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On the hydrodynamics of membrane assisted fluidized bed reactors using X-ray analysis

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ABSTRACT

The application of membrane assisted fluidized bed reactors for distributed energy production has generated considerable research interest during the past few years. It is widely accepted that, due to better heat and mass transfer characteristics inside fluidized bed reactors, the reactor efficiency can outperform other reactor configurations such as packed bed units. Although many experimental studies have been performed to demonstrate and monitor the long term performance of membrane assisted fluidized bed reactors, the hydrodynamics of membrane-assisted fluidized bed reactors has thus far only been studied in pseudo-2D geometries. In this work the solids concentration inside a real 3D fluidized bed reactor geometry was measured using a fast X-ray analysis technique. Experiments were conducted in absence and presence of two different membrane modules with different configurations and number of membranes (porous Al_2O_3 tubes) for two types of particles, viz. 400–600 µm polystyrene (Geldart B type) and 80–200 µm Al_2O_3 (Geldart A/B type). Results from the experiments with Geldart B type particles revealed that the membrane modules (both the membranes and the spacers) can significantly reduce bubble growth along the fluidized bed resulting in a smaller average bubble diameter, expected to improve the bubble-to-emulsion mass transfer, whereas for the experiments with fine Geldart A/B particles, and at a very high extraction values (40% of the inlet flow), a densified layer with high solids concentration was formed near the membrane, which may impose an additional mass transfer resistance for gas components to reach the surface of the membranes (concentration polarization). The results from this study help designing and optimizing the positioning of the membranes and membrane spacers for optimal performance of fluidized bed membrane reactors.

1. Introduction

The application of membrane assisted fluidized bed reactors for distributed power production has attracted quite some research interest over the last few years [1]. In a membrane assisted reactor, reaction and separation steps are integrated in one single unit and a high degree of process intensification can be achieved, thereby strongly reducing the required reactor volume and increasing the energy efficiency of the process [2]. It is widely accepted that fluidized bed membrane reactors can outperform packed bed membrane reactor configurations due to their better mass and heat transfer properties [3]. Most of the literature on this topic has been devoted to provide a proof-of-concept at lab-scale or to monitor the long term performance of the membranes at different operating conditions and fluidization velocities [4].

On the material part, the main research effort has been put on the fabrication of membranes with lower price and better permeation properties, i.e. increased permeability and perm-selectivity [3,5–9], whereas for the efficient demonstration of such units it is essential to understand and quantify the reactor design and scale-up parameters that account for the presence of membranes with different permeation values. De Jong et al. performed an extensive study on the hydrodynamics of fluidized beds in the presence of horizontally integrated membranes inside a pseudo 2D fluidized bed [10]. For this study a combined particle image velocimetry and digital image analysis (PIV/DIA) technique was used. The experimental results confirmed that for the membrane assisted bed the average equivalent bubble diameter was decreased by a factor of about 3 in comparison with the case where no membrane was integrated due to the increased bubble break-up (while the average bubble size was hardly affected by the permeation ratio through the membranes). In another study it was confirmed that the presence of horizontal membranes in the bed decreases the average bubble size, but the formation of gas pockets around the tubes need to

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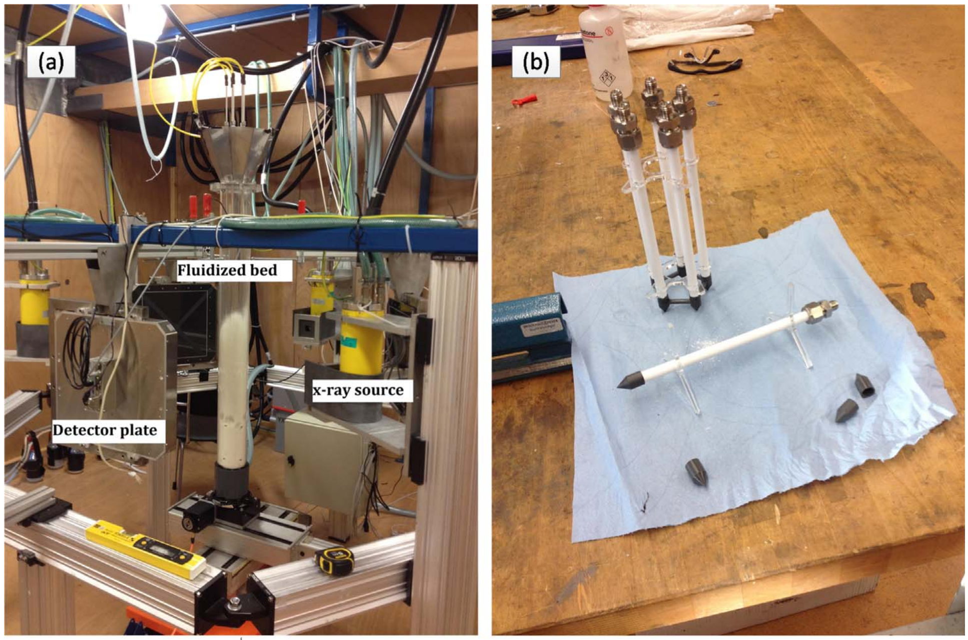

Fig. 1. (a) The designed fluidized bed placed between the X-ray source and the detector plate (b) Membrane modules of one and five membranes with spacer plates and sealing.

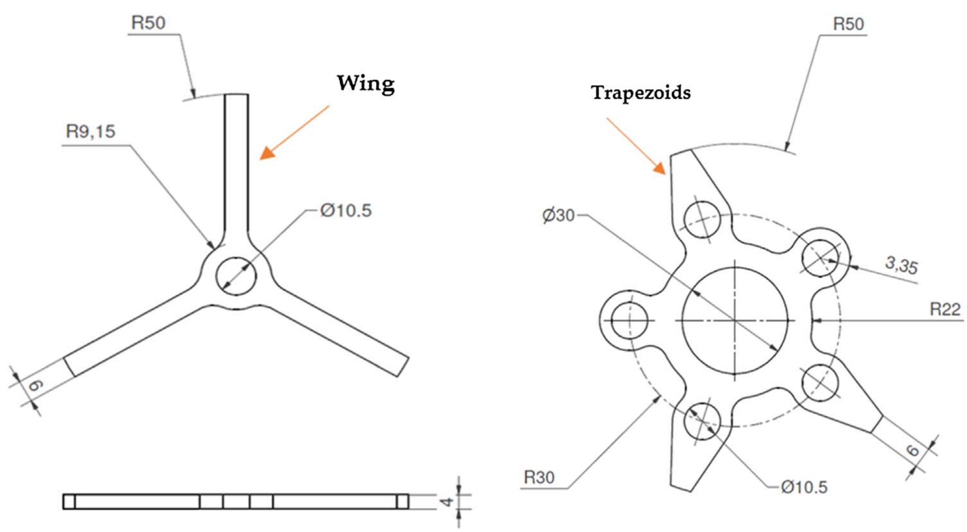

Fig. 2. Spacer plates (left) spacer designed for the membrane module with one single membrane in the middle of the reactor and (right) spacer plate designed for the membrane module with five membranes in a star shape configuration (all measures are in mm).

Table 1
Relative area of the spacers to the reactor cross sectional area.

Module	Number of membranes	Spacer section area 10^{-4} m^2	Reactor cross section area 10^{-4} m^2	Spacer area/ Reactor cross section area (%)
I	1	9.12	78.5	11.6
II	5	19.8	78.5	25.2

Table 2
Physical properties of the used particles.

Material	Avg. particle diameter[a] [μm]	Apparent Density (g/cc)[b]	Minimum fluidization velocity[c](U_{mf}) [cm/s]	Geldart classification [23] [–]
Polystyrene	500	1.06[*]	22.0	B
Al_2O_3	160	1.691	2.4	A/B

[a] FRITSCH ANALYSETTE22.
[b] ThermoFisher SCIENTIFIC Pascal 140 series.
[c] By measuring the pressure drop over the distributor plate and the bed.
[*] From [19].

be properly accounted for when determining the average bubble size to avoid underestimation, while these gas pockets may also decrease the performance of the membrane reactor [11].

Dang et al. [12] and De Jong et al. [10] experimentally studied the solids circulation patterns in pseudo 2D fluidized beds (from relatively large beds to micro-structured beds) with gas extraction via membranes (filters) installed in the walls of the reactor also applying the combined PIV/DIA technique. It was found that in the cases where a large amount of gas is extracted via the membranes, the solids concentration in the near vicinity of the membrane increases and may result in the formation of so-called densified zones, which may impose an additional mass transfer resistance for gas components to reach the surface of the membranes. These findings are in accordance with a discrete particle simulation study done by Tan et al. [13]. These results have also been