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Pressure drop and mass transfer study in structured catalytic packings

Chengna Dai, Zhigang Lei *, Qunsheng Li, Biaohua Chen

State Key Laboratory of Chemical Resource Engineering, Beijing University of Chemical Technology, Box 266, Beijing 100029, China

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ABSTRACT

In this work, two types of structured catalytic packings (i.e. BH-1 and BH-2 types) were involved. This work tried to identify the relationship between geometric configuration and performance of pressure drop and mass transfer coefficients for BH-1 and BH-2 types by means of the combination of experiments and computational fluid dynamics (CFDs). The cold model experimental results showed that under the same operating conditions pressure drops for BH-1 and BH-2 types were significantly lower than those for conventional fixed-bed reactor packed with pellet catalyst particles by one to three orders of magnitude. A 3-D CFD model (i.e. Eulerian multiphase model) was established to study the separation performance of structured catalytic packings in this work. On this basis, the design parameters of structured catalytic packings were optimized by adjusting the corrugation angle, the ratio of height to diameter and the area ratio of separation to reaction regions. Two kinds of transition structures were proposed and the calculated results revealed that they were favorable when considering pressure drop and mass transfer coefficient together. Furthermore, it was found that a low ratio of packing height to diameter was favorable for increasing mass transfer coefficient, but leads to increasing pressure drop like common structured packings; a low area ratio of separation to reaction region for BH-1 type would increase mass transfer coefficient and decrease pressure drop simultaneously.

1. Introduction

In recent years, intensification of conventional processes has been highly desired to minimize capital and operating costs. Combining reaction and separation in a single column can give rise to higher conversion of equilibrium-limited reactions, restrain side reactions, and decrease recycle costs and energy requirements [1–6]. However, the hardware loaded into the column is crucial for implementing the reaction/separation coupling processes. As a relatively new type of packings, due to their low pressure drop, high efficiency and/or capacity, and operation flexibleness [7–9], the structured catalytic packings have been widely used in distillations, absorptions, and the combination with reactions [10–15].

A number of investigations including experimental and numerical works on the performance of various structured catalytic packings have been made by some researchers. Xu et al. [16] conducted hydrodynamic tests in a 600 mm diameter reactive distillation column using the air–water system. They correlated the irrigated pressure drop and dispersed phase holdup in terms of power law models involving gas and liquid flowrates. Several investigations concerning the hydrodynamic behavior of the catalytic packing KATAPAK®-S have been presented. Moritz and Hasse obtained the pressure drop and holdup data in a 70 mm column and identified the two regions above and below the liquid load point [17]. Ellenberger and Krishna took the hydrodynamic studies with diameters of 100 mm and 240 mm [18]. The irrigated pressure drop was given in terms of an enhancement to the dry gas pressure drop with the enhancement factor expressed in terms of the liquid phase Reynolds and Froude numbers. Gŏtze et al. [19] conducted hydrodynamic studies on KATAPAK®-SP structured packing and compared the experimental values with the results of KATAPAK®-S packings. The correlations [2] for both dry gas and irrigated pressure drop with KATAPAK®-SP 12 structured packing contained in a 100 mm diameter column were provided. The main characteristics of the catalytic packing MULTIPAK® [10,12] in pressure drop, liquid holdup and separation efficiency have been determined experimentally. They investigated the performance for the whole loading range and for the types with a diameter of 50 and 100 mm, and the hydrodynamic model that takes the influence of the column diameter into account was derived. van Batten and Krishna [20,21] used CFD techniques to study the liquid-phase and gas–liquid mass transfer within the criss-crossing sandwich structures of KATAPAK-S consisting of 16 triangular tubes and 32 crossovers using CFD simulation, while with the assumption that the liquid flows only through the packed channels and the gas phase flows only through the open channels. Vervloet et al. [22] investigated the cross-flow structured packings for tubular fixed bed reactors with co-current gas–liquid flow by CFD using a pseudo-homogeneous 2D plug flow model. Behrens et al. [4]

* Corresponding author. Tel.: +86 10 64433695; fax: +86 10 64419619.
E-mail address: leizhg@mail.buct.edu.cn (Z. Lei).

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Nomenclature

a	permeability, m^2
a_p	specific geometrical area, m^{-1}
A	area, m^2
C	mass fraction, dimensionless
C_2	resistance coefficient, m^{-1}
D	diffusion coefficient of solute, m s^{-2}
d_p	diameter of catalyst particles, m
F	F factor ($F = u_g\sqrt{\rho}$), m s^{-1} (kg m^{-3})$^{0.5}$
F	Drag force, N
g	acceleration due to gravity, m s^{-2}
G	gas flow flux, kg m^{-2} s^{-1}
h	height, m
h_i	volume fraction of phase *i*, dimensionless
H	solubility coefficient, kmol m^{-3} kPa^{-1}
H_{OL}	overall height of liquid-side transfer unit, m
I	turbulent intensity, dimensionless
k	turbulent kinetic energy, J kg^{-1}
k_L	liquid-phase mass transfer coefficient, m s^{-1}
K	total mass transfer coefficient, m s^{-1}
L	liquid flowrate, m^3 s^{-1} or m^3 h^{-1}
l	width of catalyst pouch in BH-1 type, mm
N	number of experimental data, dimensionless
N_{OL}	number of the liquid-side transfer unit, dimensionless
Re	Reynolds number, dimensionless
S	source term, Pa m^{-1}
u	velocity, m s^{-1}
u_G	gas superficial velocity referred to the column cross section, m s^{-1}
u_L	liquid superficial velocity referred to the column cross section, m s^{-1}
u'	root-meat-square of velocity, m s^{-1}
u_{avg}	mean flow velocity, m s^{-1}
x	mole fraction, dimensionless

Greek letters

α	corrugation angle relative to vertical, °
γ	liquid distribution parameter, dimensionless
ε	turbulent dissipation rate, J kg^{-1} s^{-1}
ε	porosity, dimensionless
μ	viscosity, kg m^{-1} s^{-1}
ρ	density, kg m^{-3}
σ	surface tension, N m^{-1}
φ	catalyst volume fraction, dimensionless
ΔP	pressure drop, Pa m^{-1}

Subscripts

B	bottom
CB	catalyst bag
e	effective
G	gas
L	liquid
OC	open channel
T	top
t	turbulent

Superscripts

*	equilibrium

developed a geometry based Delft MCSP model to predict the hydrodynamics and mass transfer performance of modular catalytic structured packings (e.g. KATAPAK) by changing the number of corrugated sheets placed between the catalyst pouches. However, the complex multiphase transport mechanisms within structured catalytic packings with gas–liquid–solid three phases

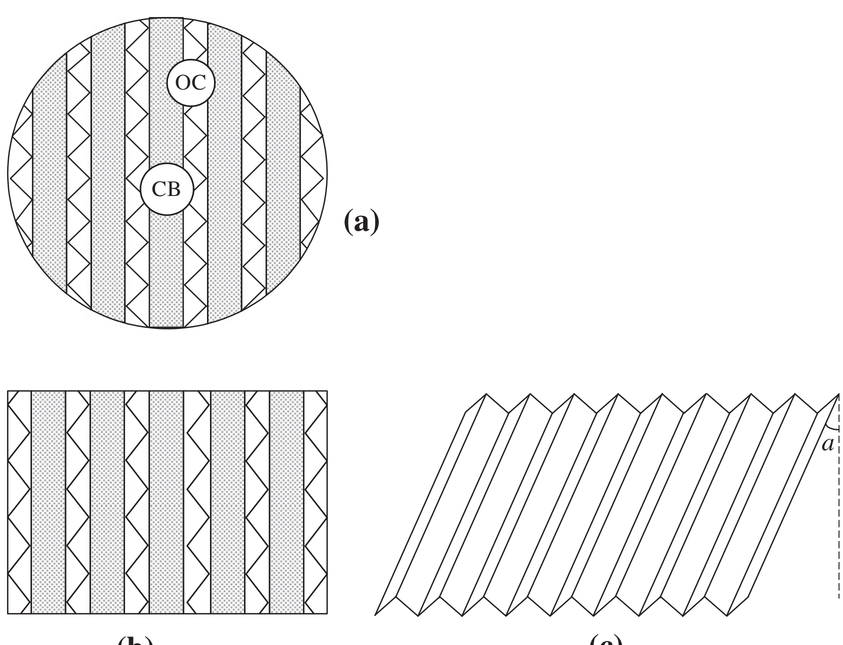

Fig. 1. Schematic representation of BH-1 type: (a) top view, (b) side view, and (c) one piece of the corrugated wire gauze sheets. OC and CB represent open channel and catalyst bag, respectively.