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Study on heat transfer characteristics of space liquid droplet radiator

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Abstract— Liquid droplet radiator (LDR) is characterized by the compact arrangement and the low mass per unit power. It is a promising cooling system for the high-power spacecraft. The characteristics of the droplet layer in LDR determine the performance of the heat dissipation. Thus, the study of the droplet radiation heat transfer mechanism is vitally important for the optimal design of the whole LDR system. In the present paper, the radiation heat transfer characteristics of a sparse LDR system are studied from the aspects of the single droplet. The results reveal that the smaller the droplet radius is, the higher the droplet radiation energy per unit mass is. The slower the initial emission speed is, the higher the radiation energy per unit mass is. The higher the initial temperature of the droplet, the higher energy of radiation power per unit mass of the droplet is. Meanwhile, the radiation heat transfer characteristics of different working mediums are also given. These conclusions can provide basis for the optimal design of the sparse droplet radiators and provide guidance for the subsequent research on LDR.

Keywords—liquid droplet radiator, thermal radiation, metal droplet, radiation power

I. Introduction

With the development of the science and technology, human's exploration of the space is getting farther and farther. The space reactor power, which can supply with the power from 100 kilowatts to megawatts, has become the first choice for the future space activities. For such a high-power spacecraft system, how to ensure the effective discharge of the waste heat has become one of the key technologies to realize the high-power spacecraft. At present, the radiators that can meet this requirement include the heat pipe radiator and droplet radiator. Compared with the heat pipe radiation radiator, the droplet radiation heat dissipation surface of the droplet radiator has no solid shell and is directly exposed to the space environment. The surface area of the droplet radiation heat dissipation is larger, and the overall heat dissipation system mass can be greatly reduced [1].At the same time, due to its simple structure, it can be installed on the space system in a very compact manner, and it is also easy to expand in the orbit [2].So the droplet radiator is an important candidate to deal with a large amount of waste heat, such as the heat dissipation power is over 1MW.

There are lots of researches and experiments on LDR since it has been proposed [3]. The flight tests of the liquid droplet heat exchanger on the reduced-gravity aircraft focusing on the two-phase flow dynamics have been completed in NASA [4]. Totani [5] designed a liquid droplet radiator for space solar-power system and experimentally studied the circulation of working fluid in the radiator. Konyukhov [6] studied the generation and collection of monodisperse droplets flowing in microgravity and high vacuum. Siegel [7] established a set of models to depict the temperature variation both on thickness and length direction, and studied the transient radiative cooling of the droplet layer with phase change. Tan [8] calculated the dimensionless radiative heat flux of one dimensional droplet layer by the ray tracing method. The radiation phase transformation model of droplet in space environment was established, and three phase transformation solidification models were analyzed by Wang [9]. Yin [10] modeled the radiation heat transfer in a droplet layer containing phase change.

The LDR is mainly composed of a droplet generator, a droplet collector, a circulation pump, a droplet accumulator, a heat exchanger and the related pipes. The schematic of LDR is shown in Figure 1. At present, the most studied and most promising LDRs are the triangular LDR and rectangular LDR. The mass of the triangular LDR can be reduced by about 40% compared to the rectangular LDR. However, under the same length and width of the LDR system, the rectangular LDR system can dissipate more heat into the space, and because the droplets are not covered, the structure of the droplet generator is relatively simpler [11].

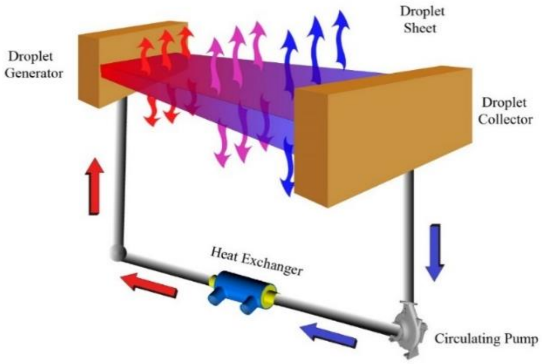

Fig.1 Schematic of the droplet radiation radiator

In this paper, the radiation heat transfer characteristics of isolated droplets is studied by changing the droplet radius, initial temperature, emission speed and working fluid, etc., so as to reveal the radiation heat transfer mechanism of the rectangular droplet radiation radiator.

II. CALCULATION METHOD

A. Calculation model of radiative heat transfer

The sparse droplets refer to the LDR system where the distance between any two droplets in the droplet layer is greater than or equal to 10 times of the droplet diameter. In this case, the interaction between droplets is very small, so the droplets can be considered as isolated droplet group processing [12]. By studying the radiation heat transfer characteristics of the isolated droplets, the radiation heat transfer characteristics of the sparse droplet layer can be obtained.

For the convenience of calculation, the model can be simplified as follows:

(1) The droplet can automatically change into an ideal spherical shape due to the surface tension once it is generated during the movement. Therefore, the droplets can be regarded as spherical.

(2) As the radius of the droplet is very small, usually in the order of 100 μm, and the working mediums of the droplet such as metal is usually with excellent thermal conductivity, it can be considered that there is no temperature gradient inside the droplet.

(3) For the candidate working mediums, the droplet vapor pressure is extremely low, the droplet evaporation rate is so small that can be ignored, so the latent heat of vaporization will not be considered [13].

(4) Since the temperature of the space is much lower than the working temperature and melting temperature of the working fluid of the droplet, the condensation phase change of the droplet is not considered.

(5) Take the temperature of the universe to be equal to 0K and the effect of the space environment on the radiation of the droplet is not considered.

According to the above assumptions, the energy conservation equation of the droplet in space can be simplified as follows:

$$\rho c_p \frac{dT}{d\tau} V + \varepsilon \sigma_b T^4 A = 0 \tag{1}$$

Here, C_p is the specific heat capacity of the working fluid of the droplet; V=4/3πr^3 is the volume of the droplet; ε is the emissivity of the droplet; σ_b is the thermal radiation coefficient of the blackbody, and $A=4\pi r^2$ is the surface area of the droplet.

Therefor Equation (1) can be simplified as follows:

$$\frac{3\varepsilon\sigma}{C_p \rho r} dt = -\frac{dT}{T^4} \tag{2}$$

According to Equation (2), the temperature of the droplet during operation can be calculated.

According to the radius, initial temperature and final temperature of the droplet, the radiation heat dissipation capacity of the droplet per unit mass can be calculated as follows：

$$\overline{C_p} = \frac{C_p(T_i) + C_p(T_o)}{2} \tag{3}$$

Where T_i and T_o are the initial temperature of the droplet and the final temperature of the droplet, respectively. Thus, the radiation heat dissipation capacity of unit mass droplets can be obtained by:

$$e = \frac{E}{m} = \frac{\overline{C_p} m (T_i - T_o)}{m} = \overline{C_p}(T_i - T_o) \tag{4}$$

B. Selection of working mediums

The performance of the droplet radiation radiator is mainly affected by the radiation heat transfer characteristics of the droplet. Therefore, it is vital to select the appropriate working medium for the LDR.

In the design of space radiation radiator, it needed to in light weight. Some experimental results of the sub-millimeter droplet emissivity of DOW CORNING 705 (Dow705) indicated that the radiator using the medium of Dow705 at temperatures of 275-335K was about 10 times lighter than the lightest heat pipe radiator [14]. Also, the LDR heat exchange fluid needs to have a very low vapor pressure, which makes the selection of heat exchange mediums quite difficult. The alternative working medium and corresponding working temperature range are shown in Figure 2.

In general, the ideal droplet working fluid should be with low vapor pressure (≤10^{-9}mmHg[2]), low viscosity, high emissivity, low absorption rate, low density, high surface tension, high specific heat capacity and high thermal conductivity rate and so on.

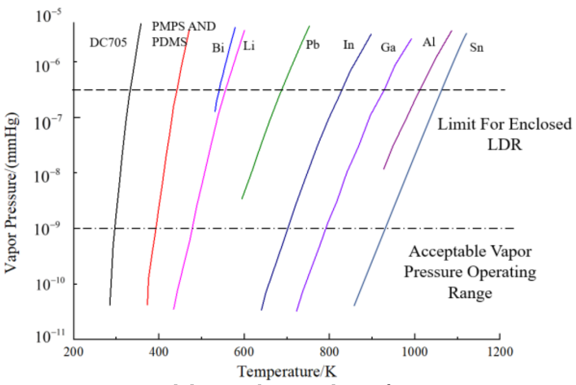

Fig.2 Candidate working mediums for LDR system

III. CALCULATION RESULTS AND ANALYSIS

According to the design of the droplet generator in Ref. 15, it is assumed that a rectangular LDR system is 90 m long. The radius of the droplet generated is 100 μm. The frequency of the droplets generated by the droplet generator is 5000 Hz. The above mentioned model is used to calculate and analyze the radiation heat transfer characteristics of the droplets.

A. Effect of the droplet radius on LDR

Reference 6 pointed out that the mass of the system can be reduced by decreasing the radius of the droplet, so the choosing of the proper droplet radius is very important for the design of LDR. In the calculation process, the indium is selected for calculation. The initial temperature of the droplet is 850 K and the emission speed is 9 m/s. By changing the radius of the droplet, the temperature variations of the droplet during the operation and the amount of radiation per unit mass are calculated. The calculation results are presented in the Fig.3 and Fig.4.

As shown in Fig.3 and Fig.4, as the droplet radius decreases, the faster the droplet temperature reduces, the lower the outlet temperature is. Moreover, the decreasing radius of the droplet can lead to the increasing radiation power per unit mass of the droplet. Therefore, reducing the droplet radius can improve the radiation heat transfer capability of the droplet.

However, the reduction of the droplet radius can also increase the evaporation rate of the droplet, thereby reducing the operating life of the LDR. Therefore, in the actual design process, the appropriate droplet radius should be selected.

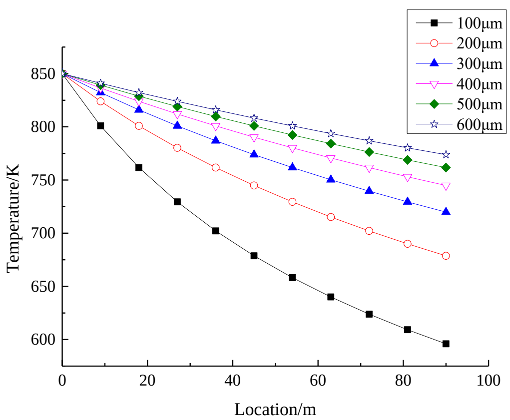

Fig.3 Droplet temperature over movement distance at different droplet radii

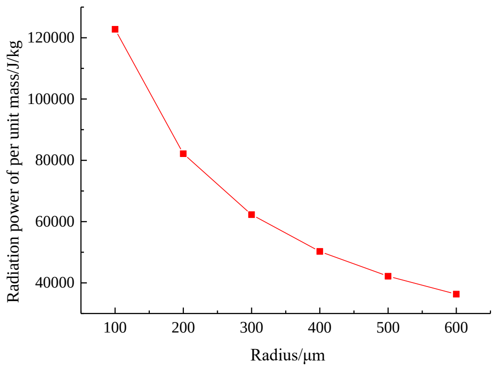

Fig.4 Radiation power per unit mass over droplet radii

B. Effect of the droplet velocity on LDR

The droplet emission speed has great influence on the radiation heat transfer characteristics of the droplet. In the calculation process, the indium is selected for calculation. The initial droplet emission temperature is 850K, and the initial droplet radius is 600 μm. By changing the droplet emission speed, the calculation results of the variation of temperature and the radiation power per unit mass of droplets during the operation are shown in the Figure 5 and 6.

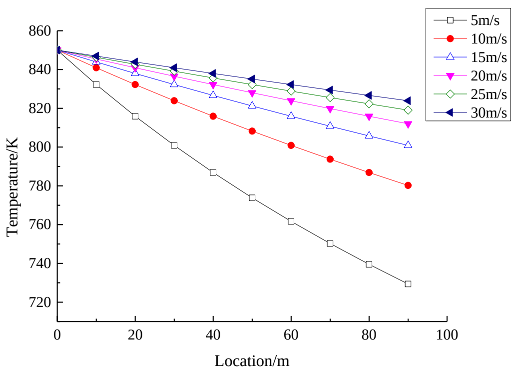

Fig.5 Droplet temperature over movement distance at different velocities

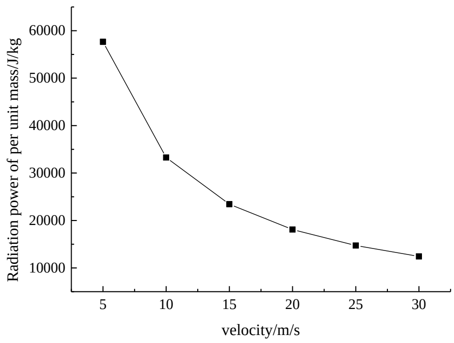

Fig.6 Variation of unit mass radiation with different velocity

It can be seen from the Fig.5 and Fig.6 that the as the droplet velocity decreases, the droplet exposure time increases, and the radiation heat dissipation capacity increases. However, at the same time, it should also be considered that the longer the exposure time, the greater the effect of evaporation on the droplets, thereby reducing the operating life time of LDR. Therefore, it is possible to increase the radiation heat transfer capability of droplets by reducing the droplet speed.

C. *Effect of the initial temperature on LDR*

In this case, the radius of the droplet is 600 μm and the droplet velocity is 25 m/s. By changing the initial temperature of the droplet, the effect of the change of the initial temperature of the droplet on the radiation heat dissipation of the droplet is calculated. The calculation result is shown in the Fig.7 and Fig.8.

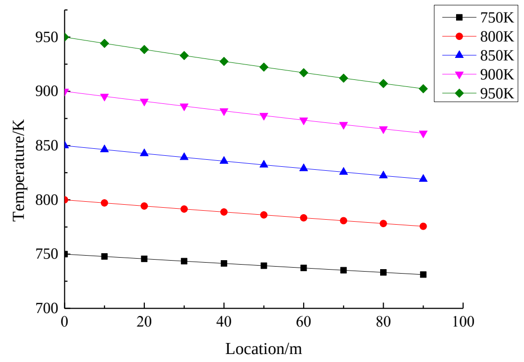

Fig.7 Droplet temperature at different initial temperature

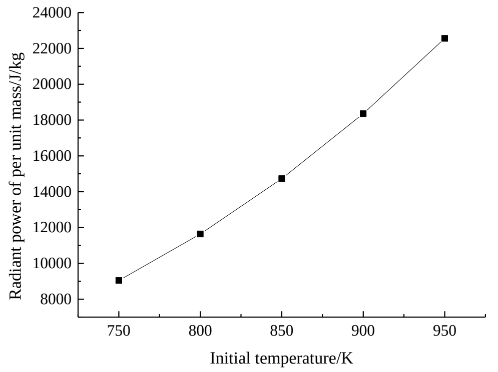

Fig.8 Radiation power per unit mass over the droplet initial temperature

It can be seen from the figure that the higher the initial temperature of the droplet, the higher the final temperature, and the greater value of the temperature drop, as well as the higher the amount of radiation per unit mass. However, as can be seen from the change in the vapor pressure of the working fluid above, the higher the temperature of the droplet, the higher the vapor pressure of the droplet, which is not conducive to the operating life of LDR. Therefore, the radiation heat transfer performance of the droplet can be improved by appropriately increasing the initial temperature of the droplet.

D. *Optimal selection of working mediums*

For the space nuclear power system, since the core outlet temperature reaches 1500K, the waste heat export temperature may reach about 850K. As can be seen from the figure, the working fluids that can meet this temperature condition are aluminum, indium, gallium, and tin. This article mainly calculates In, Al and Sn. The initial temperature of the selected droplet is 850K, the radius is 600 μm, and the emission speed is 25 m/s. The calculation results are given in Fig.10. Table 1 gives the detailed initial parameters of three metals and the radiation heat dissipation per unit mass.

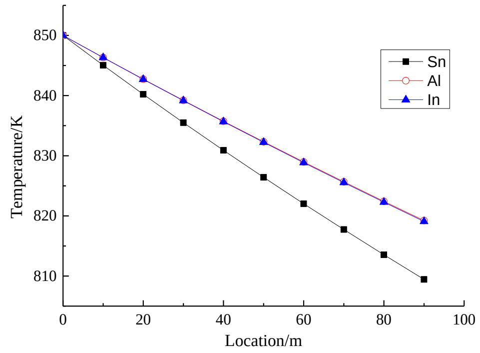

Fig.9 Temperature changes of droplets with different mediums

TABLE.I INITIAL PARAMETERS AND RADIATION POWER PER UNIT MASS OF DROPLETS WITH DIFFERENT MEDIUMS

Working medium	***ρ*** **kg/m³**	***c_p*** **J/(kg·K)**	***ε***	***e*** **J/kg**
Aluminum	2392.38	1180	0.18	36319
Tin	6794.8	226.4768	0.13	18499
Indium	6701.8	237.9240	0.1	22557

It can be seen from Fig. 9 that the temperature changes of indium and aluminum are almost the same, and the temperature change of Tin is greater. It can be drawn from TABLE. I that aluminum is with light weight, large specific heat, high emissivity, large amount of radiation power per unit mass, which indicate that aluminum performs the best, and followed by indium and tin. However, it can be seen from Fig. 2 that the vapor pressure of the liquid aluminum is too high, which has greater effects on the evaporation characteristics of the droplet during the actual operation process, and the suitable working range is narrow (933-975K[14]), which is not suitable as the LDR working medium. Besides, the performance of liquid indium is excellent, but the applicable operating temperature range is relatively low (600-800K) and indium is expensive. In addition, as to liquid tin, the density is large; the specific heat capacity is poor; and the radiant heat exchange per unit mass is low. However, the price of tin is inexpensive, and the suitable working temperature range is higher (500-1000K [14]).Therefore, the best comprehensive performance of tin can be obtained through the above analysis

In the actual choices of working medium, the appropriate working medium can be selected considering the design needs, such as rejection temperature, economical efficiency and so on.

IV. SUMMARY AND CONCLUSION

In the present paper, the influence of the operating parameters on the radiation heat transfer characteristics of the isolated droplets is investigated. In addition, three types of working mediums including indium, aluminum and tin were selected, and the heat exchange characteristics of three mediums and their advantages and disadvantages were calculated and analyzed. The conclusions have been made as follows

(1) The smaller the droplet radius, the better the radiation heat transfer capacity.

(2) The smaller the emission droplet velocity, the better the radiation heat transfer capacity.

(3) The higher the initial droplet temperature, the better the radiation heat transfer performance.

(4) Reducing the radius of the droplet, emission velocity, and increasing the initial temperature of the droplet can reduce the operating life time of the LDR, so comprehensive analysis should be conducted during the design process.

(5) Aluminum has the best radiative heat transfer performance, but it is not suitable as the heat exchange working medium due to the high vapor pressure. Followed by indium and finally tin. Moreover, considering economic factors and other factors, tin is the most suitable for heat exchange medium.

The conclusions can provide guidance for the design and analysis of the sparse droplet radiation radiator and lay basis for the subsequent LDR research.

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