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Study on separation abilities of moisture separators based on droplet collision models

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ABSTRACT

Moisture separators are widely used for eliminating the droplets from the gas–water/steam mixture flows. The volume fraction of droplets is often not small in most separators, so the collision behavior of droplets is crucial in changing their velocity, size and number distributions to affect the separation abilities of these separators. In this paper, the collision models of droplets are established to simulate the droplet-laden flows in the moisture separators. First, a stochastic searching algorithm to find the collision droplet pairs is performed by utilizing the collision kernels and defining the mean free path of a droplet. Second, the criteria to distinguish the different regimes of binary droplet collision are carried out. The regime map drawn by these criteria is highly consistent with that from previous experiments. Third, a set of formulas to predict the velocity, size and number distributions of droplets after bouncing, coalescence, reflexive and stretching separation are proposed based on the conservation law and some empirical relations. Finally, the separation abilities of the cyclone and swirl-vane separators are investigated by simulating the droplet-laden flows coupled with the droplet collision models. As for the cyclone, the simulation separation efficiencies are in good agreement with the experimental data. It is further shown that the separation efficiency curve begins to climb up very quickly in the region with small droplet diameters, and then keep constant as the droplet diameter increasing. As for the swirl-vane separators, the simulated separation efficiencies are little larger than those of the experiment within 5% difference, which is mainly due to the fact that coalescence dominates the collision behaviors from the simulation results. The theoretical and simulation results show that these collision models present a new view to study the flowing behaviors of the droplets in the moisture separators.

1. Introduction

Moisture separators are crucial devices to provide dry-saturation steam to keep turbines working safely and obtain high economic and safety effects in nuclear power plants (Xiong et al., 2013; Liu and Bai, 2016; Zhang et al., 2016). In order to minimize the damage to the turbines, an industry accepted standard of the efficiency of the moisture separators is now frequently quoted as low as not exceed 0.1% (Green and Hetsroni, 1995).

Since the gas-droplet flows in moisture separators are complex in the interaction patterns of fluid-droplet, droplet-wall and droplet-droplet, etc., most works are focusing on the experimental studies of the separation abilities (Kataoka et al., 2008; Lu et al., 2013; Xiong et al., 2013, 2014; Liu and Bai, 2016). These experiments are not only fundamental in satisfying our intuitional observations that how moisture separators work, but also providing solid data in developing physical models to predict gas-droplet flows in various separators. The physical models often contain the interaction forces, such as drag force, lift force, added mass force, and body force, etc., between a droplet and the fluids, which govern the linear and rotational motion laws of droplets flowing in the gas phase (Saito et al., 1994; Nakao et al., 1998; Li et al., 2007; Dostal and Takahashi, 2008; Zhang et al., 2016). Further, the models of droplets impacting on the walls of separators are also performed in some literatures (Nakao et al., 1999; Wang et al., 2003). Moreover, it is indicated that droplet-droplet collision must be considered in modeling droplet-laden flows when the fractions of droplets are not dilute (Balachandar and Eaton, 2010; Crowe et al., 2012). Practically, since a plenty of droplets are carrying within the gas-liquid mixtures, the liquid volume fraction Φ_d is often high as droplets entering the moisture separators (Green and Hetsroni, 1995). Therefore, droplet-droplet collisions are dominant when droplets are clustering near the vanes of swirl-vane separators (Li, 2013; Lu et al., 2013; Xiong

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Nomenclature

b	geometric relation between two droplets (m), seeing in Fig. 1
C_D	coefficient of drag force
C_M	coefficient of total moment
C_{Ma}	coefficient of Magnus lift force
C_{Sa}	coefficient of Saffman lift force
C_{vs}	separation volume efficiency
d	droplet diameter (m)
d_l	diameter of the larger droplet (m)
d_s	diameter of the smaller droplet (m)
e	coefficient of restitution
e_{coal}	efficiency of coalescence
E_{dissip}	viscous dissipation in the interaction region (J)
$E_{stretch}$	total effective stretching kinetic energy (J)
E_{surten}	surface energy in the region of interaction (J)
$\boldsymbol{g}$	gravitational acceleration (m/s^2)
I	impact parameter
k_t	turbulent kinetic energy of carrier phase (m^2/s^2)
k_1, k_2	empirical constant in Eq. (31)
n_s	total number of droplets in a cell
n_{coll}	expected number of collision events that a droplet undergoes per unit time (s^{-1})
N_{tot}	total number of droplets in the bulk flow field
$N_{coll}{}^{i,j}$	collision events between droplet i and j in per unit time in a cell (s^{-1})
$N_{coll}{}^{i}$	collision events that droplet i experiences in per unit time in a cell (s^{-1})
N_{coll}	total number of collision times occurring per unit time in a cell (s^{-1})
r	droplet radius (m)
r_0	radius of a droplet whose volume equals to the total volume of satellite droplets (m)
$\overline{r_{bu}}$	non-dimensional ligament radius
r_l	radius of the larger droplet (m)
r_n	diameter of coalescence droplet (m)
r_{sat}	radius of one satellite droplet (m)
r_s	radius of the smaller droplet (m)
T_λ	time cost in a Mean Free Path (MFP) of a droplet (s)
t_λ	time that a droplet has cost in its MFP (s)
T	characteristic time to determine satellite droplets (s)
t	time (s)
Δt	time step (s)
$\boldsymbol{u}$	carrier phase velocity (m/s)
$\boldsymbol{u}_{in}$	inlet velocity of the air and droplets (m/s)
V_{cell}	cell/mesh volume (m^3)
$\boldsymbol{v}$	linear velocity of the droplet (m/s)
$\boldsymbol{v}_l$	velocity of the larger droplet (m/s)
$\boldsymbol{v}_n$	velocity of coalescence droplet (m/s)
$\boldsymbol{v}_{l0}$	velocity of the larger droplet in the center of mass system (m/s)
$\boldsymbol{v}_{n,l}$	velocity of the larger droplet after collision (m/s)
$\boldsymbol{v}_{n,s}$	velocity of the smaller droplet after collision (m/s)
$\boldsymbol{v}_{n,l0}$	velocity of the larger droplet after colliding in the center of mass system (m/s)
$\boldsymbol{v}_{n,s0}$	velocity of the smaller droplet after colliding in the center of mass system (m/s)
$\boldsymbol{v}_{rel}$	relative velocity of binary droplets (m/s)
$\boldsymbol{v}_s$	velocity of the smaller droplet (m/s)
$\boldsymbol{v}_{sat}$	velocity of a satellite droplet (m/s)
$\boldsymbol{v}_{s0}$	velocity of the smaller droplet in the center of mass system (m/s)
We	Weber number
We_s	symmetric Weber number
We_0	Weber number of a droplet whose volume equals to the total volume of satellite droplets
$\boldsymbol{x}$	position of droplet (m)
z	proportion coefficient in Eq. (40)

Greek symbols

α	empirical constant
β	droplet collision kernel (m^3/s)
Δ	drop size ratio
η	separation efficiency
λ_1-λ_5	normalization coefficients in Eqs. (51)–(53)
μ	dynamic viscosity (Pa·s)
ρ	density (kg/m^3)
τ	coefficient defined in Eq. (11)
τ_λ	remaining time in MFP (s)
φ	volume fraction
Φ'	shape factor
χ_1	coefficient defined in Eq. (11)
ψ	volume fraction of the satellite droplets obtained from one of two colliding droplets
$\boldsymbol{\omega}$	angular velocity of droplet (rad/s)

Subscripts

$coll$	collision
d	droplet phase
d_i	diameter of droplet i (m)
d_j	diameter of droplet j (m)
f	carrier phase
i	droplet i
in	inlet
j	droplet j
l	the larger one of two colliding droplets
s	the smaller one of two colliding droplets
sat	satellite droplet
$\beta_{i,j}$	collision kernel between droplet i and j (m^3/s)
μ_d	dynamic viscosity of liquid phase (Pa·s)
μ_f	dynamic viscosity of steam phase (Pa·s)
ρ_d	liquid density (kg/m^3)
ρ_f	gas density (kg/m^3)
$\tau_\lambda{}^i$	τ_λ of droplet i (s)
φ_l	volume fraction of the larger droplet
φ_s	volume fraction of the smaller droplet
Φ_d	liquid volume fraction
ψ_l	volume fraction of the satellite droplets obtained from the larger droplet
ψ_s	volume fraction of the satellite droplets obtained from the smaller droplet

et al., 2014), swirling in cyclones (Kim and Lee, 1990; Wang et al., 2016), and going through the venture scrubber (Majid et al., 2013). Besides, in other facilities of nuclear power plants, such as the spraying system of Pressurized Water Reactor (PWR) (Malet et al., 2013; Lan et al., 2014), droplet collisions also play an important role in changing the velocities and sizes of droplets. Hence, the droplet collision models promise a wide application in studying the droplet flowing behaviors in some nuclear power equipment.

Unfortunately, to our knowledge, the droplet-droplet models are seldom regarded in the research literatures about simulating the gas-droplet flows in the aforementioned moisture separators. We consider that there are two main reasons. On one hand, it is challenging to count

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