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A new approach for scale-up of bubble column reactors

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ABSTRACT

The reactor of choice for the Fischer-Tropsch synthesis is a slurry bubble column. One of the few disadvantages of bubble columns is the difficulties associated with their scale-up. The latter is due to complex phases' interactions and significant back-mixing.

For a proper scaling dimensionless numbers should be kept constant in the various scales in order to ensure both dynamic and geometrical similarity. With the complex nature of the flow in these systems, this becomes very hard to achieve. Hence, innovative approaches to provide a firm scale-up methodology are needed.

Controlling the effect of scale using heat exchanging internals by means of reactor compartmentalization is proposed in this study. Preliminary results show that radial gas holdup profiles as well as other bubble dynamics inside the compartments exhibited similar behavior as inside a solid wall column, since the comparison between the single tube bundle compartment and data obtained in 6 inches steel bubble column shows good match.

Keywords: Bubble columns; Internals; Hydrodynamics; Scale-up; Compartmentalization

1. Introduction

The scaling of bubble column reactors is a challenging task. Duduković (2007) summarizes the scale-up issue as follows: "Once the reaction system is successfully run in the laboratory to produce the desired conversion, yield, and selectivity, reproducing these results at a commercial scale is next". For this to be achieved, Euzen et al. (1993) list three types of experiments that need to complement each other: laboratory studies, pilot-plant studies, and mock-up (cold flow models) studies. The first category includes the thermodynamics and kinetics assessments and their experimental verification in lab scale units; the second involves the simultaneous analysis of physical and chemical mechanisms and implies mathematical models that are transposable to industrial units; and the last category typically includes, for example, the utilization of dimensional similarity residence time distribution (RTD) measurements via tracer studies, assessing hydrodynamics similarity, validating computational fluid dynamics (CFD), and others.

Deckwer and Schumpe (1993) differentiate between two types of scale-up based approaches, namely 'know-how' and 'know-why'. In the first, conventional scaling rules and dimensional analysis guidelines are followed, while for the second, an estimation of the rates and limiting steps of the entire process are normally considered as a starting point. Along these lines, Duduković (2009) classifies scaling into 'vertical scale-up' where an increase in size is implied and 'horizontal

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Nomenclature

c	parameter for non-zero void fraction at the wall
D	diameter of column, m
d_p	catalyst particle diameter, m
Eo	Eötvös number ($g\,\Delta\rho d_b{}^2/\sigma$)
g	gravitational acceleration, m/s^2
M	Morton number ($g\,\Delta\rho\mu_L{}^4/(\rho_l{}^2\sigma^3)$)
m	constant
P	pressure, bar
r	radial coordinate
r/R, φ	dimensionless radial coordinate
R	column radius, m
Re_g	Reynolds number of the gas phase ($U_g D_R/\nu_L$)
Re_L	Reynolds number of the liquid phase ($\rho_l U_L d_p/\mu_L$)
U_g	superficial gas velocity, m/s
u_l	liquid velocity, m/s
$u_{l,\,wall}$	liquid velocity at the wall formed by the tubes bundle, m/s
u_l^*	liquid velocity in the annular region (from locus of maximum downward liquid velocity to the wall), m/s
$D_{c,\,min}$	minimum column diameter to avoid wall effects, m
z	coordinate in the axial direction
β_d	ratio of densities (ρ_p/ρ_l)
β_U	ratio of superficial velocities (U_g/U_l)
$\Delta\rho$	density difference between liquid and gas phases, kg/m^3
$\bar{\varepsilon}$	cross-sectional average gas holdup
λ	dimensionless radial position where the downward liquid velocity is maximum
σ	surface tension, N/m
τ_w	wall shear stress, N/m^2
ν_m	kinematic viscosity of the liquid phase, m^2/s
τ	(turbulent) shear stress, N/m^2
$\varepsilon(r)$	local gas holdup
ρ_l	liquid phase density, kg/m^3
μ_l	dynamic viscosity of the liquid phase, Pa s

scale-up' or scale out (scale-in-parallel). In the latter, a multiplication of the small units is adopted keeping geometry, flow pattern and regime the same.

Bubble columns as multiphase reactors (or contactors) are favored for a wide range of applications in the chemical, biochemical, petrochemical, and metallurgical industries (Duduković, 2000). Chlorination, oxychlorination, carbonylation, and alkylation are examples of 2-phase bubble column applications. On the other hand, 3-phase slurry bubble columns are used for hydrogenation, polymerization, coal liquefaction, and Fischer–Tropsch synthesis among many other uses.

Bubble columns are preferred to other types of multiphase reactors in these applications for a number of reasons. Compared to fixed beds, their superior heat transfer properties allow close to isothermal operation, leading to improved selectivity (Shetty et al., 1992). Unlike agitated tanks, they provide good mass and heat transfer without moving parts. Moreover, their ease of construction and operation put bubble columns ahead of both fluidized bed (or ebulated three phase fluid beds) and fixed bed (or trickle bed) reactors. However the backmixing of the phases and the scale up issues are the main limitations of these multiphase reactors.

With a diameter of 5 m and a height of 22 m, Sasol is operating its slurry bubble column reactor for Fischer–Tropsch synthesis (Krishna, 2000). Laboratory scale bubble column units have diameters of about 25 cm (Krishna et al., 2001). Such huge difference between the two scales indicates that proper scale-up calculations are essential for approaching industrial applications.

It is noteworthy that anticipated scale-up problems of a slurry bubble column for the Fischer–Tropsch synthesis were among the main reasons Shell decided to implement the multi-tubular trickle bed technology in their plant in Malaysia, for a quicker and safer route (De Swart, 1996).

2. Preview

The development of bubble column scale up criteria has been attempted by a number of researchers, but considering the complex flow behavior and the interrelated parameters affecting the performance of these reactors and other multiphase reactor systems, the quest remains elusive. Examples of past studies include Degaleesan (1997), Inga (1997), Safoniuk et al. (1999), Safoniuk (1999), Macchi et al. (2001) and Macchi (2002), Forret et al. (2006), and most recently, Shaikh (2007) and Youssef et al. (2013a).

Nottenkamper (1983) and others assert that the overall gas holdup is not a function of a column's diameter (in columns of more than 15 cm diameter) for superficial gas velocities up to 20 cm/s. Hence, equal overall gas holdup has been used for scale-up (Degaleesan (1997)).

Inga (1997) proposed a methodology for scaling up/down of slurry reactors. He claimed similarity between a 4 l stirred tank reactor and a 0.3 m diameter slurry bubble column, based on maintaining constant gas/liquid mass transfer and reaction rates.

Forret et al. (2006) worked out a scale-up methodology based on phenomenological models that require the knowledge of overall gas holdup, center-line liquid velocity, and axial dispersion coefficient in columns up to 1 m diameter. They reported that the overall gas holdup is independent of the column's diameter for columns larger than 15 cm in diameter. Shaikh (2007) proposed a dynamic similarity methodology based on matching radial gas holdup profiles which was validated in one size column at different conditions. The methodology needs to be evaluated for at least two different scales and with internals in order to qualify as a scaling method.

Earlier studies only met with limited success since they have one or more of the following drawbacks: (1) they examined only global parameters (overall gas holdup, mass transfer coefficient, etc.); (2) they are applicable only for the bubbly flow regime; (3) they do not account for the presence of internals; (4) they are based on dynamic similarity but with no actual scaling validation; (5) they are missing experimental validation in large scale units for CFD simulations studies. It is, thus, clear that local parameters need to be examined during the validation phase of the scale-up process

Some emphasis is given here on selected studies that, mostly, followed the conventional scaling rules as derived from mass and momentum balances resulting in dimensionless hydrodynamic numbers like Reynolds (*Re*) and Froude (*Fr*). For example, Van den Bleek and Schouten (1993) suggested that for proper scaling these numbers should be kept constant,