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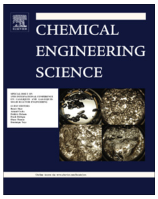

Investigation of effective interfacial area in a rotating packed bed with structured stainless steel wire mesh packing

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HIGHLIGHTS

- Four structured stainless steel wire mesh packings were designed and built.
- Gas-liquid mass transfer interface area in the RPB was investigated.
- Utilization ratio of packing's specific surface area in the RPB was presented.
- A modified correlation for the effective interfacial area of the RPB was proposed.

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ABSTRACT

Packing plays an important role on the mass transfer and mixing in a rotating packed bed (RPB) which is regarded as an important gas-liquid reactor or contactor for process intensification. Stainless steel wire mesh packing exhibits good mass transfer performance when applied in a RPB. However, its construction repeatability and mechanical strength should be improved. Therefore, we introduced and designed a novel structured stainless steel wire mesh packing, aiming to overcome the above problems. In this work, the effective interfacial area (a_e) in the packing and cavity zones of a RPB with four different types of structured stainless steel wire mesh packings was investigated at various rotational speeds, gas flow rates, and liquid flow rates by using a NaOH-CO_2 mass transfer system. A brief analysis of the gas-liquid mass transfer interface area (A) and utilization ratio of packing's specific surface area (w_p) is presented. A modified correlation for the effective interfacial area in the packing zone of the RPB with structured stainless steel wire mesh packing was also proposed, and the predicted values were found to be in agreement with the experimental values with deviations generally within ±15%.

1. Introduction

A rotating packed bed (RPB) is a novel gas–liquid reactor or contactor which can provide centrifugal acceleration of up to several hundred times magnitude in excess of gravitational acceleration (Zhao et al., 2010). Under the large centrifugal field, liquid is broken into thin liquid films and tiny liquid droplets, resulting in an increase in the gas-liquid interfacial area in the case of gas-liquid reaction or separation systems. All of these can consequently lead to the enhancement of the mass transfer coefficient of a RPB up to 1–3 magnitude orders of the traditional packed bed (Zhao et al., 2010). Furthermore, both size and capital cost of the processing system can be significantly minimized (Sun et al., 2009). Owing to these distinctive advantages of RPBs, they have been successfully applied not only to gas-liquid system, but also liquid-liquid, gas-solid, and gas-liquid-solid systems, such as distillation (Luo et al., 2012a; Chu et al., 2013) and absorption (Jassim et al., 2007; Agarwal et al., 2010), sulfonation (Zhang et al., 2010), Fischer-Tropsch synthesis (Chen et al., 2012), preparation of nanomaterials (Chen et al., 2000; Chen et al., 2003; Sun et al., 2011) and catalytic hydrogenation (Dhiman et al., 2005), etc.

The packing of a RPB has a strongly influence on gas and liquid hydrodynamics, and consequently affects its mass transfer and mixing performance. Materials, including stainless steel, nickel foam, plastics, and silicon carbide, are usually employed as the RPB's packings (Guo et al., 1997; Chu et al., 2014; Bai et al., 2015; Chu et al., 2015b). Being one of the typical indicators of mass

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Nomenclature

a_e	effective interfacial area (m^2/m^3)
a_p	specific surface area of packing (m^2/m^3)
a_{ep}	effective interfacial area in packing zone III (m^2/m^3)
a_{ec}	effective interfacial area in cavity zone IV (m^2/m^3)
$\overline{a_{ep}}$	average effective interfacial area in packing zone III (m^2/m^3)
A	mass transfer interface area (m^2)
A_p	mass transfer interface area of packing zone III (m^2)
A_c	mass transfer interface area of cavity zone IV (m^2)
$\overline{A_p}$	average mass transfer interface area of packing zone III (m^2)
$\overline{A_c}$	average mass transfer interface area of cavity zone IV (m^2)
$\overline{A_s}$	average mass transfer interface area of zone III and IV (m^2)
c_i	gas concentration at the gas–liquid interface (mol/L)
d	fiber diameter (mm)
d_p	effective diameter of packing=$6(1-\varepsilon)/a_p$
D	diffusivity of CO_2 in solution (m^2/s)
D_i	inner diameter of rotor (m)
D_o	outer diameter of rotor (m)
G	gas flow rate (m^3/s)
k_1	pseudo-first-order rate constant (1/s)
k_L	liquid side mass transfer coefficient (m/s)
L	liquid volumetric flow rate (L/h)
N	rotational speed (r/min)
N_i	absorption rate of CO_2 (kmol/ s)
Q_G	gas flow rate (m^3/s)
Q_L	liquid flow rate (m^3/s)
w_p	utilization ratio of specific surface area of packing
Z	height of rotor (m)

Greek symbols

ϕ	pore diameter (mm)
β	corrugation angle (deg)
ρ_L	density of the liquid (kg/m^3)
υ_L	kinematic viscosity of liquid (m^2/s)
υ_G	kinematic viscosity of gas (m^2/s)
σ	surface tension of liquid (kg/s^2)
ε	porosity of packing
ω	angular speed (rad/s)

Dimensionless groups

Re_L	$Q_L d_p/(2\pi rz)\upsilon_L$
Re_G	$Q_G d_p/(2\pi rz)\upsilon_G$
Fr_L	${Q_L}^2/r\omega^2(2\pi rz)^2 d_p$
We_L	${Q_L}^2 \rho_L d_p/(2\pi rz)^2\sigma$
φ	$\phi^2/\phi+d^2$

transfer performance, the effective interfacial area (a_e) in the packing and cavity zones of RPBs with different packings is extensively studied. Munjal et al. (1989) performed experiments in a RPB filled with glass beads in the rotor to study a_e in the packing zone, while a_e in the cavity zone was examined from experiments involving the RPB without packing in the rotor. Yang et al. (2011) installed a sampling tube close to the outer edge of the rotor of a RPB to collect liquid samples that immediately flowed out of the packing in order to measure the real a_e in the packing zone. Experimental results revealed that the mass transfer contribution of the cavity zone was about 13–25% of the overall mass transfer in the entire RPB. Rajan et al. (2011) employed chemisorption of CO_2 into aqueous NaOH to investigate a_e of a RPB with a split packing that allowed for both co-rotation and counter-rotation of adjacent packing rings, and proposed the following correlations:

$$\left(\frac{a_e}{a_p}\right)_1 = 54999{Re_L}^{-2.2186}{Fr_L}^{-0.1748}{We_L}^{1.3160}\ (Co-rotation) \tag{1a}$$

$$\left(\frac{a_e}{a_p}\right)_2 = 11906{Re_L}^{-1.8070}{Fr_L}^{-0.0601}{We_L}^{0.9896}\ (Counter-rotation) \tag{1b}$$

Luo et al. (2012b) measured a_e in the packing zone of a conventional RPB with eight stainless steel wire mesh packings consisting of four different stainless steel fibers and open sizes, and proposed an empirical correlation for the effective interfacial area in the packing zone (a_{ep}) of the RPB with stainless steel wire mesh packing as shown:

$$\frac{a_{ep}}{a_p} = 66510{Re_L}^{-1.41}{Fr_L}^{-0.12}\ {We_L}^{1.21}\ \ \varphi^{-0.74} \tag{2}$$

Guo et al. (2014) reported a new experimental approach which involved isolation of the packing zone from the entire RPB by using nitrogen gas flow to measure a_e in the packing and cavity zones. Tsai and Chen (2015) investigated the effective interfacial area in a RPB with static baffles and found that adding static baffles in the RPB can increase the effective interfacial area by 16–34% by the generation of vigorous turbulence between the rotor and the baffles. Chu et al. (2015a) employed nickel foam to be used as a structured packing in a RPB and then measured the effective interfacial area.

Stainless steel wire mesh is popularly employed as RPB's packing due to its higher mass transfer performance (Chen et al., 2006). However, most of the stainless steel wire meshes were used as the unstructured packing in the RPB. Generally, the stainless steel wire mesh is manually rolled around the cylindrical packing support layer by layer closely from the inner packing support to the outer packing support and eventually forms an entire packing fixed in the rotor. There are usually no links or connections between the adjacent wire mesh layers, which leads to poor repeatability in construction and inadequate mechanical strength. It is therefore necessary to improve the construction repeatability and mechanical strength of the stainless steel wire mesh packing, especially for the industrial RPBs with a long-time running. As compared to unstructured stainless steel wire mesh packing, structured packing has the advantages of low pressure drop, large production capacity, high efficiency, and are widely applied in many chemical processes (Spiegel and Meier, 2003; Aferka et al., 2011). Experiences in the design and manufacture process of structured packings in the conventional packed columns or fixed beds will be beneficial to the packing structure promotion in RPBs.

This work was a first time attempt to use stainless steel wire mesh layers to build a structured stainless steel wire mesh packing, aiming to obtain a structured packing with good mass transfer performance, repeatable construction, and mechanical strength. Mass transfer experiments involving the system of chemisorption of CO_2 into NaOH solution were carried out to measure the effective interfacial area in the packing and cavity zones of a RPB with four different types of structured stainless steel wire mesh packings at various rotational speeds, gas flow rates and liquid flow rates. For a more accurate description of the effective interfacial area in the cavity zone (a_{ec}) of the RPB, two ring baffles were separately