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Validation of a Novel Approach for Co_2/N_2 Gas Separations by means of a Hybrid Ceramic Membrane

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Abstract: Global warming has been documented as one of the world's foremost ecological concerns. Although it is difficult to totally end human related global warming, there is a possibility to alleviate these effects through a wide spectrum of options. One such possibility is the reduction of atmospheric carbon dioxide emissions, a major greenhouse gas widely thought to be responsible for global warming. This paper therefore looks at an experimental validation of gas separation by means of a high selective membrane for CO_2 recovery applications. Analysis of the results obtained is in good agreement with literature experimental data. Additional results show that CO_2 selectivity factor is reasonable for capture of CO_2 from N_2 as a key constituent in a flue gas stream.

Introduction

While capture of carbon dioxide with amine solvents is the most established technology, another potential and efficient candidate is gas separation membranes. This technology has been improved further by recent developments in materials process engineering resulting in the innovation of novel materials with the thermal and mechanical stability required for most gas separations. In particular, inorganic gas separation membranes are examined. Membrane technology is a viable option to conventional separation methods since it offers cheaper capital investment and is relatively less energy consuming. As a result, there is high demand for this technology in environmentally demanding processes leading to an upshot in membrane technological market. To achieve optimization in membrane separation systems performance in an economical manner, the development of a reliable way of dealing with the design of membrane technology is gaining great attention [1]. An accurate description of the process behaviour in the membrane separation process is an important factor in order to reduce some technical risks which could be encountered especially in relation to traditional separation technique. In addition, designing of process models for membrane gas separation in particular is vital and requires an extremely thorough and careful approach. Thus an accurate and dependable simulation of the entire system can be employed for the design of the separation process. Subsequently, efforts made towards development of a detailed model for membrane gas separation has not gained enough grounds at the moment and not very readily available in most published literatures, although a limited number of unit models exists in some literatures [2] [3] [4].

Mathematical Model

Figure 1 shows binary gas permeation through a hybrid ceramic membrane operating in a one directional flow (concurrent) and cross flow mode. It is also necessary to observe that the concentration of the permeate exiting the membrane coated surface, Y^I is not the same as the bulk

permeate leaving the porous layer, Y_i. However both flows are equal at the end of the membrane [5].
The model is based on a binary gas mixture whereby the feed gas is on the coated side of the asymmetric membrane. Combination of permeate fluxes of different components does not take place inside the porous supporting layer of the membrane. The resistance of gas flow (feed) of the support layer as well as diffusion of flow through the membrane pore path is negligible as a result of the high level permeate influx. Membrane distortion under pressure is also negligible. All operating conditions in the simulation were used for experimental validation. The main objective of the model is to ascertain and validate the degree of CO_2 recovery occurrence using a single stage membrane simulation model.

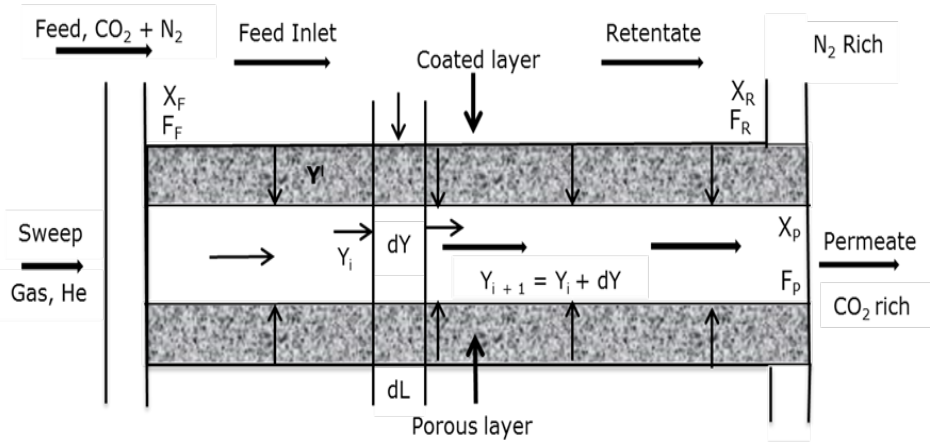

Fig. 1: Binary gas permeation through a Nanostructured Ceramic membrane

Experimental methods.

The commercial ceramic membrane used was purchased from Ceramiques Techniques et Industrielles (CTI SA), France and made up of 77% α-alumina + 23% TiO2 with an average pore diameter of 6000nm. The membrane has 20 mm and 25 mm internal and outer diameter respectively, and an effective penetrable length of 318 mm. The feed pressure applied was between 1 to 5 bar. Gas permeation experiments were carried out to investigate and test CO_2 and N_2 gas mixtures permeation behaviours as well as separation performance process under relevant operating conditions. Experimental values were used as input data in the membrane simulation. The selectivity of the membrane was assumed so as to enable comparison of experimental and model parameters.
For a single stage membrane process, applicable parameters used in this work including operational conditions are pressure, temperature and gas flow rates. Others are selectivity, permeability, membrane surface areas and inlet feed composition. Other variables that contribute to the membrane performance are the membrane selectivity also called “separation factor” usually predicted and calculated from the permeability ratio of pure gases [6]. An estimation of CO_2 selectivity to N_2 can be calculated from the ratio of CO_2 permeance to that of N_2 using the formula below:

$$\text{Selectivity, } \alpha = \frac{\text{Permeance of } CO_2}{\text{Permeance of } N_2}$$

Results and Discussions

Experimental values were obtained using ceramic membranes module parameters at simulation operating conditions as well as its selectivity while that of literature was obtained from results using polymeric membrane for CO_2 removal from flue gas [7].

Tables 1- 3 show the simulation, experimental and literature values respectively. Figure 2 depicts a comparative analysis of CO_2/N_2 selectivity to CO_2 removal based on experimental and literature values. In this case, all model parameters were kept constant with varying polymeric membrane selectivity inputs. For both scenarios, at a relatively low selectivity, the trend shows that more CO_2 was recovered with our experimental input compared to that of literature values having higher selectivity but lower permeability properties being characteristic features of organic membrane while the ceramic membrane exhibited high permeability and enhanced CO_2 recovery characteristic.

Table 1: Model Values

Simulation benchmark	
CO_2/N_2 Selectivity	CO_2 Percentage Recovery
10	35.5

Table 2: Experimental Values

Experimental Values	
CO_2/N_2 selectivity	CO_2 Percentage Recovery
0.75	4.66
1.52	11.13
2.43	18.02
3.48	25.31
3.83	27.96

Table 3: Literature Values

Literature Values	
CO_2/N_2 selectivity	CO_2 Percentage Recovery
19.3	0.7615
21	1.7993
24.2	1.2361
17.1	0.9882
29.1	1.5884

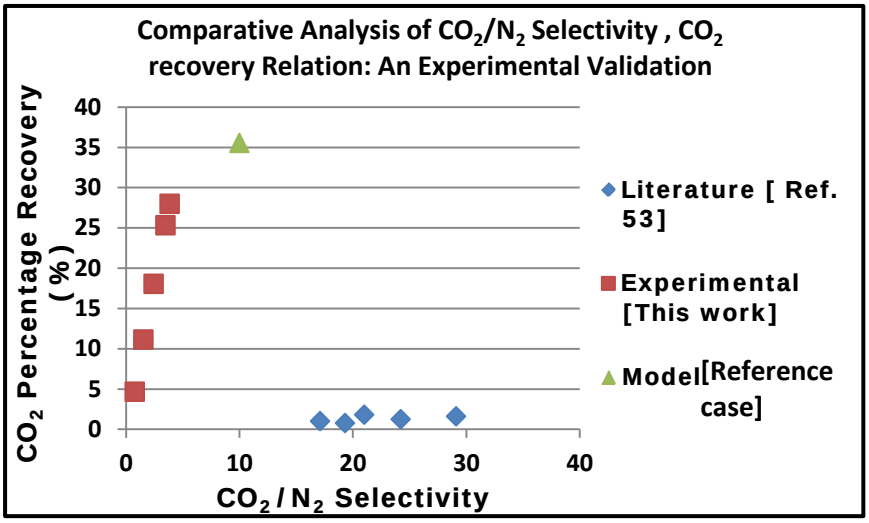

Fig. 2: Comparative analysis of CO_2/N_2 selectivity and CO_2 removal: Experimental Validation

Conclusion

A hybrid inorganic ceramic membrane has been prepared by immersion in a silica solution forming an asymmetric structure for CO_2/N_2 gas separations. The experimental results obtained from the permeation study indicate a good agreement between the experimental, literature and model. This therefore validates the experimental and literature results by the model which ultimately can now be used for a range of parametric studies for fuel gas separation applications for CO_2 recovery.

Nomenclature

F_F = Flow rate of gas component in the feed side (l/min)
F_R = Flow rate of gas component in the retentate side (l/min)
F_P = Flow rate of gas component in the permeate side (l/min)
X_F = Mole fraction of gas component in the feed side (%)
X_R = Mole fraction of gas component in the retentate side (%)
X_P = Mole fraction of gas component in the permeate side (%)

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