Journal of Membrane Science 530 (2017) 20–32

Contents lists available at ScienceDirect

Journal of Membrane Science

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

Membrane contactors for process intensification of gas absorption into physical solvents: Impact of dean vortices

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ARTICLE INFO

Keywords:
Membrane
Contactors
Absorption
Intensification
Dean vortices

ABSTRACT

Membrane contactors are considered as one of the most promising intensification technologies for gas-liquid absorption processes. For chemical absorption systems, such as flue gas CO_2 absorption in amine solutions, the mass transfer resistance is significantly located in the membrane due to the accelerating effect exerted by the reaction in the liquid. For physical absorption systems however, such as CO_2 absorption in water for biogas purification, most of the resistance is located within the liquid phase. Process intensification requires an increase of the gas-liquid interfacial area (provided by the membrane) together with increased mass transfer performances in the rate limiting phase, namely the liquid. In the liquid phase, a boundary layer is formed, in which the solute concentration is higher than at the bulk, thus decreasing the driving force for the transfer. This study investigates the use of Dean vortices as a tool to increase mass transfer performance in membrane contactors. These vortices, generated by a helical hollow fiber, are applied to CO_2 absorption in water using dense polymeric membranes. A straight hollow fiber with water flowing in the lumen is compared to different helical shaped hollow fibers. Firstly, Dean vortices, calculated by a CFD approach, are successfully compared to the velocity maps experimentally obtained by MRI, a non-invasive spectroscopy. Hydrodynamic simulations are thus validated, offering parametric studies and design optimization perspectives. The experimental results for the mass transfer performances of a hollow fiber under different liquid velocity conditions are further compared to simulations. A parametric study, combining CFD and mass transfer simulations, shows that Dean vortices enable an increase of the mass transfer coefficient by a factor of 3, with a moderate increment in pressure drop or energy expenditure, when compared to the straight fiber. Lastly, the best helical geometry, with maximal CO_2 mass transfer at the expense of minimal energy requirement is investigated. For a given application, it is shown that a large process intensification effect is attainable; with the same energy requirement, a 2-fold decrease in the surface area is achieved. The potential of the concept for practical hollow fiber modules design and applications are finally discussed.

1. Introduction

Membrane contactors are considered as one of the most promising intensification technologies for mass transfer unit operations (separation processes) or reactive systems (chemical reactors). Promising perspectives have been reported for a broad range of applications such as carbon capture, biogas purification, bioreactors for the production of biofuels, potable water production (desalination, wastewater treatment), recovery and purification of pharmaceuticals, ultrapure water production for microelectronics [1], food and pharmaceutical industry with degassing of aqueous solutions in the food and carbonated beverages, nitrogenation of beer, concentration of juices [2], blood oxygenators, oxygen enriched air production, VOC recovery from water, among others [3,4].

Membrane contactors for gas-liquid absorption processes have been particularly investigated in order to decrease the size (or weight) of classical gas absorption equipment such as packed columns. Post combustion carbon capture by gas-liquid absorption into chemical solvents has received considerable attention; given the high liquid mass transfer coefficient provided by the chemical reaction in the solvent (e.g. amine solution), a very high membrane mass transfer coefficient is required in that case [5]. This characteristic addresses a major challenge in terms of membrane material design. For gas-liquid absorption processes into physical solvents however, the liquid mass

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http://dx.doi.org/10.1016/j.memsci.2017.02.016
Received 7 December 2016; Received in revised form 10 February 2017; Accepted 12 February 2017
Available online 14 February 2017

Table 1
Summary of studies in membrane separation involving Dean vortices.

Process	Fluid	Membrane	Comment	Ref.
CFD studies (no membrane separation)				
–	Water	U shape solid tube.	NMRI visualization of vortices and numerical analysis in a U-shaped pipe.	[26] [27,28]
–	Water	Solid wall	Wall shear stress calculations in a curved tube with non-porous walls.	[19]
–	Aqueous suspension of polystyrene particles	Solid tube	Laser visualization of fluid trajectories and comparison to simulation.	[20] [29]
Heterogeneous fluids (microfiltration, ultrafiltration): fouling prevention, concentration polarization limitation				
Microfiltration	Latex, silica, yeast suspensions	Flat Polysulfone	Flat sheet membrane positioned after a narrow curved channel. Increase in permeation up to 30%	[21] [22]
Microfiltration	Bentonite suspension	–	Evaluation of Dean vortices at industrial conditions. The beneficial effect of the secondary flow was maintained for larger modules.	[30]
Ultrafiltration	Bentonite suspension Dextran solution	Cellulose-acetate fibers	The permeate flux is three times higher for coiled modules than for straight ones.	[17]
Ultrafiltration	Dextran solution	Cellulose acetate fibers	Comparison of woven fibers with helical and straight fibers: Results obtained in woven hollow fiber module and in helical modules are similar.	[18]
Membrane extraction	30% TBP (in kerosene)–phenol–water	Polysulfone	The improvement factor was in the range of 2 – 4.	[31]
Nanofiltration	–	Polyethersulfone	Water permeability and pressure drop measurements.	[32]
Homogeneous fluids: liquid phase mass transfer improvement				
Membrane contactor (oxygenation)	Water (flowing inside the tube)	Dense silicon rubber tubing (PDMS)	Experimental study, mass transfer coefficients are 2–4 times higher than for straight fibers.	[15]
Pervaporation	Homogeneous liquid (n butanol ± water and chloroform ± water)	Dense silicon rubber tubing (PDMS)	The presence of Dean vortices has a beneficial effect when the boundary layer resistance controls mass transport.	[16]
Membrane contactor (deoxygenation)	Aerated water Sweeping gas: Nitrogen	Hydrophobic porous membrane (PP)	Mass transfer can be enhanced on both tube and shell side in coiled hollow fiber modules. Maximum improvement factor obtained is 3.5.	[25]
Membrane contactor (CO_2 dissolution)	Water Gas phase: CO_2	Dense silicon rubber (PDMS)	MRI visualization of Dean vortices, comparison to CFD simulations. Evaluation of intensification potentialities and energy efficiency..	This study