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Analysis of the hydrodynamics of a periodically operated trickle-bed reactor—A shock wave velocity

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ABSTRACT

The relationship describing the shock wave velocity was formulated for the trickle-bed reactor operating at periodically changed feeding the bed with liquid phase. The values of shock wave velocity calculated from derived equations were compared with experimental values obtained for both fast and slow mode of base–pulse periodic liquid feeding and using liquids differing in physicochemical properties. A good agreement between these two sets of values of shock wave velocity was obtained. It has to be emphasized that the relationship (Eq. (26)) derived in this study enables to estimate the values of the shock wave velocity when only mean values of variables of a process are known.

Keywords: Multiphase flow; Trickle-bed reactor; Hydrodynamics; Periodic operation; Continuous shock wave regime; Slow and fast mode of operation

1. Introduction

A trickle-bed reactor is a commonly used type of a three-phase reactor in which both the gas and the liquid flow down co-currently through a fixed bed of catalyst pellets. This type of reactor is widely employed in refineries and in the chemical and petrochemical industries in the processes of hydrodesulphurization, hydrocracking, hydrorefining, oxidation and hydrogenation. A trickle-bed reactor usually operates in the gas continuous flow regime (GCF) associated with low flow rates of both phases. Since the overall process rate is often governed by mass transfer resistance, then it would be advantageous to carry out the process in the pulse flow regime (PF) (Burghardt et al., 1995). One cannot forget that to generate a pulse flow in a reactor, relatively high flow rates of both phases are necessary. As a result, the residence time of the reacting substances in a reactor is very short, which unfavorably influences their final conversion. Moreover, if a reactor operates at elevated pressure, then the regime transition line GCF/PF moves toward higher flow rates values of both phases (Burghardt et al., 2004).

Many of the solid-catalyzed gas–liquid reactions can be broadly classified as either limited by gas or liquid phase reactant. Changing the feed strategy may reduce mass transfer resistance and thus intensify the process rate leading in consequence to the increase of reactant conversion or reduction of reactor's dimensions (Bhaskar et al., 2004; Boelhouwer et al., 2001; Gunjal and Ranade, 2007; Khadilkar et al., 1999; Silveston and Hudgins, 2013). In a liquid cyclic operation a constant gas flow is fed into the reactor while the liquid feed flow rate is periodically switched between two values i.e. low (base) and high (pulse). This modulation is called BASE–PULSE MODE. Such periods can last up to several minutes (SLOW MODE) or just a few seconds (FAST MODE) at different high and low liquid feed velocities and split (ratios of period part with the higher flow rate to period length). However, when the low (base) liquid flow rate value is set to "zero" then it is assigned as ON–OFF MODE of liquid modulation (Atta et al., 2010).

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Nomenclature

d_e	equivalent diameter (m)
d_p	diameter of packing (m)
E_1, E_2	Ergun constants
$F_{g\text{–}L}$	drag force ($\mathrm{N\,m^{-3}}$)
g	gravity acceleration (m/s)
$Re_z = 4\Gamma/\eta$	Reynolds number
s	film thickness (m)
U	voltage (V)
V_α	real velocity (m/s)
V_w	shock wave velocity (m/s)
W	wetted circumference (m)
w_α	superficial velocity (m/s)
$w_{\alpha x}$	fluid velocity along the vertical flat surface (m/s)
y	coordinate perpendicular to the vertical flat surface

Greek letters

Γ	wetting rate ($\mathrm{kg\,m^{-1}\,s^{-1}}$)
ε	bed porosity
ε_α	total hold-up of phase α
ε_{Ld}	dynamic liquid hold-up
η	viscosity (Pa s)
ρ	density ($\mathrm{kg/m^3}$)
σ	surface tension ($\mathrm{N\,m^{-1}}$)

Subscripts

av	average value
b	base
g	gas
L	liquid
p	pulse
w	water
α	L or g

In the early 1990s large number of studies about the effect of periodic liquid flow on the efficiency and selectivity of the processes appeared (Haure et al., 1989; Lange et al., 1999; Stradiotto et al., 1999; Liu and Mi, 2005; Massa et al., 2005; Szczotka et al., 2010). By far, in literature, more attention was paid to the operation of a reactor carried out using the ON–OFF method, since it seems very favorable for processes limited by gas phase reactant (Banchero et al., 2004; Muzen et al., 2005; Ayude et al., 2007).

Several industrial reactors operate under liquid-limited conditions which is mainly caused by a very low concentration of the key reactant in the liquid phase (Dudukovic et al., 1999). Good distribution of liquid on the surface of catalyst particles to avoid dry spots on its surface is crucial to such processes. In such a situation the operation of TBR in a natural pulse flow (PF) is most appropriate (Turco et al., 2001). An alternative could be to carry out the process at lower mean velocities of the liquid phase, changed cyclically using the BASE–PULSE method, at which it is possible to induce natural pulsations in the pulse of the liquid (LIPF regime, Liquid Induced Pulsing Flow regime) (Boelhouwer et al., 2002a; Giakoumakis et al., 2005; Bartelmus et al., 2006; Gancarczyk et al., 2007; Bartelmus et al., 2008). If, however, the flow regime during both high and low liquid flow rates corresponds to the trickle flow regime (GCF), then the reactor operates at the continuity shock waves regime (CSW) (Boelhouwer et al., 2002b).

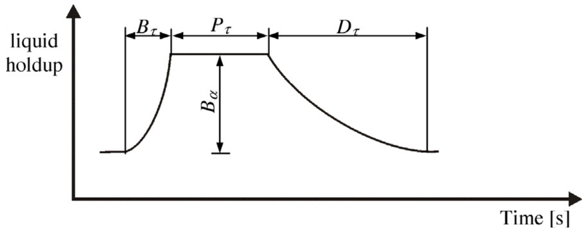

Fig. 1 – Parameters describing the shape of the wave (Aydin et al., 2006).

A shock wave can be described by means of four basic parameters (Fig. 1): the breakthrough amplitude (B_α), the breakthrough time (B_τ), the plateau time (P_τ), the decay time (D_τ) (Aydin et al., 2006). Continuity shock waves, resulting from the step change in liquid flow rate, decay while moving down the reactor by leaving liquid behind their tail. For this reason, a shock wave can vanish in the lower part of the bed (Boelhouwer et al., 2002a).

Numerous studies, whose authors analyzed the changes in liquid holdup values during the migration of a shock wave along the bed, can be found in literature (Boelhouwer et al., 2001, 2002a; Giakoumakis et al., 2005; Aydin et al., 2006; Trivizadakis et al., 2006; Aydin et al., 2007, 2008; Aydin and Larachi, 2008). Boelhouwer et al. (2001) determining, for the air–water system, the time lag between two signals from neighboring conductivity probes, calculated the velocity of the moving liquid front. Its velocity increased both with the increase in the gas velocity and with the increasing difference between pulse and base liquid flow rate. Moreover, the velocities of the moving front are much higher than the linear liquid velocity. Calculating the shock wave velocity from the relationship suggested by Wallis (1969) in the form

$$V_w = \frac{w_{Lp} - w_{Lb}}{\varepsilon_{Lp} - \varepsilon_{Lb}} \tag{1}$$

the authors obtained good agreement between determined experimentally and calculated values, as well qualitatively as quantitatively. The accuracy of the calculated values increases with the increase in the difference between high (pulse) and low (base) liquid holdup. The authors (Boelhouwer et al., 2002a) re-carried out the tests in a 3.2 m long column stating that shock wave velocity remains constant along the column height and are not affected by the decay process as long as a shock wave plateau is observed. The decaying process results in the decrease in the length of the shock wave plateau and consequently in the increase in the length of the tail. Aydin et al. (2006, 2007, 2008) analyzed the influence of temperature and pressure on liquid holdup values for air–water and air–CMC solution (carboxymethylcellulose) systems. The authors used long cycles of changes in feeding the bed with liquid (60 s/60 s for the first system and 120 s/120 s for the other). Since the change in temperature alters, first of all, liquid viscosity, then the authors' conclusions can be viewed as the influence of the changes of liquid viscosity on the shock wave parameters. The authors confirm that the wave evolves while moving down the bed, which can be seen from the decreasing wave amplitude. The phenomenon is the more intensive for lower liquid viscosity. The increase in temperature, that is the decrease in the viscosity of the liquid, causes the increase in the plateau duration. The shock wave velocity increases with

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