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

Wen-Long Cheng *, Yu-Hang Peng, Hua Chen, Lei Hu, Han-Ping Hu

*Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei, Anhui 230027, China*

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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.



## 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

* Corresponding author. Fax: +86 551 63600305.
*E-mail address:* wlcheng515@163.com (W.-L. Cheng).

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**Nomenclature**

| | | | |
|---|---|---|---|
| $h_s$ | spray height, mm | $h$ | heat transfer coefficient, W/(K·cm$^2$) |
| $q$ | heat flux, W/cm$^2$ | $q_v$ | volume flow rate, L/h |
| $T_{sur}$ | heating surface temperature, K | $\lambda$ | thermal conductivity of brass, W/(K·m) |
| $T_i$ | mean temperature of $i$ layer, K | $\delta$ | distance between the two layers, m |
| $T_{equ}$ | saturation temperature, K | $\Delta t$ | temperature difference, °C |
| $P$ | heating power, W | $\theta$ | atomization angle, rad |

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. [18] 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 VSFEC, which are inexistence in the conventional spray cooling [24–29]: 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 [30]. In VSFEC, 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.

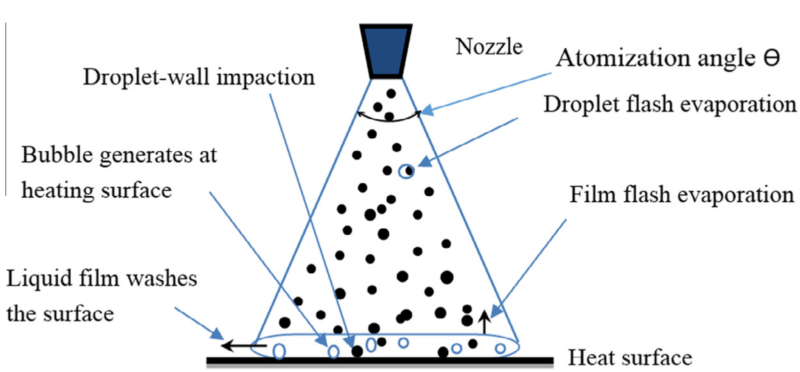


**Fig. 1.** Droplets behavior model of the VSFEC.