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The effects of particle properties, void fraction, and surface tension on the trickle-bubbly flow regime transition in trickle bed reactors

Gregory S. Honda [a], Jorge H. Pazmiño [b], Eric Lehmann [a], Daniel A. Hickman [c], Arvind Varma [a,*]

[a] School of Chemical Engineering, Purdue University, 480 Stadium Mall Drive, West Lafayette, IN 47907, USA
[b] Engineering and Process Science, The Dow Chemical Company, 2301 North Brazosport Blvd., Freeport, TX 77541, USA
[c] Engineering and Process Science, The Dow Chemical Company, 1776 Building, Midland, MI 48674, USA

HIGHLIGHTS

- Trickle-bubbly flow regime transition depends strongly on void fraction, particle shape, and surface tension.
- Transition was observed to be relatively independent of gas velocity for all cases.
- Applicability of extending existing models for the trickle-pulsing transition is reviewed.
- Correlation developed in this work provides accurate prediction of experimental results.

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ABSTRACT

The hydrodynamics of trickle bed reactors operating near the trickle-bubbly flow regime transition have not been fully characterized in the literature. In this work, an air–water system is used to investigate the effects of particle size, particle shape, void fraction, and surface tension on the trickle-bubbly flow regime transition in trickle bed reactors. The flow regime transition is detected based on standard deviation of pressure drop with confirmation by visual observation. For all cases, the liquid superficial velocity required for the trickle-bubbly transition was found to be relatively independent of the gas superficial velocity ($v_G = 4$–40 mm/s). Literature models, defined for the trickle-pulse transition, are unable to predict this trend when extrapolated to low gas superficial velocities ($v_G \leqslant 40$ mm/s). To address this gap, a correlation is proposed based on the experimental data gathered in this work.

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1. Introduction

This work evaluates the effects of particle size, shape, bed void fraction and liquid surface tension on the transition from trickle to bubbly flow that occurs at low gas and high liquid superficial velocities in a trickle bed reactor. In the previous literature, the hydrodynamics of trickle bed reactors have not been thoroughly investigated for low gas superficial velocities ($v_G \leqslant 40$ mm/s) [1]. Models and correlations developed based on data at higher gas flows may not accurately represent the hydrodynamics when extended beyond their original scope. Since several industrial reactors operate in the bubbly flow regime, evaluation of hydrodynamics at low v_G is necessary. While a number of hydrodynamic characteristics are important for reactor design, flow regime in particular has been shown to have a significant effect on reactor performance [2]. It is therefore essential to accurately characterize the flow regime transition in order to achieve the preferred reactor performance. Observed regimes in the reactor include the low interaction trickle flow (low to moderate v_G and v_L) and high interaction regimes of pulsing (moderate v_G, high v_L), bubbly (low v_G, high v_L), and spray flow (high v_G, low v_L) [3]. Research has typically been focused on the transition between trickle and pulsing flow, although it may be beneficial to operate closer to the trickle-bubbly transition for certain exothermic reactions. Doing so allows for reduction in hot spot formation by improvements in liquid contacting that occur at low gas and high liquid superficial velocities. Despite the potential benefits, the transition from trickle to bubbly flow has not been fully characterized in the literature.

Earlier related articles instead placed emphasis on evaluation of the flow regime transition from pulsing to bubbly flow that occurs at very high liquid superficial velocities (typically, $v_L > 25$ mm/s) for a given gas superficial velocity. Sato et al. described this boundary, as well as the trickle-pulse transition, but did not evaluate low

* Corresponding author.
E-mail address: avarma@purdue.edu (A. Varma).

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Nomenclature

Notations

A	cross sectional area of imaged particle (m^2)
d_C	column diameter (m)
d_p	effective particle diameter (m)
d_v	volume based diameter of the particle (m)
g	gravitational constant (m/s^2)
h_U	height of the high interaction regime relative to column height
L	length of the extrudate particle (m)
L_C	length of column pressure drop (m)
m_p	mass of particles added to column (kg)
$q_{i,3}$	volume based fraction of particles having a given diameter
v_G, v_L	superficial gas (G) and liquid (L) velocities (m/s)
v_{LT}	superficial liquid velocity required for transition at given v_G (m/s)
V	volume of single particle (m^3)
V_C	volume of column (m^3)
W	width of cylindrical extrudate (m)

Greek letters

α	sphericity of the particles
ϵ	void fraction of the bed
$\psi_L = \frac{-\Delta P}{g\rho_L L_C} + 1$	dimensionless pressure drop
ρ_L	density of the liquid (kg/m^3)
$\rho_{p,env}$	envelope density of the particles (kg/m^3)
σ_{liquid}, σ_{water}	air–fluid surface tension (dyn/cm)
$\sigma_R = 1 - \sigma_{measured}/\sigma_{baseline}$	standard deviation of pressure drop relative to baseline

enough gas superficial velocities ($v_G < 50$ mm/s) to observe the trickle-bubbly transition [4]. Tosun conducted experiments at sufficiently low v_G (16–40 mm/s) to observe bubbly flow at more moderate v_L (~10 mm/s) [5]. This regime was labeled as liquid continuous and incorrectly considered to be a low interaction regime. In addition, the boundary between trickle and bubbly flow was not defined. Rather, the transition between bubbly and a more finely dispersed bubbly flow was delineated based on qualitative visual observations. Wammes et al. observed dispersed bubbly flow but were unable to define a clear boundary with trickle flow [6]. More recently, Jo and Revankar investigated the coalescence and breakup of bubbles in bubbly flow [7]. As a part of this effort, an approximate flow regime map was developed which suggested differences between trickle-pulse and trickle-bubbly transitions in the dependence of v_{LT}, the liquid superficial velocity required for the transition, on v_G. Although the trickle-bubbly flow transition was observed, it was not accurately defined as the focus was on evaluating fundamental behavior of the bubbly flow.

Recent work by our group to evaluate the effect of pre-wetting on the trickle-pulsing and trickle-bubbly transition has shown significant differences between the two [8]. For a packing of 3 mm ceramic beads the transition between trickle and bubbly flow was relatively independent of the gas flow. This is in contrast to literature where an increase in v_{LT} with decreasing gas superficial velocity is reported for the trickle-pulsing transition [1]. Our results also indicated a stronger effect of pre-wetting conditions on the trickle-bubbly transition relative to the trickle-pulsing transition. In the current work, a single pre-wetting procedure is used, and the effects of different packing material and surface tension are evaluated.

The effects of particle size, void fraction, and surface tension are well documented for the trickle-pulsing transition. For a given gas superficial velocity, decreases in void fraction and surface tension result in transition at a lower liquid superficial velocity [9]. The effects of particle size and shape, while investigated in the literature, are less clear. Trivizadakis et al. observed relatively little effect of particle size while they did report an effect of shape [10]. However, these effects were not presented independently of void fraction, which changes with particle size and shape. While these effects have been investigated for the trickle-pulse transition, they have yet to be evaluated for the trickle-bubbly transition. Therefore, the objective of this study is to investigate and develop a correlation for the effects of bed void fraction, particle properties, and surface tension on the trickle-bubbly flow regime transition.

2. Materials and methods

Two setups at different scales were used to conduct the experiments. The first consisted of a 51 mm ID acrylic column operated at Purdue University, as shown in our prior work [8]. The other was operated at The Dow Chemical Company and used a larger, 152 mm ID acrylic column with other elements of the setup scaled appropriately. In both cases, the systems were operated with air and water supplied at 20 °C and atmospheric pressure. Flow regime transition was detected based on the standard deviation of pressure drop with visual confirmation. The measured variables include the dimensionless pressure drop (ψ_L), relative standard deviation of pressure drop (σ_R), and relative height of the higher interaction regime (h_U). These are defined relative to the liquid density, standard deviation of the baseline pressure drop, and total column height, respectively. For the small diameter column, the qualitative nature of the high interaction regime (bubbly or pulsing) was evaluated based on playback of video from a high speed camera captured at 500 frames per second. The focus in this work is placed on the trickle-bubbly flow transition. Therefore, in the 51 mm ID column the gas superficial velocities evaluated included 4, 8, 16, and 40 mm/s (0.005, 0.010, 0.024, 0.049 $kg/m^2/s$). An additional point was recorded for the trickle-pulsing transition at $v_G = 80$ mm/s (0.098 $kg/m^2/s$). For the 152 mm ID column, gas velocities varied but fall within the same range. The types of packing media evaluated in this work include ceramic beads, alumina spheres, and cylindrical alumina extrudates. Respective physical properties of particle diameter (d_p), column diameter (d_C), sphericity (α), and void fraction (ϵ) are listed in Table 1. The packing name follows material/shape (CB – ceramic bead; S – alumina sphere; EX – alumina extrudate), the nominal diameter/width listed by the manufacturer, and lastly column internal diameter. It should be noted that experiments and results for the 3.41 mm ceramic beads,

Table 1
Material and bed properties.

Packing	Material	d_p (mm)	d_C (mm)	α	ϵ
CB3-51	Ceramic bead	3.41	51.0	1.00	0.380
CB2-51	Ceramic bead	2.24	51.0	1.00	0.362
S1.8-51	Alumina	1.79	51.0	1.00	0.356
EX3.1-51	Alumina	4.55	51.0	0.85	0.345
EX2.3-51	Alumina	3.50	51.0	0.82	0.350
S1.8-152	Alumina	1.79	152	1.00	0.360
EX3.1-152	Alumina	4.55	152	0.85	0.353
EX2.3-152	Alumina	3.50	152	0.82	0.362

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