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Research Paper

Modeling of spray flash evaporation based on droplet analysis

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HIGHLIGHTS

- A model was developed to analyze spray flash evaporation.
- The temperature variations against distance are obtained from the model.
- The model shows good agreement with experimental results.
- The effects of influencing factors are studied.

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ABSTRACT

To enable a more in-depth understanding of the flash evaporation from the downward jet and extend the research range of spray flash evaporation, a mathematical model based on the diffusion-controlled evaporation model was proposed and developed. The droplet motion, droplet size variation and temperature variation are taken into account in the present model. The model was validated against the experimental data sets from literature sources. The temperature variation against the traveled distance was obtained and analyzed. Four variables, namely, flow velocity, pressure attenuation ratio, droplet size and relative humidity, were investigated by means of this model.

1. Introduction

When the water is exposed to a sudden pressure drop lower than the saturation pressure which corresponds to the water temperature, the flash evaporation can occur. The flash evaporation can be used in the field of desalination and spray cooling due to its significant performance on separation and heat transfer.

According to different states of the working fluid, flash evaporation can be divided into two types, i. e., static flash evaporation and spray flash evaporation. Throughout previous literature, many researchers experimentally investigated static flash evaporation [1–6]. Compared with static flash evaporation, spray flash evaporation had a higher evaporation performance and faster evaporation rate than static flash evaporation [7]. To characterize the flash evaporation, the non-equilibrium fraction (NEF) was first defined by Miyatake et al. [8] and then was used by other researchers in successive studies. Miyatake et al. [9] first experimentally studied spray flash evaporation occurring in a superheated jet injected into a low-pressure zone. Ide et al. [10] carried out a series of experiments to study the effect of the injection of bubble nuclei. Uehara et al. [11] made an experimental study about the effect of nozzle shape on spray flash evaporation with the initial water temperature of 303.15 K. Ikegami et al. [12] carried out a series of experiments to analyze the effect of the injection direction on spray flash evaporation by comparing the upward jet flash evaporation with the downward jet flash evaporation. Mutair et al. [13,14] experimentally studied spray flash evaporation from the upward jet with the superheat degree from 2 to 13 K. Aleiferis et al. [15] experimentally investigated spray penetration, cone angle, droplet sizes and velocities of gasoline, iso-octane, n-pentane, ethanol and n-butanol at 293.15, 323.15, 363.15 and 393.15 K injector body temperature. The spray and evaporation characteristics of ethanol and gasoline fuels were investigated using the high speed Shadowgraphy imaging technique by Huang et al. [16]. The spray shape and penetration were analyzed applying the experimental and numerical methods with the injection temperature of 333.15 K by Klan et al. [17]. They proposed a spray injection model in the near nozzle region considering both the axial velocity and radial velocity component. Guo et al. [18] investigated spray collapses at the fuel temperature of 293.15 K and 353.15 K.

In addition to the experimental studies on spray flash evaporation introduced above, a few researchers applied numerical methods to analyze spray flash evaporation. Shin et al. [19] performed a

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Nomenclature

F	force, N
m	mass, kg
g	gravity acceleration, N/kg
V	volume, m^3
A	area, m^2
C_D	drag coefficient
u	velocity, m/s
Re	Reynolds number
D	diameter, m
s	distance, m
D_v	diffusion coefficient of vapor, m^2/s
M	molecular weight, kg/mol
R	universal gas constant, J/(mol·K)
P	pressure, Pa
T	temperature, K
c	specific heat capacity, J/(kg·K)
Q	heat, W
k	thermal conductivity, W/(m·K)
$\dot{m}$	mass evaporation rate of a droplet, kg/s
h_{fg}	latent heat of vaporization, J/kg
Pe	Peclet number
R_d	droplet radius, m
r	radial distance in droplet coordinate, m
E_p	partial expansion energy, J/kg
h	enthalpy, J/kg
v	specific volume, m^3/kg
PAR	pressure attenuation ratio

Greek letters

ρ	density, kg/m^3
υ	kinematic viscosity, m^2/s
π	constant, 3.14
δ	collision diameter, m
Ω	collision integral for mass diffusion
ϕ	correction factor
λ	molecular mean free path, m
φ	relative humidity
σ	Stefan-Boltzmann constant
ε	emissivity
$\theta_{l,ave}$	the bulk dimensionless temperature difference
ΔT	superheat degree, K

Subscripts

v	vapor
d	droplet
∞	surrounding
eff	effective
sat	saturated
ave	average
0	initial
s	saturation

theoretical study to examine spray flash evaporation based on the diffusion-controlled evaporation model. Duan et al. [20,21] simulated flashing jets with the moving particle semi-implicit method (MPS) under high temperature and pressure. Mutair et al. [22] modeled liquid-side heat transfer with the surface evaporation of superheated water drops. They found that the effective thermal conductivity of the liquid should be larger than the mere molecular thermal conductivity. Grosshans [23] applied the CFD code to model a three-dimensional evaporating spray. Nie et al. [24] simulated spray flash evaporation of pentane by using ANSYS Fluent. Wu et al. [25,26] modeled the flash evaporation of a water droplet by developing diffusion-controlled partial differential equations. The temperature variations and droplet radius variations against time were obtained and analyzed in their study. Cheng et al. [27] modeled vacuum flash evaporation cooling (VFEC) by considering both the droplet flash evaporation and the film flash evaporation. Wang et al. [28] modeled the droplet flash evaporation in vacuum spray cooling based on Fick's law and energy conservation law. Xi et al. [29] analyzed the nucleation and bubble growth of the dimethyl ether based on the homogenous nucleation theory. Huang et al. [30] investigated spray characteristics of ethanol direct injection sprays using ANSYS Fluent. Price et al. [31] mainly investigated near nozzle spray characteristics with considering in-nozzle phase change phenomenon using an Eulerian/Lagrangian two-phase method.

From the review of the previous experimental investigations, these studies only offered general conclusions under finite working conditions at system level. Little or no information was available on the droplet heat and mass transfer process due to the infeasibility of experimental studies. Due to limitations of experimental investigations, the numerical method should be applied. From the review of the previous numerical modeling of spray flash evaporation, two points can be obtained. First, some authors focused on spray characteristics while didn't analyze the temperature variation. Second, some authors studied the temperature variation over time without considering the motion of the flashing jets. In the present study, a mathematical model that considers the droplet velocity, droplet diameter was developed. To obtain the temperature variation, the heat conduction, heat convection and heat radiation were all considered. The model was verified by the comparison with previous experimental results. Based on the model, the influence of the ratio of pressure decay, droplet size, flow velocity and relative humidity on the characteristics of temperature variations along the centerline of the downward jet was analyzed.

2. Mathematical model

To evaluate the temperature variation at the centerline of the jet against the distance, the time-dependent temperature variation and velocity variation should be obtained. As the temperature variation of the droplet is affected by the droplet size, the droplet size variation is also considered and calculated to improve the accuracy of the calculation.

2.1. Velocity variation

For the simplicity of calculation, the droplet is regarded as a sphere with homogeneous thermal properties. The corresponding force analysis for a single droplet is depicted in Fig. 1. It can be seen that the movement of the droplet is related to the gravity F_g, buoyancy force F_b, drag force F_d and additional mass force F_a. As the droplet rotation velocity is neglected, both the Magnus lift force and the Saffman lift force are not considered in the present study. They can be calculated via the following equations.

$$F_g = mg \tag{1}$$

$$F_b = \rho_v g V \tag{2}$$