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Droplet phase change model and its application in wave-type vanes of steam generator

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ABSTRACT

When an entrained droplet travels through the steam-water separator of the steam generator in a nuclear power station, pressure decreases continuously along the droplet trajectories due to the local flow resistance and structure variation. This movement-induced pressure drop will result in droplet evaporation, which eventually affects the steam-water separation performance. To investigate the influence of the droplet motion on its phase change, a phase change model for single moving droplet is developed by combining static droplet phase change model and droplet motion model. The model well reproduces the droplet evaporation process, showing a fast evaporating stage followed by a thermal equilibrium evaporation stage. The discrepancies between the predicted results and the experimental measurements are within ±2%. Furthermore, the model is adopted in the Euler-Lagrange frame to obtain the phase change characteristics of droplets moving in the wave-type vanes. Based on the simulation, the effects of phase change on the droplet movement trajectory, radius, velocity, terminal position and separation efficiency are examined. In addition, the critical pressure difference that could affect the wave-type vanes separation efficiency about 0.01 % is proposed. The theoretical and numerical work can provide guidance to the design and optimization of the steam-water separating apparatuses as well as other applications where both of the droplet movement and phase change occur simultaneously.

1. Introduction

The steam-water separator system in the nuclear power plant is comprised of the primary steam-water separator, steam drier, gravity separation space and auxiliary equipment. The steam-water separation performance is crucial to the operation efficiency, utility ratio, safety and reliability of steam generator and turbine. With the demands of steam generator power increase for large-power nuclear power plant and the compact space for vessel steam generator, the steam quality must be improved including the steam pressure and dryness. In another aspect, the density ratio of saturated water to saturated steam becomes smaller with increase of the operating pressure of steam generator, which increases the difficulty of steam-water separation. In addition, large circulating ratio is required to reduce the accumulated mud on the pipe board of steam generator and prohibit drying up and chemical enrichment of the heat transfer tubes. Meanwhile the inlet volume fraction of liquid phase increases with the increase of circulating ratio, which further increases the difficulty of steam-water separation. In the steam-water separator, many complex phenomena related to droplets exist including the droplet production, droplet motion in the steam, mutual collisions between droplets, droplet extinction and evaporation. It is necessary to study the microscopic behavior of the droplet to find out the steam-water separation mechanism, based on which modification methods are proposed to improve the separation performance and provide high-quality steam in conditions of higher steam pressure, higher power load and larger circulating ratio.

Many researchers have studied steam-water separation performance and some scholars have explained the details in the steam-water separator. Prabhudharwadkar et al. (2010) carried out experiments to study liquid carryover in the separator drum. Li et al. (2007) conducted experimental research of separation efficiency on wave-type vanes steam-water separator. Nakao et al. (1998) and Saito et al. (1994) analyzed the droplet behavior in the BWR dryer and separator with four stage wave-type vanes using the computer program HIJET-AFIMA. Galletti et al. (2008) developed Euler-Lagrange models of two wave-plate mist eliminators using

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Nomenclature

a	thermal diffusivity
c	pressure wave velocity
c_p	specific heat capacity at constant pressure
C_D	drag force coefficient
C_M	rotation moment coefficient
C_{Ma}	Magnus lift force coefficient
C_{Sa}	Saffman lift force coefficient
$\boldsymbol{F}_A$	additional mass force
$\boldsymbol{F}_B$	buoyancy
$\boldsymbol{F}_D$	drag force
$\boldsymbol{F}_G$	gravity
$\boldsymbol{F}_M$	Magnus lift force
$\boldsymbol{F}_S$	Saffman lift force
$\boldsymbol{F}_V$	volume force
$\boldsymbol{g}$	gravity acceleration
G	the mass flow density
h	convective heat transfer coefficient
I	droplet moment of inertia
m	droplet mass
$\dot{m}$	mass vaporization rate
M	molar mass of water
$\boldsymbol{M}$	rotation moment of flow field
nr	the position n fold droplet radius distance to the droplet center
p	operating pressure
P	droplet pressure
P_g	gas or vapor pressure
P_l	the saturated pressure corresponding to T_l
P_r	droplet surface pressure
P_{nr}	fluid pressure at position nr
P_∞	fluid pressure at infinity
r	droplet radius
R	gas constant
$(R_\mu)^2$	internal circulation coefficient
t, t_1, t_2, t_3	time
t_p	the pressure spread time
T	droplet temperature
T_l	the liquid phase temperature
T_g	gas or vapor temperature
T_r	droplet surface temperature
T_{nr}	fluid temperature at position nr
T_∞	fluid temperature at infinity
$\boldsymbol{U}, \boldsymbol{u}(t)$	gas or vapor velocity
$\boldsymbol{V}, \boldsymbol{v}(t)$	droplet velocity
Vx	droplet velocity in x direction
$\boldsymbol{V}_r$	relative of vapor and droplet
$\boldsymbol{x}(t)$	droplet displacement

Greek symbols

α	liquid-vapor interface evaporation-condensation coefficient
ρ_d	droplet density
ρ_f	fluid density
ρ_r	vapor density at the droplet surface
ρ_{nr}	vapor density at the position nr
ρ_v	vapor density
$\boldsymbol{\Omega}$	curl of flow field, $\boldsymbol{\Omega} = \nabla \times \boldsymbol{u}$
$\boldsymbol{\omega}$	droplet rotation velocity
ξ	pressure loss coefficient
ν	fluid kinematic viscosity
γ	latent heat of vaporization of water
μ_f	fluid dynamic viscosity
η	separation efficiency considering phase change
η_{no}	separation efficiency without considering phase change
Δp	pressure loss in the wave-type vane
ΔP	pressure difference between droplet surf-ace and environment

computational fluid dynamics. The systematic research on the separation mechanism is quite few (Nakao et al., 1999; Eck and Schmidt et al., 2008; Kataoka et al., 2009). The authors' research group develops a novel research route to investigate the steam-water separation mechanism on the microcosmic behavior of the droplet. It is comprised of the droplet production model (Ma, 2014), droplet movement model (Zhang and Bo, 2010), multi droplets movement and collision model (Zhang et al., 2015a), and so on.

However, theoretically, pressure decreases continuously due to local flow resistance and structure variation, although the steam vapor and the droplet are almost in saturated status during moving in the steam-water separator. The liquid-vapor equilibrium is broken, since the temperature variation is much slower than pressure, which will result in the droplet evaporation and the steam-water separating characteristics are influenced as a result (Zhao et al., 2016a). In another aspect, reports on the droplet mass transfer in the steam-water separator are rather scarce (Sazhin, 2006a; Wang and Li, 2014). It is meaningful to conduct theoretical study and develop model of droplet phase change due to the pressure variation such as in situations of the steam-water separator.

Many experimental and numerical researches on the droplet evaporation have been reported (Erbil, 2012). Wang (2002) performed molecular dynamics researches on the evaporation and condensation phenomena. Gao et al. (2012) studied the droplet flash evaporation of mixed dehumidification solution using the droplet flash evaporation theory. Ran and Zhang (2010) and Wang et al. (2011) investigated the motion, evaporation of droplet in quencher and low-temperature flue gas considering only gravity, drag force, buoyancy, respectively. Abramzon and Sirignano (1989) developed one-dimensional droplet vaporization model for spraying combustion calculations. Kryukov et al. (2004) compared hydrodynamic and kinetic methods in solving the problem of diesel fuel droplet evaporation. Sazhin et al. (2005a, 2005b, 2006b, 2007) developed and optimized the droplet movement evaporation model and studied the droplet evaporation progress used kinetic model, finite thermal conduction model. Irannejad and Jaberi (2015) studied spray interactions with the gas flow and turbulence generated by the spray using non-equilibrium, finite-rate heat and mass transfer models and large eddy simulations of high speed evaporating sprays. Yin (2015) modeled heating and evaporation of n-Heptane droplet towards a generic model for fuel droplet/particle conversion. Perrin et al. (2015) obtained the characteristics of the evaporation of interacting droplets using combined optical techniques. Zhou et al. (2013) evaluated evaporation models of single moving droplet with a high evaporation rate. Other researches have been reported on droplets spray evaporation and the heat transfer progress when colliding with walls (Gopireddy et al., 2012; Negeed et al., 2014). The existing researches mainly focused on droplets evaporation due to temperature difference and evaporation during the irrigation process, fire extinguishing, fuel oil or the rocket propulsion (Erbil, 2012). As far as the authors' concerned, there are few investigations on droplet phase change during moving due to the pressure variation (Zhao et al., 2016a).

The present paper explained the mechanism of droplet phase change during moving, then, based on which a single moving