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Experimental and CFD studies on the effects of surface texture on liquid thickness, wetted area and mass transfer in wave-like structured packings

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ABSTRACT

A novel wave-like polyline-arc (WPA) structured packing is proposed to improve hydrodynamic performance and mass transfer. The experimental results show that the WPA packing yields a lower pressure drop, a higher capacity and a higher mass transfer efficiency compared with the traditional Mellapak 125.X packing. A multi-scale CFD (Computational Fluid Dynamics) model is used to analyse the hydrodynamic performance, and a user-defined function (UDF) is added to the Fluent solver to evaluate the mass transfer efficiency. In the hydrodynamic simulation, we use unsteady 2D and 3D VOF models to explore the effects of surface texture on the liquid thickness and effective wetted area. The CFD results show that a rough surface has a positive effect on both the average film thickness and the wetted area, and the effect on the average film thickness is greater. The mass transfer results indicate that a rough surface enhances the local gas–liquid contact efficiency by disturbing the fluid flow and prolongs the liquid–gas contact time. The simulation results show that the surface texture has a smaller effect on the wet pressure drop than on the mass transfer efficiency and are in agreement with the experimental data.

1. Introduction

Structured packings are widely used in industrial separation processes because of the higher capacity and efficiency due to the high void fraction and low liquid holdup (Olujić et al., 2000). Generally, the higher the capacity of a structured packing is, the lower its efficiency is (Olujić et al., 2007, 2003). Considering the wide applications of structured packings, a small optimization in a design may yield remarkable energy saving (Lei et al., 2003; Schultes and Chambers, 2007). Since gauze packings were invented by Sulzer Chemtech, many modifications of structured packings have been investigated. For example, the Montzpak, Rombopak, Raschig-Superpak, and Optiflow packings have been proposed to meet the requirements of industrial applications (Olujić et al., 2009).

Experimental work is the traditional way to study the performance of a novel structured packing. However, it is time-consuming and unable to provide the flow details. Although many theoretical, semi-empirical, and empirical correlations for predicting the performance of structured packings (Brunazzi and Paglianti, 1997; Fair et al., 2000; Iliuta and Larachi, 2001; Olujić et al., 2004; Rocha et al., 1996, 1993) have been reported, most of the models are applicable under some definite restrictive conditions. In the last two decades, computational fluid dynamics (CFD) has become a popular tool for optimizing the design of novel structured packings (Dai et al., 2012; Hoffmann et al., 2005; Huang et al., 2015; Larachi et al., 2003; Lautenschleger et al., 2015; Xu et al., 2014). CFD can reveal the nature of fluid flow phenomena and predict a fluid's dynamic behaviour, which cannot be done using experiments. The CFD method reduces the number of experiments and offers further understanding of the hydrodynamic and mass transfer performance of a structured packing.

CFD was used to simulate the single phase in early work. For investigating the phenomena of liquid flow through a packing filled with catalytic pellets, van Gulijk (1998) simplified the multiple phases to a single phase in the channels. A "Toblerone-like" triangular flow chan-

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Nomenclature

C	Concentration of solute, kg/m^3
D	Diffusion coefficient, m^2/s
$\vec{F}$	Momentum source term, N/m^3
g	Gravitational acceleration, m/s^2
h_L	Liquid holdup
k_L	Liquid-side mass transfer coefficient, m/s
l	Length of falling film in simulation region, m
P	Pressure, Pa
Re	Reynolds number
S_{LG}	Mass source ($kg/m^3/s$)
t	Contact time, s
u	Velocity, m/s

Greek letters

ρ	Density, kg/m^3
a	Volume fraction
a_q	Volume fraction of phase q
θ	Angle of inclined corrugation to the horizontal (°)
σ	Surface tension coefficient, N/m
μ	Viscosity, kg/(m s)
δ	Liquid film thickness, m
κ	Free surface curvature, l/m
ε	Void fraction of packing

Subscripts

G	Vapor phase
L	Liquid phase
q	The qth phase

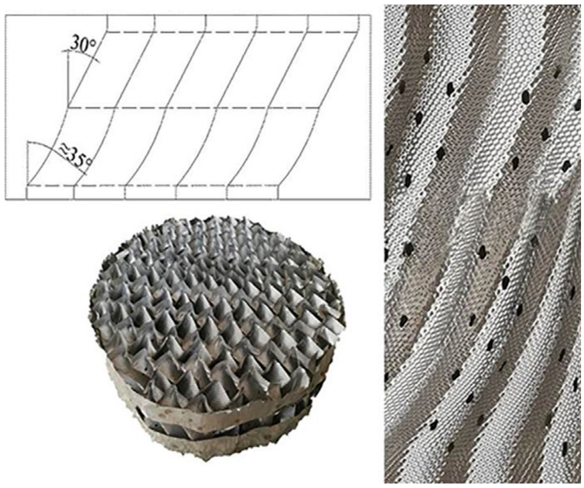

Fig. 1 – Geometric configuration of the WPA structured packings.

Table 1 – Geometrical characteristics parameters of the new packings.

Packing type	WPA packings	Mellapak 125X
a_p (m^2/m^3)	125	125
Height of element (m)	0.130	0.130
ε(%)	98.8	98.8
Corrugation angle in the top and bottom 1/8 part (°)	0	30
Corrugation angle in the middle 3/4 part (°)	30–35	30
Channel dimension(m)		
Height *h*	0.0236	0.0236
Base *b*	0.0418	0.0418

nel was used as a geometric model by other researchers (Higler et al., 1999; Shojaee et al., 2011; van Baten and Krishna, 2001). Larachi et al. (2003) divided a structured packing into four three-dimensional representative elementary units (REUs) and calculated the pressure drop across each REU. Later, other researchers (Armstrong et al., 2013; Chen et al., 2009; Raynal et al., 2009; Raynal and Royon-Lebeaud, 2007; Said et al., 2011) used only crisscross junction REUs to predict the dry pressure drop of a structured packing, and the results were quite good. For a two-phase flow, which is more realistic, Szulczewska et al. (2003) initially employed a 2D counter-current gas–liquid flow model to study the hydrodynamics of Mellapak 250.Y. Later, Raynal et al. (2004) simplified the gas–liquid flow path in the structured packing to a 2D zigzag channel and used a volume of fluid (VOF)-based approach to estimate the thickness of the liquid film and the liquid holdup. Hosseini et al. (2012) used CFD to investigate the liquid holdup, the effective area and the liquid thickness. Gu et al. (2004) and Valluri et al. (2005) simulated a liquid film flowing on sinusoidal surfaces but did not use the results to calculate the liquid holdup. Lautenschleger et al. (2015) and Sebastia-Saez et al. (Sebastia-Saez et al., 2014; Sebastia-Saez et al., 2015a,b) estimated the influence of the flow behaviour on the mass transfer. Because of the limited computational resources, the simulations were restricted to small computational domains, and industrial-scale simulations were almost impossible.

The multi-scale method combines macro and micro scales, which solves the problem of simulating a structured packing column on a large scale using the details of the flow behaviour in an element with the available computing power. Raynal and Royon-Lebeaud (2007) presented a multi-scale approach that has a three-step procedure for calculating the column pressure on an industrial scale. They discussed the influence of the surface texture on the liquid holdup in a concurrent gas–liquid flow. Sun et al. (2013) proposed another multi-scale approach, which was a 3D VOF simulation of a geometric model (small scale) integrated with a unit network model (large scale) to predict the liquid holdup distribution throughout the column. Li et al. (2016) proposed a modified multi-scale CFD model based on Raynal and Royon–Lebeaud's work. In their study, the effective wetted area was not the geometric area but rather, was integrated using ANSYS CFD-Post.

In this study, based on previous research (Li et al., 2016, 2009; Olujić et al., 2003), we proposed new wave-like polyline-arc (WPA) structured packings and explored the hydrodynamic and mass transfer performance using experiments and numerical simulations for comparison with Mellapak 125.X. In the simulations, we focused on the effect of the surface texture on the liquid thickness, the effective wetted area, the liquid holdup and the wet pressure drop using multi-scale CFD (Li et al., 2016). Additionally, the mass transfer process was characterized by adding a user defined function (UDF) and the effect of the surface texture on the mass transfer efficiency was discussed.

2. Experimental

The WPA packings are shown in Fig. 1. Considering the improvements in the hydrodynamic performance of Montz packings (Olujić et al., 2003) and Type C packings (Li et al., 2016), the top and bottom parts of the WPA packing sheets were bent to make them smoothly vertical. In the upper 1/2 of the middle section, a corrugation angle of 30° was used, and the lower 1/2 was designed as an arc to increase the turbulence of the flow and the gas–liquid contact time. The novel packings were expected to have a higher capacity and be more efficient. The detailed characteristic parameters of the WPA packings are listed in Table 1.

Fig. 2 shows a schematic of the experimental setup. The WPA and Mellapak 125.X structured packings were tested in a Plexiglas column with an internal diameter of 0.47 m. The column contained packings that were 1.02 m high. The pack-