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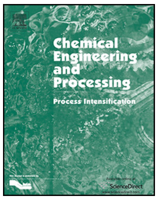

Gas–Liquid mass transfer in a rotor–stator spinning disc reactor: Experimental study and correlation

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ABSTRACT

The gas–liquid mass transfer of rotor–stator spinning disc reactors is studied for various operating conditions and different reactor geometries with rotor radii between 0.065 and 0.135 m. A new reactor setup with a perforated disc containing 119 narrow channels for direct dispersal of gas into the reactor cavity is examined. High volumetric mass transfer coefficients of up to 12 $m_l^3\ m_R^{-3}\ s^{-1}$ can be observed due to the large energy input at high rotational disc speeds of up to 2000 rpm. The combination of high turbulence and small gas bubbles as a result of the large shear forces in the cavity is identified to be responsible for the acceleration of the mass transfer at high rotational disc speeds. Correlation with an extended power law model equation allows the first-time quantification of the impact of the main operating parameters such as gas and liquid flow rate and rotational disc speed on the volumetric mass transfer coefficients for different reactor geometries.

1. Introduction

In recent years chemical industry has been increasingly striving to design processes which are smaller, more efficient and inherently safe. The principles of process intensification summarize these efforts, which are driven by a growing environmental consciousness in public, but also by stricter legal regulations enforced by the governments. The rotor–stator spinning disc reactor (*RSSDR*), as further development of the conventional spinning disc reactor (*SDR*) [1–6], is a promising tool for process intensification in the field of multiphase operations. Rapid mass transfer not only increases productivity at constant reactor size, but can also increase selectivities of multiphase reactions resulting in less purification and downstream effort.

For gas–liquid operations as absorptions, chemical reactions and fermentation, the agitation of aerated liquids is one of the decisive operating parameters to enhance mass transfer in contactors. In the rotor–stator spinning disc reactor the agitation is accomplished by a rotating disc. The rotor is shrouded by a hollow, cylindrical housing in narrow distance, thus inducing high shear forces into the fluid in the gap. Consequently, bubble break up occurs accompanied with rapid turbulent mixing, resulting in large interphase areas and high mass transfer coefficients [7–11].

In previous works, the effects of different rotational disc speeds, gas and liquid flow rates and locations of gas injection on the gas–liquid flow patterns and mass transfer characteristics were studied on exemplarily selected operating conditions [8–10]. The present paper comprises a novel reactor setup with a perforated disc for direct gas-injection into the gap and a comprehensive parameter study on the effect of varying operating conditions on the gas–liquid mass transfer. For this purpose, two reactor setups with a disc radius R_D of 0.065 m, comprising a perforated and a solid disc and one setup with a solid disc having a radius of 0.135 m are examined. Focus is laid on the determination and correlation of volumetric mass transfer coefficients $k_l a$ and their discussion in context with results found in literature.

The newly developed perforated disc is compared to the reactor setups with solid discs under a large amount of different experimental conditions in a quantitative manner by means of empirical correlation. This first time comprehensive analysis allows identification and quantification of the crucial operating parameters and a systematical optimization of the reactor's operation and geometry for specific mass transfer applications. Due to the wide range of studied parameters and the diversity of the resulting hydrodynamic patterns, a phenomenological analysis of the two-phase flow is not covered within this paper.

Abbreviations: SDR, spinning disc reactor; *RSSDR*, rotor–stator spinning disc reactor; PMMA, poly(methyl methacrylate).

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Nomenclature

List of symbols

A	Interfacial area per unit reactor volume, $m_l^2\, m_R^{-3}$
α,β	Empiric model coefficients
C_t	Torque coefficient
c	Concentration, mol L^{-1}
D_l	Molecular diffusivity of a component in liquid, m s^{-2}
d_b	Bubble diameter, m
ε_d	Specific power dissipation, W m^{-3}
η	Eddy length
G	Dimensionless axial clearance ($G = hR_D^{-1}$),
$H_{i,l}$	Henry coefficient of component i, m_l^3 Pa mol^{-1}
h	Axial clearance, m
k_l	Liquid side mass transfer coefficient, m s^{-1}
K	Empiric constant,
μ	Dynamic viscosity, Pa s^{-1}
n	Rotational disc speed, rpm;
$\boldsymbol{\nu}$,	Kinematic viscosity, $m^2\, s^{-1}$
P_D	Specific dissipated power, J $m^{-3}\, s^{-1}$
p_{O2}	Partial pressure of oxygen, kPa
$Q_{g,l}$	Gas, liquid volume flow, $L_{g,l}$ s^{-1}
R	Gas constant, J $mol^{-1}\, K^{-1}$
R_C	Channel radius in perforated disc, m
R_D	Disc radius, m
Re	Reynolds number ($Re = \omega R_D^2 \nu^{-1}$)
r	Radius, m
ρ	Density, kg m^{-3}
T	Temperature, °C
T_D	Torque, N m
t	Time, s
τ_c	Contact time, s
u	Root mean square of fluctuation velocity, m s^{-1}
V_R	Reactor volume, m^3
ω	Rotational disc speed, rad s^{-1}

2. Theoretical background

2.1. Rotor–stator spinning disc reactor

In the last decades, the single phase flow in narrow gaps over moving or rotating parts has been studied extensively, primarily in association with turbo machinery [12–16]. The principles of single phase flow are described in the works of Meeuwse et al. [9] and de Beer et al. [17] and will only be outlined broadly here. The flow patterns in the gap are based on the induction of shear stress from the rotating disc into the fluid, resulting in a tangential and centrifugal acceleration of the fluid close to the rotor in the so called von Kármán layer and a centripetal flow in the Bödewadt layer close to the stator [18,19]. In case the boundary layers are merged, the regime is called torsional Couette flow [14]. For small axial clearances and high Reynolds numbers as deployed in the experiments of this study, the flow regime is found to be turbulent torsional Couette flow [15].

For torsional Couette flow with superposed throughflow, two generally different states of flow are distinguished. In small distance to the rotation axis and low rotational disc speeds, the superposed throughflow dominates the flow behavior (throughflow governed regime), resulting in unidirectional flow over the whole axial clearance h. With increasing r and n, the tangential and radial velocities increase in both boundary layers [13,14,20]. As a result, recirculation is observed in the Bödewadt layer over large radial distances (rotation governed regime) [14,17].

The power input from the disc into the fluid can be calculated according to the following equations within the boundaries of the turbulent torsional Couette regime [15,21]:

$$\varepsilon_d = T_D \omega V_R^{-1} \tag{1}$$

$$T_D = 0.5 C_t \rho \omega^2 R_D^5 \tag{2}$$

$$C_t = 0.08 G^{-\frac{1}{6}} Re^{-\frac{1}{4}} \tag{3}$$

The theory outlined so far has been deduced for single phase flow. For multiphase flow only little information is present in literature. Meeuwse et al. [8–10] examined the fundamentals of two-phase flow in their studies on gas–liquid mass transfer in rotor–stator spinning disc reactors in co-current flow. For their studies, liquid was initially fed to the top stator and gas was injected either through the bottom stator [8] or premixed with the liquid from the top stator inlet [9,10].

Two fundamentally different flow patterns are observed within the reactor for the latter case. In the top cavity thin film flow is observed and waves can be formed depending on the rotational disc speed [3,22,23]. The gas flows non-dispersed towards the rim of the disc. At the rim, single gas bubbles are sheared off from the gas phase and accelerate towards the center of the disc due to the centrifugal forces and the density differences. The relative velocity between gas bubbles and continuous liquid phase strongly depends on the radial and axial position of the bubble in the cavity as well as on the reactor's operating parameters such as superposed flow velocity and rotational disc speed [9]. Furthermore, the bubble size itself influences the velocity. Small gas bubbles, formed at high rotational disc speeds (large shear rates), have smaller radial velocities, leading to higher gas holdups with increasing rotational disc speeds [8].

Although the effect of gas bubbles on the formation and delimitation of the previously outlined flow regimes for single-phase flow is not fully understood, it is improbable that the development of the boundary layers and the resulting flow regimes completely fail to appear for two-phase flow [10]. Consequently, a throughflow governed volume fraction close to the rotation axis and a convectionally backmixed rotation governed volume at larger radii are assumed to exist for multiphase flow as well.

Previous studies in single stage rotor stator spinning disc reactors focused on the determination of $k_l a$ values in the context of two-phase hydrodynamics using selected operating conditions. Meeuwse et al. [8,9] examined the RSSDR in their first two studies at two respectively three different gas flow rates and constant liquid flow rate for one mode of gas-dispersal each (either via the bottom stator or together with the liquid at the inlet). The effects of varying axial clearances are outlined in Meeuwse et al. [10] in a reactor setup with larger rotor radius ($R_D = 0135$ m) for different gas flow rates. The setup with an axial clearance of 1 mm showed the best performance, which is the reason this gap width is chosen for the experiments executed here. Due to the previously rather exemplary depiction of mass transfer behavior in context with elaborate hydrodynamic studies, a comprehensive quantitative investigation focusing on the measurement of $k_l a$ values is essential for an optimized operation of RSSDRs. So far, little information is present about optimum operating conditions and the prediction of the interrelation between operating conditions and reactor geometry.