Chemical Engineering Science 170 (2017) 355–364

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Modeling and experimental studies of mass transfer in the cavity zone of a rotating packed bed

Le Sang, Yong Luo, Guang-Wen Chu *, Ya-Zhao Liu, Xing-Zheng Liu, Jian-Feng Chen

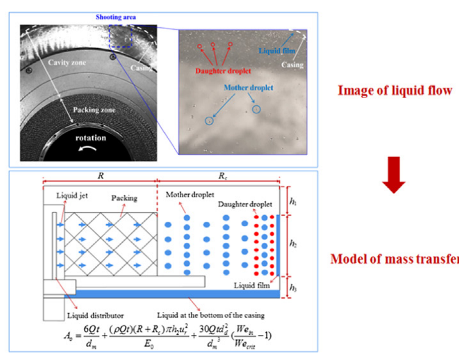
State Key Laboratory of Organic-Inorganic Composites, Beijing University of Chemical Technology, Beijing 100029, PR China
Research Center of the Ministry of Education for High Gravity Engineering and Technology, Beijing University of Chemical Technology, Beijing 100029, PR China

HIGHLIGHTS

- A model was established to predict the mass transfer area of the cavity zone in a RPB.
- The average droplet velocity was obtained by analyzing the images taken by a high-speed camera.
- Correlations for the average droplet velocity were proposed.
- The predicted mass transfer area by the model agreed well with the experimental data.

GRAPHICAL ABSTRACT

The mass transfer model of the cavity zone of a RPB was established based on the visual studies of liquid flow.



ARTICLE INFO

Article history:
Received 16 August 2016
Received in revised form 5 November 2016
Accepted 16 December 2016
Available online 22 December 2016

Keywords:
Rotating packed bed
Cavity zone
Modeling
Droplet velocity
Mass transfer area

ABSTRACT

A rotating packed bed (RPB), which creates a high gravity environment by the centrifugal force, is one of the typical process intensification equipment. The cavity zone is an important mass transfer zone of a RPB. However, there have been very few studies to date on the modeling of mass transfer in the cavity zone. In this work, the liquid droplet velocity in the cavity zone was obtained by analysing the images taken by a high-speed camera and correlations for droplet velocity were fitted. Combining the above imaging results and other parameters, a mathematical model was established to predict the mass transfer area of the cavity zone. The mass transfer system of chemisorption of CO_2 into NaOH solution was employed and mass transfer experiments were carried out at various rotational speeds, liquid initial velocities, and outer packing radii. The predicted mass transfer area from the model agreed well with the experimental data within a deviation of ±20%.

1. Introduction

A rotating packed bed (RPB), which creates a high gravity environment by the centrifugal force, is one of the typical process intensification equipment. Liquid phase introduced to the rotor of the RPB is split into fine droplets, ligaments, and thin liquid films by the rotating porous packing, thus intensifying the mass transfer and micromixing. Until now, RPBs have been widely applied in chemical processes, such as absorption (Chu et al., 2014; Peel et al., 1998), distillation (Agarwal et al., 2010; Kelleher and Fair, 1996), production of nanoparticles (Chen et al., 2003), and polymerization (Chen et al., 2010).

* Corresponding author.
E-mail address: chugw@mail.buct.edu.cn (G.-W. Chu).

http://dx.doi.org/10.1016/j.ces.2016.12.041
0009-2509/

Nomenclature

A	mass transfer area (m^2)
A_b	mass transfer area of liquid film on the middle annular surface of casing (m^2)
A_d	mass transfer area of daughter droplets (m^2)
A_e	experimental mass transfer area in the cavity zone (m^2)
A_f	mass transfer area of liquid film (m^2)
A_m	mass transfer area of mother droplets (m^2)
A_o	predicted mass transfer area of mother droplets (m^2)
a	gas-liquid effective interfacial area (m^2/m^3)
D	outer rotor radius (m)
d	average droplet diameter (mm)
E_K	kinetic energy of mother droplets ($=\frac{1}{2}mu_r^2=\frac{1}{2}\rho Qtu_r^2$ J)
$E_{\max}$	maximum kinetic energy of mother droplets in the mass transfer experiment condition ($=\frac{1}{2}mu_r^2=\frac{1}{2}\rho Qtu_r^2$ J)
$E_{\min}$	minimum kinetic energy of mother droplets in the mass transfer experiment condition ($=\frac{1}{2}mu_r^2=\frac{1}{2}\rho Qtu_r^2$ J)
E_0	standard kinetic energy of mother droplets (J)
K	splash criterion
K_Ga	overall gas side volumetric mass transfer coefficient (mol/m^3s)
K_La	overall liquid side volumetric mass transfer coefficient (mol/m^3s)
k_Ga	gas-side volumetric mass transfer coefficient (1/s)
k_La	liquid-side volumetric mass transfer coefficient (1/s)
k_L	liquid-side mass transfer coefficient (m/s)
m	mass of droplet (kg)
n	number of droplet
N	rotational speed (r/min)
q	liquid initial velocity number
Q	liquid flow rate (m^3/s)
Oh	Ohnesorge number
R	outer packing radius (m)
Re	Reynolds number
t	average residence time (s)
u	average droplet resultant velocity (m/s)
u_0	liquid initial velocity (m/s)
u_r	average liquid radial velocity (m/s)
We	Weber number

Greek symbols

μ	viscosity (Pa s)
ρ	liquid density (kg/m^3)
σ	surface tension (N/m)
ω	angular velocity (1/s)
λ	calibrated spatial resolution of the droplet photograph (mm/pixel)
ψ	diameter stretched ratio

Subscripts

crit	critical
d	daughter droplet
e	experimental
f	liquid film
m	mother droplet
max	maximum
min	minimum
in	impinging
o	overall

The mass transfer zone in a RPB includes the packing zone (end zone and bulk zone) and cavity zone that is an annular space between the outer edge of the packing and the inner edge of the casing (Guo, 1996), as shown in Fig. 1. The mass transfer parameters, including overall gas-side volumetric mass transfer coefficient (K_Ga), overall liquid-side volumetric mass transfer coefficient (K_La), gas-side volumetric mass transfer coefficient (k_Ga), liquid-side volumetric mass transfer coefficient (k_La), and gas-liquid effective interfacial area (a), were determined in a RPB based on two methods.

The first method is to build empirical correlations which are in term of mass transfer coefficients associated with experimental conditions. Reddy et al. (2006) presented correlations for k_Ga and k_La of the RPB with split packing fitted by the experimental data measured by means of the absorption of SO_2 into NaOH and the stripping of oxygen into nitrogen, respectively. Chen et al. (2006) obtained a correlation of k_La with various packings and found that the values of k_La of the RPB with the stainless steel wire mesh packing is the highest, compared to other packings. According to the two-film theory, Chen (2011) suggested a correlation of k_Ga in a RPB fitted by numerous experimental data. Luo et al. (2012) proposed an empirical correlation of a that took the effects of the fiber diameter and opening size of the stainless steel wire mesh into consideration in the packing zone of a RPB. Although this method is commonly used, most of the correlations proposed are based upon experimental results having the limited ranges of operation conditions and fluid properties, which are lacking of universality.

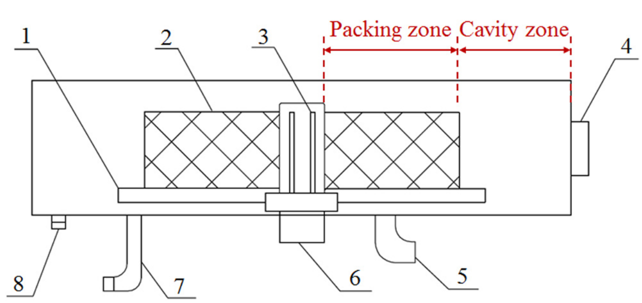


Fig. 1. Schematic of RPB. (1) rotor; (2) packing; (3) liquid distributor; (4) gas inlet; (5) gas outlet; (6) shaft; (7) liquid inlet; (8) liquid outlet.

The second method is to develop mass transfer models in view of the hydrodynamics of the liquid flow pattern and size, etc. Munjal et al. (1989) evaluated the liquid-side mass transfer coefficient (k_L) of the RPB by the assumption of laminar film flow on a rotating blade or a rotating disk. Guo et al. (1997) developed models of K_Ga and K_La considering liquid films on the packing surface and droplets in the voids of the adjacent packing layers in a RPB based on the surface renewal model. Yi et al. (2009) took the different liquid droplets' diameters in the end zone and bulk zone into consideration and presented values of K_Ga in a RPB with CO_2 absorption by Benfield solution. Qian et al. (2009) proposed a mass transfer model for the CO_2-MDEA system according to Higbie's penetration theory with the assumption of liquid film flow in the packing zone. Li et al. (2010) established a mass transfer model for a devolatilization process with a syrup-acetone system, based upon the penetration theory and mass conservation. The model is well applicable to high viscous media in a RPB. On account of the total surface area of the droplets and the penetration theory, Zhang et al. (2011) proposed a model of k_La in a RPB with the system of absorption of CO_2 by ionic liquid. Predicted values from the above models have been found to be consistent with experimental results, and the majority of these models have been conducted in connection with the packing zone or the whole RPB, not the cavity zone.