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Performance comparison between different sparger plate orifice patterns: Hydrodynamic investigation using ultrafast X-ray tomography

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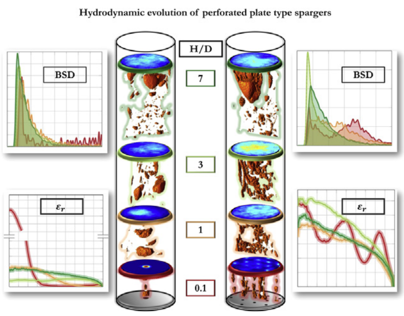
HIGHLIGHTS

- Sparger performance assessed via local and global hydrodynamic data.
- Non-intrusive measurement via ultrafast X-ray tomography.
- Evaluation of bubble column performance towards sparger design.
- Comparison with available literature correlations.

GRAPHICAL ABSTRACT



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ABSTRACT

In this work, the effect of the sparger design on the hydrodynamic performance in a bubble column of 0.1 m ID downstream a single (coarse) and multi-orifice (fine) perforated plate sparger was studied using the ultrafast X-ray tomography. The liquid was kept in semi-batch mode and the superficial gas velocity was varied between 0.011 and 0.025 m s^{-1} to ensure non-jetting flow through the sparger holes. The effect of the orifice patterns on the hydrodynamic performance was evaluated through bubble size distribution (BSD), radial gas holdup profile and overall gas holdup as well as Sauter mean bubble diameter and magnitude of the interfacial area. To evaluate sparger and bubble column performance, respectively, also the mass transfer was investigated. Due to the high turbulence induced by the large bubbles released from the coarse sparger, the equilibrium BSD was already reached at a dimensionless height of h/D = 1.0. However, average bubble characteristics, such as interfacial area and Sauter mean diameter, were similar for both sparger types at a column height of h/D $\geqslant$ 7.0. Based on a comprehensive hydrodynamic analysis, requirements for sparger refinement were derived depending on respective reaction rates, mixing properties, heat production and removal duty. Eventually, adapted correlations are proposed for radial holdup profile and Sauter mean diameter accounting for various plate refinements using liquids which inhibit coalesce of gas bubbles.

1. Introduction

Bubble column reactors (BCRs) are widely used as multiphase contactors in the chemical process industry. They find their application in oxidation, hydrogenation and bioprocesses, etc. [1–3]. BCRs are basically cylindrical vessels in which the liquid phase can either be kept in continuous or semi-batch mode and the gas phase is dispersed through a gas sparger, typically at the bottom of the column. Furthermore, since BCRs are constructed without moving parts, they are simple in design as well as maintenance. BCRs provide superior heat and mass transfer characteristics at

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Nomenclature

Acronyms

ADM	axial dispersion model
AARE	absolute average relative error
BCR	bubble column reactor
BSD	bubble size distribution
CSTR	continuous-stirred-tank-reactor
CT	computed tomography
LDA	Laser-Doppler-Anemometry
PDF	probability density function
PSO	particle swarm optimization
SMD	Sauter mean diameter

Roman symbols

A_o	opening area, %
a	interfacial area, m^{-1}
a_1, a_2, a_3	fitting parameters, –
b_i	fitting parameters, –
c_i	concentration of i^{th} phase (i = gas, liquid), mol m^{-3}
c_l^*	saturation concentration, mol m^{-3}
C_{norm}	normalized concentration $C_{norm} = \frac{C_l - C_0}{C_\infty - C_0}$, –
d_{32}	Sauter mean diameter, m
$d_{32,corr}$	Sauter mean diameter from correlation, m
$d_{32,meas}$	Sauter mean diameter from measurement, m
d_e	equivalent diameter, m
$d_{i,e}$	equivalent bubble diameter in i^{th} class, m
d_{mean}	mean pore diameter of sintered plate type spargers, m
d_o	orifice diameter, m
D	column diameter, m
$D_{z,i}$	dispersion coefficient for i^{th} phase (i = gas, liquid), $m^2\ s^{-1}$
e	error, –
G	volumetric flowrate, $m^3\ s^{-1}$
g	earth acceleration, m s^{-2}
H	Henry constant, –
H_c	column height, m
H_{CL}	clear liquid height, m
H_D	dispersed liquid height, m
h/D	dimensionless distance from the sparger, –
k_l	gas/liquid resistance, m s^{-1}
$k_l a$	volumetric mass transfer coefficient, s^{-1}
k_m	friction factor, –
N	number of measurement points, –
n_i	number of bubbles in i^{th} class, –
n, c	fitting parameters, –
px	pixel, pixel
q_0	number distribution, –
$\frac{r}{R}$	dimensionless radius, –
t	time, s
u_g	superficial gas velocity, cm s^{-1}
$u_{g,o}$	hole superficial gas velocity, m s^{-1}
V_b	bubble volume, m^3
$V_{b,v}$	pixel bubble volume, $pixel^3$
V_{vox}	voxel volume, $pixel^3$
y_m	measurement quantity for AARE calculation
y_p	predicted quantity for AARE calculation
z_i	axial distance from the sparger, m

Greek symbols

Δd_e	equivalent diameter within one bubble class, m
$\Delta \varepsilon_g$	gas holdup difference within one bubble class, –
Δt	time difference in dependence on the measurement frequency, s
$\varepsilon_{g,corr}$	overall gas holdup from correlation, –
$\overline{\varepsilon}_{g,i}$	overall gas holdup depending on measurement technique (i= CT, LS), –
$\varepsilon_{g,meas}$	overall gas holdup from measurement, –
$\varepsilon_{g,r}$	radial gas holdup, –
ε_l	liquid holdup, –
ν_l	kinematic liquid viscosity, $m^2\ s^{-1}$
μ_i	gas or liquid dynamic viscosity, Pa s
ρ_i	gas or liquid density, kg m^{-3}
σ_l	surface tension, N m^{-1}

Dimensionless numbers

$Bo_{d_0} = \frac{\rho_l g d_0^2}{\sigma_l}$	Bond number depending on the orifice diameter
$Fr_g = \frac{u_g^2}{g D_c}$	Froude number
$Fr_{d_0} = \frac{{u_g}_{d_0}^2}{d_0^2 g}$	Froude number depending on the orifice diameter
$Ga_{d_0} = \frac{\rho_l^2 d_0^3 g}{\mu_l^2}$	Galileo number depending on the orifice diameter
$Mo_l = \frac{g \mu_l^4}{(\rho_l - \rho_g)\sigma_l^3}$	Morton number
$Re_g = \frac{D_c u_g (\rho_l - \rho_g)}{\mu_l}$	Reynolds number

comparably low energy input, which make them a competitive reactor type against conventional fixed bed or stirred tank reactors [4].

There are several sparger types which may be used to disperse the gas into the column. That are, perforated plates, ring- and pipe-type spargers, just to mention few ones. Many investigators have already pointed out that the design of the sparger for a specific column geometry as well as for a particular reaction system is very crucial for the overall bubble column performance [1,2,5,6]. Furthermore, designing a sparging device, which covers all hydrodynamic flow regimes, is very challenging as maldistribution may occur for low superficial gas velocities [7,8]. The sparger type and the sparger holes, respectively, determine the initial bubble size at the bottom. The bubble size, in turn, determines the bubble rise velocity and with it the average gas holdup as well as its radial profile. Furthermore, it is well-known that the liquid velocity profile follows the gas holdup profile [9,10] and is decisive for the mixing behavior. Therefore, among others, the design of the gas sparger determines the overall bubble column hydrodynamics and, thus, the bubble column performance [1,5,11].

A variety of studies have been carried out to evaluate the sparger performance and to draw conclusions about the optimal sparger designs (Table 1). Walke et al. [12] studied the influence of the pitch pattern (triangular and square) of perforated plate type spargers with various liquids using a high-speed camera. They found that the transition point between homogeneous and heterogeneous flow regime is independent of the hole size, which is contradictory to the investigations of [13–16], who reported a strong effect of the sparger orifice diameter regardless of the opening area. Furthermore, the pattern type of the sparger showed an influence on the hydrodynamics in terms of overall gas holdup if water was used as the liquid phase. For spargers with a triangular pitch, coalescence at the orifice is promoted leading to lower gas holdups compared to the square pitch counterpart. For other liquid systems (see Table 1), however, the pitch type did not have any influence on the global hydrodynamic parameters [12]. In terms of effect of opening area on the overall gas holdup, Su and Heindel [17] carried out a series of experiments with three perforated plate type spargers varying the number of holes only, while keeping the hole size constant. They concluded that the opening area has an effect at