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Hydrodynamics and flow mechanism of foam column Trays: Contact angle effect

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HIGHLIGHTS

- The effects of wettability on pressure drop, weeping and gas distribution are studied.
- Flow mechanism in foam ceramics illustrating Contact Angle Effect is proposed.
- A new four-components pressure drop decomposition strategy is proposed.
- A new component of pressure drop called CA-induced pressure drop is proposed.
- A new measuring strategy for obtaining CA-induced pressure drop is proposed.

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ABSTRACT

Wettability has significant influence on fluid flow inside foam ceramics. Foam SiC valves with various wettability were prepared by a facial bottom-up strategy. Subsequently, pressure drop, weeping and gas distribution were studied. Results indicate that pressure drop decreases remarkably with increasing contact angle (CA), 43% at most; weeping rate presents a peak at CA<90°but monotonous decrease at CA>90°; gas distribution becomes more uniform with increasing CA at small F-factor but presents obvious boundary effect at large F-factor. To illustrate the CA effect, we propose a new strategy for pressure drop decomposition, introducing the fourth part called CA-induced pressure drop by modifying classical three-component strategy, which also catalyzes a new pressure drop measuring strategy. In the meanwhile, the mathematical model to predict pressure drop is proposed and shows good agreement with experiments. Moreover, process model to illustrate the mechanism is proposed based on interfacial phenomena, force analysis and flow patterns.

1. Introduction

Foam materials have attracted more and more attention as a support for both physical process and chemical reaction process in chemical industry (Gao et al., 2015; Hutter et al., 2011; Li et al., 2015a, 2015b, 2016a; Pangarkar et al., 2008; Piątek et al., 2017; Wallenstein et al., 2015; Zhang et al., 2012, 2013). Foam materials are designed as structured catalysts and reactors (Pangarkar et al., 2008). They have also been prepared into various shapes as distillation column internals, known as structured packing and column tray (Gao et al., 2015; Li et al., 2015a, 2015b; Zhang et al., 2012, 2013).

Foam valve tray and foam monolithic tray are two typical types of developed distillation column trays. Their overall performances, namely hydrodynamics and mass transfer efficiency, are previously investigated in detail (Gao et al., 2015; Zhang et al., 2012, 2013). Also, Gas distribution is investigated by conductive probe technique (Li et al., 2015a). However, the results indicate that there are still high pressure drop and non-ideal gas distribution, which will increase energy consumption, reduce mass transfer efficiency and affect operational stability in distillation separation process. The unsatisfactory results may be highly correlated with pore size distribution and interfacial properties, which call for further research.

Wettability, usually characterized by contact angle and tuned by surface modification, is one typical interfacial property. For gas-liquid-solid system, contact angle is conventionally measured where a liquid-gas interface meets a solid surface. And 90° and 150° are used to divide the surface wettability into hydrophilic, hydrophobic, superhydrophobic based on water measurement (Myers, 1999; Tian et al., 2014).

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Nomenclature

Roman letters

A	constant coefficient
A_c	cross-sectional area of active channels, m^2
C	constant coefficient
CA	static contact angle, degree
d_h	average pore diameter, m
$D_{B\max}$	maximum bubble diameter on forming, m
f	function mapping relationship
F	gas kinetic factor, $u\sqrt{\rho_G}$, $Pa^{0.5}$
F_G	liquid weight, N
F_i	gas impact force, N
F_{if}	interface friction force, N
F_N	normal force perpendicular to the channel wall, N
F_{ST}	surface tension force, N
g	Acceleration due to gravity, m/s^2
h_w	Weir height, m
h_{CL}	the height of clear liquid layer, m
H	liquid height inside the channel, m
k	Interface friction coefficient
L_w	liquid weir loading, $m^3 \cdot h^{-1} \cdot m^{-1}$
P	total pressure drop, Pa
P_{dry}	dry tray pressure drop, Pa
P_{quasi}	quasi-dry tray pressure drop, Pa
P_r	residual pressure drop, Pa
P_σ	bubble formation resistance, Pa
P_{CA}	CA-induced pressure drop, Pa
Re_a	pore average Reynolds number
u_G	gas velocity in the active channel, m/s
$u_{G,m}$	average gas velocity in active channels, m/s
u_h	average gas velocity based on dry state of foam valve, m/s
u_s	liquid velocity at the wall, m/s

Greek letters

λ	boundary slip length, m
μ	fluid viscosity, $Pa \cdot s$
σ	surface tension force, N/m
θ	departure contact angle between bubble interphase and tray, degree
ξ	orifice coefficient
ε	fraction of gas holdup in froth layer
$\bar{\varepsilon}$	average fraction of gas holdup in froth layer
ε_{ac}	available porosity of active channels
ρ_L	liquid density, kg/m^3
ρ_G	gas density, kg/m^3

Surface modification is an effective way to solve the hydrodynamic problem. Firstly, wetting conditions present obvious influence on bubble formation at orifice in an inviscid liquid (Byakova et al., 2003; Gnyloskurenko et al., 2003; Kulkarni and Joshi, 2005); moreover, research in the microchannel indicates that wall wetting properties will affect flow regimes and their transitions (Shao et al., 2009). In addition, superhydrophobic and hydrophobic surfaces present remarkable friction drag reduction in laminar or turbulent flow (Golovin et al., 2016). These results inspire that it is necessary and of great significance to carry out comprehensive study on the effect of surface contact angle (CA) on the performances of foam column trays. However, there are rare reports about the effects of surface CA on pressure drop, weeping and gas distribution.

Pressure drop, weeping and gas distribution are the fundamentals in distillation. These hydrodynamic properties vary regarding operation conditions (gas and liquid flow rate), geometrical parameters (pore size, pore structures etc.) and material types, which have been extensively investigated.

Pressure drop is an important aspect in hydrodynamics. Extensive research papers are published on pressure drop experimentally and mathematically (Bennett et al., 1983; Biddulph and Thomas, 1995; Brahem et al., 2013; Wang et al., 2014; Zuiderweg, 1982). Total pressure drop is the apparent parameter and generally resolved into several parts. In general, there are two methods to describe total pressure drop's decomposition and relevant empirical or semi-empirical models. One method is shown in Eq. (1), in which total pressure drop is divided into two parts, namely valve pressure drop P_{valve} and clear liquid head $\rho_L \cdot g \cdot h_{CL}$; this is commonly used in float valve tray which can ignore residual pressure drop because of large size of valves (Brahem et al., 2013; Wang et al., 2014). The other one is that total pressure drop is divided into three parts, namely dry tray pressure drop P_{dry}, clear liquid head $\rho_L \cdot g \cdot h_{CL}$ and residual pressure drop P_r, as shown in Eq. (2), which is commonly adopted in sieve tray (Bennett et al., 1983; Biddulph and Thomas, 1995; Zuiderweg, 1982). One existing paper indirectly investigates the effect of interfacial property on pressure drop by changing substance species, which incorporates the effect into residual pressure drop by empirical correlation (Biddulph and Thomas, 1995). But there are some innate drawbacks, for example, small regulation range, introducing other interferential variables and not probing into the mechanism. So it is better to isolate this part of pressure drop induced by interfacial property, mainly surface CA.

$$P = P_{valve} + \rho_L \cdot g \cdot h_{CL} \quad (1)$$

$$P = P_{dry} + \rho_L \cdot g \cdot h_{CL} + P_r \quad (2)$$

In addition, weeping and gas distribution are another two significant features. Weeping may cause severe liquid back-mixing and hence generate a negative influence on mass transfer efficiency (Kulkarni and Joshi, 2005; Lockett et al., 1984; Zarei et al., 2013). And weeping point and rate are usually proposed as characteristic parameters (Wang et al., 2014; Zarei et al., 2013). Gas distribution, as a microscale parameter, determines the available region for gas-liquid mass transfer on the column trays, and sometimes results in upset operation (Kister and Olsson, 2011; Mohan et al., 1983a,b).

In chemical equipment, flow mechanism for explaining overall performances is always illustrated by fluid flow regime (Taitel et al., 1980). Flow patterns and pattern transition are paid special attention, especially in a vertical tube and in a fixed granular bed. In a vertical tube, flow patterns are commonly classified into bubble flow, slug flow, churn flow, and annular flow; pattern transition is also well stated mechanistically and mathematically (Taitel et al., 1980). In fixed granular bed, whose typical example is the trickle bed reactor, five flow patterns, namely film flow, trickle regime, spray regime, pulse regime and bubbly regime, are pictured (Gunjal et al., 2005). Two-dimensional flow maps for pattern transition are also widely established, typically with gas/liquid flow velocity as the axis. Recently, a phenomenological study using computed tomography is performed to illustrate the flow path in foam ceramics (Wallenstein et al., 2015). As mentioned above, surface CA also presents remarkable effect on