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Pressure drop and its reduction of gas–non-Newtonian liquid flow in downflow trickle bed reactor (DTBR)

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ABSTRACT

The influences of concurrent flow of air–Newtonian and non-Newtonian liquid systems on pressure drop and on its reduction in downflow trickle bed reactor are presented in the present work. The pressure drop at different flow regimes in the trickle bed is enunciated by the dynamic interaction model based on the framework of the momentum balance. From the analysis, it is observed that the non-ideality factor of bubble flow regime is higher than that of pulse and trickle flow regimes which may influence efficiency of the reactor. The present work also concludes that the percentage of pressure reduction increases with increasing the surfactant concentration. However there is a limitation of change of concentration, above which no more reduction can be obtained. The present study may be useful for further understanding and modelling of multiphase reactor with non-Newtonian liquid, which has great industrial applications.

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Keywords: Trickle bed; Flow regime; Non-Newtonian liquid; Pressure drop; Drag reduction; Downflow

1. Introduction

A downflow trickle-bed reactor (DTBR) is a reactor in which gas and liquid both concurrently flow downward through a packed bed of particles. Most commercial trickle-bed reactors are used for hydrogenations, oxidations and desulfurization. It is operated in several flow regimes. At present, steady state operation in the trickle flow regime is common in industrial applications. Cocurrent downward flow is preferred because of some advantages like, high throughput, high interaction between gas and solid phase as the liquid to gas ratio is less, more economic compared to others, less pumping action is required etc. Various parameters significantly influence the performance of a given reactor and commonly encountered in commercial-scale trickle beds and therefore understanding the nature and characteristics of the hydrodynamics (Satterfield, 1975; Larachi et al., 1999; Attou and Ferschneider, 2000; Burghardt et al., 2004; Lim et al., 2004; Iliuta et al., 2006; Iliuta and Larachi, 2009). Pressure drop governs the energy required to move the fluids through the bed and is therefore one of the most important parameters in design, scale-up and operation of packed beds, even for forecasting gas–liquid and solid–liquid mass transfer. The energy is required against the gas–liquid flow resistance in porous media. Gas–liquid flow resistance in porous media is mainly caused by: friction forces due to fluid viscosity at the gas–liquid, gas–solid (partially wetted conditions) and liquid–solid interfaces, inertial forces caused by successive acceleration and/or deceleration of the fluids across the packing, turbulence due to local velocity of both the gas and the liquid phases and interfacial (capillary) forces. The relative importance of these forces naturally depends upon the flow regime in the reactor. In the high interaction regime, the main part of the mechanical energy dissipation is due to inertia of the gas and/or the liquid flows, but in the trickling regime, the resistance to flow is essentially controlled by shear forces and capillary forces. The pressure drops in the trickling, pulsing, bubbly dispersed flow regimes and trickling-pulsing and pulsing-bubbly dispersed transitions depends upon packing pattern (Wammes et al., 1991). Gandhidasan in 2002 (Gandhidasan, 2002) reported that the pressure drop across a packed bed is less for structured packing than that of random packing. He proposed a model and

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Nomenclature

A	interfacial area [m^2]
d	bubble diameter [m]
d_0	orifice diameter [m]
d_p	particle diameter [m]
D	column diameter [m]
g	acceleration due to gravity [$m\,s^{-2}$]
G	superficial mass velocity of gas [$kg\,m^{-2}\,s^{-1}$]
h	height of trickle bed [m]
L	superficial mass velocity of liquid [$kg\,m^{-2}\,s^{-1}$]
N_b	rate of bubble formation [s^{-1}]
ΔP	pressure drop [$N\,m^{-2}$]
Re_g	gas Reynolds number ($=(\rho_g V_{sg} d_c)/\mu_g$)
Re_{nN}	non-Newtonian liquid Reynolds number ($=\{d_c^n V_{sl}^{2-n}\rho(4n)^n\}/\{8^{n-1}K(3n+1)^n\}$)
s	factor defined as in Eq. (14)
S	cross-sectional area of the column [m^2]
V'	superficial velocity [$m\,s^{-1}$]

Greek letters

α	empirical constant
α_b	non-ideality factor
β	total liquid saturation based on void volume
δ	dimensionless pressure drop ($=\Delta P/\rho g h$)
ε	bed porosity
μ	viscosity [$kg\,m^{-1}\,s^{-1}$]
ρ	density [kg/m^3]
γ_g	dimensionless factor ($=1-\gamma_l$)
γ_l	dimensionless factor ($=(L/\rho_l)/(L/\rho_l+G/\rho_g)$)
σ	surface tension [N/m]
τ	shear force [$N\,m^{-2}$]
φ	energy dissipation [$N\,m\,s^{-1}$]
ψ'	friction factor ($=\Delta P/(\rho V^2/2)(d_p/h)$)

Subscripts

F	friction
g	gas
i	interface
l	liquid
lg	two-phase
s	single phase

Superscript

0	single phase

validated for a wide range of operating values available in the literature. Specchia and Baldi (1977) studied the pressure drop and liquid holdup for two-phase cocurrent downward flow in packed bed at a poor and a high gas–liquid interaction regimes. They considered both foaming and non-foaming systems. They concluded that in the poor interaction regime, the pressure drop by gas flow can be restricted by the presence of liquid in a bed. Sindhu and Sai (2003) proposed a macroscopic model for pressure drop and liquid saturation in concurrent gas–liquid upflow through packed bed. They evaluated the three model parameters: two accounting for the effect of reduction in cross sectional area available for each phase due to the presence of the other, the third accounting for the effect of bubble formation. Bartelmus and Janecki concluded that foaming systems result in values of higher pressure drop and lower liquid holdup than non-foaming systems at the same velocities of both phases (Bartelmus and Janecki, 2003). Guo and Al-Dahhan (2004) carried out experiment at room temperature and elevated pressure (0.8–2.2 MPa) with air–water system. They found that pressure drop increases with increasing liquid and gas flowrates whereas liquid holdup increases with increasing liquid flowrate and decreases with increasing gas flowrate. The trickle to pulse transition boundary moves towards higher flowrate of both liquid and gas at higher operating pressure (Urseanu et al., 2005). Simulation of the trickle bed reactor at high pressure with different spherical particle shows that decreasing the diameter of particle, liquid holdup and pressure drop of the bed increases (Lopes and Quinta-Ferreira, 2008). The increase in pressure drop is more pronounced in two-phase flow because of enlargement of liquid holdup which decreases the available void space for the gas in the trickle bed reactor. Al-Naimi et al. (2011) studied the hydrodynamics of trickle bed reactor in non-ambient condition with air–water and air–acetone (pure organic liquid of low surface tension) systems. They reported that the pressure drop tends to increase with increase superficial gas and liquid velocities whereas it tends to decrease with increasing bed temperature. The liquid and gas phase experience pressure in trickle bed reactor because of friction at the gas–liquid, liquid–solid and solid-gas interfaces. The pressure is more for liquid of high surface tension and high solid–liquid interaction. Also pressure increases due to blocking of void space due to high liquid holdup that leads to high gas–liquid interfacial friction. The pressure in trickle bed reactor can be reduced by elevating operating temperature, improving porosity of bed by effective packing or by using pressure reducing agent like surfactant. The aim for the pressure reduction is to improve the fluid-mechanical efficiency. Various authors reported the variations of the pressure drop with drag reducing agent. Aydin and Larachi (2008a) studied hydrodynamics in trickle-bed reactors with pressure reducing agent (PRA) at non-ambient conditions for foaming liquids (air–cetyltrimethylammoniumbromide (CTAB)). Patel and Majumder (2011) carried out an experimental investigation of pressure reduction in a packed bed. They studied the pressure reduction at particle Reynolds number in the range 10–250 and found to depend on the concentration of PRA and fluid velocity. The maximum pressure reduction was found to be 38% for single phase non-Newtonian liquid. Based on the literature review, the hydrodynamics of Newtonian liquids in trickle bed reactor is largely studied in recent years but very few works have been done with non-Newtonian liquids in trickle bed reactor. There is a scope of study the hydrodynamics of non-Newtonian liquid and pressure reduction in trickle bed reactor. Pressure reduction is useful in reactor design and cost effectiveness. In the present work an attempt has been made to study: (i) the flow regime map in trickle bed reactor with air–Newtonian and air–non-Newtonian liquid systems, (ii) the influences of dynamic variables with Newtonian and non-Newtonian liquid systems on the pressure drop, (iii) analyze the pressure drop by a mechanistic model and (iv) analyze the degree of pressure reduction in a trickle bed reactor.

2. Experimental setup and procedure

The experimental setup consists of a borosilicate glass column, extended pipeline contactor and accessories such as valves, two rotameters, two manometers, one pump and one

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