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Hydrodynamics and gas–liquid mass transfer in a horizontal rotating foam stirrer reactor

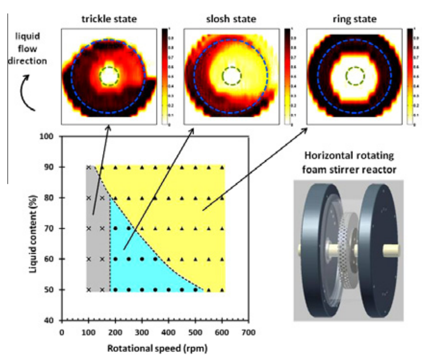
M.A. Leon [a,*], R.J. Maas [a], A. Bieberle [b], M. Schubert [b], T.A. Nijhuis [a], J. van der Schaaf [a], U. Hampel [b,c], J.C. Schouten [a]

[a] Laboratory of Chemical Reactor Engineering, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
[b] Institute of Fluid Dynamics, Helmholtz-Zentrum Dresden-Rossendorf, P.O. Box 510119, 01328 Dresden, Germany
[c] AREVA Endowed Chair of Imaging Techniques in Energy and Process Engineering, Dresden University of Technology, 01062 Dresden, Germany

HIGHLIGHTS

- Rotating foam stirrer reactors have promising applications for multiphase processes.
- Gas–liquid mass transfer rates are comparable to slurry reactors.
- The horizontal foam stirrer can be operated in the trickle, slosh and ring regimes.
- Slosh regime leads to a high gas–liquid mass transfer due to a higher interfacial area.
- Baffles design is important for optimizing reactor performance.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper describes a new multiphase reactor, the horizontal rotating foam stirrer reactor, which uses a donut-shaped foam block mounted on a horizontal shaft functioning as a stirrer and as a catalyst support. The effect of different operational conditions such as stirring speed, reactor length, foam porosity, foam thickness and the presence of baffles on the gas–liquid mass transfer and the gas–liquid flow distribution is discussed for the systems water/air and glycerol/air. The rate of gas–liquid mass transfer is measured spectrometrically while the hydrodynamics of the reactor is studied by γ-ray tomography. For a partially filled reactor, three flow states could be distinguished: the trickle state, the slosh state and the ring state. In the trickle state the liquid flows in a thin stream over the foam while in the slosh state the liquid is pushed upward by the stirrer and sprayed, leading to the formation of fine liquid droplets and fine gas bubbles. The transition between the trickle state and the slosh state occurs at 200 rpm. This is drastically affected by the liquid viscosity and in some extent by the reactor length and the foam thickness. When the stirring speed is constant, the ring state, which results in a cylindrical liquid layer on the inside wall, appears with increasing the liquid content in the reactor (above 70%). Due to a large gas–liquid interface in the slosh state, a high gas–liquid mass transfer is achieved. $k_{GL}a_{GL}$ values up to 0.32 s^{-1} are found. This is comparable to gas–liquid mass transfer rates in slurry reactors. However, in case of the foam stirrer a higher power input per liquid volume is needed in order to achieve the minimum stirrer speed required for complete dispersion of the gas. It is shown that mass transfer coefficients decreased with increasing viscosity, while the centrifugal force revealed to be effective in enhancing mass transfer in a viscous media. Conclusions on the optimal reactor configuration are drawn for the application in the fine chemical industry.

* Corresponding author.
E-mail addresses: m.a.leonmatheus@tue.nl (M.A. Leon), j.c.schouten@tue.nl (J.C. Schouten).

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1. Introduction

Several novel types of multiphase reactors have been developed to address some of the problems associated with the use of conventional reactors such as packed columns, bubble columns and stirred tanks. High gravity rotating packed bed reactors (HIGEEs) have been developed for absorption, distillation, stripping, extraction and other separation processes [1–7]. In these reactors a donut-shaped foam block is rotated at rotational speeds up to several thousand rotations per minute. From the stirrer shaft, liquid is sprayed onto the foam structure and driven outward due to the centrifugal forces. By superimposing gravity by centrifugal force, the tendency of flooding is reduced and the mass transfer efficiency is greatly intensified. Because of the mass transfer enhancement, the size of the equipment for mass transfer limited reactions is considerably reduced as compared with the conventional packed bed. However, these reactors show a high flow maldistribution and insufficient wetting of the solid phase. Therefore, these reactors have been only used as gas–liquid contactors [8].

With a design comparable to HIGEE-reactors, rotating foam stirrer reactors have been developed in our group for application in the fine chemical industry [9–15]. In these reactors solid foam structures are used as stirrers in order to mix the reaction components and disperse the gas phase as fine bubbles but act also as catalyst support. The solid foam is completely immersed into the liquid which ensures a good wetting of the catalyst surface. In addition, the reaction mixture can be drained off easily without any need of a catalyst separation step. Other problems related to the use of slurry catalysts such as particle agglomeration or attrition do not occur, which allows a simple re-use of the catalyst. Rotating foam stirrer reactors have been developed as a blade stirrer and as a foam block stirrer. Previous works [9–15] have shown that both stirrer configurations have better mass transfer characteristics compared to a slurry reactor equipped with a conventional Rushton stirrer. The enhanced mass transfer rates are attributed to a higher interfacial area as well as to a higher mass transfer coefficient. Likewise, other reactor types based on highly porous materials have been developed for enhancing mass transfer. Examples are monolithic stirrers and mixers based on fiber structures [16–19]. Compared to monolithic stirrers, some difficulties can be overcome by using solid foams. Typically the distribution problem of gas and liquid can easier be solved since the foams have a random structure. Moreover, better mixing of the phases is achieved due to the radial flow through the foam rather than the axial flow through the monoliths. Overall, rotating foam stirrer reactors have promising applications for multiphase processes as substitute for stirred tank reactors.

In order to further improve the mass transfer in rotating foam stirrer reactors, a new stirrer design is developed. A donut-shaped foam block is mounted on a horizontal shaft and the reactor is partially filled with liquid (Fig. 1). The advantage of this configuration is the alternating contact of the solid foam with the gas and liquid phases. Due to the centrifugal force at high rotational speeds, the gas is separated from the catalyst only by a very thin liquid film. This enhances the gas to catalyst mass transfer which is often the rate determining step in hydrogenation or oxidation reactions. Furthermore, near-plug flow conditions along with high intensity mixing can be achieved if a multistage horizontal rotating foam stirrer reactor is used. In this case, the horizontal vessel is divided in several compartments by donut-shaped baffles and several foam block structures are mounted on the same stirrer shaft. The plug flow behavior in this reactor is expected to result in higher selectivity towards the desired product in selective reactions with unwanted consecutive reactions.

Based on these expected benefits, the feasibility of applying such type of reactor for multiphase processes is studied. The focus of this work is to determine the hydrodynamics and the gas–liquid mass transfer in the horizontal rotating foam stirrer reactor with one compartment. Liquid–solid mass transfer and residence time distribution measurements are in progress and will be reported at a later date. For studying the hydrodynamics of the horizontal rotating foam stirrer reactor, the liquid and gas holdups are measured by γ-ray tomography. Tomographic imaging techniques are noninvasive methods that do not alter the flow patterns [20–22]. The effect of different operational conditions on the gas–liquid distribution and gas–liquid mass transfer rate is studied. The parameters varied are stirring speed, liquid volume in the reactor, foam porosity, foam thickness, the reactor length, the liquid viscosity and the presence of baffles. The aim is to determine the optimal reactor configuration for enhancing gas to liquid mass transfer.

2. Experimental section

2.1. Horizontal rotating foam stirrer reactor

A glass reactor having an inner diameter of 200 mm is used for the gas–liquid mass transfer measurements. The length of the

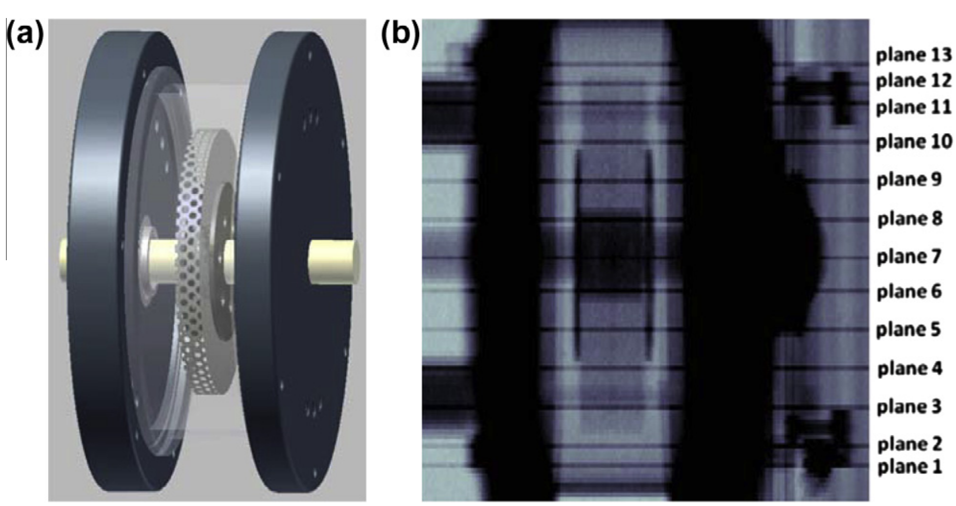

Fig. 1. (a) The horizontal rotating foam stirrer reactor, (b) Gray-value coded and stretched radiography of the horizontal rotating foam stirred reactor with the measuring planes positions (dark lines).