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Effect of droplet flash evaporation on vacuum flash evaporation cooling: Modeling

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ABSTRACT

In consideration of droplet flash evaporation and film flash evaporation, a comprehensive mathematical model of vacuum flash evaporation cooling (VFEC) was presented in this paper. Pure water was considered to be the working fluid. The droplet flash evaporation was modeled based on the diffusion-controlled evaporation model, while the film flash evaporation was modeled based on the film penetration theory. The droplet flash model coincided well with the experimental results reported in the literature and the comprehensive mathematical model was validated by experiment results in this paper. The droplet temperature and diameter after droplet flash evaporation were obtained numerically, and then analyzed. The effect of droplet flash evaporation on the surface temperature distribution, heat flux density, and heat transfer ratio of different mechanisms was studied based on the model. It can be concluded that the droplet flash evaporation, which can be expressed by the ratio of droplet-wall impaction heat transfer, had a great effect on vacuum flash evaporation cooling heat transfer. The droplet-wall impaction and film flash heat transfer were dominant in the vacuum flash evaporation cooling. The spray characteristics such as droplet diameter and temperature decreased a lot after droplet flash evaporation, compared to the initial parameters (measured by the PDA). After taking droplet flash into account, the surface temperature decreased and the heat flux increased.

1. Introduction

Vacuum flash evaporation cooling (VFEC) is an advanced spray cooling technique in evaporation mode in the vacuum environment. In VFEC, the flashing spray impinges on the heating surface in vacuum environment, removes heat from the surface by both flash evaporation and convection, resulting in intense, short-duration cooling. Due to its advantages of small size, light weight and high heat flux removal capacity, Compact Flash Evaporator System has become an alternative thermal control system in NASA Orion Crew Exploration Vehicle spacecraft [1,2]. But little published literatures on the cooling mechanism of VFEC were found.

Two flash evaporation processes occurs during VFEC: one is the flash evaporation of the droplets before they reach the heating surface which is called droplet flash, and another is the flash evaporation of the working fluid film covering the heating surface which is called film flash. Flash evaporation is a very quick phenomenon caused by an abrupt pressure drop which leaves the liquid superheated. It has been widely researched due to its widely industrial applications, such as water desalination [3], and food dehydration [4]. However, little published literatures on the overall effect of droplet flash and film flash were found.

Most of the researches focus on the flash evaporation of liquid film in pool. Miyatake et al. [5] introduced Non-equilibrium Temperature Coefficient (NETC) and non-equilibrium fraction (NEF) to characterize temperature evolution of water film and evaluated final completeness of flash phenomenon in a given system. They suggested that flash can be divided into fast evaporation stage and gradual evaporation stage according to the speed of film temperature drop. Kim et al. [6] carried out experiments on static flash of water film and studied critical time (the time from the rapid boiling stage to the surface evaporation stage) and the initial temperature of the least Non-equilibrium Temperature Difference (NETD). Saury et al. [7,8] 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. Jin et al. [9,10] 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. Zhang et al. [11,12] studied the steam-carrying effect in static flash of both pure water and aqueous NaCl solution. Non-equilibrium

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Nomenclature

A	area
C_p	specific heat capacity
D	mass transfer coefficient
D_v	binary diffusion coefficient of air–vapor mixture
k	thermal conductivity
k_{eff}	effective thermal conductivity inside the droplet
L	water vaporization latent heat
$\dot{m}$	mass evaporation rate of droplet
Nu_{drop}	Nusselt number
P	pressure
Pe_L	Peclet number of the droplet
R	transient radius
R_0	initial radius
r	radius
T	temperature
t	time
Q	heat transfer rate

Greek letters

ρ	density
θ	effective conductivity factor
η	an efficiency defined in Eq. (11)
δ	distance between two layers of thermocouples, m

Subscripts

bub	bubble
drop	droplets
envi	environments
film	film
liq	liquid phase
rad	radiation
sat	saturated
s	droplet surface
w	heating wall
∞	surrounding
0	initial

fraction (NEF), evaporated mass and heat transfer coefficient were studied based on static/circulatory flash evaporation experimental systems.

The freezing of liquid droplet is of interest for many engineering process, such as ice production [13]. Therefore, the researches on droplet flash evaporation are also popular. Most of the studies based on experimental results. Miyatake et al. [14] carried out experiments on the spray flash evaporation and examined the influences of the degree of superheat, the spray flow rate and the orifice diameter on the characteristic of flash spray. Zhou et al. [15] observed the formation and the dynamic characteristics of spray flash evaporation by PDPA system. Satoh et al. [16] experimentally examined the freezing of a water droplet due to evaporation. They found that the water droplet was effectively cooled by the evaporation of water itself, and that the cooling rate of the water droplets was dominated by heat transfer within the droplet.

Numerically modeling of droplet flash evaporation has not yet been fully addressed in the current literature. So far, most existing models based on diffusion-controlled evaporation model. Shin et al. [17] studied the freezing of water sprayed into an evacuated chamber experimentally and theoretically. Spherical ice particles of size below 300 mm were obtained by experiment at pressure below the freezing point of water, and the formation of ice particle were theoretically studied by the diffusion-controlled evaporation model. Wu et al. [18] developed a numerical diffusion-controlled partial differential equations model to analyze droplet behavior in an evaporating chamber. Temperature and particle diameter variation with time were studied.

Although above researches provided some useful information on the flash evaporation of liquid film and droplet, the results have not given an overall effect of spray droplet flash and liquid film flash on the VFEC. In VFEC, the liquid film is formed by droplets adhering to the heating surface after droplet flash evaporation. The droplet flash decreases the droplet diameter and temperature, which will affect the formation of liquid film on the heating surface [19], and consequently will affect the film flash heat transfer. Therefore, it is necessary to combine both droplet flash evaporation and film flash evaporation, and build an overall model of VFEC. What is more, the temperature gradient and the convection in a droplet during the evaporation were ignored in above researches. But other researchers found that there was a large temperature gradient within droplet. Liu et al. [20] studied the freezing of water droplet suspended on a thermocouple experimentally. The visualized experiment data indicated a large temperature difference within the droplet. Therefore, it is of importance to consider the temperature gradient in the flashing droplet, and figure out the convective heat transfer inside the droplet.

The present work is aimed at building a comprehensive model to describe the integrated VFEC process by considering both spray droplet flash and liquid film flash, and studies the influence of spray droplet flash evaporation on the total heat transfer performance. The droplet flash evaporation model is based on the diffusion-controlled evaporation model with the convective heat transfer inside the droplet simplified through an effective conductivity factor [21]. The film flash evaporation was modeled based on the film penetration theory. The droplet flash evaporation model coincides well with the experimental results reported in the literature, and the comprehensive mathematical model was validated by experiment results in this paper. The spray droplets characteristics and VFEC heat transfer performance are analyzed based on the model build in this paper. In addition, as water is easily available and has excellent thermodynamics and chemical properties, such as high critical point, high latent heat of vaporization, water is used as the working fluid.

2. Numerical model

The cooling system simulated in this paper is described as below. As shown in Fig. 1, the working fluid water sprays from a

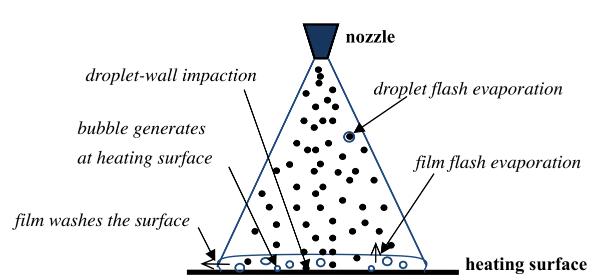

Fig. 1. Heat transfer mechanism of vacuum flash evaporation cooling.