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Modelling on the dynamics of droplet impingement and bubble boiling in spray cooling

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ABSTRACT

A spray cooling model incorporating a spray characteristics submodel and a heat transfer submodel to simulate the dynamics of spray characteristics, droplet impingement, and bubble boiling is presented. The spray characteristics submodel based on a Monte Carlo algorithm simulates the droplet diameter, velocity and spatial droplet flux distributions in actual spray conditions. The heat transfer submodel considers the spray cooling process as film flow boiling to include the processes of droplet impingement forced convection and thin film bubble boiling. Phase Doppler anemometry measurements are used as validation in the spray characteristics submodel, and as boundary conditions in the heat transfer submodel. Reasonable comparison is observed between the experiments and simulations. Parametric effects on the heat transfer performance and bubble dynamics are investigated. The simulation shows that increasing heat flux tends to increase the bubble growing frequency thereby causes the higher bubble collapsing flux and bubble puncturing flux. By fixing the droplet impinging velocity and flow rate, the surface temperature non-uniformity is found to be influenced by droplet diameter. A smaller impinging droplet diameter with a higher impinging droplet flux is favourable to bubble boiling due to more secondary nuclei and larger fractions of bubbles punctured at bigger diameters.

1. Introduction

Spray cooling is one of the eminent phase change cooling techniques ideal for high heat flux power electronics applications in high performance computing hardware, automobiles, aircraft and spacecraft [1–4]. Spray cooling works by forcing liquid through a small orifice to disperse it into fine droplets, which then impact onto the surface being cooled. When the surface superheat is sufficiently high, the impinging droplets interact with the bubbles growing in the liquid film to reject heat through forced convection and phase change.

Extensive experimental studies were conducted to understand the heat transfer mechanisms of spray cooling in the past decades. Shedd and Pautsch [5,6] reported that the heat transfer process in spray cooling was dominated by droplets induced single phase convection. Abbasi et al. [7] showed the correlation between the droplets exerted local dynamic pressure to the local heat transfer coefficient. They found that a higher local impinging droplet flux resulted in a higher local dynamic pressure, which gave a higher local heat transfer coefficient. The results suggested that the impinging droplets induced heat transfer played a dominant role in the single phase regime of spray cooling. Xie et al. [8] reported that the local surface temperature is sensitive to the local droplet flux. A higher local impinging droplet flux led to a lower local surface temperature. In the phase change regime, Yang et al. [9] suggested that the high heat flux obtained by spray cooling was due to the tiny bubbles entrapped by the impinging droplets when they were striking on the liquid film. These tiny bubbles worked as nucleation sites (secondary nuclei) in the liquid film to enhance bubble boiling in spray cooling. In the fundamental study conducted by Rini et al. [10], it was experimentally observed that the nucleation sites in spray cooling was much more than that in pool boiling at the same surface superheat. They attributed the increased nucleation sites to the secondary nuclei resulting from the droplet impingement process.

Chen et al. [11,12] systematically investigated the effects of spray characteristics, such as droplet flux, droplet velocity and droplet diameter on critical heat flux (CHF) of spray cooling by varying one parameter but keeping the others constant. However, without in-

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Nomenclature

D_{32}	Sauter mean diameter $\sum_{i=1}^{n} D_i^3 / \sum_{i=1}^{n} D_i^2$, [µm]
D_d	diameter of the impinging droplet, [µm]
D_m	maximum bubble diameter, [µm]
D_p	punctured bubble diameter, [µm]
Ja	Jacob number $C_p(T_{surf} - T_{sat})/\Delta H_{vap}$, [−]
k	thermal conductivity, [W/m·K]
L_m	size of numerical grid cell, [m]
$\dot{m}$	droplet mass flow rate, [kg/s]
n_d	increment ratio of impinging droplet flux, [−]
n_p	increment ratio of bubble puncturing flux, [−]
n_{di}	heat transfer ratio by droplet impingement, [−]
n_{nb}	heat transfer ratio by bubble boiling, [−]
N_d	droplet impinging flux, [/cm^2 s]
N_p	bubble puncturing flux, [/cm^2 s]
P_r	Prandtl number, [−]
q_{di}	heat transfer rate by droplet impingement, [W]
q_{nb}	heat transfer rate by bubble boiling, [W]
q''	applied heat flux, [W/cm^2]
R_b	radius of the growing bubble, [m]
T_{surf}	surface temperature, [°C]
t	time, [s]
V	velocity, [m/s]
We	Weber number, $\rho_l V_{ave}^2 D_{32}/\sigma$, [−]
Greek letters	
α_l	thermal diffusivity of liquid, [m^2/s]
Δt_D	small time step, [s]
Δt_H	large time step, [s]
η	droplet impingement heat transfer effectiveness, [−]

depth investigation on the spray characteristic effects on the liquid film flow where the heat and mass transfer takes place, it is still unclear about the respective influence of each spray characteristics. Such in-depth experimental investigation on the liquid film flow is too difficult to conduct due to the complex phenomena involved. Recently, most of the fundamental studies on the liquid film flow in spray cooling are through computational simulation by simplifying the spray cooling process. Selvam et al. [13,14] developed a numerical model to simulate the process of a single droplet impinging on a thin liquid film with and without a growing bubble inside. Chen et al. [15] simulated the interaction of the impinging droplets and growing bubbles in the liquid film under a uniform droplet flux impingement. The relationships between droplet flux and bubble size, droplet flux and bubble puncture rate, along with their effects on the heat transfer performance were investigated. Xie et al. [16] derived an analytical model in the non-boiling regime of spray cooling which is capable to predict the distributions of liquid film thickness and surface temperature by using the experimental spray characteristics as the boundary conditions. Zhao et al. [17] and Cheng et al. [18] developed a numerical model to investigate the heat transfer rates due to different heat transfer mechanisms such as droplet-film impaction, film-surface convection, and bubble boiling.

However, all these spray cooling models either consume a lots of computation time, or only consider one or two aspects of spray cooling. Few studies have simulated the spray cooling process in a more general way. In this paper, a dynamic spray cooling model which includes simulating the dynamics of droplet impingement, bubble boiling, and their interactions is presented. Using the experimental spray characteristics as boundary conditions, the model predictions are comparable with the experimental results. The parametric effects including the droplet diameter, droplet impinging flux, and bubble dynamics are investigated, and the heat transfer rates due to different heat transfer mechanisms are discussed.

2. Simulation model

As shown in Fig. 1, the spray cooling process mainly includes two parts. First, the liquid atomization process which is to generate droplets with different velocities and diameters, and spatially distributed droplet fluxes. Second, the heat transfer process which includes the heat transfer by droplet impingement as well as bubble boiling in the liquid film formed on the heated surface. Therefore, the presented simulation model focuses on these two parts which are discussed in the following sections.

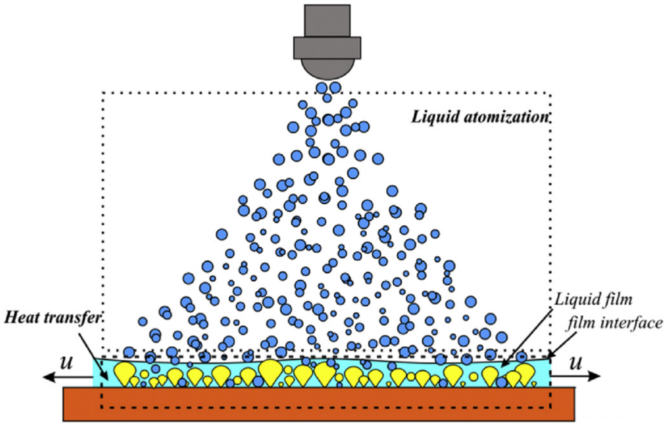

Fig. 1. Schematic of the spray cooling process.

2.1. Spray characteristics model

In the present study, the experimental spray characteristics were obtained from the Phase Doppler anemometry (PDA) measurements [8]. The results show that the probability density distributions of the droplet diameter and droplet velocity are unique for the spray nozzle operating at different axial distances and pressure drops. Moreover, the spatial droplet flux distribution is also unique for the spray nozzle operating at different conditions. To simulate the spray cooling process generally and accurately, it is necessary to import the experimental spray characteristics as boundary conditions in the simulation. In the proposed model, three aspects of droplet hydrodynamics have been considered: (1) probability density distribution of droplet diameter; (2) probability density distribution of droplet velocity; (3) spatial distribution of droplet flux.

To simulate the droplet dynamics, Monte Carlo algorithm proposed by Kreitzer and Kuhlman [19] is adopted. The concept of this approach is to generate a group of random numbers which satisfies the specified probability density distributions of the spray characteristics obtained in experiments. Practically, an inverse