Experimental investigation on the heat transfer characteristics of vacuum spray flash evaporation cooling

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Abstract

Vacuum spray flash evaporation cooling (VSFEC) is considered as an alternative effective method for dissipating high heat flux in the field of space thermal control. In this paper, a VSFEC experiment system has been developed to investigate the influence of spray flow rate and spray height on the heat transfer characteristics of VSFEC. The experiment results show that the heat flux can be removed efficiently from the heat source in VSFEC system with a very small spray flow rate, which is only one third of that of conventional spray cooling under the same heat flux. And an optimal flow rate exists in VSFEC, at which the heat transfer approaches to a highest value, it is different from conventional spray cooling in which the heat flux increases with the increasing of spray flow rate all the time, in VSFEC, the heat flux firstly increases and then decreases with increasing of flow rate. Since VSFEC system is an open-loop heat dissipation system, it has very important significance that based on the optimal flow rate to reduce working medium consumption, especially for space thermal control system which has a strict limit on weight. In addition, spray height has an important effect on the heat transfer characteristics of VSFEC and an optimal spray height is also obtained at which the maximum value of heat flux can be achieved.

Keywords: Vacuum spray flash evaporation cooling, spray flow rate, spray height, heat transfer characteristics

1. Introduction

Vacuum spray flash evaporation cooling (VSFEC) is a highly efficient method for high heat flux removal. Due to the advantages of compact structure, strong heat removing capability and low flow rate of working fluid, Compact Flash Evaporator System has become an alternative thermal control system in NASA Orion Crew Exploration Vehicle spacecraft [1, 2]. However, little published literature on the VSEFC was found.

Fig.1 shows droplets behavior model of the VSFEC. When the working fluid sprays from nozzle towards the heat surface which placed in vacuum chamber, it is atomized into a large amount of tiny droplets. Before reaching the heating surface, these droplets rapidly evaporate because of a sudden depressurization in vacuum environment, becoming smaller and colder droplets. Then, these droplets impact the heating surface, some of them rebound off the surface, while the rest adhere to the surface, forming a liquid film. Because of exposed to vacuum environment, flash vaporization appears at the liquid film surface, resulting in the temperature declines, the low temperature film washes the heating surface and induces the film-surface convection. Meanwhile, boiling bubbles grow and remove the heat from the heating surface if the surface is superheated. It can be concluded that the heat transfer mechanism of VSFEC consists of five parts: droplet-wall impaction heat transfer, liquid film flash evaporation heat transfer, film-surface convective heat transfer, boiling bubbles inducing heat transfer, environmental heat transfer.

Flash evaporation has been world-wide researched in recent years, due to its industrial and iatrical applications, such as water desalination, food fresh keeping, binary ice production, dermatologic laser surgery, superheats water jets and energy recycle (i.e. geothermal power plant) [3-9].

Most of the researches focus on the flash evaporation of liquid film in pool. Miyatake et al. [10] carried out experiments on static flash and introduced non-equilibrium fraction (NEF) to characterize temperature evolution of water film and evaluate final completeness of flash phenomenon in a given system. **They** found that flashing occurs in two consecutive stages: the initial very rapid, indicating vigorous ebullition, followed by relatively quiescent evaporation. Moreover, Miyatake et al. [11] introduced flash evaporation rate coefficient. This coefficient was almost independent of time or superheat, but was strongly influenced by final equilibrium water-film temperature. Saury et al. [12, 13] carried out experimental study on the water mass evaporated by flash evaporation and examined the influences of water film height and depressurization rate on NEF elevation and evaporated mass. Results validated that final evaporated mass was proportional to superheats and could be calculated by

the heat balance with relative error less than 10%. Kim et al. [14] carried out experiments on pool flash evaporation and identified the critical time at which the rate of ebullition and evaporation diminishes abruptly and the critical initial water temperature at which the expected observed trend of decreasing non-equilibrium temperature difference (NETD) with decreasing depth reverses itself. Jin et al. [15, 16] studied the flow patterns of flash evaporation experimentally and theoretically. The influence of water level and flow rate on flow patterns was studied with high speed camera technology and PIV measurement. They found that there was a recirculating region near the inlet gate with vortices. The size of the recirculating region and the vortex number varied with flow conditions. In addition, there were **main** applications for flash evaporation in desalination, and static flash evaporation of aqueous NaCl solution was also focused on. Gopalakrishna et al. [17] carried out experiments using both degassed fresh water and a degassed 3.5% (by weight) aqueous NaCl solution in a similar vessel but of 152 mm diameter, at water depths of 165, 305 and 457 mm, at initial temperatures from 25 to 80°C, and initial superheats of 0.5-10 °C. Liu et al. [18] did experiments on flash evaporation of aqueous NaCl droplet, and found the evaporation rate can be minimized by higher concentration or environment pressure. Zhang dan et al. [19, 20] carried out experiments on static flash evaporation of aqueous NaCl solution and analyzed influence of parameters on flash speed and heat transfer, such as initial water film concentration, initial water film height, superheat, initial water film concentration.

Droplet flash evaporation is of interest to many researchers. Cheng et al. [21] numerically simulated and **experimentally** investigated the influence of the characteristics of the non-isothermal flashing droplet on the vacuum flash spray cooling. Shin et al. [22] obtained the characteristics of the changes from the droplets to the ice by using the diffusion-controlled evaporation model. Isao et al. [23] developed a theoretical model which can predict the variation in droplet temperature when the pressure is suddenly dropped. Liu et al. [24] experimentally investigated the flash evaporation process of saltwater droplets released into vacuum, and found that component and solution concentration has great influence on the evaporation process.

Both of above flash evaporation processes occur during VSFE, which are inexistence in the conventional spray cooling [25-30]: one is the droplets flash evaporation before they reach the heating surface, and the other is the fluid film flash evaporation covering the heating surface [31]. In VSFE, the liquid film is formed by droplets adhering to the heating surface after droplet flash evaporation. The droplet flash evaporation decreases the droplet diameter and temperature, which will directly affect the

formation of liquid film on the heating surface and the distribution of temperature of the heat surface, and consequently will affect the film flash evaporation heat transfer.

Due to different application backgrounds, most of researchers focus on either only the single of influence of liquid film evaporation or droplet evaporation, and few researchers investigate the combined effect of both liquid film evaporation and droplet evaporation, and the public reporting of the overall influence of droplet flash and liquid film flash on the VSFEC has also not been given. Furthermore, few researchers take into account the effect of flash evaporation on thermal control, especially for space thermal control. In addition, most of the conventional spray cooling systems are close-cycle systems, which are not very concerned about the issue of flow rate, however, the VSFEC system is an open heat dissipation system, which has very strict requirement for its heat transfer capacity and flow rate. In the case of heat transfer capacity meeting the demand of system, it is crucial importance for the open heat dissipation system to investigate a minimum flow rate of the system.

Aiming at above problems, the experimental study is carried out based on a VSFEC experimental system for pure water in this paper to investigate the influence of spray flow rate and spray height on the heat transfer characteristics of VSFEC and to study the effect of liquid film evaporation and droplet evaporation on spray cooling.

Fig.1. Droplets behavior model of the VSFEC

Nomenclature

h_s	Spray height, mm	h	Heat transfer coefficient, $W/(K \cdot cm^2)$
q	Heat flux, W/cm^2	q_v	Volume flow rate, L/h
T_{sur}	Heating surface temperature, K	λ	Thermal conductivity of brass, $W/(K \cdot m)$
T_i	Mean temperature of i layer, K	δ	Distance between the two layers, m
T_{equ}	Saturation temperature, K	Δt	Temperature difference, $^{\circ}C$
P	Heating power, W	θ	atomization angle, rad

2. Experimental system

2.1 Experimental apparatus and procedure

(1) Reservoir	(8) Float flow meter	(14) Dehumidified device
(2) Condenser	(9) Thermometer	(15) Vacuum pump
(3) Feed pump	(10) Pressure gauge	(16) Heating system
(4) Buffer	(11) Pressure transducer	(17) High vacuum diaphragm valve
(5) Filter	(12) Nozzle	(18) Data acquiring system
(6) Adjusting valve	(13) Visualization flash chamber	(19) Liquid storage tank
(7) Preheater		

Fig.2. Schematic of experimental setup

Fig3. Figure of experiment installing

As shown in Fig.2 and Fig.3, experimental system for VSFEC is composed of six parts, including feed-water system, spray system, heating system, vacuum system, cooling system and data acquisition system. The distilled water as working fluid is delivered to spray nozzle. Due to a sudden depressurization, through the nozzle, the working fluid is atomized into a large amount of smaller and colder droplets. These droplets impinge onto the heating surface, some of them rebound off, and others form a liquid film, the liquid film can flash evaporates because of being exposed to vacuum environment. The heat that generated from the heating surface is removed through ways of conduction and convection. The liquid droplet and liquid film flash evaporation produce a lot of steam, the steam flows into a condenser, then is cooled and gathered. The fluid film of the heating surface flows along the drained cells into liquid trap and finally is drained out. To achieve visualization, a tempered glass window is used to flash chamber. The condenser is a little inclined to horizontal surface, making it easier for the condensed water to flow into liquid trap and finally drain out. **The nozzle of experiment adopted is a commercial DANFOSS nozzle. The nozzle orifice size is 0.5 mm, the spray cone angle is 45°, and the shape of atomization is solid cone.**

As shown in Fig.4, In order to realize more heat accumulation, the heater is composed of a small upper cylinder ($\text{Ø}12 \times 40$) and a big lower cylinder ($\text{Ø}68 \times 125$). Five 2000W electrical heating rods are installed in the lower cylinder and the heating power is controlled by a transformer. The heating surface is the top surface of the upper cylinder, whose area is 1 cm^2 . The heated body temperatures are measured by four layers of type-T thermocouples. These thermocouples are arrayed 1, 6, 11, and 16

mm beneath the heated surface, respectively. There are three thermocouples at each layers, the radial distances between the thermocouples and the axis of the cylinder are 2, 4, and 6 mm, respectively. Detailed layout of thermocouples is shown in Fig.5. The heater except heating surface is enclosed by an expanded-perlite heat insulator layer. High thermal conductivity paste is applied to the thermocouples ensuring good contact between the copper hole and the thermocouple. The temperature of a layer is evaluated as the arithmetic mean value of the temperature measured by thermocouples in the layer.

Fig.4. Schematic of heating system

Fig.5. Schematic of thermocouples installation

Generally, according to the Fourier conduction law, the heat flux q (W/cm^2) is calculated by the temperature gradients on axial direction which assumed one-dimensional thermal **conduction**. It is described as:

$$q = \lambda \frac{T_i - T_{i+1}}{\delta} \quad (1)$$

Where T_i and T_{i+1} are mean temperature of the adjacent two layers in the heater ($^{\circ}\text{C}$), δ is the distance between the corresponding to two layers (m), and λ is the thermal conductivity of H-62 brass [$\text{W}/(\text{K}\cdot\text{m})$].

The heat transfer coefficient h of spray cooling can be defined as:

$$h = \frac{q}{T_{sur} - T_{equ}} \quad (2)$$

Where h is heat transfer coefficient [$\text{W}/(\text{K}\cdot\text{cm}^2)$], T_{sur} is the heating surface temperature ($^{\circ}\text{C}$), which is obtained by extrapolation method from the mean temperature of the four layers; T_{equ} is the flash chamber pressure($^{\circ}\text{C}$) corresponding to the saturation temperature when experiment finally keeps stable.

2.2 Experimental uncertainty

The measurement uncertainty depends on the measurement uncertainties of the temperature, spray height, and so on. The thermocouples accuracy is $\pm 0.1^{\circ}\text{C}$ and the temperature measurement accuracy by the data acquisition instruments is $\pm 0.2^{\circ}\text{C}$. The spray height measurement accuracy is $\pm 0.1\text{mm}$.

According to the error propagation law [32], the indirect error can be evaluated as follows:

$$\sigma_y = \sqrt{\sum_{i=1}^n \left(\frac{\partial f}{\partial x_i}\right)^2 \sigma_{x_i}^2} \quad (3)$$

Therefore, the measurement uncertainties of the heat flux, heat transfer coefficient was $\pm 2.3\%$, $\pm 6.5\%$, respectively.

3. Results and discussion

3.1 The effect of flow rate on heat transfer performance

The heat transfer performance is very sensitive to spray flow rate in VSFE, and a small change of the spray flow rate may result in a great difference in the heat transfer performance. Therefore, the effect of spray flow rate on heat transfer performance is investigated firstly by experiments, While the spray flow rate changed within 0.8–2.2 L/h with every 0.1 L/h adjustment at heating power $P=500\text{w}$, and the initial pressure of vacuum flash chamber is less than 50 Pa, and when the experiment finally keeps stability, the pressure of vacuum chamber ranges from 1.4 kPa and 1.5 kPa.

Fig.6. Surface temperature changes with flow rate at different spray heights

The surface temperature at the different spray flow rates are shown in Fig.6. For the different spray heights, the variation trends of heat transfer curves between surface temperature and flow rate are similar, which surface temperature firstly decreases and then increases with the improving of spray flow rate. The surface droplets behaviors are shown in Fig.7. With a small spray flow rate, the flow of the liquid on the heating surface is poor. While the droplets impact on the heating surface, most of the droplets deposit on the heating surface and form a thick layer of liquid film. Meanwhile some bubbles may appear and stick on the heating surface. The thick liquid film and the bubbles can increase the local heat transfer resistance, resulting in the heat transfer exacerbation. However, with the increasing

of spray flow rate, droplet velocity and atomization angle θ (Fig.1) increases, resulting in that the thickness of fluid film decreases and the scour of fluid increases and the disturbance of liquid enhances. Therefore, the heat transfer performance gets better and the surface temperature drops (as shown in Fig.7 (a) ~ (c)). However, as the flow rate continues to increase, atomization angle θ increases. The spray mainstream region moves toward the edge of the heating surface, a dry wall region appears and expands in the heating surface, even the spray area oversteps the heating surface, resulting in that the coverage area of fluid film on the heating surface reduces and the effective volumetric flow rate decreases, as a result, the heat transfer performance gets worse and the surface temperature rises (as shown in Fig.7 (d) ~ (f)).

Fig.7. Surface behaviors of liquid in VSFEC with flow rate improved

Fig.8. Surface heat flux changes with flow rate at different spray heights

The experiment studied the association between flow rate and surface heat flux at different spray heights. As shown in Fig.8, in the case of different spray heights, the variation trends of heat transfer curves between the surface heat flux and flux are similar, and the surface heat flux firstly augments to a peak value and then decreases with the increasing of flow rate. It is concluded that the optimal flow rate exists in VSFEC and makes heat flux achieve the maximum value under a certain height.

Fig.9. Heat transfer coefficient changes with flow rate at different spray heights

Spray flow rate is one of the most important physical parameters in VSFEC. It determines the total quality of working medium directly. The experiment studied the association between flow rate and heat

transfer coefficient at different spray heights. As shown in Fig. 9, In the case of different spray heights, the variation trends of heat transfer curves between heat transfer coefficient and flow rate are similar, heat transfer coefficient firstly augments to a peak value and then decreases with the increasing of flow rate. The peak value is obtained at $h_s=8$ mm and the heat transfer coefficient reaches $8.19 \text{ W}/(\text{K}\cdot\text{cm}^2)$ with the flow rate of 1.5 L/h.

3.2 The effect of spray height on heat transfer performance

Fig.10. Spray cooling curves at different spray heights

With the same flow rate of 1.5 L/h, three spray heights of 5mm, 8mm and 10mm were studied under different heating powers of 500W, 600W, 700W, 800W, and 900W. Fig.10 shows the heat flux versus the temperature difference between heating surface and inlet fluid (10 °C) at different spray heights. It can be found that heat flux firstly increases and then decreases with the increasing of spray height. The best performance is obtained at 8 mm within the scope of the experiment, and the heat flux is as high as $263 \text{ W}/\text{cm}^2$ with temperature difference of 59.3°C . However, compared to spray flow rate 4.2 L/h for conventional spray cooling [33], the flow rate in VSSEC is only one third of that of conventional spray cooling under the same heat flux. It can be explained as follows: the droplet diameter and temperature decrease a lot after droplet flashes evaporation in VSSEC, these droplets impact the heating surface, forming a liquid film. Because of exposed to vacuum environment,

flash vaporization appears at the liquid film surface, resulting in the liquid film temperature declines, and the augment of superheat between the heating surface and the liquid film, as a result, the heat transfer is non-equilibrium state on the interface of heat transfer and the heat transfer effect is greatly enhanced.

Fig.11. Surface temperature changes with spray height at higher spray flow rates

Fig.11 shows the association between surface temperature and spray height at larger spray flow rates. The greater the flow rate, the bigger atomization angle θ . With the increasing of spray heights, the heating surface enters into complete atomization area where the droplets in tiny particles impact the heating surface, resulting in that the heat transfer performance gets better and the surface temperature drops. However, when the spray height continues to increase, the spray mainstream region gradually moves toward the edge of the heating surface. Therefore, the dry wall region increases and the coverage area of liquid film on the heating surface is less and less, even the mainstream region moves out of the heating surface and the whole heating surface turns to dry out. Finally, the heat transfer performance deteriorates sharply and the surface temperature rises quickly.

Fig.12. Surface temperature changes with spray height at smaller spray flow rates

Fig.12 shows the association between surface temperature and spray height at smaller spray flow rates. With a small flow rate, the atomization angle θ is small. At a low spray height, the heating surface is under the non-atomization area or partial atomization area, the droplet velocity is low and the thickness of fluid film is great, affecting the flow of fluid on the heating surface, so the heat transfer performance is weakened. However, with improving of the spray height, the heating surface gradually enters into complete atomization area, which makes the thickness of fluid film decrease and impact effect of droplets increase, the heat transfer performance gets better. Nevertheless, the spray height continues to increase, resulting in that the droplets momentum decreases and the effect of droplets impingement is gradually weakened and liquid droplets deposit on the heating surface, thus, heat transfer begins to deteriorate.

Fig.13. Maximum heat flux and minimum surface temperature at different spray heights

The maximum heat flux and minimum surface temperature at different spray heights are shown in Fig.13, It can be found that the maximum heat flux firstly increases with the increasing of spray height, and then decreases, **nevertheless** the minimum surface temperature has a contrary trend. The best performance is obtained at 8 mm within the scope of the experiment, and the maximum heat flux reaches 114.52 W/cm^2 with flow rate of 1.5 L/h and heating power of 500 W, which is increased by 17.9%, 9.3%, 4.7% and 8.7% compared with that of 3mm, 5mm, 10mm and 13mm, respectively.

Fig.14. Maximum heat transfer coefficient and optimal flow rate at different spray heights

The optimal flow rate in this paper is defined as the flow rate which makes heat flux reach the

maximum value at a certain spray height. The maximum heat transfer coefficient and the optimum flow rate at the different spray heights are shown in Fig.14. It can be found that the maximum heat transfer coefficient and optimal flow rate firstly increase with the increasing of spray height, and then decrease. It is also concluded that there is an optimal value for spray height, which makes the heat transfer performance best. This is because that the droplet velocity is low and the thickness of fluid film is great under the non-atomization area or partial atomization area, the increasing of flow rate can make the disturbance of liquid enhance and the heat transfer get better. Nevertheless, when the heating surface gradually enters into complete atomization area with the increasing of spray heights, if the atomization angle θ keeps constant (that is to say, the flow rate is constant), with the increasing of spray heights, the spray mainstream region moves toward the edge of the heating surface, and a dry wall region appears and expands in the heating surface, even the spray area oversteps the heating surface, resulting in that the coverage area of fluid film on the heating surface reduces and the effective volumetric flow rate decreases, thus, the heat transfer performance gets worse. In order to avoid this situation, the flow rate should be corresponding decreased to ensure adequate coverage area of fluid film when the spray height is increased.

4. Conclusions

Experiments were implemented to investigate the effects of spray flow rate and spray height on the heat transfer characteristics of VSFEC. The main conclusions are deduced as follows:

- 1) The heat flux can be removed efficiently from the heating surface in VSFEC system with a very small spray flow rate, and the flow rate is only one third of that of conventional spray cooling under the same heat flux.
- 2) The experiment indicated that the droplet-wall impaction heat transfer and the liquid film flash evaporation heat transfer are dominant in VSFEC.
- 3) Differ from conventional spray cooling, the optimal spray flow rate is found in VSFEC, and the heat flux firstly increases and then decreases with improving of flow rate.
- 4) The optimal spray height, at which the heat flux can reach maximum value, is obtained in VSFEC, and can help to use working fluid more sufficiently.

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