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Review

Review and analysis of micromixing in rotating packed beds

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HIGHLIGHTS

- Distance between packing and liquid distribution has large influence on micromixing.
- Inner packing radius more important for mixing than outer radius and bed length.
- Different flow patterns for different rotational speed but same tangential velocity.
- RPBs especially suitable for mixing at high liquid flow rates and high viscosities.

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ABSTRACT

This paper gives an overview of the fundamentals of liquid micromixing in rotating packed beds (RPBs) and delivers an assessment of RPB micromixing based on the Villermaux-Dushman protocol. This analysis is structured into four parts. In the first two parts, general trends for the operation and design of RPBs to ensure fast micromixing are derived. For this purpose, the influence of operational parameters, such as rotational speed, liquid flow rate, volumetric ratio, and viscosity, on micromixing is investigated. Afterward, design parameters, such as inner packing radius, outer packing radius, and packing type, are addressed. Additionally, rotational speed and inner packing radius are for the first time presented and compared based on the corresponding tangential velocities. This comparison reveals the particular influence of the liquid distribution and the impingement zone on mixing in RPBs. In the third part, model parameters, such as the micromixing time parameter in the incorporation model, are discussed. Finally, micromixing results for RPBs with structured packing are compared to results for non-structured RPBs and other continuous mixing devices, such as spinning disc reactors (SDRs), high shear mixers (HSMs), and T-mixers.

1. Introduction

Since rotating apparatuses were established as concept of process intensification under the term "HiGee technology" by Ramshaw [1], many authors have underlined their importance for improving existing processes. By replacing gravity with up to 500 times larger centrifugal forces, the mass transfer efficiency can be dramatically increased and the equipment size remarkably decreased [2]. Thus, the hold-up of liquids, gases, and solids is reduced, allowing for more expensive coating materials and reducing potentially hazardous situations [3]. Among rotating devices, rotating packed beds (RPBs) have attracted the most attention. RPBs have been successfully applied to the deaeration of brine, the production of hypochloric acid, and the preparation of nanoparticles, with a broad range of other processes being investigated as possible fields of application [4]. Nevertheless, the chemical industry is still skeptical of this technology and has not yet taken full advantage of its potential [5].

The performance of most industrial liquid–liquid processing techniques is affected by the mixing of miscible fluids and mass transfer between immiscible fluids. Particularly fast and intense mixing is crucial to obtain a defined particle size distribution in precipitation processes, high selectivity and turnover in fast competing parallel or consecutive reaction schemes, and a defined molecular weight distribution in polymerization processes [6]. The two key principles to ensure fast and intense mixing are (1) creating a region of high energy dissipation and (2) ensuring liquid streams pass through this region [7]. Indeed, a high energy dissipation rate was found to be the only relevant parameter to obtain fast mixing in all mixing devices [8]. To either increase the energy dissipation rate or improve the passage of liquid through the region of highest energy dissipation, operational parameters and design parameters need to be optimized. However, despite the potential of RPBs, so far, no systematic research has been conducted in this field.

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Nomenclature

Latin letters

c	concentration mol m^{-3}
c_0	initial concentration at t_0 mol m^{-3}
c'_0	initial concentration before mixing mol m^{-3}
C_j	concentration of species j mol m^{-3}
$C_{j,10}$	concentration of species j in the surrounding liquid mol m^{-3}
D	diffusivity m^2 s^{-1}
g	growth function in the incorporation model
K_{eq}	equilibrium constant of reaction (iii) m^3 mol^{-1}
K_La	liquid-phase mass transfer coefficient -
L	premixed distributor length m
Q	total volumetric flow rate m^3 s^{-1}
r_i	inner packing radius m
t	time s
T	temperature K
t_{DS}	characteristic diffusion and shear time scale s
t_m	characteristic mixing time scale s
t_{mix}	micromixing time parameter of the incorporation model s
t_r	characteristic reaction time scale s
u_{tang}	tangential velocity m s^{-1}
$\dot{V}_{acid}$	volumetric flow rate of the acid m^3 s^{-1}
$\dot{V}_{buffer}$	volumetric flow rate of the buffer solution m^3 s^{-1}
$\dot{V}_{buffer+acid}$	volumetric flow rate of buffer solution and acid combined m^3 s^{-1}
V_2	aggregate volume m^3
$V_{2,0}$	initial aggregate volume m^3
V_{PM}	perfectly mixed volume m^3
V_{ST}	segregated volume m^3
X_s	segregation index
Y	ratio of protons bound in reaction (ii) to protons initially added to the mixture
Y_{ST}	Y value under total segregation

Greek letters

α	micromixedness ratio -
β	premixed distributor pipe angle °
ε	energy dissipation rate m^2 s^{-3}
μ	dynamic viscosity Pa s
ν	kinematic viscosity m^2 s^{-1}
τ	residence time s
ω	rotational speed rpm (min^{-1})

Abbreviations

CFP	ceramic foam packing
HSM	high shear mixer
NNP	nickel foam packing
RPB	rotating packed bed
SDR	spinning disc reactor
SNP	surface-modified nickel foam packing
WMP	wire mesh packing

Consequently, this review will present and thoroughly analyze results previously obtained by other authors, and general trends for the most important operational and design parameters will be deduced. As most publications on mixing in RPBs focus on the assessment of structured packings with a Villermaux-Dushman protocol, they will be in the focus of this review and analysis. To further assess the technological potential in this field, mixing results from RPBs will be compared with the results of other continuous mixing devices.

1.1. RPB technology

RPBs are a promising tool for process intensification. As shown in Fig. 1, they are apparatuses consisting of a rotating part, i.e., an annular rotor with a packed bed, and a static part, i.e., the housing. Both parts are connected with bearings and seals. The empty center of the rotor is called the "eye", which can be defined by the eye ring and contains the liquid distribution. The rotor is driven by a motor, which can be placed either underneath or to the side of the apparatus, depending on the rotation axis. Both horizontal and vertical rotation axes are commonly used. The speed of rotation can be adjusted according to the process demands, offering an additional degree of freedom in comparison to conventional gravity-based equipment.

While countercurrent operation is common for gas–liquid processes in RPBs, only cocurrent operation has been investigated for liquid–liquid processes in RPBs so far. For these, the liquid streams are distributed in the eye of the rotor, impinge on the rotating packing (impingement zone), flow through the packing in the direction of the applied centrifugal force to the outer rim, and are then ejected into the housing, leaving the whole apparatus through the liquid outlets.

To distribute the liquids into the rotating packing, three different approaches have been published. The first involves distribution pipes and consists of two separate pipes with small holes at the lower end to spray liquid onto the rotating packing (Fig. 2a). The second involves premixed distributors, in which two separate pipes are located at the lower end and are connected to only one pipe with one opening (Fig. 2b). Thus, the two formerly separate liquids are already macromixed within the liquid distributor. The third involves impinging streams, which are sprayed against each other in the eye of the rotor before splashing onto the rotating packing (Fig. 2c).

As in conventional distillation columns, the packed bed can consist of either structured or non-structured packing. Structured packings usually consist of wire mesh, ceramic foam or metal foam. The way in which liquid flows through different packings is still under investigation.

Based on computer tomography (CT) scans, Yang et al. found that

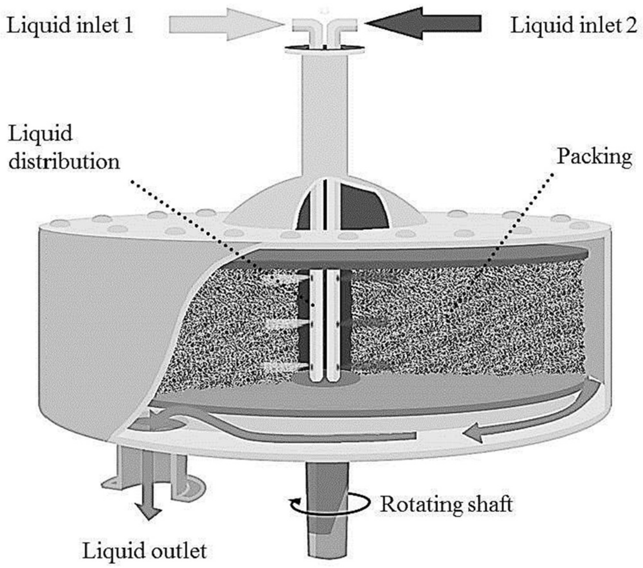

Fig. 1. Schematic drawing of an RPB.