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Parametric investigation of radiation heat transfer and evaporation characteristics of a liquid droplet radiator

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ABSTRACT

The liquid droplet radiator (LDR) as a frameless heat removal system is considered as a promising solution for the waste heat dissipation of megawatt aerospace applications. The radiation heat transfer and evaporation characteristics of the LDR working fluid are tightly coupled with the operational performance of the liquid droplet generator. In this paper, the effects of operational parameters of droplet generator on the radiative heat transfer and evaporation loss rate are clarified, including the pressure disturbance frequency, pressure difference between the inside and outside of the droplet generator. It is observed that higher coolant mass flow rate does not assure higher heat transfer power for the LDR. For cases with higher pressure difference, where the coolant flow rate is higher consequently, the evaporation loss rate increases continually with pressure difference while the heat transfer power does not increase any more. The disturbance frequency has inconspicuous impact on the evaporation characteristics. Besides, cases with higher pressure differences have wider suitable frequency ranges according to the droplet formation restriction. Generally, a relatively higher pressure difference coupled with a higher disturbance frequency (such as 0.3 MPa and 12 kHz) is suggested to achieve a higher heat transfer power and low evaporation loss rate. This paper may provide favorable reference for determining the operational parameters of the droplet generator in consideration of radiation heat transfer and evaporation characteristics.

1. Introduction

The increasing demand and interest for aerospace exploration and scientific research put higher and more rigorous requirements on the energy supply [1,2], and several design optimizations for efficient energy utilization have been proposed [3,4]. The space nuclear reactor will play indispensable role in the future space exploration due to its long-time service and low power-to-weight ratio [5,6]. The space nuclear reactor can provide 1 MW_e with weight less than 10 t and service life up to 10 years [7], which is nearly impossible for traditional energy sources. The space nuclear reactor system consists of the nuclear reactor, shadow shield, automatic control system, energy conversion system, waste heat dissipation system, and spacecraft load, as shown in Fig. 1. The radiation heat transfer is the only way for waste heat dissipation in space, and the efficient and reliable radiators have been searching and investigating for several decades. The loop-type radiator [8] and heat pipe radiator [9] have been utilized successfully, while the investigations for some novel conceptual radiators are abandoned because of their extreme complexity, such as moving belt radiator and Curie point radiator, etc. [10] Being much more portable and lightweight, the liquid droplet radiator (LDR) as a frameless heat removal system has received increasing attention.

The LDR layout is shown in Fig. 2, which is composed of droplet generator, droplet collector and droplet layer [11]. Millions of minute droplets are produced by the forced capillary breakup of jets in the droplet generator, then they are cooled during the flight time by radiating to the space. The droplets will be collected at the droplet trap and recirculate in the loop. The LDR has immense heat transfer surface and minimal thermal resistance, and it is estimated to be 5 to 10 times lighter than heat pipe radiators [12]. Additionally, it is immune to the meteoritic breakdown. Therefore, the LDR is regarded as the promising heat radiator for aerospace applications, especially for megawatt space nuclear reactors.

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Nomenclature

a	entrance coefficient of a nozzle	
c_p	specific heat capacity	J·kg^{-1}·K^{-1}
d	droplet diameter	μm
D	nozzle diameter	μm
E_1, E_2	exponential integral functions	
f	pressure disturbance frequency	kHz
h	droplet layer thickness	m
I	source function in participating layer	
k	non-dimensional wave number	
l	nozzle length	μm
m	mass flow rate	kg·s^{-1}
M	molecular weight	g·mol^{-1}
n	droplet number density	m^{-3}
p	saturated vapor pressure	MPa
P	pressure	MPa
q	evaporation mass flux	kg·m^{-2}·s^{-1}
Q	heat transfer power	W
R	universal gas constant	J·mol^{-1}·K^{-1}
s	space between droplets	μm
t	time	s
T	temperature	K
v	velocity	m·s^{-1}
w	droplet layer width	m
x	x-coordinate (thickness direction)	
y	y-coordinate (length direction)	

Greek symbols

α	absorption coefficient	
κ	optical thickness	
ν	kinematic viscosity	m^2·s^{-1}
ξ	pressure loss coefficient at the nozzle entrance	
ρ	Density	kg·m^{-3}
σ_s	scattering coefficient	

Subscripts

0	initial
a	area average
d	droplet
e	end
ev	evaporation
n	nozzle
r	radiation
t	total
v	vapor

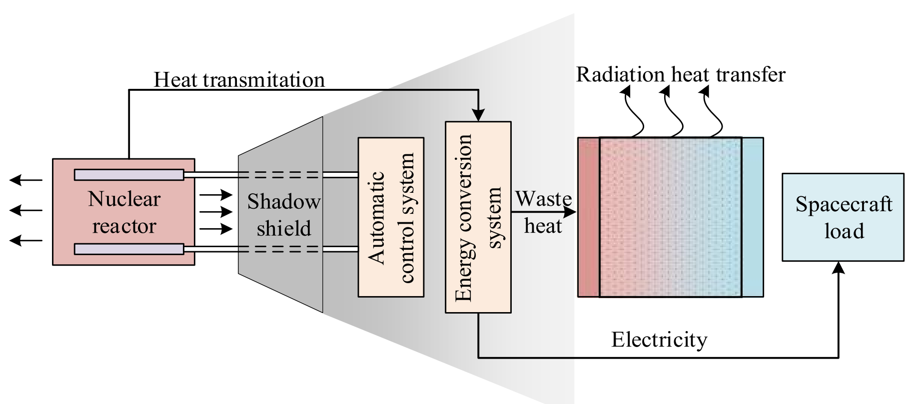

Fig. 1. Layout of the space nuclear reactor.

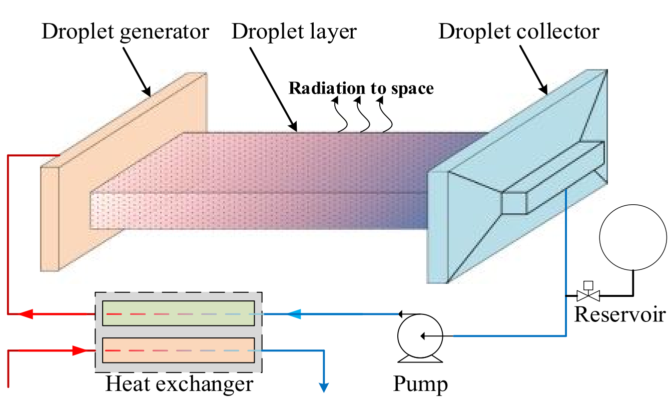

Fig. 2. Layout of the liquid droplet radiator.

Lots of theoretical and experimental investigations have been conducted concerning the LDR working performance including droplet generation, droplet radiation heat transfer and droplet collection, which will be briefly introduced. (1) Theoretical investigation: Siegel [13,14] presented theoretical calculation models and analysis of the LDR radiation heat transfer, based on which the primary thermal design of the LDR have been conducted [15]. Safronov et al. [16] studied the radiation characteristics of the droplet layer in the presence of external thermal radiation. The shape factors between droplets are derived by Chen et al. [17] to calculate the thermal performance of rectangle LDRs. Yulong et al. [18] deduced a novel method to consider the evaporation loss of the working fluid. Based on the mathematical models, a detailed heat transfer and evaporation characteristics analysis is presented by Hao et al. [19]. In view of the droplet generation, Safronov [20] theoretically studied the forced capillary breakup of the liquid jet, and the analytical models have been verified by the experimental data [21]. (2) Experimental investigation: In order to study the droplet generation mechanism, the uniform droplet formation has been elaborately investigated under microgravity and deep vacuum conditions [22,23]. The relationships between the operational parameters of the droplet generator and the geometric and dynamic features of the droplets are given [24]. Besides, to obtain the droplet collection characteristic, Koroteev et al. [25] and Totani et al. [24] experimentally studied the interaction between droplets and collector surfaces, clarifying the attainability of steady mode of droplet trapping without splashing under space conditions.

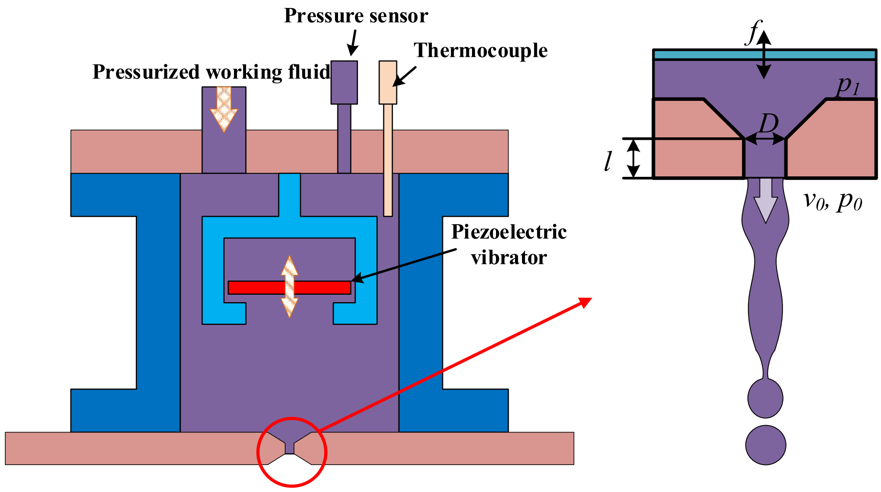

Fig. 3. Schematic diagram of the liquid droplet generator.

However, the current investigations of the droplet layer, droplet generator and collector are not associated with each other. In fact, the radiation heat transfer and evaporation characteristics of the droplet layer is also affected by the operational parameters of the droplet generator, such as the pressure difference and pressure vibration frequency, which determine the geometric and dynamic features of the droplets. Coupling the characteristics of droplet generator and droplet layer is essential for the thermal design of the LDR. This paper aims to give a parametric investigation on the radiation and evaporation characteristics of the LDR, and to figure out how the LDR heat transfer power and evaporation loss rate affected by the droplet generator.

The paper is arranged as follows: The research background of the frameless heat removal system LDR is introduced in section 1. Section 2 presents the system description of the droplet generator, and section 3 illustrates the mathematical models involving the calculation. The results and discussion are presented in section 4, and the paper is concluded in section 5.

2. System description

The simplified diagrammatic look of the liquid droplet generator is shown in Fig. 3 [24]. The working fluid is transformed into liquid droplet by the pressure disturbance produced by the piezoelectric vibrator. The geometric and dynamic parameters of the liquid droplet are determined by the liquid droplet generator, such as the pressure difference (ΔP) between the inside and outside of the generator and the frequency of pressure disturbance (f).

It has been experimentally clarified that under microgravity the droplet diameter d and spacing between droplets s can be obtained from the mass conservation equation [15]:

$$d = (3\pi/2k)^{1/3} D \tag{1}$$

$$s = (\pi/k)D - (3\pi/2k)^{1/3} D \tag{2}$$

where D is the nozzle diameter, and the non-dimensional wave number k is expressed as follows.

$$k = \pi D f / v \tag{3}$$

The droplet number density n is calculated as

$$n = f/(s^2 v) \tag{4}$$

where s and v represent the nozzle spacing and droplet velocity respectively.

Table 1
Referenced droplet generator operation conditions.

Parameter		Value
nozzle	space s/μm	100
	diameter D/μm	100
	length l/μm	500
pressure difference ΔP/MPa		0.3
pressure disturbance frequency f/kHz		12
inlet temperature T_0/K		320
liquid droplet layer	thickness h/m	1
	length L/m	50
	width w/m	10

The mass flow rate m of the working fluid is presented as

$$m = 1/6 \cdot \pi d^3 \cdot nwhv\rho \tag{5}$$

The radiation heat transfer power Q is written as

$$Q = mc_p(T_e - T_0) \tag{6}$$

Totani et al. [15] gave a relationship between the droplet velocity v and the operation parameters of the droplet generator through their experimental research:

$$v = \frac{1}{2}\left[\sqrt{\left(\frac{64\nu l}{D^2} + \frac{\xi\nu l}{aD^2}\right)^2 + \frac{8\Delta P}{\rho}} - \left(\frac{64\nu l}{D^2} + \frac{\xi\nu l}{aD^2}\right)\right] \tag{7}$$

in which, ν and ρ are kinematic viscosity and density of the working fluid; a, l and ξ are the structural parameters of the droplet generator. To maintain the consistency with the data utilized in Ref. [15], the entrance coefficient of the nozzle a and the pressure loss coefficient at the nozzle entrance ξ are set as 0.065 and 2.3, respectively.

The working parameters of liquid droplets can be obtained based on the relations listed above. To figure out the effects of the pressure difference and pressure vibration frequency of the droplet generator on the heat transfer and evaporation characteristics of the radiator, a referenced droplet generator is assumed, and the operation conditions are listed in Table 1. The silicon oil DC705 is chosen as the working fluid, and the physical properties involved in the relations are given below [26].

$$\rho = 1569 - 1.625T \tag{8}$$

3. Physical and mathematical models

The radiative heat transfer and evaporative characteristics of a liquid droplet layer under a predefined condition have been investigated in our previous work [19], where the droplet layer is treated as a radiative participating medium. The gray medium assumption and isotropic scattering are adopted to simplify the calculation, which is acceptable for primarily thermal analysis [18]. The physical and mathematical models will be briefly introduced below, and detailed descriptions can be found in Ref. [19].

3.1. Radiation heat transfer

The width of the droplet layer is much larger than the thickness, therefore the temperature distribution along the width direction can be regarded as uniform. In this case, the three-dimensional droplet layer can be reasonably simplified into two-dimensional calculation (length direction and thickness direction). The original expression of the energy conservation equation of the liquid droplet layer in the space is written as

$$D(\rho c_p T)/Dt = -\nabla \vec{q}_r \tag{9}$$

Considering that the velocity on the x direction is zero, and the change of radiative flux on the x direction plays the dominant role, the energy equation can be simplified as

$$v\frac{\partial(\rho c_p T(x, y))}{\partial y} = -\frac{\partial q_r}{\partial x} \tag{10}$$

Since the constant droplet velocity on the y direction ($y = v \cdot t$) and the optical coordinate $\kappa = (\alpha + \sigma_s)x$, Eq. (10) becomes

$$\frac{1}{\alpha + \sigma_s}\frac{\partial(\rho c_p T(\kappa, t))}{\partial t} = -\frac{\partial q_r}{\partial \kappa} \tag{11}$$

and

$$-\frac{\partial q_r}{\partial \kappa} = 2\pi \int_0^{\kappa_D} I(\kappa', t)E_1(\left|\kappa - \kappa'\right|)d\kappa' - 4\pi I(\kappa, t) \tag{12}$$

in which, I is the source function in participating layer, and E_1 represents the first order exponential integral function. Besides, the optical thickness is expressed as follows.

$$\kappa_D = h \cdot 1/4 \cdot \pi d^2 \cdot n \tag{13}$$

where h is the droplet-layer thickness, d is the droplet diameter and n represents the droplet number density in the layer.

The droplet temperature at the droplet collector can be obtained through the radiation heat transfer model, and the radiation power can be calculated using Eq. (6) consequently.

3.2. Evaporation of the droplet layer

Although the extreme low vapor pressure is emphasized as one of the criteria of the working fluid, it will evaporate during the cooling process when exposing to the vacuum environment, which will shorten the LDR service life. Hence, figuring out the evaporation characteristics of the droplet layer is essential for the LDR design.

The evaporation rate of a single droplet E_{ev} is expressed as follows:

$$E_{ev}(\kappa, t) = p_v(\kappa, t)\sqrt{\frac{M}{2\pi RT(\kappa, t)}} \tag{14}$$

where M and p_v is the molecular weight and droplet saturated vapor pressure of the working fluid; R is the universal gas constant.

In the droplet layer, the molecular evaporated from a droplet may be absorbed by other droplets. Therefore, the holistic evaporation loss rate of the droplet layer is not simply the evaporation summation of all the droplets. The evaporation loss rate per area E_a of the droplet layer is expressed as follows [27].

$$E_a = 4\int_0^{\kappa_D} E_{ev}(\kappa', t)E_2(\kappa')d\kappa' \tag{15}$$

where E_2 is the second order exponential integral function. The total evaporation loss rate E_t should be written as:

$$E_t = v\int_0^{t} E_a dt' \tag{16}$$

in which, t represents the droplet flight time.

It can be found from the formulas listed above that the evaporation is related with the temperature field which is determined by droplet diameter, flight velocity, and number density, et al. Meanwhile, these operational parameters of the droplets are concerned with the working performance of the droplet generator. In order to find the appropriate operation range of the droplet generator, the physical and mathematical models are jointly solved. The numerical method has been introduced in our previous work [19], which will not be presented here. It should be noted that, to the authors' best knowledge, there has no experimental data about the droplet radiation heat transfer and evaporation characteristics. Hence, it is not applicable to validate the simulation method by comparing the calculation results with the experimental data. The validity of the numerical model can be guaranteed by the correctness of the physical and mathematical models and the calculation method. Actually, the numerical method has been widely adopted [18], showing that it is reliable. The calculation results and the discussion are presented below.

4. Results and discussion

In this section, the radiative and evaporative characteristics of the LDR at designed conditions will be firstly introduced, which is the basis to conduct the parametric investigation. The working conditions are listed in Table 1, being taken as a reference case. Then, the effects of pressure disturbance frequency f and pressure difference ΔP on the LDR performance will be presented through comparison.

4.1. Radiative and evaporative characteristics at designed conditions

The heat flux and evaporation loss rate variations with coordinate positions are given in Fig. 4. During the calculation, different time steps (0.01 s and 0.001 s) are adopted, and the results are almost coincided, showing that the results are time step independent. In the subsequent calculation, the time step of 0.01 s is adopted.

The radiative heat flux decreases because the droplet layer temperature decreases along the length direction. Similarly, the evaporative loss rate also decreases. It can be found from the gradients that the evaporation intensity has more significant dependency on the radiation intensity. Especially within the high temperature range, the evaporation loss rate has a higher sensitivity to the temperature increase. The detailed temperature distribution along the length and thickness directions is shown in Fig. 5. The uniform initial temperature becomes a parabolic distribution during

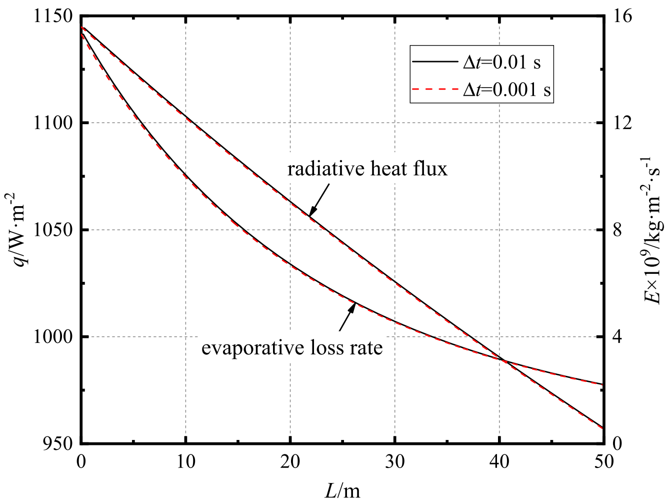

Fig. 4. Heat flux and evaporation loss rate variations with coordinate positions. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

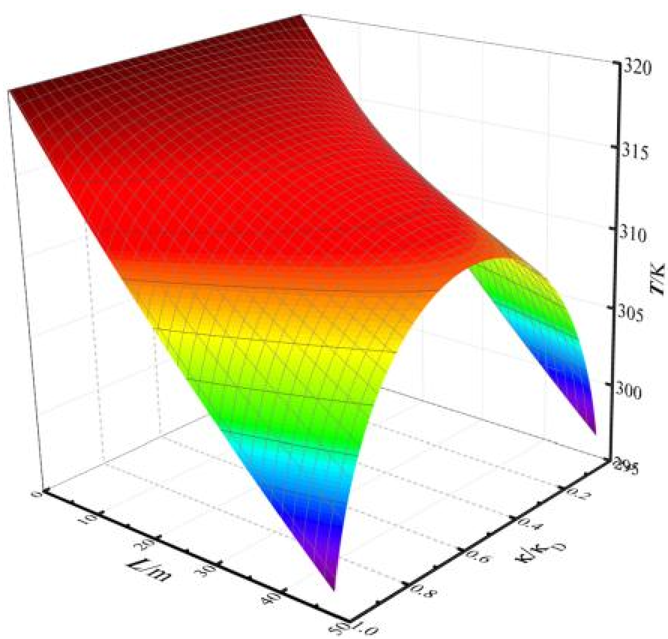

Fig. 5. LDR temperature distribution at designed operation condition.

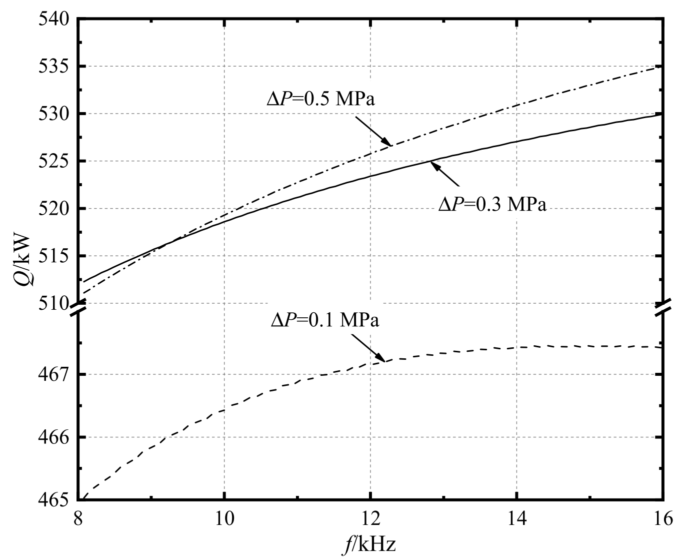

Fig. 6. Effects of pressure disturbance frequency on heat transfer performance.

the cooling time since the droplets at the margin have much more efficient radiative heat transfer. For droplets in the middle region of the layer, the temperature drop is inapparent due to the interference brought by the neighbor droplets.

4.2. Effects of pressure disturbance frequency

The LDR performance is related with the droplet layer parameters such as droplet diameter, droplet number density, working fluid flow rate, etc., which are determined by the pressure disturbance frequency and pressure difference. According to Eq. (1) to Eq. (7), the relationships between these parameters are summarized as follows: $v \sim \Delta P^{1/2}$, $d \sim \Delta P^{1/6}/f^{1/3}$, $n \sim f/\Delta P^{1/2}$, $m \sim \Delta P^{1/2}$, $\kappa_D \sim f^{1/3}/\Delta P^{1/6}$.

The droplet diameter and droplet number density will decrease and increase respectively with disturbance frequency, which is advantageous for droplet cooling. In this case, the radiation power increases with the disturbance frequency, as shown in Fig. 6. However, the radiation power growth rate declines since the droplet layer is too thick to radiate effectively. When the disturbance frequency is high, droplets are generated much more frequently, and the scattering and absorbing will play dominant role in the radiation process within the droplet layer, weakening the effective radiation for droplet cooling. Therefore, for an operational pressure difference, there is a "cut-off frequency", above which the radiation power will not increase any more. The "cut-off frequency" for the droplet generator with pressure difference at 0.1 MPa is approximately 14 kHz. Besides, a higher operational pressure difference has a higher "cut-off frequency".

It can be found from the figure that for the same disturbance frequency ($f > 9$ kHz), a higher pressure difference leads to a higher radiation power. The optical thickness of droplet layer will decrease when rising the pressure difference, enhancing the radiation heat transfer. Meanwhile, the droplet flight velocity increases with the pressure difference, shortening the cooling time. Hence the droplet temperature drop will not be significant. For lower disturbance frequency, the droplet diameter will be bigger, and the droplet layer will be sparser, decreasing the total heat transfer power. Therefore, to obtain a better radiation performance, a higher pressure difference should be coupled with a higher pressure disturbance frequency.

The evaporation loss rate variations with pressure disturbance frequency are shown in Fig. 7. The monotonicity of these four curves are different within the disturbance frequency range. The evaporation loss rate is negatively related with the droplet diameter and droplet number density. The higher disturbance frequency represents smaller droplet and thicker droplet layer. Therefore, the general evaporation loss rate is a tradeoff between droplet diameter and number density. It can be extrapolated that for a certain pressure difference, the evaporation loss rate increases first and then decreases with the disturbance frequency. The variation accounts about 5% of the absolute value. Besides, the disturbance frequency corresponding to the extreme point differs for variable pressure difference cases. The evaporation loss rate with lower pressure difference firstly attains the maximum.

For the same disturbance frequency, higher pressure difference brings higher evaporation loss rate. The droplets have much faster flight velocity and shorter cooling time when operating with higher pressure difference. Hence, the droplet layer remains a relatively high temperature, bringing higher evaporation loss rate. Therefore, a relatively lower pressure difference of the droplet generator is preferred in view of the evaporation characteristics.

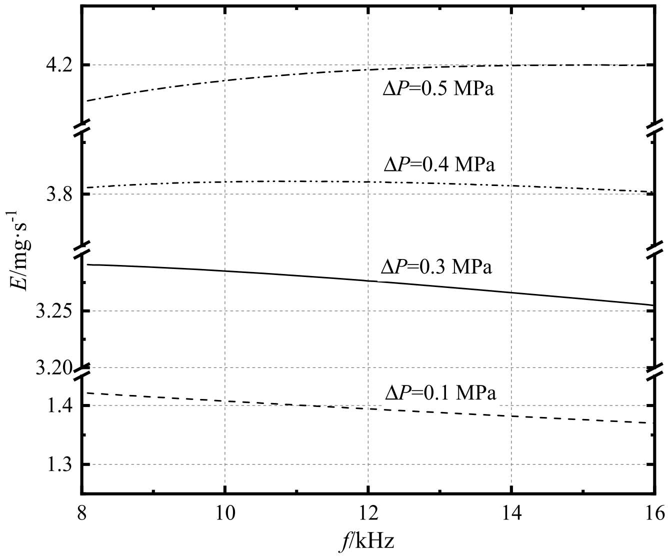

Fig. 7. Effects of pressure disturbance frequency on evaporation characteristics.

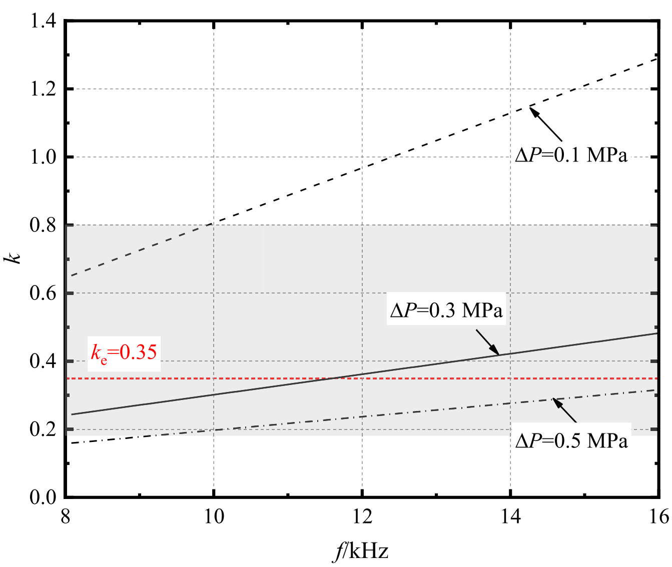

Fig. 8. Non-dimensional wave number variations with pressure disturbance frequency.

Besides the radiation heat transfer and evaporation characteristics, the operation stability of the droplet generator should also be taken into consideration before the suitable pressure difference and disturbance frequency are determined. Experimental investigations have pointed out that the uniform droplet streams can be successfully generated when the non-dimensional wave number is at the range of 0.2–0.8. Otherwise, the droplet will collide with each other, disrupting the regular operation. The non-dimensional wave number variations with pressure disturbance frequency are shown in Fig. 8. For a certain pressure difference, the k increases with the disturbance frequency, and the gradient is negatively related to the square root of the pressure difference. Hence, the suitable range of operational disturbance frequency is larger for cases with higher pressure differences. Furthermore, the appropriate disturbance frequency increases with pressure difference. For example, taking the $k = 0.35$ as the desired value, the disturbance frequency should be set as 11.8 kHz for cases with pressure difference at 0.3 MPa, while the frequency should be larger than 16 kHz for cases with pressure difference at 0.5 MPa.

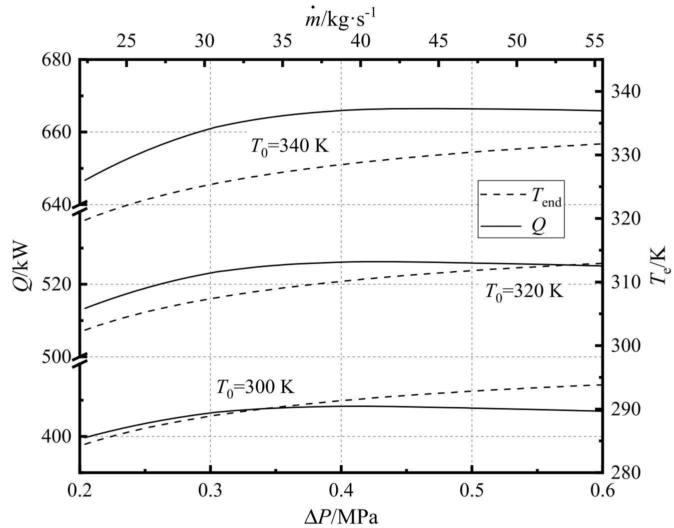

Fig. 9. Effects of pressure difference on heat transfer performance.

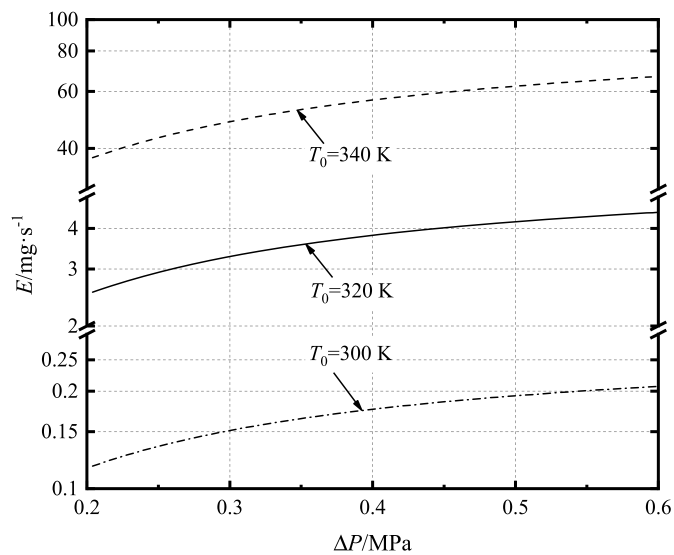

Fig. 10. Effects of pressure difference on evaporation characteristics.

4.3. Effects of pressure difference

Rising the pressure difference between the inside and outside of the droplet generator can increase the mass flow rate of the working fluid, however, the higher flow rate may not lead to higher heat transfer power, as illustrated in Fig. 9. The radiation heat transfer power of the droplet layer increases first, and it remains nearly constant. For higher pressure difference, the optical thickness is lower, which is beneficial for radiation. In this case, however, the droplet velocity is high, and the cooling time is short, leading to a higher temperature at the droplet collector (T_{end}). Therefore, the total heat transfer power is not as high as expected.

The effects of the initial temperature at the droplet generator on the heat transfer performance are also shown in the figure below. The higher initial temperature (T_0) brings higher radiation power, and a 6% increase of initial temperature could lead to approximate 20% increase of heat transfer power. For $\Delta P > 0.4$ MPa, the final temperature and the mass flow rate increase, and the temperature drop decreases, resulting a nearly constant heat transfer power.

The evaporation loss rate of the working fluid increases successively with pressure difference, as shown in Fig. 10. The dominant factor of the evaporation loss is the temperature field of the droplet layer. As shown in Fig. 9, the final temperature continues to increase with the pressure difference, suggesting higher layer temperature. Therefore, more working fluid will evaporate into the space. For a certain initial temperature, the pressure increase may lead to 100% increase of the evaporation loss rate. Moreover, the initial temperature plays considerable roles in the evaporation. The evaporation loss rate may rocket tenfold for a 20 K increase of the initial temperature. Comparing with Fig. 9 and Fig. 10, it can be found that for $\Delta P > 0.4$ MPa, the evaporation loss rate increases continually while the heat transfer power does not increase any more. In view of this, the operational pressure difference is suggested to be lower than 0.4 MPa for this kind of droplet radiator.

5. Conclusions

Parametric investigation of the radiation heat transfer and evaporation characteristics are conducted for the frameless waste heat removal system LDR. The physical and mathematical models of the droplet generator and droplet layer are jointly solved and analyzed. The effects of the pressure difference and disturbance frequency of the droplet generator on the radiation heat transfer power and working fluid evaporation loss rate are figured out, and the main conclusions are listed below.

1. There is a “cut-off frequency” for a certain pressure difference, above which the heat transfer power will not increase any more. The “cut-off frequency” for the droplet generator with pressure difference at 0.1 MPa is approximately 14 kHz. The evaporation loss rate ascends at first and descend at last with the increasing disturbance frequency, but the variations are slight, accounting approximately 5% of the absolute value.
2. The higher pressure difference brings higher coolant mass flow rate, but it not necessarily means higher radiation heat transfer power. During the high-pressure difference ranges, the evaporation loss rate increases continually while the heat transfer power does not increase any more, and the increasing range of the evaporation loss rate can be up to 100%.
3. In terms of the formation of the stable uniform droplet streams, the suitable range of disturbance frequency is larger for cases with higher pressure differences. The disturbance frequency should be set as 11.8 kHz for cases with pressure difference at 0.3 MPa.

Based on the parametric investigation, a relatively higher pressure difference coupled with a higher disturbance frequency (such as 0.3 MPa and 12 kHz) is preferred in consideration of better radiation heat transfer performance and lower evaporation loss rate. It is noteworthy that the calculation and analysis presented in the paper, especially the specific quantitatively conclusions, are suitable for cases adopting pressure disturbance driven droplet generator and silicon oil as the working fluid. The qualitative conclusions are reasonable and considerable for determining the appropriate operation range of the droplet generator to obtain higher heat transfer power and lower working fluid evaporation loss.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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