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Liquid dispersion and gas absorption in a multi-stage high-speed disperser

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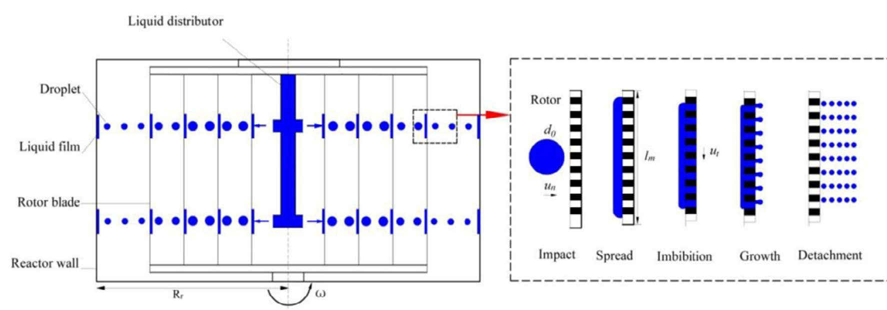
HIGHLIGHTS

- Liquid dispersion on rotors includes five stages according to liquid flow pattern.
- A modified impact model describes droplet-film transformation process on rotors.
- A model calculates area of droplets in cavity zones and liquid films on walls in HSD.

GRAPHICAL ABSTRACT



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ABSTRACT

Liquid dispersion and gas absorption in a high-speed disperser with four rotors were studied by experiments and models. The liquid films on the rotors and the droplets in the cavity zones of an air-water system were captured by a high-speed camera. When liquid is dispersed on the rotors, its flow pattern transforms from initial droplet, liquid film, rivulet, and ligament into a large number of small droplets in the next cavity zone. Moreover, a modified inclined impact model was established to describe the impact and spread of the initial droplet. The effects of rotational speed and liquid flow rate on liquid film maximum spread length and mean droplet diameter were evaluated. A novel mass transfer area model based on the dispersion process was proposed to calculate the total mass transfer area. The total mass transfer area includes the area of the liquid films on the inner surface of the four rotors and the reactor wall, as well as the area of the droplets in the four cavity zones. The chemical absorption of CO_2 into a NaOH solution was conducted, and a chemical method was adopted to verify the mass transfer area model. The total mass transfer area and absorption quality under different operating conditions such as rotational speed, gas flow rate, and liquid flow rate were measured. In addition, the increases of droplet area and liquid film area were compared, and it was found that the effect of rotational speed on the droplet area and the effect of liquid flow rate on the liquid film area were significant.

1. Introduction

Process intensification can greatly decrease the capital cost, environmental impact, and energy consumption under finite equipment space and short reaction time. As a typical technology for process intensification, Higee (high gravity) uses high speed rotation to generate high centrifugal acceleration 100–1000 times of general gravity for enhancing mass transfer and improving chemical reaction processes [1]. So far, this technology has been applied in many processes such as gas absorption [2], desorption [3], distillation [4], and liquid-liquid

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Nomenclature

Variables

a_c	centrifugal acceleration (m/s^2)
a_0	characteristic centrifugal acceleration (m/s^2) $a_0 = 100\,m/s^2$
$a_{d,i}$	interfacial mass transfer area of droplets in the *i*th cavity zone (m^2/m^3)
A	mass transfer area of liquid in the reactor (m^2)
$A_{d,i}$	mass transfer area of droplet in the *i*th cavity zone (m^2)
A_d	mass transfer area of droplet (m^2)
$A_{f,i}$	mass transfer area of liquid film on the *i*th rotor (m^2)
A_f	mass transfer area of liquid film (m^2)
A_t	total mass transfer area in the reactor (m^2)
C_{in}	CO_2 concentration at the gas inlet
C_{out}	CO_2 concentration at the gas outlet
d	single droplet diameter in the image (m)
d_1	major axis of droplet (pixel)
d_2	minor axis of droplet (pixel)
$d_{m,i}$	maximum spread diameter of circular liquid film on the *i*th rotor (m)
d_i	mean droplet diameter in the *i*th cavity zone (m)
E_{K1}	kinetic energy of impinging droplet (J)
E_{K2}	surface energy of impinging droplet (J)
E_{S2}	surface energy of the droplet at the maximum condition (J)
h	height of rotor (m) $h = 0.052\,m$
H_i	radial thickness of the *i*th cavity zone (m)
L_b	width of vertical blades (m)
L_s	width of vertical slots (m)
$l_{m,i}$	maximum spread length of the elliptical liquid film on the *i*th rotor (m)
l	thickness of rotor (m)
n_i	the number of liquid films on the *i*th rotor
N	rotational speed (rpm)
Q_L	liquid flow rate (L/h)
Q_G	gas flow rate (L/h)
R_i	radius of the *i*th rotor (m)
R_5	radius of reactor wall (m)
s	calibrated spatial resolution of the droplet image
$S_{max,i}$	maximum spread area of single liquid film on the *i*th rotor (m^2)
t	liquid residence time in the reactor (s)
t_d	detachment time of ligament on the rotor (s)
t_f	spread time of liquid film on the rotor (s)
t_i	imbibition time of rivulet on the rotor (s)
t_t	liquid residence time on the rotor
$u_{n,i}$	liquid normal velocity on the *i*th rotor (m/s)
$u_{t,i}$	liquid velocity on the *i*th rotor in the tangential direction (m/s)
$u_{wt,i}$	liquid tangential velocity on the *i*th rotor (m/s)
u_0	characteristic liquid flow velocity (m/s) $u_0 = 0.01\,m/s$
$u_{d,i}$	superficial liquid flow velocity in the *i*th cavity zone (m/s)
$V_{d,i-1}$	droplet volume in the (*i*-1)th cavity zone (m^3)
$V_{f,i}$	liquid film volume on the *i*th rotor (m3)
W	energy lost to viscous dissipation (J)
X_A	dimensionless excess spread area
$Re_{n,i}$	normal Reynolds number in the *i*th cavity zone
$We_{n,i}$	normal Weber number in the *i*th cavity zone
$We_{t,i}$	tangential Weber number in the *i*th cavity zone

Greek symbols

δ	liquid film thickness (m)
$\varepsilon_{d,i}$	liquid holdup in the *i*th cavity zone
η	absorption quality (%)
θ_i	impact angle of droplets on the *i*th rotor (°)
θ_a	contact angle of water and rotor (°)
μ	kinematic viscosity of liquid (Pa·s)
ρ	liquid density (kg/m^3)
σ	surface tension (N/m)
τ_d	droplet residence time in the cavity zone (s)
ω	angular velocity (rad/s)

dispersion [5].

The liquid flow pattern in high-speed rotating reactors has a great effect on mass transfer performance. With a camera, Burns and Ramshaw [6] observed the liquid flow pattern in a rotating packed bed (RPB) and found that a maldistribution of liquid would decrease the mass transfer area and mass transfer efficiency. Yan et al. [7] investigated the droplets in an RPB by experimental and statistical analyses and proposed that the droplet formation and collision with the packing would increase the mass transfer area and mass transfer efficiency. Yi et al. [8] developed models on the droplet diameter in the packing of RPB and found that the droplet diameter reaches a maximum in the end effect zone but decreases in the bulk zone, resulting in the dominant mass transfer in the end effect zone. High-speed photograph technology has become a common method to capture the droplet behavior in high-speed rotating reactors. Many researchers adopted it to investigate the relationship between mean droplet diameter, droplet diameter distribution, liquid flow pattern, and operating and structural parameters [9–12].

However, the existence of packing in an RPB makes it difficult to derive the mass transfer area of the disperse phase by high-speed camera. Thus, the chemical absorption method was proposed and accepted on account of its convenience. Since first reported by Munjal et al. [13], the NaOH-CO_2 absorption method in the RPB was employed by a number of researchers to study the effects of operating parameters and packing structure on the mass transfer area [14–17].

Because liquid film is a typical flow pattern in high-speed rotating reactors, its effect on mass transfer cannot be neglected. Ramshaw et al. [18] proposed that the mass transfer of liquid film on a spinning disc was dominated by the rotational speed and was a weak function of the liquid flow rate and disc radius. Burns et al. [19] used the limiting current technique to measure the liquid film thickness on a spinning disc reactor and reported that an increasing rotational speed and decreasing liquid flow rate would decrease the liquid film thickness and enhance the mass transfer. Guo et al. [20] established a mass transfer model based on the liquid films on the packing and the droplets in the voids of an RPB [21] and revealed that the liquid flow pattern would affect the mass transfer characteristics. Yan et al. [22] conducted experiments to capture the liquid trajectories in an RPB and found that the boundary layer in the liquid film had a significant effect on mass transfer.

The formation of liquid film is the result of droplet-wall collision. The impact of a single droplet on a dry surface can be classified into three types: spread, splash, and rebound [23]. Bergeron et al. [24] investigated the rebound of a droplet on a hydrophobic surface and found that the rebound can be inhibited and the spread can be enhanced by adding flexible polymers. Šikalo et al. [25] observed the collision of a droplet on an inclined surface and revealed that the droplet would spread into a liquid film at large impact angles and the maximum spread diameter of the liquid film was affected by the impact velocity, impact angle, and surface properties. Mao et al. [26] found the maximum spread diameter depended strongly on the liquid viscosity and developed a model based on the Weber number, Reynolds number, and

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