**Separation Science and Technology**
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

# The Effect of Pulsatile Flows on the Transport Across Membranes: An Analytical and Experimental Study

Aaron M. Thomas[a]; Aashika Jain[b]
[a] University of Idaho, Moscow, ID [b] Semitool, Inc., San Jose, CA

**To cite this Article** Thomas, Aaron M. and Jain, Aashika(2007) 'The Effect of Pulsatile Flows on the Transport Across Membranes: An Analytical and Experimental Study', Separation Science and Technology, 42: 9, 1931 — 1944
**To link to this Article: DOI:** 10.1080/01496390701401337
**URL:** http://dx.doi.org/10.1080/01496390701401337

*Separation Science and Technology*, 42: 1931–1944, 2007

ISSN 0149-6395 print/1520-5754 online
DOI: 10.1080/01496390701401337

# The Effect of Pulsatile Flows on the Transport Across Membranes: An Analytical and Experimental Study

**Aaron M. Thomas**
University of Idaho, Moscow, ID

**Aashika Jain**
Semitool, Inc., San Jose, CA

**Abstract:** Pulsatile flows have shown to increase the permeation flux in reverse osmosis studies and to reduce fouling that exists in using membranes for separation processes. However, this study demonstrates that permeation from the inside of a hollow fiber with a membrane boundary to the outside decreases once pulsations are added to the inside of the membranes. The increase in the axial flux due to the flow pulsations are the reason for the increased permeation in reverse osmosis and the decrease in transport from inside to outside. An analytical model for a two-dimensional system is presented along with experimental results in separating oxygen from air using polycarbonate based hollow fiber membranes.

**Keywords:** Pulsatile, membranes, mass transfer, gas separation, analytical, experimental

## INTRODUCTION

The process of transporting gases or liquids through a membrane boundary in a steady flow field is related to the classic Graetz (1) problem that analyzes the concentration (or temperature) profile of a fluid steadily flowing through a tube that undergoes a step change on the boundary. The calculated profile for the Graetz problem can then provide the Sherwood (or Nusselt) number to

Received 18 December 2006, Accepted 4 March 2007
Address correspondence to Aaron M. Thomas, Department of Chemical Engineering, Buchanan Engineering Lab 310, P. O. Box 441021, Moscow, ID 83844-1021, USA. Tel.: 208-885-7652; Fax: 208-885-7462; E-mail: amthomas@uidaho.edu

determine mass transfer (or heat transfer) from the tube wall to the moving fluid. Superimposing an oscillating flow to the steady flow in the tube will alter the flow profiles and thus will alter the concentration and mass transfer of the system. Krasuk and Smith (2) examined the oscillating flow problem and determine that the mass transfer from a napthol-coated tube to a water stream did indeed increase with the introduction of flow oscillations. Although they were not able to solve for the concentration profiles explicitly, they were able to approximate the ratio of the mass transfer in steady flow to oscillating flow by examining the ratio between the shear stress exhibited by each configuration. The trends of their analytical finding agreed with their experiments.

This work examines a slightly different configuration, but still draws comparisons with the Graetz problem and the work of Krasuk and Smith. Instead of a boundary coated with a given species, we will analytically and experimentally examine a permeable membrane and determine whether or not the mass transfer through the membrane increases or decreases with the introduction of an oscillating flow field. If it can be shown that adding a pulse in the lumen of an existing membrane system will increase the transport of species through the membrane, this will increase the membrane efficiency. A simplified system that will analyze the transport of oxygen in a nitrogen carrier, a simulated air mixture, is presented in order to analytically answer this question.

## ANALYTICAL PROCEDURE

Although the lumen described above and that is also used in the experiments that follow is tubular in shape, a two-dimensional geometrical configuration is presented with an oscillating fluid flowing between two parallel flat plates. In a way, the channel between the flat plates can be considered a "stretched out" cylinder. The trends observed in this two-dimensional model will be the same as the trends observed in a cylindrical geometry. For the model, the fluid is oscillating between the plates due to an oscillating pressure gradient given by

$$-\frac{\partial P}{\partial x} = \frac{P_{\max}}{L}\sin(\omega t) = -\frac{iP_{\max}}{2L}\left(e^{-i\omega t} - e^{-i\omega t}\right) \tag{1}$$

where $P_{\max}$ is the maximum amplitude of pressure applied, $L$ is the distance along the plates, $\omega$ is the frequency of oscillation, and $i$ is the imaginary number, $\sqrt{-1}$. Let us assume that we are purifying an air stream where the membrane preferentially selects oxygen to pass through and nitrogen will be purified at the end of the membrane. The binary fluid then consists of species $A$ (oxygen) present in carrier $B$ (nitrogen) that enters with an initial amount $C_{A1}$. Species $A$ will then exit the system with a much smaller concentration of $C_{A2}$. At the boundary, we will assume that the surface concentration is constant at some value $C_s$. Ideally, one would use a continuity of flux through both surfaces of the membrane and into the outside stream; however, for our simplified calculation, the surface concentration will be held fixed. $C_s$ will need to be less than the entrance and end concentrations ($C_{A1}$ and $C_{A2}$) to model a system where the desired species transports from the lumen, through the membrane, and to the outside stream. Although a small amount of nitrogen will also pass through the membrane, this model focuses entirely on the transport of the oxygen (Figure 1).

The calculation of the velocity profile is straightforward. The result, assuming anincompressible Newtonian fluid that is axi-symmetric about the centerline and has the noslip condition at the wall, gives

$$V_x(y) = \hat{V}_x(y)e^{i\omega t} + \tilde{V}_x(y)e^{-i\omega t} = \frac{iP_{max}}{\rho\omega L}\left\{\left[\frac{\cos\mathrm{h}(\alpha y/h)}{\cos\mathrm{h}(\alpha)} - 1\right]e^{i\omega t} + \left[1 - \frac{\cos\mathrm{h}(\alpha' y/h)}{\cos\mathrm{h}(\alpha')}\right]e^{-i\omega t}\right\} \tag{2}$$

where $\alpha = h\sqrt{i\omega/v} = \Omega\sqrt{i}, \alpha' = h\sqrt{-i\omega/v} = \Omega\sqrt{-i}$, $v$ is the kinematic viscosity of the gas mixture, and "*" and " $\sim$ " denote complex conjugates. The Womersley number, $\Omega$, can be considered a dimensionless frequency. The dimensionless velocity can be written as

$$V_x^*(y^*) = \hat{V}_x^*(y^*)e^{it^*} + \tilde{V}_x^*(y^*)e^{-it^*} = i\left\{\left[\frac{\cos\mathrm{h}(\alpha y^*)}{\cos\mathrm{h}(\alpha)} - 1\right]e^{it^*} + \left[1 - \frac{\cos\mathrm{h}(\alpha' y^*)}{\cos\mathrm{h}(\alpha')}\right]e^{-it^*}\right\} \tag{3}$$

where $y^* = y/h$; $x^* = x/L$; $t^* = \omega t$; and $V_x^* = V_x\rho\omega L/P_{mzx}$.

For the concentration, the species conservation equation is given by

$$\frac{\partial C_A}{\partial t} + V_x\frac{\partial C_A}{\partial x} = D\left(\frac{\partial^2 C_A}{\partial x^2} + \frac{\partial^2 C_A}{\partial y^2}\right) \tag{4}$$

given a dilute species with a constant molecular diffusion coefficient, $D$, no chemical reaction, and Fickian diffusion. The concentration will involve two terms, one based on the profile with flow pulsations superimposed upon the profile without flow pulsations, or $C_A = C_{NP} + C_P$ denoting no-pulsations (*NP*) and pulsations (*P*) present. It was initially assumed that these terms would be of the form

$$C_{NP} = C_{NP}(x, y) \tag{5}$$

and

$$C_P = \hat{c}(x, y)e^{i\omega t} + \tilde{c}(x, y)e^{-i\omega t} \tag{6}$$

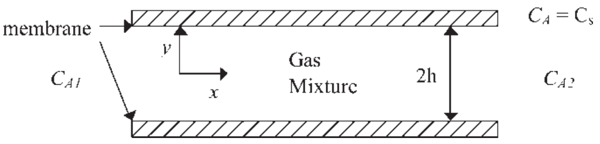

***Figure 1.*** Two-dimensional membrane geometry.

Upon substitution into the species conservation equation, and grouping like orders of the exponentials (as they are independent of one another), the resulting equations are for terms with $e^0$

$$\hat{V}_x \frac{\partial \tilde{c}}{\partial x} + \tilde{V}_x \frac{\partial \hat{c}}{\partial x} = D\left(\frac{\partial^2 C_{NP}}{\partial x^2} + \frac{\partial^2 C_{NP}}{\partial y^2}\right) \tag{7}$$

with $e^{i\omega t}$

$$i\omega\hat{c} + \hat{V}_x \frac{\partial C_{NP}}{\partial x} = D\left(\frac{\partial^2 \hat{c}}{\partial x^2} + \frac{\partial^2 \hat{c}}{\partial y^2}\right) \tag{8}$$

and with $e^{2i\omega t}$

$$\hat{V}_x \frac{\partial \hat{c}}{\partial x} = 0 \tag{9}$$

Similar results occur for the $e^{-i\omega t}$ and $e^{-2i\omega t}$. Note that Eqn. (9) suggests that $\hat{c}$ must be constant in $x$ in order to satisfy this equation. The same conclusion can be drawn if $C_P$ was taken as a Fourier Series of the form

$$C_P = \sum_{n=1}^{\infty} [\hat{c}_n(x, y)e^{in\omega t} + \tilde{c}(x, y)e^{-in\omega t}] \tag{10}$$

However, if $C_P$ is of the form

$$C_P = \sum_{n=1}^{\infty} [\hat{c}_n(x, y)e^{in\omega t} + \tilde{c}_n(x, y)e^{-in\omega t}] \tag{11}$$

an analytical solution would not be possible. Therefore, we will force $\hat{c}$ and $\tilde{c}$ to be a function of $y$ only in order to satisfy Eqn. (9) and therefore modify Eqn. (6). The new equations for $e^0$ and $e^{i\omega t}$ are then

$$D\left(\frac{\partial^2 C_{NP}(x, y)}{\partial x^2} + \frac{\partial^2 C_{NP}(x, y)}{\partial y^2}\right) = 0 \tag{12}$$

and

$$D\frac{\partial^2 \hat{c}(y)}{\partial y^2} - i\omega\hat{c}(y) = \hat{V}_x(y)\frac{\partial C_{NP}(x, y)}{\partial x} \tag{13}$$

With $\hat{c} = \hat{c}(y)$, terms with $e^{2i\omega t}$ do not appear in the final result.

When no flow pulsations are present, species transport is purely by molecular diffusion with a concentration profile of the form

$$\begin{aligned} C^*_{NP}(x^*, y^*) = \sum_{m=0}^{\infty}\Bigg[&\frac{2/b_m(-1)^m C^*_0 - e^{b_m/k}}{1 - e^{2b_m/k}} e^{b_m x^*/k} \\ &+ \frac{2/b_m(-1)^m C^*_0 - e^{b_m/k}}{1 - e^{2b_m/k}} e^{b_m x^*/k}\Bigg]\cos(b_m y^*) \end{aligned} \tag{14}$$

where

$$C_{NP}^{*}=\frac{C_A-C_s}{C_{A2}-C_s},\quad C_0^{*}=\frac{C_{A1}-C_s}{C_{A2}-C_s},\quad k=\frac{h}{L},\ \text{and}\quad b_m=\left(\frac{2m+1}{2}\right)\pi \tag{15}$$

This result is based on an axi-symmetric concentration profile, constant concentration at the boundary, and at the ends of the membrane.

When analyzing the term when pulses are present, Eqn. (13) needs to be solved for $\hat{c}(y)$. However, taking the gradient of $C_{NP}$ in the $x$-direction as shown on the right hand side of the Eqn. (13) gives a result that is a function of both $x$ and $y$. This would necessitate that $\hat{c}$ is a function of both $x$ and $y$ and contradict our need to have $\hat{c}$ as a function of $y$ only. However, we have also shown that $\hat{c}$ must be a constant in $x$ to satisfy Eqn. (9). In order to overcome this problem, the exponentials in $x$ for $C_{NP}$ will be expanded as a series, and only the terms that do not include $x$ once the derivative is taken will be kept. Therefore,

$$\begin{aligned}\frac{dC_{NP}^{*}}{dx^{*}}&=\frac{2}{k}\sum_{m=0}^{\infty}\left[\frac{\begin{array}{c}2/b_m(e^{b_m/k}-e^{b_m/k})\\+(-1)^m C_0^{*}(e^{2b_m/k}-e^{2b_m/k})\end{array}}{(1-e^{2b_m/k})(1-e^{2b_m/k})}\right]\cos(b_m y^{*})\\&=-\frac{2}{k}\sum_{m=0}^{\infty}f_m\cos(b_m y^{*})\end{aligned} \tag{16}$$

will be the representation used to find $\hat{c}(y)$. The solution to $\hat{c}(y)$ that is axi-symmetric about the centerline and is constant at the boundary wit h a value $C_s$ is then

$$\hat{c}^{*}(y^{*})=\left\{\begin{array}{l}\dfrac{Pe}{2\beta}\displaystyle\sum_{m=0}^{\infty}f_m\frac{\begin{array}{c}(\beta-\alpha)\cos(b_m y^{*})\cosh(\alpha y^{*})\\-b_m\sin(b_m y^{*})\sinh(\alpha y^{*})\end{array}}{\cosh(\alpha)[(\beta-\alpha)^2+b_m^2]}\\+\dfrac{Pe}{2\beta}\displaystyle\sum_{m=0}^{\infty}f_m\frac{\begin{array}{c}(\alpha+\beta)\cos(b_m y^{*})\cosh(\alpha y^{*})\\+b_m\sin(b_m y^{*})\sinh(\alpha y^{*})\end{array}}{\cosh(\alpha)[(\beta+\alpha)^2+b_m^2]}\\+\dfrac{Pe\tanh(\alpha h)}{2\beta\cosh(\beta h)}\cosh(\beta y^{*})\displaystyle\sum_{m=0}^{\infty}(-1)^m f_m\\\left[\dfrac{b_m}{[(\alpha+\beta)^2+b_m^2]}-\dfrac{b_m}{[(\alpha-\beta)^2+b_m^2]}\right]\\+\dfrac{C_1^{*}}{\cosh(\beta)}-Pe\displaystyle\sum_{m=0}^{\infty}f_m\frac{\cos(b_m y^{*})}{\beta^2+b_m^2}\end{array}\right\} \tag{17}$$

where $\hat{c}^{*}=\hat{c}/(C_{A2}-C_s)$, $C^{*}{}_1=C_s/(C_{A2}-C_s)\beta=h\sqrt{i\omega/D}=\Omega\sqrt{iSc}$, and $Pe=P_{max}h/\omega D$.

## ANALYTICAL RESULTS

Now that the concentration profiles are known, one can then determine if the flow oscillations increase or decrease the transport across the membranes and thus increase the membrane efficiency. Normally, the flux at the wall is determined and used to find a mass transfer coefficient for the process. However, when calculating the flux at the wall,

$$J_y|_{y=h} = -D\frac{\partial C_A}{\partial y_{y=h}}$$

and time averaging this over one period of oscillation, the flow oscillations have no effect on the flux as it time averages out to zero. Krasuk and Smith (2) were able to overcome this issue and determine a mass transfer coefficient by taking the shear stress at the wall and using this as an indicator of the mass transfer coefficient in much the same way as using Reynolds analogy to approximate a mass transfer coefficient. We will use a different approach. In this system, species will transport in the $x$-direction down the plates and also in the $y$-direction across the membranes. If no flow oscillations are present, the sum of the mass transfer in both $x$ and $y$ can be found by taking the time- and spatially-averaged flux in $x$ and $y$ to give the total number of moles that are transfer per unit of time. However, if a pulse is added to the system, the sum of the mass transfer in both directions will not change from the value found with no flow oscillations as mass is not being added to the system and the pulse is purely oscillatory so that no net flow is present. Therefore, if the pulsations increase the mass transfer in the $x$-direction along the plates compared to the no pulse case, it must then decrease the transport through the membranes. The reverse is true if the $x$-direction mass transfer decreases due to the pulsations. Although the flux and mass transfer in the $y$-direction does not yield useful results, the results for mass transfer in the $x$-direction will provide insight to the effect of flow pulsation on the transport through the membranes.

When no flow oscillations are present, the flux and mass transfer in the $x$-direction are

$$J_x = -D\frac{\partial C_{NP}}{\partial x} \tag{18}$$

and

$$Q_x = \int_{-h}^{h} J_x dy = 2\int_{0}^{h} J_x dy = -2D\int_{0}^{h} \frac{\partial C_{NP}}{\partial x} dy \tag{19}$$

respectively. Because of the two-dimensional geometry, the mass transfer will be in units of moles/time per unit width. When the pulsations are added, the flux becomes

$$J_x = -D\frac{\partial}{\partial x}(C_{NP} + C_P) + V_x(C_{NP} + C_p) \tag{20}$$

After time averaging over one period and recalling that $C_P$ is only a function of $y$, the flux is now

$$\bar{J}_x = \frac{\omega}{2\pi}\int_0^{2\pi/\omega} J_x dt = -D\frac{\partial C_{NP}}{\partial x} + 2\Re\{\tilde{V}_x\hat{c}\} \tag{21}$$

where $\Re$ represents the real part of $\tilde{V}_x\hat{c}$. The mass transfer will then be

$$\bar{Q}_x = -2D\int_0^h \frac{\partial C_{NP}}{\partial x}dy + 4\Re\left\{\int_0^h \tilde{V}_z\hat{c}dy\right\} \tag{22}$$

or in dimensionless form

$$\bar{Q}_x^* = -2k\int_0^1 \frac{\partial C_{NP}^*}{\partial x^*}dy^* + 4Pe\Re\left\{\int_0^1 \tilde{V}_x^*\hat{c}^*dy^*\right\} \tag{23}$$

with $\bar{Q}_x/D(C_{A1} - C_s)$. Note that the first term on the right hand side of the mass transfer is the same as the mass transfer when no pulse is present Eqn. (14). The effect of the pulse then lies in the second term, and this will then be the focus of our attention.

Plotting the second term, or the convective portion of the mass transfer, versus frequency of oscillation in Fig. 2 reveals that the mass transfer is both positive and decreases for increasing frequency of oscillation. This indicates that the flow pulsations cause more mass to be transported along the plates and less mass is being transferred through the membranes. Therefore, the separation of the gases flowing between the membrane boundaries decreases once the flow oscillations are started. The results also show that as the frequency of

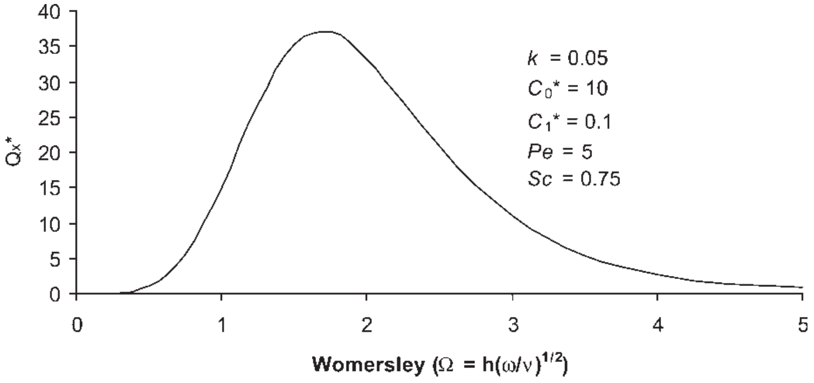

***Figure 2.*** Convective mass transfer versus Womersley number for oscillating flow between two flat membranes.

oscillation increases, the mass transfer in the *x*-direction asymptotes toward zero that says that it will eventually approach the no pulse system. Experiments were then performed in order to verify these results.

## EXPERIMENTAL SETUP

Experiments were performed using substituted polycarbonate based hollow fiber membrane fabricated by GENNERON® to purify nitrogen from an air stream by separating out the oxygen through the membranes. 180 of these fibers are encased in a tube with each fiber ranging in diameter from 120–140 mm and having a length of 61 cm. The range of the separation factor of these membranes was 6–8 which is defined as the oxygen to the nitrogen flow rate in the permeate stream. Here the reject is defined as the stream that exits the membranes and the permeate is the stream that runs on the outside of the membranes as the given species “permeates” or transports through the membranes to the outside stream. During these experimental runs, no sweep gas was used on the permeate side, and the permeate stream was configured in a counter-current fashion with one end completely closed and the other open to the atmosphere.

The schematic of the experimental setup is depicted in Fig. 3. Compressed air is fed to the membranes using a gas cylinder, and mass balances where initially done to determine if leaks where present in the experiment. Once the original mass balance was performed, the pressure in the lines into and out of the reject and permeate were monitored to see if any air leaks were present. These leaks were then found using a soap solution and fixed.

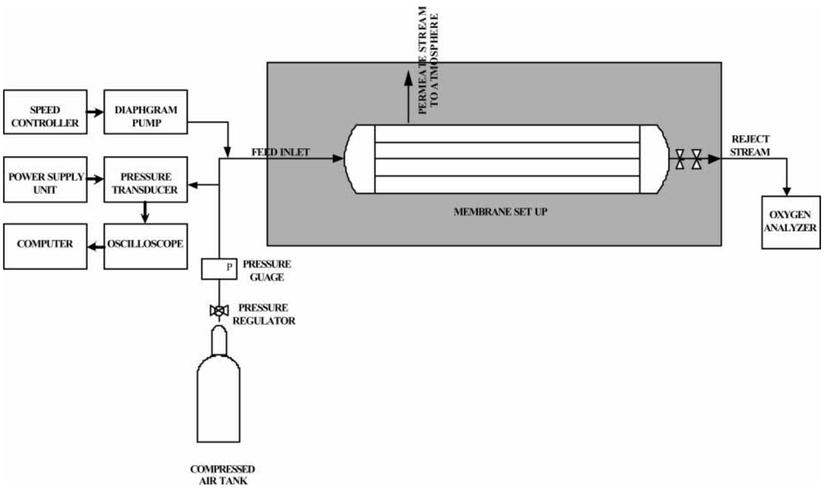

***Figure 3.*** Schematic of the experimental apparatus.

The flow pulsations were produced using a CRANE® pump with a diaphragm motor. The pump was then connected to a 3-speed controller so that the frequency of pump pulsations could be controlled. Pump pulsations at the inlet were observed using a pressure transducer connected to an oscilloscope and recorded with a computer. Flow pulsations were evident at the outlet using a hand-held flow meter that showed an oscillating flow rate. Although the outlet pulsations were not recorded, the aim was to ensure the pressure pulsations were observed at the outlet. The change in the percentage of oxygen in the reject stream was measured using a TELEDYNE® 3300PA oxygen analyzer.

Again, it may seem that the experiments and theoretical setup are not related. The experiment is a cylindrical geometry with pulsations imposed upon a steady flow while the theory is for flat plates without a steady flow. The change in the geometry will not qualitatively affect the trends observed in the model. The shapes of the velocity profiles in the channels will be similar to the velocity profile shapes in the cylinder. Therefore, the trends in the model demonstrate that the amount of oxygen in the reject stream will increase leaving less oxygen in the permeate stream thus indicating a decrease in the separation once the flow pulsations are introduced. This result should also be evident in the experiments. Further, as the flow oscillations increase, the effect should become less and less as predicted by the model. These observations in the model will not be effected by either a change in geometry or by adding a steady flow to the system. Although the results would be more accurate if these changes were added, the qualitative trends would remain the same.

## EXPERIMENTAL RESULTS

For the experiments, the pressure at the inlet of the membranes averaged 117 psig and 109 psig at the outlet. The maximum pressure change at the highest motor speed was observed to be 2 psig. Figure 4 depicts the average oxygen concentration for the flow pulsation above the average steady flow value measured from the experiments in the reject stream as a function of motor speed. Recall that the membranes are designed to remove oxygen in order to have a purified nitrogen stream in the reject. Figure 4 shows that as the flow pulsations are imposed upon the feed stream, the oxygen concentration rises in the reject indicating that less separation is evident with the introduction of the pulsations. A peak is reached around 1250 RPMs and decreases as the motor speed increases. This is similar to the analytical result that indicated the difference between the mass transfer for a pulsed and non-pulsed system would decrease for increasing frequency. Now, a motor speed of 750 RPM does not correspond to oscillating occurring 750 times a minute. For 750 RPM, a pulse cycle takes about 1.5 seconds and about 0.66 seconds at 1750 RPM. The ratio of the flow rates of the reject to the permeate stream

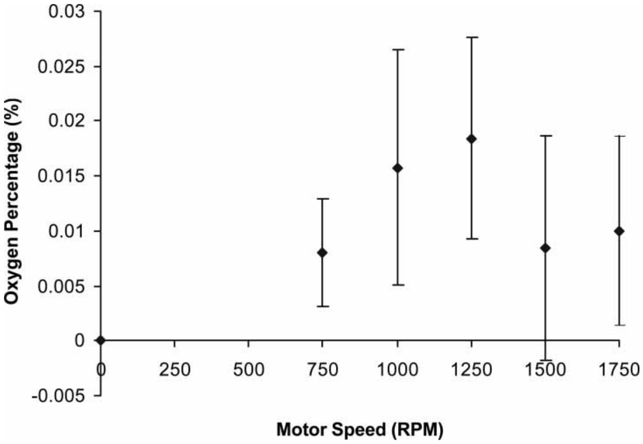

***Figure 4.*** Oxygen concentration above the steady flow value versus the motor speed of the pump.

averaged to be about 14%, and this ratio did not change with the addition of the flow pulsations.

## EXPLANATION OF RESULTS

Even though the model correctly predicted the experimental results, the findings were not expected considering the work of Krasuk and Smith (2) who were able to prove that increasing the frequency and amplitude of pulsations improved the mass transfer of ß-naphthol into water. Furthermore, using pulsating flows in reverse osmosis studies (3, 4, 5) show an increase in the permeation flux through the membranes due to the flow pulsations. The question becomes why our results show a decrease in separation whereas these other studies show an increase in permeation flux and mass transfer.

First, in the experiments of Krasuk and Smith, they transferred mass (ß-naphthol) from the wall into the bulk (water) by superimposing a pulse on the steady flow of the water. In this case, the flow pulsations produced a higher mass transfer, though the direction of species movement was from wall boundary into the bulk. In contrast for the membranes, transfer of mass needs to be in the opposite direction or from the bulk to the wall boundary to increase efficiency.

The proposed explanation for this difference is that pulsations not only increase the overall radial concentration gradients, but also increase the axial transport of species down the tube (6–8). Therefore, the increase in $O_2$ transport along the tube and out of the reject is much more than the effect of the increased radial concentration gradients, which will in turn produce a higher $O_2$ concentration in the reject stream. Furthermore, as the pulsation frequency increases, the time scale of oscillations compared to the time scale for species transport through the membranes must be important. In other words, as the time it takes to complete one oscillating cycle diminishes, the less time the species has to react to the oscillating flow profile. Eventually, the oscillations will occur so rapidly, that it will seem that the oscillations do not exist. Then, the result will begin to approach to the runs with no flow pulsations.

With the transfer of species from the wall to bulk, as is the case in Krasuk and Smith's study, the flow oscillations help increase the radial concentration gradients and aid in increasing the mass transfer down the tube. If one looks at the concentration difference between the wall and the bulk, it would be higher for pulsating flow as the gradients increase and the species is swept down the tube at a greater rate. This is depicted in Fig. 5 from situation a, with no pulses to b, when pulses are added.

Because the concentration difference is the driving force for mass transfer from the wall, the flux would therefore increase. The same is true for species that pass from the outside of the membranes, through the membrane wall, and into the lumen of the membrane. In steady flow, a buildup of species will form on the inside of the membrane wall causing a polarization of the membrane that in turn decreases the driving force across the membrane. Flow pulsations will reduce polarization by transporting species away from the wall and down the length of the membrane. This then increases the permeation flux through the membrane as the driving force becomes higher. However, the opposite situation occurs for the problem analyzed in this study. The flow pulsations have actually decreased the driving force through

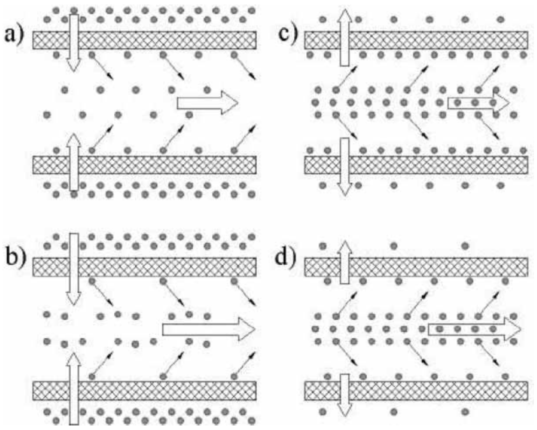

***Figure 5.*** a) Transport from outside the membranes to the lumen in steady flow. b) Transport to the lumen once pulses are added. c) Transport from lumen to the outside of the membranes in steady flow. d) Transport to the outside once pulses are added.

the membranes as species is being more rapidly transported from the entrance to the exit of the membrane as shown in Fig. 5c and d. There is less time for the species to transport through the membrane before it exits on the reject side. Therefore, the mass transfer through the membrane is less and the concentration in the reject stream is higher when flow pulsations are added.

## EXPERIMENTS WITH AIR ON THE OUTSIDE

It was decided to try and replicate the results of others with the current experimental set-up. This time, the airflow was changed to the outside of the membranes while the entrance of the membrane was attached to the pump with the exit open to the atmosphere to create the pulsations in the lumen. Measurements were again taken in the reject stream, the same side as the inlet air stream that is now on the outside of the membranes, so that a low $O_2$ concentration indicates a larger transport of $O_2$ through the membranes into the lumen. The results of this configuration depicted in Fig. 6 show that flow pulsations cause a decrease in the oxygen content in the permeate stream over that due to purely steady flow. Therefore, more oxygen is being transported through the membranes and out of the reject. The flow pulsations increase the mass transfer along the length of the tube and thus “draw” more oxygen through the walls of the membrane. This is consistent with the results one would expect based on the findings of Krasuk and Smith (2) and the explanation given previously.

It is important to note that although these experiments were performed on gas species, the same types of results would arise for liquid separations as well. Despite the 5 orders of magnitude difference in diffusion coefficients

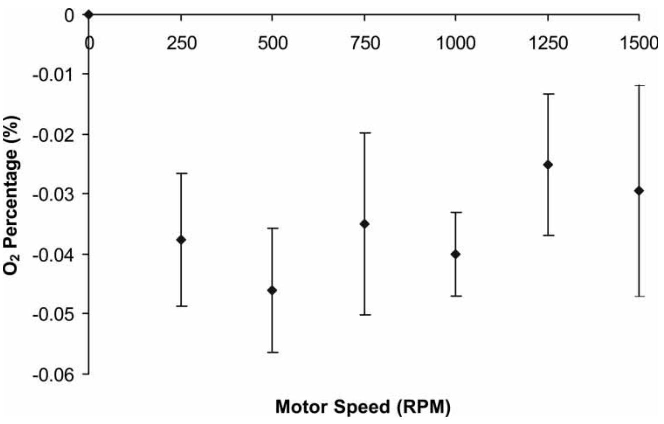

***Figure 6.*** Oxygen concentration below the steady flow value versus the motor speed of the pump for air on the outside of the membranes.

and the lower kinematic viscosity of liquids, the transport mechanism from the bulk flow to the boundary of the membranes is still the same. The effect of the flow pulsations on liquid separations would agree with the results for gas separations.

## CONCLUSIONS

Models were developed to predict the effect of flow pulsations on the mass transfer and resulting separation of species in a gas stream traveling through a system bounded by a permeable membrane. The simplified, two-dimensional model shows that the flow pulsations reduce the transport across the membrane boundary and thus reduce the purification of the gas stream. Experiments demonstrated that the purification of $N_2$ from a standard air stream traveling through hollow fiber membranes used to separate out $O_2$ indeed decreased as the flow pulsations were added. Flow pulsations increase the axial transport down the tubes so that it reduces the interaction time of the oxygen with the membrane boundary. For these processes, it is evident that flow pulsations that may arise due to improper flow control be eliminated as much as possible so that the highest membrane efficiency can be achieved. However, if one flows on the outside of the membranes, transport through the membranes into the lumen increases with flow pulsations added to the lumen.

## ACKNOWLEDGEMENTS

The authors would like to sincerely thank Dr. Wudneh Admassu and GENNERON® for their contributions to this work.

## REFERENCES

1. Graetz, L. (1883) Ueber die wärmeleitungsfähigkeit von flüssigkeiten. *Annalen der Physik und Chemie.*, 18: 79.
2. Krasuk, J. and Smith, J. (1963) Mass transfer in a pulsed column. *Chem. Eng. Sci.*, 18: 591.
3. Bellhouse, B., Bellhouse, F., Curl, C., MacMillan, T., et al. (1973) High efficiency membrane oxygenator and pulsatile pumping system and its application to animal trials. *Trans. Am. Soc. Artif. Intern. Organs*, 19: 72.
4. Kennedy, T., Merson, R., and McCoy, B. (1974) Improving permeation flux by pulsed reverse osmosis. *Chem. Eng. Sci.*, 29: 1927.
5. Baikov, V. and Znovets, P. (2004) Membrane processes of separation of solutions in a pulsating flow. *J. Eng. Phys. and Thermophys.*, 77 (4): 802.
6. Harris, H. and Goren, S. (1967) Axial diffusion in a cylinder with pulsed flow. *Chem. Eng. Sci.*, 22: 1571.

7. Jaeger, M. and Kurzweg, U. (1985) Tuning effect in enhanced gas dispersion under oscillatory flow conditions. *Phys. Fluids*, 29: 1324.
8. Thomas, A. and Narayanan, R. (2001) Physics of oscillatory flow and its effect on the mass transfer and separation of species. *Phys. Fluids*, 13: 859.