Design Parameters for a Research Prototype Contactor

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Abstract— **Rotating spiral contacting is a novel technology that allows an excellent control of contacting between two or more phases flowing countercurrently through spiral channel. This method solve the issues can arise from mixing fluids by using the centrifugal effect to enforce the fluids to flow side by side in a narrow channel in parallel layers without mixing. In this work the wide channel model was used to identify the design parameters for a research prototype rotating spiral contactor, and examine the performance within a wide range of operating conditions. The study included air – water system and started by selecting the optimum liquid layer thickness, ξ, that lead to optimum specific throughput, Φ_N^*, and the appropriate molar flow rate ratio, q_n for absorption process. Drawing the design envelope for pressure difference as a function of channel height was the best way of selecting the appropriate channel height, h, and also study the effect of using different values of spiral angle, $R\sin\alpha$. This later allow of selecting the suitable value of the distance between channel revolutions, t. Finally, this work presents the effect of using wide range of solute values, f' on the pressure difference, phases flow rates, and the rotation rate for fixed design parameters of a research prototype.**

Index Terms: **Fluid phase contacting, Design parameters, Rotating spiral channel, wide channel model, separation approach.**

I. INTRODUCTION

Your Separation processes commonly depend on bringing two fluid phases into close contact. This ‘phase contacting’ is achieved in a wide range of equipment that has evolved over many years to handle principally differing requirements of relative flow rates of the two phases. Conventionally, these separation processes have been carried out depend on mixing the two different phases using equipment capable of counter-current flow, and hence multiple stages of separation, includes packed columns, spray columns and bubble columns. The main purpose of mixing these phases is achieving close contact between the two phases so that solute species may be transferred rapidly and in a compact space. However, difficulties arise from the fact that the particle size of the dispersed phase and hence mass transfer efficiency is sensitive to the phase properties including those of the phase interface. Mainly, that serves relative velocity restriction results from small particle size and small separation distance.

Size of particles and spacing may have a broad distribution (same small particles with good mass transfer and same large particles with poor mass transfer. Finally, can say the particle size and distribution as well as relative velocity depends strongly on properties. Thus, using a given device for a range of phase and solute systems is not usually possible (Coulson et al, 2002; McCabe et al. 1985).

A novel approach to counter-current phase contacting that appears to avoid most of the difficulties and limitations of existing equipment has been proposed by MacInnes et al. (2005) and investigated further in subsequent work . This technology avoids passing one of the phases through the other, instead arranging the phases are allowed to flow countercurrently in parallel layers along a rotating spiral channel. This technology has the advantage of allowing phase contacting without mixing of the phases and gives a high level of control over the phase flow rate ratio and the relative thickness of phase layers (Fig. 1). This control is by adjustment of rotation rate and pressure gradient, both of which can be changed easily during operation.

The new technology has been demonstrated experimentally (MacInnes et al. 2010) in a successful implementation of counter-current multi-stage distillation. The experimental device used a self-contained batch process producing a situation of quasi-steady operation during which data could be recorded. The spiral channels were 255µm wide and 95µm deep, and the results obtained show an effective contacting can be achieved over long channel distances which produce large number of separation stages. MacInnes et al. (2005), introduced preliminary modelling of the spiral operation and computations to determine the importance of Coriolis motion was presented. The analytical solution model explains the way of fluid phase contacting where the phases are made to flow counter currently along spiral channel in parallel layers controlled by centrifugal force and pressure gradient.

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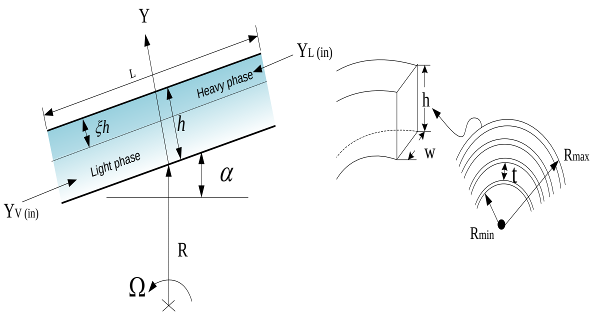

Figuare 1. Nomenclature and Geometry for two – Phase Parallel Flow in Rotating Spiral Channel

The modelling work followed successful demonstration experiment of multistage distillation by MacInnes et al. (2010) in which seven stages of separation were produced. The model has been developed by MacInnes et al. (2012) to include a comprehensive explanation of the analytical solution equations for parallel laminar flow of two phases in a uniform section spiral channel and provides a theoretical basis for equipment design.

The aim of this study is to present the requirements of a research prototype rotating spiral contactor for gas – liquid system. These requirements include produce high quality data of relevant concentrations at relevant points in the contacting process which means wide range of purification factor, a_V ($a_V = Y_V(in)/Y_V(out)$). Also, the research prototype should have the ability of reaching high flow rate and hence the upper stability limits. The analytical equations presented by MacInnes et al. (2012) show increasing the value of upper stability limits can occur by using larger channel height, h, larger rotation rate, Ω, or larger channel angle, $R\sin\alpha$ which already has the same effect of increasing the rotation rate. On the other hand, the research prototype should allow operation at low stability limits which means low Ω, small h, and small R_{min} (the minimum radial position). Changing the channel geometric parameters (L, h, $R_{\min}$, and $R\ \sin\alpha$) would require making a new spiral and the prototype should allow spiral geometry to be changed with considering minimal cost and time. Thus, a design with spiral element insets requires simplest possible fabrication steps in addition to cutting the spiral that should be used.

II. WIDE CHANNEL MODEL

For design purposes, the specific throughput, Φ_{v}, considered one of the important measures of performance, which is the flow rate of the vapour phase per passage volume for one equilibrium stage. Using a characteristic diffusion time scale, τ_{v} to non-dimensionalise specific throughput and light properties to scale the various parameters produces the non-dimensional specific throughput parameter:

$$\Phi_V^* \equiv \Phi_V\,\tau_V = -K_V^* \frac{\left(1+f^{'}q_n\right)}{\ln\left(-f^{'}q_n\right)} \tag{1}$$

Where,

$$\tau_V = \left(\left(h^{-1}\right)^2 D_V\right)^{-1} \quad K_V^* = \frac{K_V\,h}{n_V\,D_V}\ .$$

The specific throughput measures of mass transfer efficiency as its relative to the diffusion in vapour phase, D_v , and for a give diffusion length, h^{-1}, phase conditions (n_v, f and D_v), and the molar flow rate ratio, q_n, the specific throughput will be at the greatest value in a device giving the largest non-dimensional mass transfer coefficient, K_v. In general this can be used to guide selection of the most suitable molar flow arte ration, q_n and the appropriate liquid layer thickness, ξ. The ratio between the non- dimensional volume flow rates of the light and heavy phase presents the flow rate ratio, q:

$$q = \frac{q_n}{n_r} = \frac{Q_V^*}{Q_L^*} \tag{2}$$

Where;

$$Q_V^* = \frac{\left(1-\xi\right)^2\left[3\left(1-\gamma\right)\mu_r\xi^2+\left(1-\rho_r\gamma\right)\left(1-\xi\right)\left(1-\xi+4\mu_r\xi\right)\right]}{1-\left(1-\mu_r\right)\xi} \tag{3}$$

$$Q_L^* = \frac{\mu_r\xi^2\left[3\left(1-\rho_r\gamma\right)\left(1-\xi\right)^2+\left(1-\gamma\right)\xi\left(4\left(1-\xi\right)+\mu_r\xi\right)\right]}{1-\left(1-\mu_r\right)\xi} \tag{4}$$

The normalization of these non-dimensional flow rates can be done by using the volume flow rate per width of channel for the light phase in the same channel without rotation and with no heavy phase is defined as:

$$Q_o = -\frac{h^3}{12\mu_V}\frac{dp}{dx} \tag{5}$$

$$Q_V = Q_V^* Q_o \tag{6}$$

It clear from “(3),” and “(1),” the value of these flow rates depend on just phase properties and the value of centrifugal body force and pressure force acting on the heavy phase, γ:

$$\gamma = \frac{\rho_L R\Omega^2\sin\alpha}{dp/dx}\ ,\quad \rho_r = \frac{\rho_V}{\rho_L}\ ,\quad \mu_r = \frac{\mu_V}{\mu_L} \tag{7}$$

Forming, the flow rate ratio “(2)”, using “(3)”, and “(4)” and solving γ produces a valuable equation for this parameter in terms of the phase property ratios, the phase flow rate ratio and heavy phase fraction in the channel (MacInnes, et al. 2012).

It is obvious that, optimizing specific throughput lead to select optimum conditions of molar flow rate ratio, q_n, and the thickness of liquid layer, ξ. Choice of q_n dictated by solute distribution characterizations ($f^{'}$) where, $q_n = -1/f^{'}$. Also, choice the molar flow rate ratio depends on the cost of regeneration as a function of q. Then, the values of γ, Q_v, and Q^*_L which normalized by Q “(5)”, can be determined. After ensuring the sufficient level of rotation rate ($R\Omega^2$) that required to control surface forces and interface waves, the value of $R_{\min}$ (the minimum radial position) can be decided with considering the fittings and the central hardware of the device. Small distances between channel revolutions lead to wide range of operation but at the same time requires high level of tolerance in fabrication process

The procedure of determine a practical operating conditions starts with selecting the appropriate value of the spiral angle, *R* sin*α* which a function of the distance between channel revolutions, *t* ("Figure. 1").

Selecting of the channel height, *h*, and the upper stability limit of light phase, R_{ev}, lead to determine the volume flow rate of light phase, Q_v, and the pressure difference, *dp/dx* from " 5", and "(6)":

$$\mathrm{Re}_V = \frac{\rho_V Q_V}{\mu_V} \tag{8}$$

Consequently, the value of rotation rate, Ω, can be calculated directly using "(7)". To determine the spiral channel length, *L*, and hence the maximum radial position, $R_{\max}$, deciding the stream purities (a_V and a_L) is required, then determines the length of the spiral:

$$L = N\,\ell_e \tag{9}$$

Where, *N* is the number of equilibrium stages and l_e is the length of one equilibrium stage.

MacInnes et al. (2012) defines the number of equilibrium stages for the case of linear equilibrium curve and contact phase flow rates along the channel can be expressed in terms of solute compositions at the inlets and outlets from the channel. Therefore, in terms of relative concentrations a_V and a_L :

$$N = \frac{-\ln\left\{\left[1-f\,'a_L + f\,'q_n\left(1-a_V\right)\right]/\left[a_V - f\,'a_L\right]\right\}}{\ln\left(-f\,'q_n\right)} \tag{10}$$

Where, a_V and a_L are the concentration of solute in the light phase outlet and at the heavy phase inlet respectively.

$$a_V = \frac{Y_V(0)}{Y_V(L)} \quad \text{and} \quad a_L = \frac{Y_L(L)}{Y_L(0)} \tag{11}$$

It has been shown in the equations of wide channel model the effect of molar flow ratio, q_n on both specific throughput and mass transfer coefficient, "(10)", above shows also a direct effect of the molar flow rate ration on the number of equilibrium stages, *N*. The length of one equilibrium stage can be defined as follows:

$$\ell_e = \frac{u_V\, n_V\, h(1-\xi)}{K_V}\,\frac{\ln(-f\,'q_n)}{1+f\,'q_n} \tag{12}$$

Where, n_v is the light phase molar density, K_V is overall mass transfer coefficient for light phase, and u_v is the average velocity of light phase in the bulk.

MacInnes et al. (2012) states that a uniform parallel flow of two phases along the spiral channel can be affected by a number of different factors lead to instability situation in liquid phase layer and cause growing of waves at the phase interface. There are not reliable limitations for these different stability factors yet, but MacInnes et al. (2012) proposed the following criteria as a useful starting point for preliminary analysis:

Reynolds number (light phase),

$$\mathrm{Re}_V = -\frac{\rho_V u_V\, h(1-\xi)}{\mu_V} < \mathrm{Re}_C = 500$$

Reynolds number (heavy phase),

$$\mathrm{Re}_L = \frac{\rho_L u_L h\xi}{\mu_L} < \mathrm{Re}_C = 500$$

Froude number,

$$\mathrm{Fr} = \frac{u_L h\xi}{\sqrt{R_{\min}\Omega^2\xi^3 h^3}} < Fr_C = 0.5$$

Weber number,

$$\mathrm{We} = \frac{\rho_V\left(Q_L/\xi - Q_V/(1-\xi)\right)^2}{\sigma h} < 5.0$$

Eötvös number,

$$\mathrm{Eo} = \frac{\Delta\rho R_{\min}\Omega^2 h^2}{\sigma} > \mathrm{Eo}_C = 1.0$$

Rotation rate,

$$\frac{R_{\min}\Omega^2}{g} >> 1 \tag{13}$$

Reynolds numbers for light and heavy phases are criteria for laminar flow and the critical value ($\mathrm{Re}_C = 500$) gives the maximum laminar flow rate. Froude number and Weber number are criteria for stability of the phase interface give the limits of wave formation and interfacial tension waves, respectively. The final two criteria (Eötvös number and rotation rate) state that the centrifugal force has to be large enough to control the surface forces (MacInnes et al. 2012)

III. RESEARCH PROTOTYPE

The study focus on the requirements of an experimental apparatus that can be used to determine the true stability limits, provide high quality data over a range of operation conditions. It is envisaged that the prototype will use liquids and gases having properties similar to those of water and air. Indeed in the following computations the properties used are those of water and air at standard conditions which are listed in Table (1).

For selected phase and solute system, $f' = 1$, the liquid layer thickness, ξ, and molar flow ratio, q_n can be chosen in principle by optimizing contacting. For gas – liquid contacting, the optimum value of non- dimensional specific throughput can be at too small values of liquid layer thickness for different values of molar flow ratio, q_n ("Figure.2") which practically difficult to control, thus in this case ξ = 0.1 is assumed on practical grounds to be suitable lower limit.

With regard to selecting the molar flow rate ratio, q_n, leading to optimum overall performance, it is clear that from the equations presented in wide channel model changing the flow rate ratio will affect the number of equilibrium stages, *N*, and consequently the specific throughput. Moreover, the flow rate of solvent stream will be changed by changing the flow rate ratio. Thus, the optimum value of flow rate ratio cannot be selected

Table 1. Properties of Air and Water at 20 ^{0}C and 1 Atm

Property / **Fluid**	**Density,** ρ kg/m^3	**Viscosity,** μ **Pa s**	**Diffusivity, D** m^2/s
Air	1.20	1.8×10^{-5}	2.14×10^{-5}
Water	1000	1.0×10^{-3}	1.8×10^{-9}

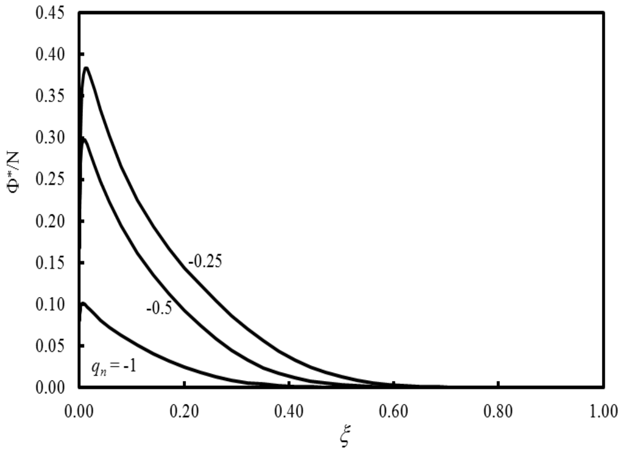

Figure 2. Optimum Non-Dimensional Throughput for Air – Water Absorption system

without comprehensive information related to the solvent stream treatment.

For air – water system the non- dimensional specific throughput calculated directly from the wide channel model as a function of flow rate ratio ("Figure. 3"). In this study assumed given purification, $a_V = d_L = 0.01$ and the solvent inters the process free of solute, $a_L = d_V = 0$.

The effect of changing the flow rate ratio on specific throughput and liquid layer thickness ξ, plotting the flow rate ratio relative to the critical value $q_{nC} = -1/f'$ at which value an infinite number of stages is required and this is when $q_n/q_{nC} = 1$ that leads to specific throughput tends to zero. The figure shows that away from the critical value $(q_n/q_{nC} = 1)$ the specific throughput changes gradually. It is clear that to the left of this point $(q_n/q_{nC} < 1)$ the figure presents the absorption process where the solute moves from light to heavy phase and to the right of this point the opposite occurs for desorption process. The optimum value of liquid layer thickness ξ decreases gradually with increasing q_n/q_{nc} and crossing the value of 0.006 at the critical flow rate ratio which is too small. Therefore, MacInnes et al. (2012) used the value of liquid layer fraction is equal to 0.1 as minimum allowed value. For this fixed value of liquid layer thickness (ξ=0.1) which appear in "Figure. 3", (dashed line), the specific throughput decreases by a factor of two for a selected value of flow rate ratio. It is too difficult to select the optimum value of flow rate ratio without a range of information about the solvent stream and its treatment. For these reasons reasonable values of flow rate ratio relative to critical are assumed to be $q_{n}= q_{nc}/2$ and $q_{n}= 2q_{nc}$ for absorption and desorption respectively.

A. Design Envelop

Using the critical values of stability limits, the design envelope can be plotted for any operating parameters of interest as a function of channel height to produce the operating region and hence identifying the appropriate channel size.

For an absorption process of air - water system, $f' = 1$, $q_n = -0.5$, and $\xi = 0.1$. Initially the distances between channel revolutions, t, is assumed to be equal to channel height ($t = h$). The design envelope plot of pressure drop as a function of channel height, h ("Figure. 4") shows the upper limit for pressure drop (that related to flow rate) is controlled by the flow-based stability parameters (Re_V, Re_L, Fr, and We) and the lower stability limits controlled by centrifugal force and Eötvös number (surface forces). In this case the Reynolds number of light phase, Re_v, dictated the upper limit of the operating region over a range of channel height. However, at small values of channel height, one can see that the stable operation may be determined by the Weber number, W_e,

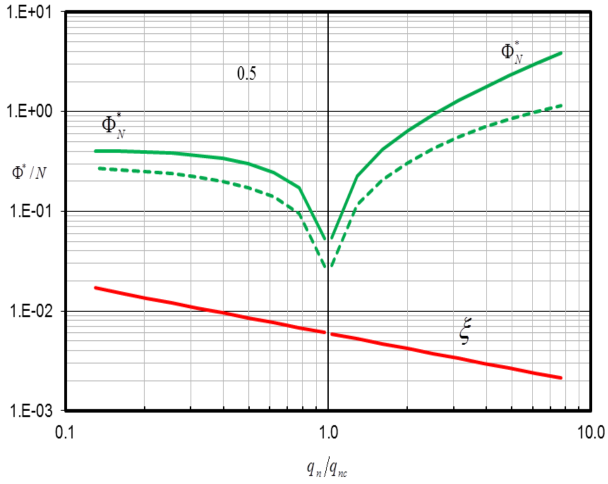

Figure 3. Optimum Liquid Layer Thickness and Specific Throughput for Standard Air – Water System

Rather than Reynolds number of light phase ("Figure. 4"). For other systems of contacting not only Reynolds number of light phase (or Weber number) can be the upper limits but also other instability modes may determine the upper boundary of operation, e.g. Fr or Re_L. "Figure. 4", illustrates that channel height of 1mm can allow acceptable wide range of pressure drop with maximum value 5000Pa at maximum flow rate (Re_v =500). The design envelope shows bigger channel height also can be used up to 3mm but this choice will limit the operating region regarding to pressure drop. Further computations in this study will consider channel height, h=1mm as a reasonable choice. Also, the channel width is assumed to take the value $w = 5mm$ depending on that the wide channel model assumes infinite width; the value of 5mm is corresponding to $w/h >> 1$ as minor approximation

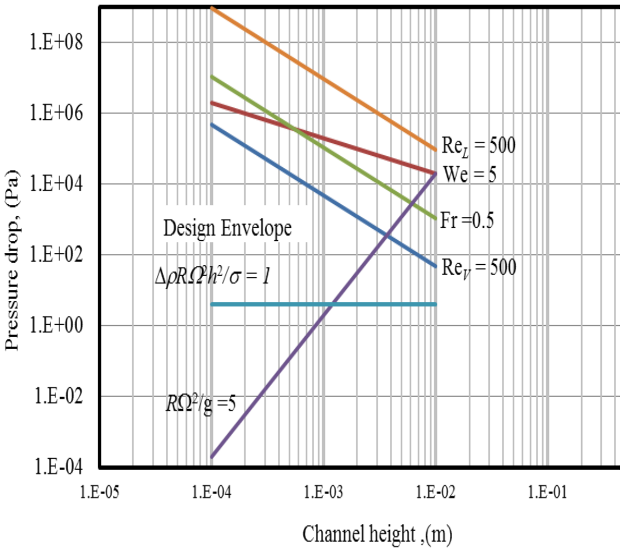

Figure 4. Stability Envelope Plot for Pressure Difference Ever ChannelL length; Standard Air-Water System

B. Speiral Channel Angle

A priority in initial prototype device will be to establish practical operating envelops of two particular importance are the maximum stability limits and the spiral channel angle. The upper limits expected to be greater than the values assumed in “13”. Impose and experiments to explore the high flow rates will be valuable. The wide channel model illustrate that the one way to increase the flow rate for an allowed maximum rpm is to increase the spiral angle. Also, small spiral angle may require an extreme cost of fabrication to ensure dimensional precision. Thus, testing a range of spiral angle in prototype device is important. Spiral channel angle, R sinα is a function of *t/h*, thus this study will consider different values of *t/h* which are, *t/h* = 1, 5, 10, and 15. “Figure. 5”, below shows the stability envelopes plot of pressure drop along the spiral channel length at different values of *t/h*.

“Figure. 5”, presents that increasing the value of *t/h* will leads to limit the operating region of selecting bigger channel size above 1.7mm. Channel size of, *h=1mm*is suitable to all values of *t/h* with maximum pressure drop allowed 5000pa (maximum flow rate). Moreover, there is more flexibility for *t/h* =1 to use bigger channel size up to around 3mm. Also, the value of *t/h* = 1 to 5h presents wide range of pressure difference allowed in comparison with value $t/h = 15$.

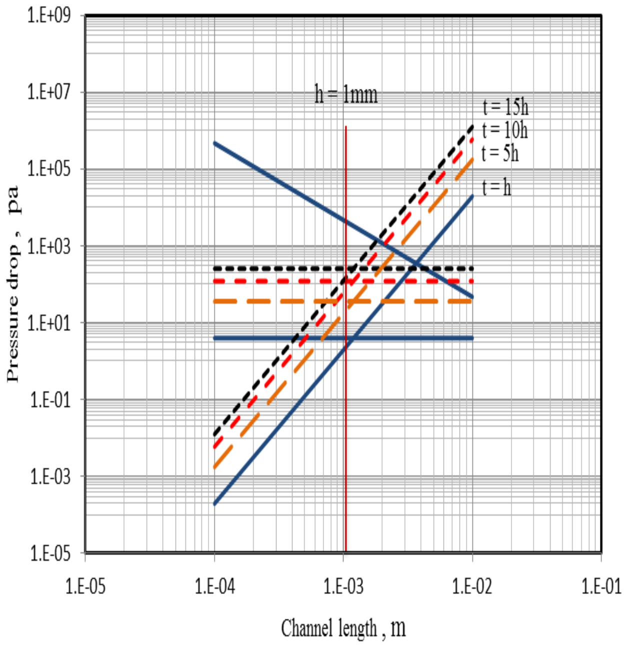

Figure 5. Stability Envelopes for Pressure Drop Along Spiral Channel Length at Different Values of *t/h*

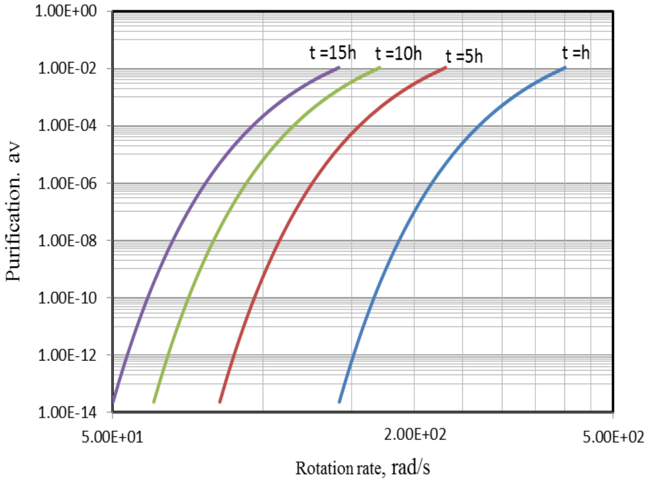

Figure 6. The Effect of Increasing the Distances between Channel Revolutions on Rotation Rate

“Figure. 6”, above shows for a fixed purification value, a_V = 0.01 (fixed channel length, L=2m) with selected channel height, h=1mm, increasing the distance between channel revolutions lead to decrease the rotation rate, Ω, which very important to be at maximum value to produce a separated layers of the two phases. Increasing the distance between channels revolutions, t lead to increase the value of R_{max} which consequently lead to reduce the rotation rate and hence the maximum flow rate. The same trend can be seen in case of fixing the spacing value (t=h) and using different channel length, L, “Figure. 7”, shows the relation between the rotation rate and the purification using different lengths of spiral channel. For a fixed value of rotation rate, e.g. 300 rad/s increasing channel length from 2m to 3m will lead to increase the purification by a factor of 32 while for a fixed purification value increasing the length requires increasing the rotation rate by a factor of 1.25.

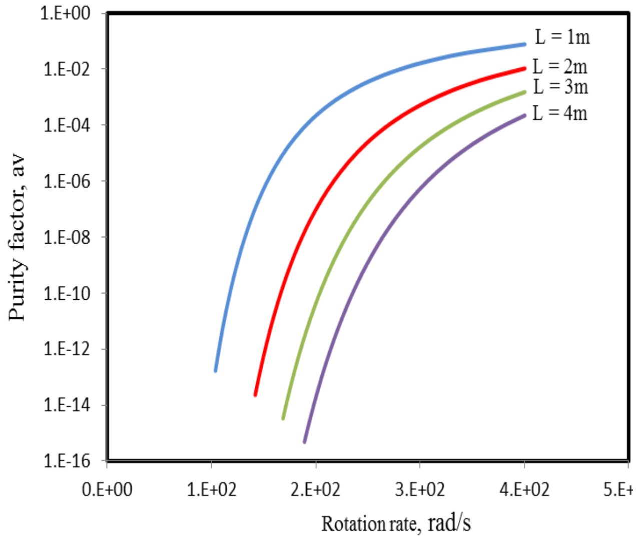

Figure 7. The Effect of Channel Length on Purification and Rotation Rate

The maximum radial position, $R_{\max}$, increasing by both increasing the distances between channel revolutions and using long spiral channel which consequently lead to unacceptable phase interface conditions. Thus, as initial expectation using spiral channel with 2m length produce reasonable of $R_{\max}$ and Ω (400rad/s and 4.03cm respectively). Also, it has been found that using small spiral angle and small spacing for multiple interleaved channels produce small dense channel packing with small value of R_{max} .

C. Phase and Solute System

Concerning the differences in solute distribution in the phases is a very important parameter since it determines the flow rate ratio ($q_n = -1/f'$). Solute molecules giving very different equilibrium distribution (f' in the model), thus will be interest in the prototype experiments to examine this parameter. Following the initial computations for $f' = 1$ at $R\sin\alpha$ corresponding to $t = h$ and other values ($t = 5h$, $10h$, and $15h$), studies are then made for a wide range of solute f' values. “Figure. 8”, below illustrates the effect of using a wide range of solute ($f' = 10^{-4}$ to 10^{4}) on the rotation rate and pressure difference.

“Figure. 8”, shows at small value of f' the rotation rate is small too because of the small value of liquid flow rate (“Figure. 9”) then the water flow rate reaches an approximately constant level due to the requirements of fixed purification. In the same region “Figure. 8”, shows the rotation rate is also nearly constant ($\approx$400 rad/s), because the rotation responsible to drive the heavy phase through the spiral channel.

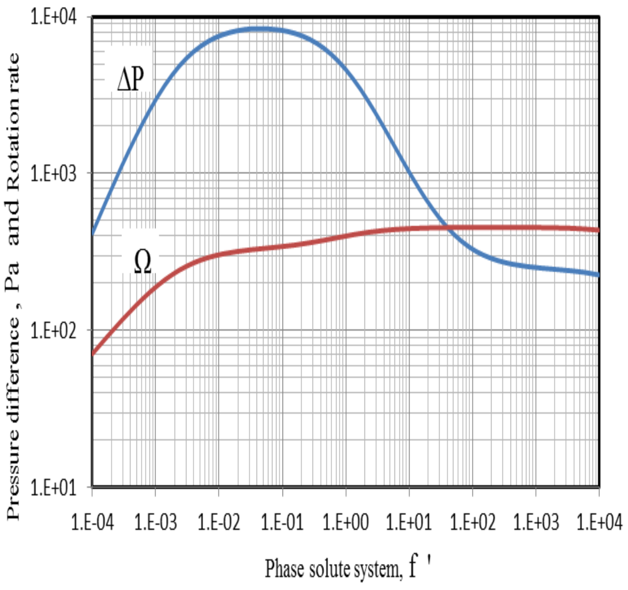

Figure 8. The effect of Changing the Phase Solute System on Pressure Difference and Rotation Rate

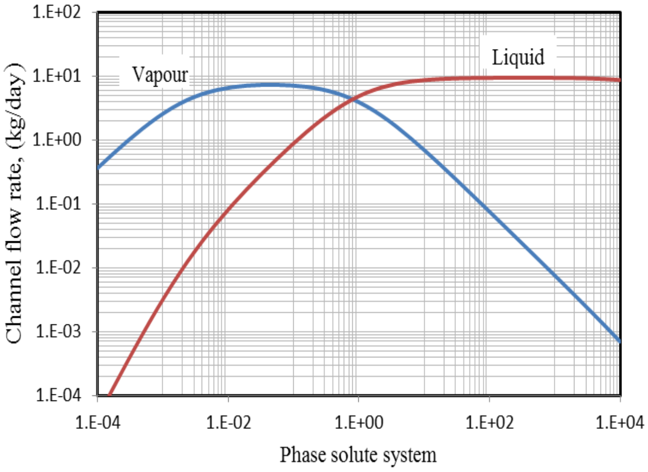

Figure 9. The Effect of Changing the Phase Solute System on Phases Flow Rates

The most important findings in this part of study is that the pressure difference, ΔP, remains small in relation to pressure absolute which mean the density of light phase ρ ρ_V , is nearly constant. The second important thing is that for a wide range of solute value (f') the rotation rate is nearly constant ($\approx$400rad/s) with fixed value of liquid layer thickness and purification (ξ = 0.1 and a_V = 0.01).This lead to an idea of one electrical motor can be suitable to run different experiments of different solute.

IV. CONCLUSION

Wide channel model presents its power to choose and identify the appropriate design parameters for a research prototype at wide range of operating conditions. Its flexibility of changing the conditions and the other parameters i.e. choosing the optimum liquid layer thickness that lead to optimum throughput makes it an important point of interest. The study showed using the way of plotting the design envelope with selected operating condition, a research prototype with channel height, h =1mm, channel length, L=2m, channel width, w =5mm, and spacing distance, $t = h$ =1mm, can be a very compact device ($R_{\max}$ =4.03cm) and handle wide range of solute values ($f' = 10^{-4} - 10^{4}$) with approximately constant rotation rate (one electric motor).

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BIOGRAPHIES

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