Chemical Engineering Journal 111 (2005) 5–11

Chemical Engineering Journal

www.elsevier.com/locate/cej

Estimation of trickle-to-pulse flow regime transition and pressure drop in high-pressure trickle bed reactors with organic liquids

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Received 16 June 2004; accepted 11 April 2005

Abstract

Flow regime boundaries and pressure drop in trickle bed reactors are crucial for design, scale-up and operation of such reactors. The flow map experiments are performed in a pilot plant reactor of 0.051 m diameter and 1.2 m height, with cumene–hydrogen system. A new technique – the acoustic signal measurement – is used for distinguishing between trickle and pulse flow regimes. The effect of operating pressure was investigated in the pressure range of 0.14–2.0 MPa. For higher operating pressures, the trickle-to-pulse transition boundary moves towards higher flow rates of both liquid and gas phases.

The pressure drop over the reactor bed is increasing with increasing operating pressure and gas/liquid throughputs. The pressure drop results obtained with hydrogen at higher operation pressures match reasonably well the results obtained with air–water at atmospheric pressure. This comparison is made using a new developed pressure drop correlation and illustrates the influence of increased gas density (high operating pressure effect). The Trickle Bed Simulator of University Laval [F. Larachi, B. Grandjean, I. Iliuta, Z. Bensetiti, A. André, G. Wild, M. Chen, Excel Worksheet Simulator for Trickle-Bed Reactors, http://www.gch.ulaval.ca/bgrandjean/pbrsimul/pbrsimul.html, 1999] was found to match reasonably well our pilot plant measured values for low and high operating pressures.

Keywords: Chemical reactors; Multiphase flow; Trickle bed reactor; Hydrodynamics; Flow map; Pressure drop

1. Introduction

Trickle bed reactors are the most widely used type of multiphase reactors. The large applicability and importance of this type of reactors arises from their major use in the petroleum industry for hydroprocessing of medium heavy and heavy oil fractions. Among these applications, trickle bed reactors are also used in biochemical and chemical industries, in wastewater treatment and electrochemical processing. The liquid and gas flow co-currently down through a fixed bed of catalyst particles. The commercial trickle bed reactors operate usually adiabatically, at high temperatures and pressures, and often involve hydrogen and organic liquids. Industrial trickle beds have typically diameters of 2–4 m and heights of 15–25 m. Laboratory and pilot plant experiments used in the development of new processes or optimisation of the existent ones should give accurate results, reliable for design and scale-up. It is an important issue to know what the basic requirements are for using downscaled reactors that lead to meaningful results for integral industrial reactors. This topic is extensively presented in [2].

Knowledge of the flow regime in which the reactor will operate is very important because other hydrodynamic parameters, especially the mass transfer rates, are affected by hydrodynamics differently in each regime. In a trickle bed, various flow regimes are distinguished, depending on gas and liquid properties, throughputs, operating conditions and packing characteristics. The four main flow regimes observed are trickle flow, mist flow, bubble flow and pulsing flow. The flow regime boundaries with respect to gas and liquid flow rates are schematically shown in Fig. 1. Each flow regime corresponds to a specific gas–liquid interaction, thus having a great influence on parameters as liquid hold-up, pressure

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doi:10.1016/j.cej.2005.04.015

Nomenclature

d_p	grain equivalent diameter (m)
D_T	column diameter (m)
P	operating pressure (Pa)
$\Delta P/z$	differential pressure drop (Pa/m)
STDEV	standard deviation from pressure drop measurements (–)
T	operating temperature (°C)
U_G	superficial gas velocity (m/s)
U_L	superficial liquid velocity (m/s)

Greek letters

ε_b	bed porosity (–)
η_L	liquid viscosity (Pa s)
ρ_G	gas density (kg/m^3)
σ	surface tension (N/m)

drop and mass and heat transfer rates. The trickle flow regime occurs at relatively low gas and liquid flow rates. The liquid flows as a laminar film and/or in rivulets over the packing particles, while the gas passes through the remaining void space. At high gas and low liquid flow rates, transition to mist flow occurs. The liquid mainly travels down the column as droplets entrained by the continuous gas phase. The bubble flow regime appears at high liquid flow rates and low gas flow rates. In this case, the liquid is the continuous phase and the gas moves in the form of dispersed bubbles. At moderate gas and liquid flow rates, the pulsing flow regime is obtained. This regime is characterized by the successive passage of liquid-rich and gas-rich regions through the bed. While the existence of the various flow regimes in trickle bed reactors is well known and many efforts were done in order to establish a theoretical rule to demarcate the regime boundaries, none of them is able at this moment to accomplish such a complex task. Numerous attempts were done to model hydrodynamics of trickle bed reactors. Reviews on published models in this area can be found in [3–5].

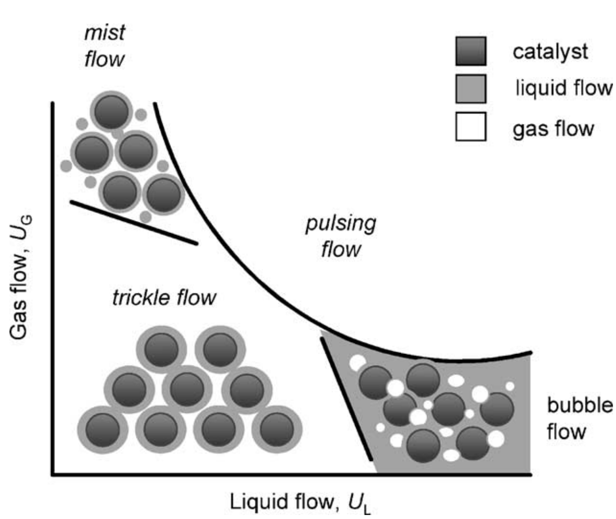

Fig. 1. Schematic illustration of the location of the trickle, mist, bubble and pulsing flow regimes with respect to gas and liquid flow rates.

As a consequence of gas flow downward through the packed bed, a pressure drop arises over the trickle bed reactor due to friction at the gas–liquid interface. The pressure drop over the column bed is an important design parameter and also essential for sizing the compression equipment. Following the approach used by Lockhart and Martinelli [6] for the pressure drop for two-phase co-current flow in tubes, several relations have been suggested in order to predict the pressure drop for co-current two-phase flow in packed beds. The influence of pressure on the two-phase pressure drop in trickle beds was previously studied by several researchers [3,4,7–13]. In spite of the vast information found in literature on two-phase pressure drop, the vast majority of the correlations are restricted to narrow ranges of operating conditions, properties of the phases and packing characteristics, and their application for large-scale industrial reactors is questionable.

The goals of this study are: (a) to generate the trickle-to-pulse flow regime transition map and (b) to analyse the influence of the operating pressure on the total pressure drop for the cumene–hydrogen system in a pressurised pilot plant reactor.

2. Experimental

2.1. Experimental equipment

Two different set-ups were used for performing the experiments. In Fig. 2(a), the schematic drawing of the pilot plant trickle bed used for the experiments with cumene–hydrogen, at high pressures, is shown. A “Brooks” mass flow controller measured the gas feed rate. The liquid phase is mixed with the gas phase in-line, just before entering the reactor. The trickle bed reactor is made up of CrNi steel and is 0.051 m in diameter and 1.2 m in bed length. The catalyst used is 2 wt.% Pd on extruded carbon from Engelhard, with a nominal particle diameter of 1.5 mm. Properties of the catalyst are given in Table 1. The complete reactor bed used in our experiments contains several layers of inert particles (bed porosity, $\varepsilon_b = 0.4$) besides the catalyst layer ($\varepsilon_b = 0.34$), as shown in

Table 1
Catalyst specifications

Property	Value
Palladium content (wt.%)	2
Bulk density (kg/m^3)	420
Bed porosity (ε_b)	0.34
Particle nominal diameter (m)	1.5×10^{-3}
Surface equivalent grain diameter (d_p) (m)	2.5×10^{-3}
Average extrudate length (m)	3.5×10^{-3}
Particle sphericity factor	0.81
BET (m^2/g)	1100