Powder Technology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Experimental investigation on the generic effects of gas permeation through flat vertical membranes

Solomon A. Wassie [a,c], Schalk Cloete [b], Abdelghafour Zaabout [b], Fausto Gallucci [c], Martin van Sint Annaland [c], Shahriar Amini [a,b,*]

[a] Norwegian University of Science and Technology, Department of Energy and Process Engineering, Trondheim, Norway
[b] SINTEF Materials and Chemistry, Flow Technology Department, Trondheim, Norway
[c] Chemical Process Intensification, Eindhoven University of Technology, Department of Chemical Engineering and Chemistry, Eindhoven, Netherlands

ARTICLE INFO

Article history:
Received 15 May 2016
Received in revised form 31 October 2016
Accepted 6 December 2016
Available online xxxx

Keywords:
Fluidized bed
Flat vertical membranes
Membrane configurations
Gas extraction
Extent of densified zone

ABSTRACT

This work reports the effects of gas extraction through flat vertical membranes on bubble dynamics in a fluidized bed. Bubble properties such as size, number, velocity and shape play a key role in the hydrodynamics and consequently heat and mass transfer characteristics of fluidized bed (membrane) reactors. Thus the main focus of this work is to understand the bubble behaviour over different fluidization velocities, particle sizes, gas extraction rates and gas extraction locations. A pseudo 2D experimental setup with flat vertical porous plates placed at the back of the column was used for simulating gas extraction through a flat vertical membrane in a fluidized bed reactor. A Digital Image Analysis (DIA) experimental technique was applied in order to extract the bubble properties.

Experimental results showed that the variation of gas extraction fraction has a minor effect on the bubble dynamics, with significant effects only present for high extraction rates and small particle sizes. Shifting the location of gas extraction more towards the centre of the bed had a larger influence on bubble dynamics. Deactivation of the two outmost membranes created a more uniform lateral bubble distribution profile which would be beneficial for reactor performance. However, deactivation of additional membranes caused the formation of central densified zones which obstructed the rising gas from reaching the central membranes. These effects could be clearly observed for small particles (196 μm), while larger particles (500 μm) showed little or no sensitivity to changes in gas extraction rate or location.

1. Introduction

The use of fluidized bed membrane reactors (FBMRs) has gained a high degree of attention in the last few years, due to a number of industrially important applications and several significant advantages over conventional reactors. FBMRs offer the advantages of excellent separation properties of membranes (for example selective product removal), which circumvent the thermodynamic equilibrium limitations, and excellent heat and mass transfer characteristics of fluidized beds. These combined advantages have led to the development of highly energy efficient FBMR concepts. A typical example of a process using FBMR technology is selective removal of hydrogen from steam methane reforming using palladium-based membranes [1–10]. It was concluded that fluidized bed membrane reactors provide a better overall reactor performance compared to fluidized bed reactors without membranes and other conventional reactors.

Despite the proven advantages, FBMRs are still a relatively young field and substantial improvement in their performance can be achieved with better understanding of the effect of membrane insertion on the overall bed dynamic behaviour. In other words, detailed fundamental research in understanding the effect of the presence of membranes and the associated gas extraction is of high importance for exploiting the full potential of this technology. Moreover, it is well known that solid mixing, heat and mass transfer phenomena, and separation performance of gas-solid fluidized bed membrane reactors are highly dependent on the bubble properties and dynamics. The spatial distribution of bubbles, their shapes, sizes, numbers, and velocity play a key role in the hydrodynamics and thereby in the overall performance of the fluidized bed membrane reactors. Thus, a deeper understanding of bubble dynamics and prediction of their properties in such system is of great practical significance for process design and scale-up.

1.1. Studies on membrane fluidized bed hydrodynamics

A number of recent studies have paid more attention to the fundamental aspect of FBMR hydrodynamics. De Jong et al. [11] demonstrated

* Corresponding author at: Norwegian University of Science and Technology, Department of Energy and Process Engineering, Trondheim, Norway.
E-mail address: shahriar.amini@sintef.no (S. Amini).

http://dx.doi.org/10.1016/j.powtec.2016.12.026
0032-5910/© 2016 Published by Elsevier B.V.

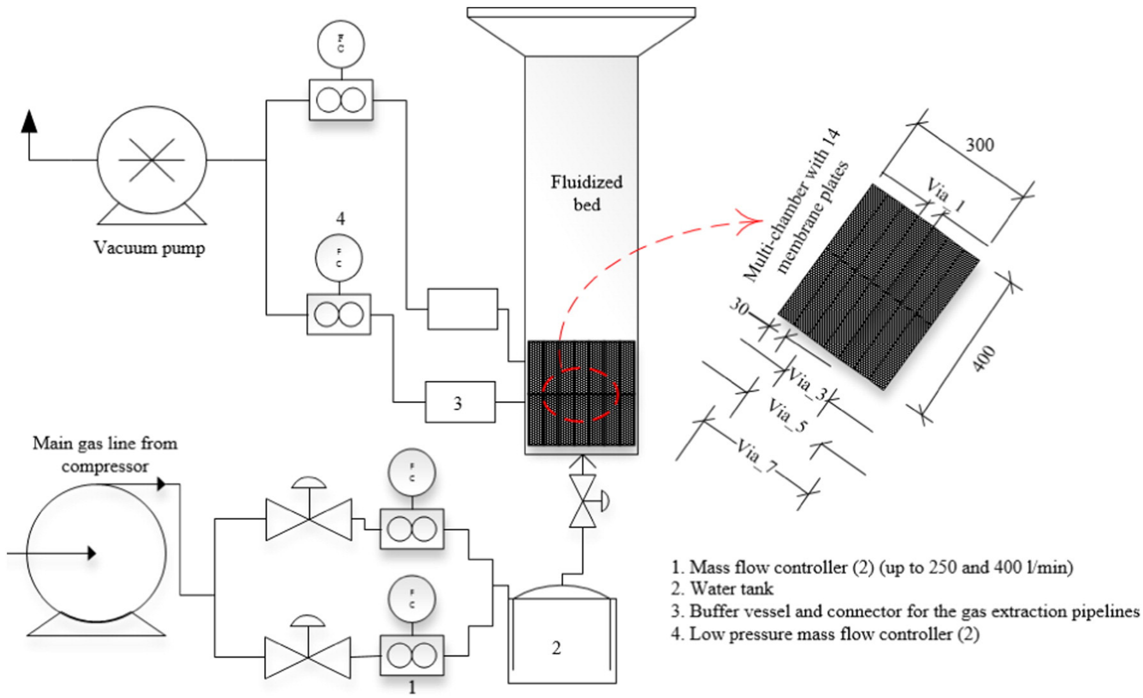

Fig. 1. Process flow diagram of the experimental setup (all dimensions in mm) (the area coverage of active membranes decreases towards to the centre — from Via_7 to Via_1).

experimentally the effect of gas permeation through horizontal membranes on both solid and bubble phase properties. Results showed that the presence of horizontal membranes enhanced bubble breakage and resulted in a decrease in the average equivalent bubble size and increase in the number of bubbles, which provides an improvement in mass transfer between the bubble and emulsion phases. It was also reported that the largest effect was caused merely by the presence of the membranes tubes: both the solids flux and the average bubble size were decreased by a factor of three compared to a fluidized bed without inserts. The permeation rate was found to have a minor effect on the extent of solids circulation in the bed. Asegehegn et al. [12] and Julian et al. [13] also confirmed that only the presence of horizontally immersed tube banks in fluidized beds, without gas extraction, influences the bubble properties and behaviour. On the other hand, Medrano et al. [14] studied the hydrodynamics in the vicinities of horizontally inserted membranes in fluidized beds, and reported the formation of gas-pockets surrounding the membranes which might be detrimental for the performance of a fluidized bed membrane reactor. Deshmukh et al. [15–17] performed both numerical and experimental works on the effects of gas permeation via membranes and also found a reduction in both bubble sizes and solids motion. Tan et al. [18–20] also studied the effect of gas permeation through vertical membranes for small scale fluidized bed reactors and reported that the influence of gas permeation decreases with decreasing permeation rate or increasing membrane area.

Fewer studies have looked at the hydrodynamic behaviour in vertically inserted membrane fluidized bed reactors. De Jong et al. [21] and Dang et al. [22] have experimentally demonstrated that gas extraction through flat membranes (placed on the wall-sides of the bed) induces a change in both solid circulation patterns and average bubble size. It was also found that gas extraction through membranes resulted in a relatively larger average bubble diameter. This results from the fact that gas extraction causes densified zones formation near the membranes, which forces moving bubbles towards the center of the fluidized bed, thereby inducing bubble coalescence. This therefore results in bubbles that are vertically stretched and larger than in the case of no-gas extraction [21].

The present authors [23] studied the effect of vertical flat membranes on the bubble dynamics in a fluidized bed reactor both experimentally and numerically. Uniform gas extraction through the entire back of the pseudo-2D fluidized bed was found to cause densified zone formations on the sides, which force the gas to rise through the centre in the form of a channel. This phenomenon becomes more pronounced as the gas extraction rate is increased. On the other hand, variation of gas extraction location (area) showed a substantially larger impact on the bubble dynamics. For example, gas extraction through the centre was found to alter the bubble behaviour to rise in two channels towards the sides of the bed. Cold flow simulations completed using the Two Fluid Model approach (TFM) closed by the kinetic theory of granular flow successfully reproduced the experimental findings, including the effect of gas

Table 1
An overview of the experimental conditions investigated in this work where Via_i represents the area coverage of active membranes (decreasing towards the center, see Fig. 1).

Experimental campaign	Mean particle sizes [μm]	Extraction percentage [%]	U/U_{mf} [−]	Number of active membrane plates [−]	Number of double frame images
For the effects of gas extraction rate	196 and 500	0	3 and 6	0	2000
		10	3 and 6	14	2000
		20	3 and 6	14	2000
		30	3 and 6	14	2000
For the effects of gas extraction location	196 and 500	0	3 and 6	0	2000
		30	3 and 6	14 (Via_7)	2000
		30	3 and 6	10 (Via_5)	2000
		30	3 and 6	6 (Via_3)	2000
		30	3 and 6	2 (Via_1)	2000

Please cite this article as: S.A. Wassie, et al., Experimental investigation on the generic effects of gas permeation through flat vertical membranes, Powder Technol. (2016), http://dx.doi.org/10.1016/j.powtec.2016.12.026