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A flow distribution study of laboratory scale membrane gas separation cells[☆]

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ABSTRACT

Gas flows in laboratory membrane test cells are often assumed to be uniform due to the relatively small feed volumes and ideal mixing of gas mixtures such as air. Scientific literature on characterization of gas flow distribution in the feed volume above the membrane in laboratory cells is limited. Any non-uniform distribution of flow is known to impact the permeance through the membrane [V.V. Ranade, A. Kumar, Comparison of flow structures in spacer-filled flat and annular channels, *Desalination* 191 (2006) 236; Nikhil Kawachale, Ashwani Kumar, Deepak M. Kirpalani, Numerical Investigation of Hydrocarbon Enrichment of Process Gas Mixtures by Permeation through Polymeric Membranes, *Chem. Eng. Technol.* 31, (1) (2008) 58]. In this work, the conventional cell used in laboratories was first examined to determine the uniformity in flow distribution and its effects on membrane performance. Using a combination of experimental and numerical methods, the feed flow distribution in the conventional cell was found to be skewed towards the far (retentate) side of the feed volume and also resulted in short-circuiting of the gas mixture to the retentate outlet. A new design for laboratory cell was proposed and experimentally validated. This modified cell was found to have a more uniform flow distribution than the conventional cell, consequently leading to improved separation performance.

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1. Introduction

Performance of laboratory membranes is generally evaluated in small test cells housing a flat sheet membrane sample that is subjected to a range of operating conditions such as feed composition, flow rate, temperature and applied pressure. Considering that the performance of a test cell is essentially related to the fluid movement through its volume, the geometry of a test cell configuration could play an important role on the membrane performance. Moreover, for developing new membranes processes and assessing the suitability and performance of new membranes, it is desirable to have uniform flow and fluid properties over the entire permeation area of the test sample. This approach determines the suitability of a membrane and also provides reliable data for estimating the scale up requirements.

In most membrane characterization procedures, fluid flow in laboratory cells is generally assumed to be uniformly distributed on the surface of the membrane and throughout the feed zone leading to the use of the entire membrane surface and providing representative performance of the whole membrane. There is a possibility that test cells are constructed in a way that unfavorable hydrodynamic conditions that leads to mal-distribution of the feed flow.

Literature on gas separation has not paid much attention to such issues in a typical membrane separation cell. In addition, detailed fluid flow pattern analyses, which provide fundamental information for designing and improving the separation by membranes, have not been described adequately [3].

In cell design, the hydrodynamics should be well defined so that other concurrent effects can be de-coupled in a clear manner, thus allowing a direct assessment of the intrinsic mass transport properties of the test membrane. In this respect, it is desirable to have a membrane module or cell with uniform flow characteristics over the permeating area for evaluating laboratory scale membranes. In practice, however, it is hard to accomplish the above characteristics due to improper boundary configuration, imperfect design, and a complex mass transfer process.

A well designed uniform flow will allow more accurate determination of mass transfer properties at the membrane surface with cross flow permeation for a range of flow rates. In recent years, Computational Fluid Dynamics (CFD) techniques have been applied by many researchers to understand the fluid flow behavior in membrane modules. The coupled CFD approach can model the mass flow through mathematical coupling of the species continuity and momentum in a compressible solver with defined permeances [2]. The probable effects of feed concentrations together with membrane stage-cuts on a desired separation can also be included within a model. Also, CFD simulations can provide the flexibility to construct computational models that could be easily adapted to wide variety of physical conditions without the

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requirement to construct a prototype of the test cells. Therefore, CFD can provide an effective virtual prototyping at a relatively low cost.

Belfort [4] reviewed the development of understanding of fluid dynamics in membrane systems up to 1989. Robert et al. [5] attempted to produce uniform hydrodynamics condition for plate and frame module by means of video camera. A design improvement such as relocating the outlet of hollow fiber membrane module was patented by Harada [6]. In their technical note, Tarabara and Wiesner [7] showed that the geometry of module has an important aspect in the enhancement of membrane performance. The flow was found to be unidirectional over the greatest part of channel area with an exception of the channel corners and the stagnation areas were observed in the dead ends at the inlet and outlet of channel. This paper showed that it is possible to improve membrane module geometry by using CFD. Darcovich et al. [8] designed a thin channel cross-flow module for the characterization of flat ceramic membranes. A total of ten variables were considered for the module design, which was used to evaluate the predicted module performance for each combination of these design variables. Three dimensional modeling of flows in spacer-filled channels with modified flat and annular channels is reported by Ranade and Kumar [1]. In their work, the spacers were designed to create directional changes in the flow in order to reduce concentration polarization and membrane fouling. Zydney and Xenopoulos [9] examined the mass transport phenomena for dextran permeation through ultrafiltration membranes. The study was conducted to examine the use of a stirred cell and a parallel plate tangential flow device with varying filtrate flux, stirring speed and feed flow rate and concluded that the stirred cell provided more accurate test results. An interesting study on membrane fouling and fluid velocity profile in various geometries by means of mapping of protein fouling has been reported by Delaunay et al. [10]. This work used ultrafiltration of skimmed milk in two different module geometries and validated the results with CFD. Feron et al. [11] proposed a novel test cell for gaseous separations. This test cell was intended for characterization of high flux flat sheet membrane with uniform mass transfer over the membrane area and the cell design was verified with numerical simulation. However, in their work the membrane was assumed to be an impermeable wall and mass transfer across the membrane was neglected in numerical procedures. Abdel-jawad et al. [12] studied the flow zones on feed and permeate sides of molecular sieve membrane. This membrane was modeled with CFD by

creating a bounded region separating the feed and permeates sides of membrane. The gas transport phenomenological equations were solved in a bounded region to obtain continuum flows on both sides without accounting for the flow profiles in feed/permeate volumes.

However, a comprehensive fluid dynamics study in order to outline design aspects of gas separation cell, that considers both high/low stage-cuts and actual mass transport across the membrane has not yet been reported in literature. The objective of the present study was to investigate the effect of cell geometry together with operating parameters on overall separation for developing an optimum design with regard to flow distribution for improved hydrodynamics and consequently the product recovery. An improved separation cell was developed using CFD technique, which was validated with experimental results. The approach and results presented in this work are expected to have significant implications for identifying suitable membranes and an accurate estimation of process parameters.

2. Experimental

2.1. Test cell

The importance of current study is to model the geometry of permeation cell together with different design elements that can be related to fluid hydrodynamics. Accordingly, the conventional test cell used in our laboratory for various gas separation experiments was considered for further studies. The generic separation cell (Fig. 1) is made from stainless steel and is mainly comprised of feed-volume (top) and permeate-volume (base) as two different components. The membrane is supported by porous metal screen (Millipore) to facilitate the permeate flow. These components are sealed together using two different o-rings and a placement metal ring with hex-head cap-screws.

As shown in Fig. 1 the conical shaped feed-channel has one feed-inlet and a retentate-outlet, both 3.18×10^{-3} m in diameter, placed opposite to each other and profiled at an angle of 32° to x -axis. The cylindrical shaped permeate-channel is mainly comprised of a porous metal support resting on a plate with series of holes to hold the membrane and facilitate the permeate flow through a permeate-outlet of 3.18×10^{-3} m diameter. The membrane physically divides the feed-volume from the permeate-volume once both the halves put together.

Fig. 1. View of conventional membrane cell design.

Fig. 2. Schematic diagram of constant pressure separation system.

2.2. Materials

A flat sheet poly (dimethylsiloxane) (PDMS)-polysulfone membrane comprised of microporous polysulfone support coated with a 0.2 μm thick PDMS layer was used for gas permeation experiments. The composite membrane was prepared from a polysulfone-*N*-methyl pyrrolidone (NMP) solution by gelation in cold water [13]. Earlier experiments demonstrated the selectivity of hydrocarbons in Alkane/Alkene- N_2 separation [13]. In this work, the separation of industrial grade air (99% purity) was examined using the same membrane for O_2 enrichment.

2.3. Permeation measurements

The experimental setup is a standard constant-pressure permeation system. The feed gas is supplied through a feed inlet to obtain a constant feed pressure and concentration in the feed volume. As shown in Fig. 2 the operating flow rate was obtained using a mass flow controller (MFC) at the feed inlet and regulated by the retentate outlet pressure using a backward control method. The control mechanism maintains the retentate gas stream flow via a solenoid valve (CV) and regulates the pressure in the feed volume indirectly (Fig. 2). Experiments were performed maintaining selected stage-cuts to avoid concentration polarization on the surface of the membrane. These selected stage-cuts were maintained for the duration of the experiments using the control loop shown in Fig. 2. The stage cut is varied over a range of $1 < \sigma < 17$ in this study to examine the effects of cell geometry at different operating conditions. The gaseous permeate and the retentate streams are analyzed for pressure and composition. A Quantek Instruments (Northboro, MA) 902P O_2 analyzer and MKS Instruments (Methuen, MA) transducers (10,000 Torr) were installed in the control system to determine oxygen concentration and pressure in the feed retentate and permeate flow channels. Preliminary experiments were performed to confirm that the control system maintains the experimental conditions at steady state with laminar flow conditions ($100 < Re < 1500$) and ambient temperature (22°C). A round membrane test sample with an effective membrane area of $1.14 \times 10^{-3} \text{ m}^2$ was used in all experiments. All the permeances were calculated in GPU ($1 \text{ GPU} = 7.5 \times 10^{-10} \text{ cm}^3(\text{STP})/\text{cm}^2 \text{ s Pa} = 10^{-6} \text{ cm}^3(\text{STP})/\text{cm}^2 \text{ s cmHg}$).

3. Numerical modeling

Flow behavior of the gas mixture inside the feed volume cannot be easily determined experimentally. Alternate approaches, such as numerical simulations, which require boundary or inlet/outlet

operating conditions, provide a suitable alternative for visualizing the flow behavior. Experimental results, obtained using the setup described earlier, provide the required boundary conditions for the simulations. During simulations, the composition at the retentate outlet is an unknown and the flow behavior is determined by an accurate prediction of the retentate outlet pressure and composition.

3.1. Governing equations

In order to simulate the flow of the gas mixture through a membrane cell, the conservation equation for mass and momentum were solved using finite volume method. In addition, a set of gas species conservation equations were solved to account for the separation. The governing equations, based on the physical principles of continuity, momentum conservation and solutes conservation are shown in Eqs. (1)–(5) and were solved for a three-dimensional domain to examine the gas flow characteristics and concentration profiles of the species [2].

Equation for conservation of mass (continuity):

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho \omega)}{\partial z} = 0 \quad (1)$$

Equation of Momentum (Navier-Stokes):

In x-direction

$$\rho \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \omega \frac{\partial u}{\partial z} \right) = - \left(\frac{\partial P}{\partial x} \right) + \left(\frac{\partial}{\partial x} \mu \left(\frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \mu \left(\frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \mu \left(\frac{\partial u}{\partial z} \right) \right) \quad (2)$$

In y-direction

$$\rho \left(u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + \omega \frac{\partial v}{\partial z} \right) = - \left(\frac{\partial P}{\partial y} \right) + \left(\frac{\partial}{\partial x} \mu \left(\frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \mu \left(\frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z} \mu \left(\frac{\partial v}{\partial z} \right) \right) \quad (3)$$

In z-direction

$$\rho \left(u \frac{\partial \omega}{\partial x} + v \frac{\partial \omega}{\partial y} + \omega \frac{\partial \omega}{\partial z} \right) = - \left(\frac{\partial P}{\partial z} \right) + \left(\frac{\partial}{\partial x} \mu \left(\frac{\partial \omega}{\partial x} \right) + \frac{\partial}{\partial y} \mu \left(\frac{\partial \omega}{\partial y} \right) + \frac{\partial}{\partial z} \mu \left(\frac{\partial \omega}{\partial z} \right) \right) \quad (4)$$

Equation of solute concentration (conservation):

$$\rho \left(u \frac{\partial(C_A)}{\partial x} + v \frac{\partial(C_A)}{\partial y} + w \frac{\partial(C_A)}{\partial z} \right) = \left(\frac{\partial}{\partial x} \rho D_{AB} \left(\frac{\partial C_A}{\partial x} \right) + \frac{\partial}{\partial y} \rho D_{AB} \left(\frac{\partial C_A}{\partial y} \right) + \frac{\partial}{\partial z} \rho D_{AB} \left(\frac{\partial C_A}{\partial z} \right) \right) \quad (5)$$

Non-slip boundary conditions at wall surface and variation in solute concentration were included in the compressible solver as well. Also, based on the empirical data, any plasticization effects were neglected and the partitioning of O₂ from the bulk feed to the membrane was not considered to be mass transfer limiting.

3.2. Boundary conditions

Model development and simulations were performed using FLUENT® 6.3 commercial CFD software. In present simulation, gas mixture properties were defined before executing the simulation loop. Operating parameters, such as mass flow rate, pressure and species concentrations were obtained and implemented as boundary conditions from empirical data for the air. The simulations were performed using unsteady-laminar flow conditions at ambient temperature. The discretization of the governing equations was performed using a segregated compressible flow solver in which each governing equation is solved separately. The Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) formulation of pressure-velocity coupling was used to obtain the necessary corrections to the pressure and velocity fields along with the face mass fluxes such that the continuity equation is satisfied [14]. In order to update the velocity field, the three-dimensional (3D) Navier-Stokes equations were solved using current values for cell nodal pressures and face mass fluxes. The convergence criteria for the continuity and velocity parameters were fixed to 0.001%. Higher convergence criterion ($1.0 \times 10^{-6}\%$) was set for O₂ to offer sufficient iterations for complete convergence between boundary and the interior mesh grid. Pressure was set to 'Pressure Staggering Option' and momentum, density and mass fractions were set to 'Second Order Upwind' discretization schemes for more accurate results [15].

3.3. Grid/domain

The dimensions of the computational domain were identical with that of the membrane separation cell that has been described earlier. GAMBIT 2.3 preprocessing software was used to generate the 3D geometry and mesh for CFD studies. An effort was made to implement the structured, uniform quad/hex grid for the entire geometry for numerical advantage. In order to accomplish this, the geometry is decomposed in such way that quad/hex scheme can be accomplished for all the segments of complex portions. The choice of Map and Cooper scheme resulted in hexahedral elements and hence rendered an efficient mesh. Structured meshing was performed to divide the gas flow domain in to sub-domains and hexahedral cells and the discretized governing equations were solved inside each cell. The continuity and momentum equations across the common interfaces between two sub-domains, the feed and the permeate side, were solved to visualize fluid flow in the entire domain. The membrane cell computational geometry consisted of a mass flow inlet, boundary for introducing the feed mixture and two pressure outlets for retentate and permeate flow. The membrane in the domain was defined as shadowed wall, while all other walls represent the barriers of the remaining cell geometry. Grid refinement was performed to achieve grid independence by analyzing the concentration gradient within the geometrical domain.

Table 1

Experimental results and membrane performance obtained using conventional cell.

Feed flow rate (m ³ /s)	Permeate flow rate (m ³ /s)	Permeate O ₂ concentration (wt%)
1.08E-06	7.46E-07	25.9
2.16E-06	7.51E-07	26.9
3.24E-06	7.55E-07	27.4
4.32E-06	7.59E-07	27.8
8.65E-06	7.60E-07	28.3
1.30E-05	7.62E-07	28.6

3.4. User defined functions (UDF)

Transport of gas across the membrane was achieved using a series of user-defined functions in FLUENT® software. Membrane modeling was addressed by incorporating permeabilities and mass fluxes as a UDF written in 'C code' [2]. The issue of hydraulic jump across the membrane was resolved by patching the cells from upper and lower zones with two different values of initial pressures. The source and sink terms in the UDF were calculated by using the simple relationship between the linear flux and the driving force, which is commonly described by Fick's law in membrane separations.

$$J_i = -D_i \frac{dC_i}{dN} \quad (6)$$

The 'Define Profile' macro was used in parallel with the adjacent cell index to link the relation between the hydrodynamics and the membrane transport phenomena. Changes in the fluid flow adjacent to the membrane interface were accounted for by the UDF with the prediction of new parameters for membrane wall along with the shadow side. Additionally, the UDF updated the solver data with new parameters at membrane wall.

4. Results and discussions

All the experiments were performed to obtain boundary conditions for simulating flow profiles within the cell and were repeated at least three times to avoid any empirical errors. Table 1 shows the range of operating conditions examined and the permeate flow rates. The O₂ wt% of feed gas was 0.198 throughout the experiments. The observed empirical boundary conditions were solved to satisfy mass and momentum equations in CFD code.

Fig. 3. Velocity magnitude vectors at inlet flow rate 0.108×10^{-5} m³/s for the conventional cell.

Fig. 4. Contours plot of velocity magnitude in the immediate vicinity above the membrane at inlet flow rate $0.108 \times 10^{-5} \text{ m}^3/\text{s}$ for the conventional cell.

4.1. Flow profile in conventional cell design

In order to investigate the fluid flow patterns, numerical simulations for different inlet flow rates ($0.108\text{--}1.29 \times 10^{-5} \text{ m}^3/\text{s}$) were performed involving the actual 3D geometry of conventional cell. The overall flow distribution within the cell was examined based on velocity vectors for a range of boundary conditions. Fig. 3 shows the results of the CFD simulation as vectors of velocity magnitude at relatively low inlet flow rate ($0.108 \times 10^{-5} \text{ m}^3/\text{s}$). As shown in Fig. 3 the flow is not well-distributed in the flow direction as the highest velocity occurs on the far-side of the cell rather than a uniform distribution as expected. Other possible shortcomings identified were the short circuiting of some of the feed gas mixture to retentate outlet without having any contact with the membrane that could have a significant impact on the performance of the membrane cell. A contour plot for velocity magnitude vectors in the immediate vicinity above the membrane is shown in Fig. 4. It was obvious that (Fig. 4) the conventional cell design has poor flow distribution, which is skewed towards the retentate side, resulting from the incorrect inlet

Fig. 5. Comparison between predicted and measured O_2 concentration at permeate outlet for different feed flowrates for the conventional cell.

configuration. The inlet flow is clearly impinging on one particular area of the test membrane rather than covering the entire membrane surface uniformly. The incoming feed is not well dispersed over the membrane area and consequently the entire membrane is not being utilized to its full potential for the desired separation.

4.2. Model validation

The fluid flow behavior in the feed volume was studied numerically over a range of inlet flow rates ($0.108\text{--}1.29 \times 10^{-5} \text{ m}^3/\text{s}$). Simulation results were validated using empirical boundary parameters as described earlier. Fig. 5 shows the O_2 concentrations at permeate outlet plotted for varying volumetric feed flow rates to determine the overall operating characteristics for test cell. CFD-predicted and empirically determined O_2 concentrations are compared for conventional cells at first. It can be seen from Fig. 5 that, though the numerical procedure underestimated the O_2 concentrations at permeate outlet by a small margin they are in good agreement with experimentally measured entities. Moreover, the theoretical CFD results for the fluxes as discussed earlier have been

Fig. 6. View of modified membrane cell design.

Fig. 7. Velocity magnitude vectors at inlet flow rate $0.108 \times 10^{-5} \text{ m}^3/\text{s}$ for the modified cell.

validated with empirical results without significant error. Therefore, it can be concluded that CFD based modeling approach is capable of closely predicting the flow distribution in gas separation membrane systems. Based on this confirmation CFD code has been useful for the understanding of fluid dynamic behavior inside the membrane cell.

4.3. Flow profile in modified cell design

After analyzing the flow distribution generated by CFD simulations in conventional cell, a modified cell with fluid zones as shown in Fig. 6 was proposed. In order to obtain improved fluid dynamic characteristics, modifications were primarily made to the inlet configuration. As shown in Fig. 6 the inlet that was profiled at an angle in conventional cell, is shifted on the top of the feed channel at an angle of 90° to x -axis extending just above the membrane in the modified cell. A diffuser-disk was fabricated around the inlet pipe in order to prevent any possible short circuiting of feed flow without being in contact with the membrane. Stainless steel diffuser-discs with different peripheral diameters and a range of clearances above the membrane were examined and an optimum configuration was

Fig. 9. Comparison of velocity magnitude for inlet flow rate $0.108 \times 10^{-5} \text{ m}^3/\text{s}$ across x -axis above the membrane in conventional and modified cells.

obtained (Fig. 6). The permeate volume together with stainless steel porous support was kept unchanged as only small fraction of feed is actually permeating through membrane, which results in very low flow rate on the permeate side.

The result of the CFD simulation as velocity vectors at relatively low inlet flow rate ($0.108 \times 10^{-5} \text{ m}^3/\text{s}$) is shown in Fig. 7. The contour plot for velocity magnitude in the immediate vicinity above the membrane is shown in Fig. 8. Comparing Fig. 4 and Fig. 8, it can be seen that the flow is relatively well-distributed in the modified cell and the velocity is spread over the entire membrane surface without any non-uniformities. Also, any possible short-circuiting in the conventional cell is completely eliminated in modified configuration.

4.4. Flow distribution and permeation performance

In order to compare the performance of conventional and modified membrane cell designs, the effects of feed-channel configurations on velocity magnitude are shown in Fig. 9. As shown in Fig. 9 which compares the velocity magnitude in the immediate vicinity across the x -axis and just above the membrane for conventional and modified cells. It can be clearly observed that for the same inlet flow rate the modified cell has higher and more even velocity distribution over the membrane as compared to conventional configuration. The range of operating conditions examined and the permeate flow rates for modified cell design are listed in Table 2 for reference. Moreover, in order to minimize any possibility of experimental errors, data considered here is based on at least three repetitions of gas separation experiments for a single set of boundary conditions. All the experiments before and after modifications were carefully performed with a single membrane sample to eliminate any discrepancy related to membrane properties.

Also, statistical analysis for the empirical data was carried out to verify the performance gains. A two tail paired t -test was performed

Fig. 8. Contours plot of velocity magnitude in the immediate vicinity above the membrane at inlet flow rate $0.108 \times 10^{-5} \text{ m}^3/\text{s}$ for the modified cell.

Table 2

Experimental results and membrane performance obtained using modified cell.

Feed flow rate (m^3/s)	Permeate flow rate (m^3/s)	Permeate O_2 concentration (wt%)
$1.08\text{E}-06$	$7.61\text{E}-07$	27.6
$2.16\text{E}-06$	$7.65\text{E}-07$	28.0
$3.25\text{E}-06$	$7.67\text{E}-07$	28.2
$4.32\text{E}-06$	$7.69\text{E}-07$	28.4
$8.65\text{E}-06$	$7.70\text{E}-07$	28.6
$1.30\text{E}-05$	$7.72\text{E}-07$	28.8

Fig. 10. O₂ permeance increment and *p*-value statistical analysis for different feed flow rates.

Fig. 11. Effect of modifications on permeate O₂ concentration and permeate flow rate for different feed flow rates.

for the entity 'O₂ permeance' to determine if the modifications were effective. O₂ permeance gain and *p*-value from the *t*-test for varying feed flow rates for air are shown in Fig. 10. It can be observed in this figure that for higher feed flow rates, O₂ permeance for the two cells shows modest difference as compared to lower feed flow rates. However, it is interesting to note that for the lower feed flow rates ($0.108\text{--}0.432 \times 10^{-5} \text{ m}^3/\text{s}$) the modified cell was found to be more effective with 3–7% gains in permeate flow rate and O₂ concentrations at around 99% significance level. An oxygen concentration in permeate together with total permeate flow rate for different inlet flow rates for conventional and modified configuration is compared in Fig. 11. It is clearly observed that the modified cell has better overall performance than the conventional test cell. Also, the performance increments are more notable for the low feed flow rates ($Q_f < 0.432 \times 10^{-5} \text{ m}^3/\text{s}$).

5. Conclusions

The feed flow distribution in the conventional cell volume was found to be non-uniformly distributed due to the angle of feed entry, which led to poor membrane performance and short-circuiting of the gas mixture directly to the retentate outlet. A new design of a laboratory cell was experimentally validated. Com-

pared to the conventional cell, the new design was found to have a more uniform flow distribution and utilized the membrane surface area more effectively while eliminating the short-circuiting. Improved separation performance observed in modified cell would have significant impact on the quality of the laboratory experimental data.

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Nomenclature

<i>C</i>	concentration (wt.%)
<i>D</i>	diffusion coefficient (m ² /s)
<i>J</i>	flux (mol/m ² /s)
<i>N</i>	space coordinate normal to the section for component <i>i</i>
<i>P</i>	pressure (Pa)
<i>Q</i>	mass-flow (kg/s)
<i>Re</i>	Reynolds number
<i>u</i>	velocity in <i>x</i> -direction (m/s)
<i>v</i>	velocity in <i>y</i> -direction (m/s)
<i>ω</i>	velocity in <i>z</i> -direction (m/s)
<i>x</i>	<i>x</i> coordinate
<i>y</i>	<i>y</i> coordinate
<i>Y</i>	mass fraction
<i>z</i>	<i>z</i> -coordinate

Greek symbol

<i>μ</i>	viscosity (kg/m/s)
<i>ρ</i>	density (kg/m ³)
<i>σ</i>	stage-cut

Subscripts

AB	components A and B
<i>i</i>	species
<i>f</i>	feed side

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