will be presented in the next section.

4. Solid particle radiator systems model

Each component in the SPR should be designed. However, the working components would affect the design factors of many other components of the SPR, so that an optimized design must necessarily match with a global system modeling, and it was able to simulate the transient and steady state in different conditions. This would be a complicate simulation process that needs a long processing when associated with optimization procedures. So, a method is adopted here in which each component was mathematically modeled to work in steady condition.

The whole design assumes the environmental conditions (apparent temperature of the space), the working conditions under where the SPR was employed (heat flux to be rejected, temperatures, flow rates, physical properties) and some geometrical parameters of the radiating sheet. The main design parameters fixed were the heat flux to be rejected (in the range 10-10000 kW), the space temperature (0 K), the expected lifetime without maintenance (10-30 years).

By means of analysis, the important parameters affecting the performance of the heat rejection system resulted to be the solid particle diameter, the solid particle emissivity, the solid particle velocity in stream, the solid particle sheet thickness and the inlet and outlet temperature of the SPR in the generator and collector.

In this study, the SPR was modeled as a cylindrical stream of solid particle. A single solid particle radiates heat as it travels through space and at any times this heat loss was given:

$$q = (4 \pi r^2) \sigma FT^4$$  

(1)

where $q$ was the solid particle heat loss rate to space, $r$ was the solid particle radius, $\sigma$ was the Stefan-Boltzmann Constant, $F$ was the average view factor for gray body solid particle at center, $T$ was the temperature of solid particle.

The instantaneous radiation rate was equal to the rate of energy loss resulting in this equation:

$$4 \pi r^2 \sigma FT^4 = -c \rho \frac{4 \pi r^5}{3} \frac{dT}{dt}$$  

(2)

where $c$ was the specific heat capacity, $\rho$ was the density of solid particle, $t$ was the variable.
where $T_i$ was the initial solid particle temperature in the generator (K), $T_r$ was the solid particle temperature in the collector (K), $t$ was the transit time

Under the initial conditions, the temperature of the solid particle decreases about $\Delta T$ during the flight of length $L$ from the generator to collector. So, the Eq (4) could be solved by:

$$ r = \frac{9\sigma FL}{c_\rho \nu} \frac{T_i}{(T_i/T_r)^3 - 1} $$

And the average rate of heat loss in per solid particle was:

$$ q = \frac{1}{L/\nu} \int_0^{L/\nu} qdt = 4\pi r^2 \sigma F T_r^4 \frac{3(1-T_i/T_r)}{(T_i/T_r)^3 - 1} $$

For the volume of solid particle stream with the whole solid particles in every cubic meter equal to $n$, and the diameter of stream is the $D$ in meters, so the total rate of heat loss in the stream was the following equation:

$$ Q = n\pi r^2 D^2 L \sigma F T_r^4 \frac{3(1-T_i/T_r)}{(T_i/T_r)^3 - 1} $$

where $\varepsilon$ was the emissivity of the solid particle surface, $\eta$ was the conservative average value for the entire solid particle

Substituting with the Eq (8) into the Eq (7), the total heat loss in the solid particle was given as:

$$ Q = BD\sigma L T_i^4 \frac{3(1-T_i/T_r)}{(T_i/T_r)^3 - 1} $$

where $D$ was the diameter of the solid particle stream, $L$ was the length of the solid particle stream.

The express of $B$ could be found [21]:

$$ B = \frac{8(1-\eta)}{1 + \frac{1}{\eta} - 1} $$

The value for $B$ was substituted into Eq (9) and the resulting equation was differentiated with respect to $\eta$ and the result set equal to zero in order to reasonably optimize the heat flow per unit area resulting in this equation for the $\eta$

$$ \eta^2 (\frac{1}{\varepsilon} - 1) + 2\eta - 1 = 0 $$

Concerning the above-mentioned solid-particle radiation modeling, it could be found that the design structure and features for application of related components in SPR were extremely similar with those in LDR. So, the resulting expression for the mass of the solid particle to carry the waste heat, the mass of the generator and collector and the pump mass in SPR could be found by the reference 21:

$$ M_p = \frac{Q(1+\beta)L}{CV(T_i-T_r)} + \frac{\pi(m_c)Q}{36} \left[\frac{(T_i/T_r)^3 - 1}{BL\sigma T_i^3 (T_i-T_r)}\right] + \frac{Q(m_s)}{C(T_i-T_r)} $$

where $\beta$ was the parameter variable, ratio of the solid particle mass in the heat exchanger to mass in stream, $m_c$ was the parameter variable, specific mass of solid particle generator and collector per unit area, $m_s$ was the parameter variable, pump specific mass.
The solid-liquid segregator was another important component for the SPR. In this new radiator design, the technologies of the water separation and filter membrane were used to separate mixture of solid-liquid. This segregator was designed to the second-stage separate, and the filter net was set at the overflow pipe in order to prevent the solid particle flow out. Later, a second filter separator with the filter net was connected at the bottom of the tail tube, and there will have the centrifugal force in the second filter separator which was driven by a little electrical power. Finally, the solid particle was separated from the liquid. According to the literate, the isolation rate of this kind solid-liquid segregator without the filter net had attained 98% above when the solid particl

\[
\text{iso} = \frac{m_{\text{solid}}}{m_{\text{total}}} 
\]

where \( m_{\text{solid}} \) was the mass of the solid particle, and \( m_{\text{total}} \) was the total mass of the system.

So, we will use this design mode and the main tube diameter of the solid-liquid segregator could be expressed:

\[
D_s = 5.7 \sqrt{q_m} 
\]

where \( D_s \) was the main tube diameter of the segregator, \( q_m \) was the volume flow rate.

\[
q_m = \frac{Q}{c_l \rho \Delta T} 
\]

where \( c_l \) was the specific heat capacity of the liquid working flow, \( \rho \) was the density of the liquid working flow

After the above design calculations of the solid-liquid segregator, then the mass model could be concluded as follows:

\[
M_s = 4.68 \pi \rho \tau_s D_s^2 - 4.69 \pi \rho \tau_s'^2 D_s + 0.8 \sqrt{\pi} \rho \tau_s D_s - 6 \rho_s D_s \tau_s'^2 + 1.5 \pi \rho_s \tau_s \rho_s D_s^2 
\]

Where \( \rho \) was the density of the segregator material, \( \tau_s \) was the thickness of the segregator, \( \rho_s \) was the density of the filter net, \( \tau_{sn} \) was the thickness of the filter net

So, the total mass of the SPR system was given by:

\[
M = M_s + M_{\text{pump}} + M_{\text{collector}} + M_{\text{generator}} + M_{\text{heat exchanger}} 
\]

Where \( M_{\text{pump}} \) was the mass of the pump mass and includes the new pump specific mass. \( M_{\text{collector}} \) was the mass of the collector. And due to the mass of immediate heat exchanger was very small, so its mass will be not considered in this calculation.

We could get the optical length(L) to minimize the system mass for the given other factors through differentiating an Eq (16) about L. And the resulting expression for the total specific mass of the system of kg/kW was

\[
M_s = \frac{3Q^{0.3}}{2(1 - \frac{T_c}{T_s})^{0.3}} \left( \frac{(1 + \beta)(T_s - T_c)}{B \sigma c T_s^3} \right) \left( \frac{m_p \pi}{18} \right)^{0.3} + \frac{\pi m_p}{c(T_s - T_c)} + M_s 
\]

\[
M_{\text{pump}} = \frac{(1 + \beta)(L / D)^{0.2} \left( \frac{T_c}{T_s} \right)^{0.3} - 1} {Q^{0.2}} \left( \frac{m_p}{c(T_s - T_c)} + \frac{\pi m_p \left( \frac{T_c}{T_s} \right)^{0.3} - 1}{12 B \sigma c T_s^3 (L / D) \left( \frac{T_c}{T_s} \right)^{0.3} - 1} \right) + M_s 
\]

At the same time, when the L/D was fixed, the stream diameter could be found:

\[
D = \frac{Q^{0.2} \left( \frac{T_c}{T_s} \right)^{0.3} - 1}{3B(L / D) \sigma c T_s^3 \left( \frac{T_c}{T_s} \right)^{0.3} (1 - \frac{T_c}{T_s})^{0.3}} 
\]

The solid particle velocity was expressed by:

\[
v = \sqrt{2c \gamma \left( T_s - T_c \right)} 
\]

5. Computational results
The optimization calculations based on the SRP systems mass model of different parameters were carried out by assuming the average solid particle temperature \( T_s \) at the collector as the objective function. The rejected waste heat here considered ranges from 10 to 10000 kW. Depending upon the
imposed constraints, the numerical procedure here investigated close to the initial values of solid particle stream temperatures as 300 K and 1000 K respectively. And the parameter values used for the calculations and the property of solid particle are shown in the Table 2 and 3. Under these conditions the optimized size of the SPR has been attained and the variations of the SPR performance parameters with the thermal load have been evaluated.

Table 2. Parameters used for calculations.

| PARAMETER | CASE1 | CASE2 |
|-----------|-------|-------|
| β         | 0.1   | 0.2   |
| γ         | 0.005 | 0.005 |
| mc        | 40 kg/m² | 100 kg/m² |
| mp        | 10 kg/(kg/s) | 25 kg/(kg/s) |
| L/D       | 250   | 250   |

Table 3. Properties of solid particle (polystyrene) used for calculation.

| Parameter          | Value           |
|--------------------|-----------------|
| Density            | 1040 kg/m³      |
| The heat capacity  | 1300 J/(kg·K)   |
| The thermal emissivity | 0.9          |

5.1. The numerical examples

Figure 2 shows the rate of mass per unit power with the variations of the system lifetimes in case1 for four kinds of space radiators at $T_g=1000$K with the variations of waste heat values. It could be seen that the rate of mass per unit power of the SPR was always lower than the heat pipe and the LDR with the Tin all above the range in the different heat waste power. But for the LDR with the Aluminum, the rate of mass per power of the SPR was also lower than that of the LDR when the system time was more than 2 years. And the rates of mass per power of the SPR are greater than that of the LDR with Aluminum for the waste heat power at $10^4$kW and $10^3$kW when the system time was less than 2 years. And, due to the value of power were differences in magnitude, so the results appear little fluctuations, but this was not affecting the trends and principle.

Figure 3 represents the rate of mass per unit power with the variations of the system lifetimes in case2 for four kinds of space radiators at $T_g=1000$K with the variations of waste heat values. The results show that the rate of mass per unit power of the SPR was always lower than the heat pipe and the LDR with the Tin all above the range in the different heat waste power. For the LDR with the Aluminum, the rate of mass per power of the SPR at the waste heat power of $10^4$kW was lower than that of the LDR when the system time was more than 7.5 years. And the rate of mass per power of the SPR at the heat waste power of $10^3$kW was lower than that of the LDR with Aluminum when the system time was less than 5 years.

Figures 4 and 5 reflect the rate of mass per unit power with the variations of the system lifetimes in both cases for four kinds of space radiators at $T_g=300$K with the variations of waste heat values. It could be obtained that the rate of mass per power of the SPR at the heat waste power of $10^4$kW was larger than the LDR in the different cases, but the value only increases by 3%. And the rates of mass per power of the SPR at the other values of waste heat power are very close to those of the LDR.

Figures 6 and 7 are the rates of the mass per unit power as a function of the rejected flux itself in both cases for the different space radiators at $T_g=300$K. It could be seen from Fig. 6 that the rates of mass per power of the SPR are always lower than those of the LDR with the different medium in the different cases. So, it was worthwhile to note that the SPR performances here evaluated for the different system time and waste heat power are better than those of traditional radiators at the same operating conditions. Figure 8 showed that the rate of mass per unit power with the variations of the initial temperature on the generator in the case1 at the Q=100kW. It could be seen that the rate of mass per
unit power decreases with the increase of the temperature. It means that the more temperature, the lower mass, the temperature of generator would be one adopt value matching with quality.

**Figure 2.** The rate mass per unit power of solid particle, tin nonfreezing and aluminum freezing radiating streams at various heat rejected levels and system times, $T=1000K$, case1.

**Figure 3.** The rate mass per unit power of solid particle, tin nonfreezing and aluminum freezing radiating streams at various heat rejected levels and system times, $T=1000K$, case2.

**Figure 4.** The rate mass per unit power of solid particle and Dow705 nonfreezing radiating streams at various heat rejected levels and system times, $T=300K$, case1.

**Figure 5.** The rate mass per unit power of solid particle and Dow705 nonfreezing radiating streams at various heat rejected levels and system times, $T=300K$, case2.
The relative influence of each component on the overall mass as resulted from the optimization calculations was sketched in Figure 9 as pie charts for different operating conditions. The major contribution to the global system mass was due to the piping and circulating pump which represent almost half of the SPR mass. The solid particle generator mass exhibits a very strong influence for the waste heat powers above 100 kW. As a single module generator has been considered. The waste heat power affects the generator volume more significantly than other related components. And the relative mass of the intermediate heat exchanger was quite low. The mass of solid-liquid segregator nearly accounts for 10 per cent of the overall mass.

5.2. The parameter variations

One of the reasons for an analytical study was to gain insights into the effect of various parameters in a solid particle radiator system. The influence of $m_c$, $m_p$, emissivity, $L/D$ and $c$ on the $M/Q$ were shown in Figure 10, 11, 12, 13 and 14.

Figure 10 presents the influence of variations of the parameter $m_c$. It could be seen that the rate of mass per unit power of the SPR was lower than that of the LDR when the value of the $m_c$ was more than
the 45 in the case1. And the rate of mass per unit power of the SPR was lower than that of LDR when the value of the $m_c$ was more than the 110 in the case2. The influence of variations of the parameter $m_p$ was expressed in Figure 10. The result shows that the rates of mass per unit power of the SPR are very similar with those of the LDR in these cases. So, we could get the conclusion that the $m_c$ has a very strong influence on the number of the rate of mass per unit power, while the $m_p$ has a little influence on it. And we could see from Figure 10 and 11 that the numbers of the rates rise with the increased numbers of $m_c$ and $m_p$ in these two cases.

The influence of the thermal emissivity $\varepsilon$ for the cases in the different space radiators at $T_e=300K$ was shown in the Figure 12. It shows that the rate of mass per unit power of the SPR in the case2 was greater than that of the LDR with Dow705, but even the value of the larger one was still very small. And the rate of mass per unit power of the SPR in the case1 was very similar with that of the LDR with Dow705. While, the numbers of the rate decrease with the increase of the numbers of thermal emissivity in these cases.

Figure 13 illustrates the effects of limiting $L/D$ of the case2 for different space radiators at $T_e=300K$. It could be clearly seen that the numbers of the rate of mass per unit power decreases with the increase of the number of $L/D$. And the rate of mass per unit power of the SPR was very close to that of rate of the LDR.

Figure 14 reflects the influence of the material property on the rate of mass per unit power of the case1 at $T_e=300K$. It could be clear seen that the values of the rate of mass per unit power decreases with the increase of the specific heat capacity. This demonstrates that the bigger specific heat capacity, the better effect of SPR.

**Figure 10.** The influence of equipment mass $m_c$ on the rate mass per unit power for the LDR-Dow705 and the SPR, $T=300K$, $t=20$years, case 1, 2.

**Figure 11.** The influence of equipment mass $m_p$ on the rate mass per unit power for the LDR-Dow705 and the SPR, $T=300K$, $t=20$years, case 1, 2.
Case 1

Case 2

LDR-Dow705

SPR

Figure 12. The influence of the solid particle emissivity $\varepsilon$ on the rate mass per unit power for the LDR-Dow705 and the SPR, $T=300\text{K}$, $t=20\text{years}$, case 1, 2.

Figure 13. The influence of the L/D on the rate mass per unit power for the LDR-Dow705 and the SPR, $T=300\text{K}$, $t=20\text{years}$, case 2.

Figure 14. The variation of the rate mass per unit power with the specific heat capacity for the SPR, $T=300\text{K}$ case 1.

6. Conclusions

In this paper, we proposed a new kind radiator concept which uses the solid particle instead of the droplet to reject the waste heat in space. This new design mode has the following distinct advantages which are the no evaporation losses and contaminate for the space environment, space installations and the planet via evaporation losses compared with the LDR. Meanwhile it has many merits which include the lightweight, the small volume, the larger radiating surface and the high rate of heat rejected just like the LDR.

The mass model and the parameter analysis of the Solid particle radiator were conducted. An optimization calculation procedure has been employed about the minimum SPR system mass per unit power as a function of the average solid particle temperature at the collector to evaluate the performance of SPR. And the results of the calculation were compared with the LDR in the same conditions. The calculation conclusions were as follows:
(a) The total rate of mass per unit power was lower than those of the Heat pipe radiator and LDR in the most cases for both condition of the environment temperature at 300K and 1000K.

(b) The temperature of solid particle stream ranges to a larger extent when the evaporation losses were not considered. Moreover, the temperature of solid particle stream has a strong influence on the rate of mass per unit power.

(c) The parameters of $m_\alpha$ and $m_\beta$ have effect on the rate of mass per unit power. The increase of the number of $m_\alpha$ and $m_\beta$ leads to the increase of the rate of mass per unit power in two cases.

(d) The value of the emissivity of the solid particle also has influence on the rate of mass per unit power in the different cases at 300K. The number of the rate of mass per unit power decreases with the increase of emissivity.

(e) The material selected for the solid particle was very important since the value of specific heat capacity has strong effect on the number of rates of mass per unit power. The rate decreases with the increase of the specific heat capacity.

These calculation results indicate that the SPR not only yields no contaminate to the space environments and the space installations from the point of design, but also has the potential of reducing the weight of space borne systems from the point of calculation. Thus, areas for further application of this design could be explored.

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