

The Efficiency of Osmotic Pipe Flows

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We present experiments and theory for flows of sugar or salt solutions in cylindrical tubes with semi-permeable walls (hollow fiber membranes) immersed in water, quantifying the strength of the osmotic driving force in relation to the dimensionless parameters that specify the system. The pumping efficiency of these flows is limited by the presence of “unstirred” concentration boundary layers near the tube walls and our primary aim is to understand and quantify these layers and their effect on the flow. We measure the outlet flow rate Q_{out} while varying the inlet flow rate Q^* , concentration c^* , and tube length L , and map out the dependence of the flow rate gain $\gamma = Q_{\text{out}}/Q^* - 1$ on these parameters. A theoretical analysis based on (1) the known velocity field for slow flow in cylindrical porous tubes and (2) a parabolic concentration profile, allows us to compute analytically how the flow gain depends on the relative magnitude of radial diffusion and advection as well as the ratio of the osmotic velocity to pumping velocity, in very good agreement with experiments and with no adjustable parameters. Our analysis provides criteria that are useful for optimizing osmotic flow processes in e.g. water purification devices.

I. INTRODUCTION

Channel flows – liquid flows confined within a closed conduit with no free surfaces – are found in many natural and man-made systems. In animals [1] and plants [2] they serve as the building blocks of vascular systems, distributing energy to where it is needed and allowing distal parts of the organism to communicate. When constructed by humans, one of the major functions of channels is to transport liquids or gasses, e.g. water (irrigation and urban water systems) and energy (oil or natural gas) from sites of production to the consumer or industry. In some cases, the channels have solid walls which are impermeable to the liquid flowing inside. In other cases, the channels have semi-permeable membrane walls allowing solvent flux while rejecting solutes.

The effect of semi-permeable porous walls is especially important in the study of biological flows due to the presence of semi-permeable membranes and porous cell walls [2] and in industrial separation processes [3]. In these cases, the exchange of water across the membrane can be driven by either hydrostatic or osmotic pressure differences, thus modifying the bulk axial flow in the channel. A serious limitation to the performance of osmotic flows is that the entry of water into the tube lowers the solute concentration next to the membrane, as shown in Fig. 1. This negative feedback leads to a decrease in trans-membrane flow that can affect the efficiency of both natural and engineered systems, such as sugar transport in the phloem vasculature of plants and water purification in filtration devices. Osmotic flows are exceptionally

complicated to analyse due to the intrinsic nonlinear nature of the flow which arises due to the coupling between the velocity and concentration fields, see e.g. [4–9]. Only in a few cases have experiments been compared directly to theory, see e.g. [10–12].

In this article, we report experimental results of osmotic flows through a long, narrow cylindrical tube with porous walls. A simple continuum model predicts that the osmotic pumping efficiency is determined solely by two parameters: a Péclet number β (see Table I and II for parameter definitions) and the maximal osmotic velocity scaled by the inlet velocity Γ . These parameters characterize the unstirred layer effects and the relative importance of feed and osmotic flows. Moreover, we observe that the pumping efficiency scales in an unexpected way with the parameters in the problem and show that our model correctly accounts for this scaling.

II. EXPERIMENTS

We flow aqueous solutions of sucrose ($\text{C}_{12}\text{H}_{22}\text{O}_{11}$) and sodium chloride (NaCl) through an experimental setup that consists of a long, narrow cylindrical hollow fiber membrane tube immersed in a reservoir containing pure water. The hollow fiber membrane was kindly supplied by Dr. Wang Rong, Singapore Membrane Technology Center, Nanyang Technological University, Singapore. It was fabricated by interfacial polymerization of a polyethersulfone substrate as described in [13, 14] where the membrane used in this study is denoted the #B type. A picture and a schematic sketch of the setup is shown in Fig. 2. We control the inlet flow rate by connecting the membrane tube to a syringe pump (Chemyx Inc., Fusion 400) and at the outlet, the solution flows into a reservoir at atmospheric pressure. The inlet flow rate and the so-

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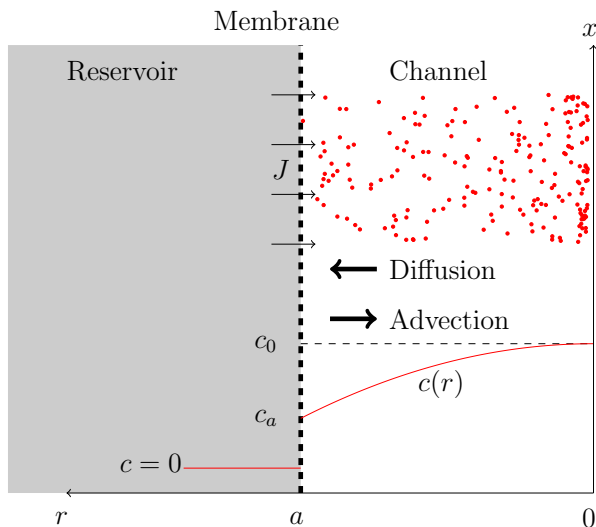


FIG. 1. (Color online) Sketch of the solute concentration $c(r)$ (solid red curve and density of dots) in a cylindrical tube of radius $r = a$ in contact with a reservoir containing pure solvent ($c = 0$). The semi-permeable membrane separating the two solutions is indicated by the thick dashed line. The concentration difference between the reservoir and channel drives an osmotic flow of solvent $J \propto c_a$ (thin arrows, see Eq. (2)) across the membrane. This dilutes the solution next to the membrane, and the concentration of solute in contact with the membrane $c_a = c(a)$ is therefore lower than the value $c_0 = c(0)$ at the center of the tube. The concentration profile $c(r)$ is set by the relative magnitude of diffusive and advective fluxes (thick arrows). At the membrane interface ($r = a$), there can be no net flux of solute molecules $J_s = -D\partial_c + Jc_a = 0$, which determines the relative magnitude of c_0 and c_a , see Eq. (12).

lute concentration is varied over an order of magnitude: the flow rate from $Q^* = 0.2 \text{ mm}^3/\text{s}$ to $Q^* = 1.7 \text{ mm}^3/\text{s}$ and the concentration from $c^* = 0.05 \text{ M}$ to 1 M for NaCl and from $c^* = 0.05 \text{ M}$ to 0.5 M for sucrose. The radius of the tube is held constant at $a = 0.5 \text{ mm}$, while the length of the tube is varied from $L = 6.2 \text{ cm}$ to $L = 13.6 \text{ cm}$. This approach allows us to measure the flow rate gain due to osmotic influx, defined as the ratio of outlet to inlet volumetric flow rates

$$\gamma = \frac{Q_{\text{out}}}{Q^*} - 1 = \frac{u_{\text{out}}}{u^*} - 1 \quad (1)$$

as a function of geometric and material properties of the problem. Here, Q_{out} and $u_{\text{out}} = Q_{\text{out}}/(\pi a^2)$ are the flow rate and average axial velocity at the outlet, respectively, and $u^* = Q^*/(\pi a^2)$ is the average inlet velocity.

We use a balance (Sartorius CP 423S) to measure mass flow at the outlet. Typical flow rate gains vary over two orders of magnitude from $\gamma = 0.1$ to $\gamma = 10$. A representative experimental graph is shown in Fig. 3(a). Here, the effect of varying inlet flow rate at fixed solute concen-

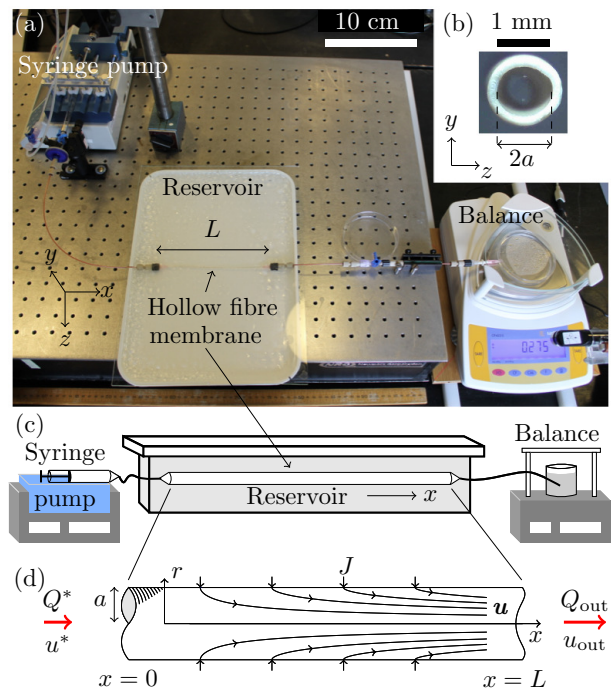


FIG. 2. Experimental setup. (a) Picture of the experimental setup. The syringe pump injects an aqueous solution of NaCl or sucrose into the hollow fiber membrane tube which is immersed in a reservoir containing pure water. The flow along the x -axis in the tube accelerates from the initial value Q^* due to osmotic exchange of water across the semi-permeable wall. We measure the resulting outlet rate Q_{out} using a balance. (b) Cross section view of the hollow fiber membrane tube. The inner diameter of the tube is $2a = 1 \text{ mm}$ and the wall thickness is $d \simeq 200 \mu\text{m}$. (c) Schematic of the experimental setup. (d) Sketch of the cylindrical flow geometry. The velocity field \mathbf{u} (streamline arrows, see Eqns. (5)-(6)) is determined by the average inlet flow velocity u^* and the trans-membrane flux J .

tration is illustrated. At large inlet flow rates, the solute is advected quickly through the tube and the osmotic flow has little effect. At low flow rates, however, we observe a strong gain. Similarly, Fig. (b) shows the effect of varying the solute concentration at fixed inlet flow rate. At low concentrations there is no net gain (i.e. $\gamma \ll 1$) since no osmotic flow occurs and we are simply observing the effect of the syringe pump. At $c^* = 1 \text{ M}$, however, the gain is significant ($\gamma \simeq 1$) and the axial flow in the membrane tube is strongly influenced by the osmotic pumping. To quantify the pumping process, we measure the gain as a function of inlet flow rate Q^* , and inlet solute concentration c^* for two different solutes which yields a total of 216 data points, shown in Fig. 3(c-d).

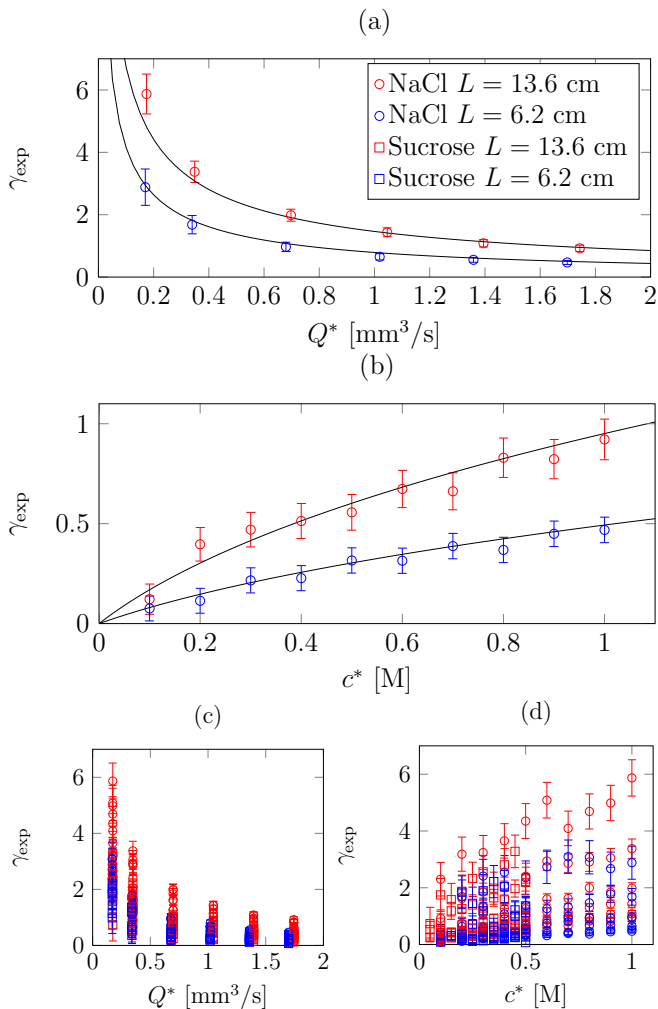


FIG. 3. (Color online) Experimental data, recorded with NaCl (a-d) and sucrose (c-d) as the solute. (a) Flow rate gain $\gamma = Q_{\text{out}}/Q^* - 1$ plotted as a function of inlet flow rate Q^* for constant inlet NaCl concentration $c^* = 1.0$ M. (b) Flow rate gain γ plotted as a function of inlet NaCl concentration c^* for constant inlet flow rate $Q^* = 1.7$ mm^3/s . In (a) and (b), solid lines show theoretical predictions from Eq. (21) with no free parameters. In (c) and (d), experimental data from all 216 experiments using sucrose and NaCl are shown.

III. THEORY OF OSMOTIC PIPE FLOWS

As previously described, we propose that the flow of water across the membrane wall is driven by osmotic pressure differences with a modification due to the presence of concentration boundary layers. Aldis was the first to consider the effect of unstirred layers on osmotic flow in a cylindrical tube [11]. He found analytical solutions for the concentration and velocity fields in the limit of strong radial diffusion (boundary layer effects negligible) and for short distances using a series expansion. Our experiments, however, satisfy neither of these criteria and we proceed to analyse the problem in the general case.

We begin by writing the water flux J across the semi-

TABLE I. Non-dimensional parameters.

| | | | |
|--------------------|----------|----------------------------------|---------------|
| aspect ratio | α | $= aL^{-1}$ | 0.004 – 0.008 |
| flow rate gain | γ | $= Q_{\text{out}}(Q^*)^{-1} - 1$ | 0.1 – 10 |
| max flow rate gain | Γ | $= 2L_pRTc^*L(u^*a)^{-1}$ | 0.08 – 20 |
| Péclet number | | | |
| - axial | Pe_x | $= u^*LD^{-1}$ | $10^3 - 10^5$ |
| - radial | Pe_r | $= L_pRTc^*aD^{-1}$ | 0.3 – 3.9 |
| - mixed | Pe | $= u^*aD^{-1}$ | 68 – 2100 |
| - boundary layer | β | $= u^*a^2(6DL)^{-1}$ | 0.04 – 2.8 |
| Reynolds number | Re | $= \rho u^* a \eta^{-1}$ | 0.1 – 1 |

TABLE II. Material parameters at $T = 20^\circ\text{C}$. Values for D , R , and η was obtained from [15]

| | | |
|---------------------------------|--------|--|
| tube radius | a | 500 μm |
| concentration at inlet | c^* | 0.05 – 1 M |
| thickness of membrane tube wall | d | 200 μm |
| diffusion coefficient | D | $5.2 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$ (S) $1.6 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$ (NaCl) |
| length of membrane tube | L | 6.2 cm, 13.6 cm |
| permeability of membrane | L_p | $3.3 \times 10^{-12} \text{ m s}^{-1} \text{ Pa}^{-1}$ |
| flow rate at inlet | Q^* | 0.2 – 2 $\text{mm}^3 \text{ s}^{-1}$ |
| gas constant | R | 8.314 $\text{J K}^{-1} \text{ mol}^{-1}$ |
| absolute temperature | T | 293 K |
| velocity at inlet | u^* | 60 – 600 $\mu\text{m s}^{-1}$ |
| viscosity | η | 1 – 5 mPa s |

permeable tube wall as

$$J = L_p(RT\Delta c - \Delta p) \quad (2)$$

where L_p is the permeability of the membrane, R is the gas constant, T is the absolute temperature, Δc is the difference in solute concentration, and Δp is the difference in hydrostatic pressure between the inside and the outside of the tube. See Appendix A for details on how L_p was measured. For clarity we use the van't Hoff value $RT\Delta c$ for the osmotic pressure in Eq. (2), which is valid only for dilute (ideal) solutions. At the concentrations relevant to our experiments ($c < 1$ M for NaCl and $c < 0.5$ M for sucrose), the error in the osmotic pressure introduced by using the van't Hoff value is $\sim 10\%$ [17]. The liquid outside the tube is pure water ($c = 0$), so the concentration difference $\Delta c = c_a$ where c_a is the concentration at the inner surface of the tube, see Fig. 1 and 2. Viscous friction which is responsible for the term Δp in Eq. (2), typically creates pressures of the order $\Delta p \simeq 8\eta u^*L/a^2 \simeq 1$ Pa where $\eta \simeq 1 - 5$ mPa s is the viscosity of the solution. These pressures are much smaller than the osmotic pressure differences $RT\Delta c \simeq 10^5$ Pa and it is therefore safe to disregard the Δp term in Eq. (2) and write instead $J = L_pRTc_a$.

The radial flux J , of water in or out of the tube is naturally related to the mean axial flow velocity u along the x -axis via volume conservation: $\partial_x u = 2J/a$. We therefore have the following equation for the average axial velocity

$$\partial_x u = 2 \frac{L_p}{a} RTc_a \quad (3)$$

The hollow fiber membrane used in the experiments is able to retain ion-sized solutes. Moreover, axial diffusion

plays very little role since the axial Péclet number $Pe_x = u^*L/D \simeq 10^4$ is large. Therefore, the axial flux of solute averaged over the cross section of the tube must be a conserved quantity, i.e.,

$$\langle cu \rangle = \text{const} = c^*u^* \quad (4)$$

where $\langle cu \rangle = 2/a^2 \int_0^a u_x(r)c(r)r dr$. The 3-D flow field (u_x, u_r, u_θ) will generally be complicated, but since the channel Reynolds number $Re = \rho u^*a/\eta \simeq 0.1$ and aspect ratio $\alpha = a/L \simeq 0.005$ are both reasonably small we expect the flow to be rotationally symmetric, laminar and to have a Poiseuille axial flow profile. As shown by e.g. Aldis [10], the velocity field $\mathbf{u} = (u_x, u_r)$ in cylindrical coordinates is then given by

$$u_x = 2 \frac{(a^2 - r^2)}{a^2} u(x) \quad (5)$$

$$u_r = \frac{r(r^2 - 2a^2)}{a^3} J(x) \quad (6)$$

Of the concentration field $c(r, x)$ we know that the radial solute flux

$$J_c = -D\partial_r c + u_r c \quad (7)$$

must vanish at $r = 0$ and $r = a$ in order to satisfy the no-flux boundary condition at the channel center line and at the membrane wall. In Eq. (7), D is the diffusion coefficient of the solute in water (see Table II). Eq. (7) leads to

$$\partial_r c = 0 \quad \text{at} \quad r = 0 \quad (8)$$

$$-D\partial_r c - L_p RT c_a^2 = 0 \quad \text{at} \quad r = a \quad (9)$$

Writing the concentration as a power series in r , $c(r, x) = a_0(x) + a_1(x)r + a_2(x)r^2 + \dots$ we realize that the lowest order approximation to $c(r, x)$ which is able to capture the balance between radial advection and diffusion determined by Eqns. (8) and (9) can be written as

$$c(r) = c_0(x) + (c_a(x) - c_0(x)) \frac{r^2}{a^2} \quad (10)$$

where $c_0(x) = c(0, x)$ is the concentration at $r = 0$ [18]. The functional form of Eq. (10) is sketched in Fig. 1. In this approximation, the no-flux boundary condition at $r = a$ (Eq. (9)) is

$$-\frac{2D(c_a - c_0)}{a} - L_p RT c_a^2 = 0 \quad (11)$$

which sets a relation between the concentration at the channel center c_0 and wall c_a

$$c_0 = c_a + \frac{L_p RT a}{2D} c_a^2 = c_a + \frac{Pe_r}{2} \frac{c_a^2}{c^*} \quad (12)$$

where $Pe_r = L_p RT c^* a / D$ is the radial Péclet number.

From the conservation of solute flux (Eq. (4)), we now have from Eqns. (5) and (10)

$$\left(c_a + \frac{Pe_r}{3} \frac{c_a^2}{c^*} \right) u = u^* c^* \quad (13)$$

To eliminate c_a from Eq. (13) we use Eq. (3) which leads to

$$\left(\frac{a}{2L_p RT} \partial_x u + \frac{Pe_a}{3c^*} \left(\frac{a}{2L_p RT} \partial_x u \right)^2 \right) u = c^* u^* \quad (14)$$

Introducing the variables $X = x/L$ and $U = u/u^*$, Eq. (14) can be written in non-dimensional form

$$\left(\partial_X U + \beta (\partial_X U)^2 \right) U = \Gamma \quad (15)$$

where the non-dimensional parameter $\beta = \alpha Pe/6$ depends on the aspect ratio $\alpha = a/L$ and the mixed Péclet number $Pe = u^*a/D$ based on axial flow and radial diffusion length scale. The quantity $\Gamma = 2L_p RT c^* L / (u^* a)$ on the right hand side of Eq. (14) is the ratio of the largest obtainable purely osmotic flow velocity $2\pi a L L_p RT c^* / (\pi a^2)$ and the inlet velocity u^* . In this non-dimensional formulation, the flow rate gain is given by $\gamma = U(1) - 1$, and Γ thus provides an upper limit to the pumping efficiency, since we must have $\gamma \leq \Gamma$.

An implicit solution of Eq. (15) can be obtained by the Legendre transformation $X = \partial_t y$, $U = t\partial_t y - y$, and $\partial_X U = t$. With this change of coordinates, Eq. (15) leads to a linear equation in $y(t)$

$$(t^2 + \beta t^3) \partial_t y - (t + \beta t^2) y = \Gamma \quad (16)$$

which has the solution

$$y(t) = \Gamma \left[-\frac{1}{2t} + \beta + t\beta^2 \log \left(\frac{t}{1 + \beta t} \right) \right] + tC \quad (17)$$

where the constant C allows us to fulfill the boundary condition $U(X(t) = 0) = 1$ (in dimensional coordinates: $u(0) = u^*$). The non-dimensional velocity $U(X(t))$ and axial coordinate $X(t)$ can be written in terms of t as

$$X = \Gamma \left[\frac{1}{2t^2} + \frac{\beta^2}{1 + \beta t} + \beta^2 \log \left(\frac{t}{1 + \beta t} \right) \right] + C \quad (18)$$

$$U = \frac{\Gamma}{t + \beta t^2} \quad (19)$$

To determine C , we note that $U = 1$ when $t = t_0 = (-1 + \sqrt{1 + 4\Gamma\beta}) / (2\beta)$. By inserting t_0 in Eq. (18) with $X = 0$, we find that

$$C = -\Gamma \left[\frac{1}{2t_0^2} + \frac{\beta^2}{1 + \beta t_0} + \beta^2 \log \left(\frac{t_0}{1 + \beta t_0} \right) \right] \quad (20)$$

The flow rate gain γ can finally be determined from

$$\gamma(\beta, \Gamma) = U(1) - 1 = \frac{\Gamma}{t_1 + \beta t_1^2} - 1 \quad (21)$$

where t_1 is found from Eq. (18) by solving $X(t_1) = 1$.

The flow rate gain γ predicted by Eq. (21) is plotted as a function of β and Γ in Fig. 4(a). In Fig. 4(b), it is compared to measured values of γ from 216 experiments. Over two orders of magnitude of variation in γ , we find excellent agreement between the experimental data and the prediction of Eq. (21) with no free parameters.

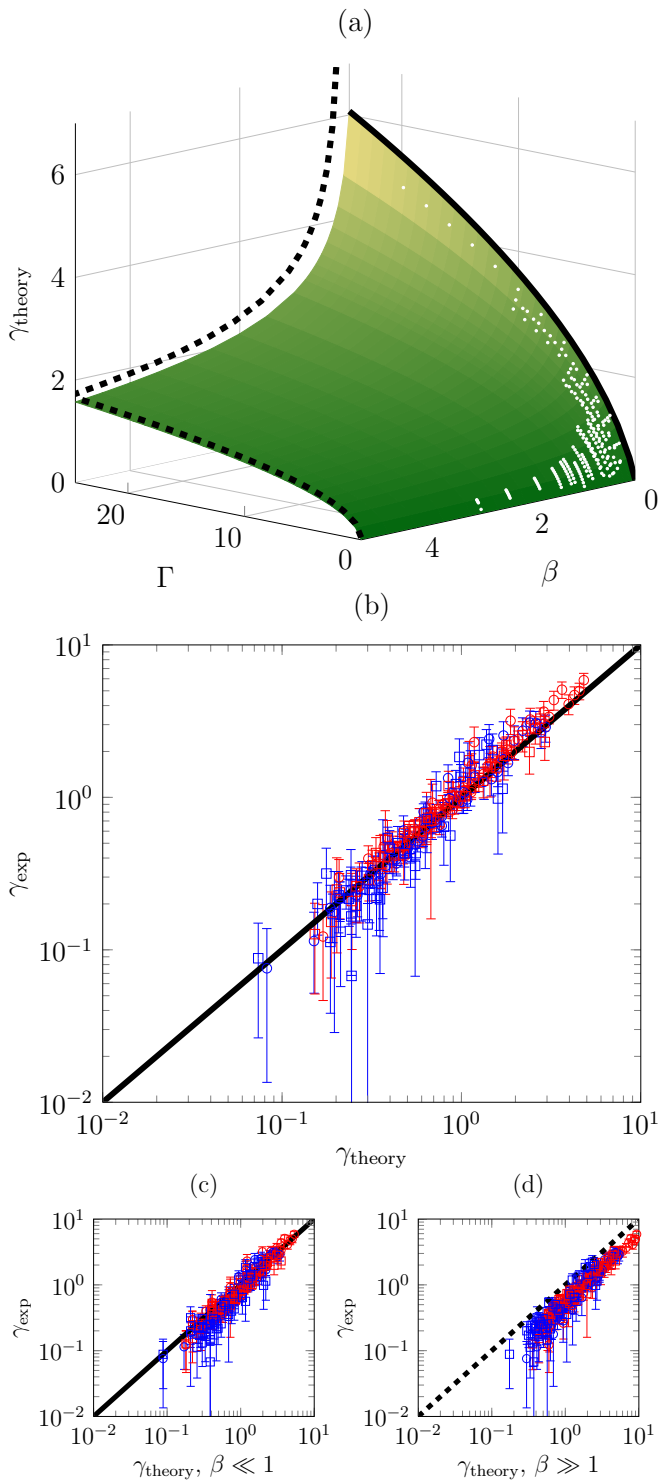


FIG. 4. (Color online) Comparison between experimental and theoretical values of the flow rate gain γ . (a) Theoretical predicted values of γ (Eq. (21)) plotted as a function of β and Γ . Solid line shows approximate analytical solutions for $\beta \ll 1$ (Eq. (23)). Dashed lines show approximate analytical solutions for $\beta \gg 1$ (Eq. (25)). Dots indicate the location in the (β, Γ) -plane of experimental data points. (b) Measured values of γ plotted as a function of the predicted values using Eq. (21). (c) Measured values of γ plotted as a function of the predicted values using Eq. (23). (d) Measured values of γ plotted as a function of the predicted values using Eq. (25). (b)-(d) uses same legend as Fig. 3(a).

A. Limiting cases

In the majority of our experiments, both β and Γ are of moderate magnitude (see Fig. 4(a) and Table II). It is therefore likely that the boundary layer contributes significantly to the flow and that the full solution of Eq. (15) is needed to rationalize the experimental data. It is, however, of general interest to consider limiting cases of Eq. (15) and we therefore consider solutions for $\beta \ll 1$ and $\beta \gg 1$ for arbitrary values of Γ below. Taking $\Gamma \ll 1$ leads to $u(x) = u^*$ (i.e. $\gamma = 0$), and is therefore of limited interest since we generally look for conditions that optimise the osmotic flow and thus maximize γ .

1. Weak unstirred concentration boundary layer effects, $\beta \ll 1$

When radial diffusion is sufficiently strong compared to both radial and axial advection, both the radial and mixed Péclet numbers $Pe_r = L_p RT c^* / D$ and $Pe = u^* a / D$ are very small. This implies that the concentration at the tube wall $c_a \simeq c_0$ (see Eq. (12)) and consequently the parameter $\beta \ll 1$. In this limit, the solution of Eq. (15) is

$$U(X) = (1 + 2\Gamma X)^{1/2} \quad (22)$$

which has previously been found by e.g. Aldis [11] and Thompson and Holbrook [19]. In this limit, the flow rate gain γ can be expressed as

$$\gamma + 1 = (1 + 2\Gamma)^{1/2} = \left(1 + \frac{4L_p RT c^* L}{u^* a}\right)^{1/2} \quad (23)$$

shown in Fig. 4(a) as a solid line. Eq. (23) provides a useful approximation to γ but only for very small values of β .

2. Strong unstirred concentration boundary layer effects, $\beta \gg 1$

When radial diffusion is sufficiently weak compared to radial as well as axial advection, both the radial and the mixed Péclet numbers $Pe_r = L_p RT c^* / D$ and $Pe = u^* a / D$ are much larger than 1. In this limit the concentration at the tube wall $c_a \ll c_0$ (see Eq. (12)) and consequently the parameter $\beta \gg 1$. In this limit, the solution of Eq. (15) is

$$U(X) = \left[\frac{3}{2} \left(\frac{\Gamma}{\beta} \right)^{1/2} X + 1 \right]^{2/3} \quad (24)$$

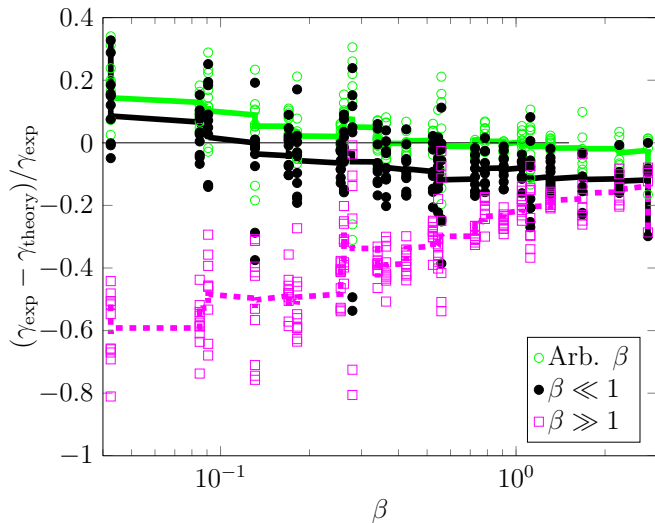


FIG. 5. (Color online) Comparison between experimental and theoretical values of the flow rate gain γ . Relative error $(\gamma_{\text{exp}} - \gamma_{\text{theory}})/\gamma_{\text{exp}}$ plotted as a function of the Péclet number β for the full model (Eq. (21), green circles), the limit $\beta \ll 1$ (Eq. (23), black dots) and the limit $\beta \gg 1$ (Eq. (25), magenta squares). Solid lines show smoothed data curves as a guide to the eye (averaged over 20 neighboring data points).

The flow rate gain γ can be expressed as

$$\gamma + 1 = \left[\frac{3}{2} \left(\frac{\Gamma}{\beta} \right)^{1/2} + 1 \right]^{2/3} \quad (25)$$

$$= \left[\frac{3}{2} \left(\frac{12L_p RT c^* L^2 D}{a^3 (u^*)^2} \right)^{1/2} + 1 \right]^{2/3} \quad (26)$$

shown in Fig. 4(a) as dashed lines. Eq. (25) provides a simple approximation to Eq. (21) for large values of β , where the flow rate gain scales as $\gamma \propto (\Gamma/\beta)^{1/3}$. For $\beta \geq 1$ and $\Gamma \geq 1$ the error in Eq. (25) is typically less than 10% when compared to Eq. (21).

The flow rate gains predicted by Eqns. (23) and (25) are compared to the experimentally obtained values in Fig. 4(c)-(d), and the relative error $(\gamma_{\text{exp}} - \gamma_{\text{theory}})/\gamma_{\text{exp}}$ is plotted as a function of β in Fig. 5. While both Eq. (23) and (25) show reasonable agreement between theory and experiment, the deviation between theory and experiment clearly depends on the value of β . Fig. 5 thus illustrates that the parameter β plays an important qualitative role in determining the scaling of the flow rate gain

γ with the parameters of the problem.

IV. CONCLUSION AND DISCUSSION

In this paper, we have studied the effect of concentration boundary layers on osmotic flows in cylindrical tubes with porous walls. By varying the inlet flow rate Q^* , inlet solute concentration c^* , and tube length L , we have experimentally documented the dependence of the flow rate gain γ (Eq. (1)) on these parameters.

To explain our experimental observations, we have developed a simple model. The model quantifies the change in axial flow velocity due to osmotic exchange of water across the tube wall, and gives a first approximation to the effect of concentration boundary layers (Eq. (21)). We have compared theory and experiment with good results, as shown in Fig. 4(b).

Our theoretical predictions give interesting indications of how to develop and optimize devices that utilize osmotic pumps, such as membrane modules for forward osmosis applications based on hollow fibers [20, 21]. To obtain the greatest osmotic effect, it is clearly desirable to maximize Γ and minimize β , see Fig. 4(a). This can be done in a number of ways, e.g. by using a long membrane tube ($\Gamma \propto L$, $\beta \propto L^{-1}$), or by injecting fluid slowly ($\beta \propto u^*$, $\Gamma \propto (u^*)^{-1}$). The greatest potential for improvement, however, is in making the tube radius a as small as possible, since $\beta \propto a^2$ and $\Gamma \propto a^{-1}$. This increase in γ , however, will only continue as long as the back pressure due to viscous resistance $\Delta p \simeq 8\eta Lu^*/a^2$ remains small compared to the osmotic pressure $RTc^* \simeq 10^5$ Pa, c.f Eq. (2). For water ($\eta = 1$ mPa s) flowing at $u^* = 1$ mm/s in a $L = 1$ m tube, the two pressures are of equal magnitude when $a \simeq 100$ μm . This indicates that using sub-100 μm tubes in filtration devices is undesirable, although a more thorough analysis is needed to determine the optimum tube dimensions in the presence of viscous effects, and more generally non-linear concentration effects such as deviations from the van't Hoff relation.

V. ACKNOWLEDGEMENTS

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Appendix A: Membrane permeability

The membrane permeability L_p was determined by applying a known hydrostatic pressure differential Δp across a membrane section of area A . By measuring the resulting flow rate Q , the permeability $L_p = Q/(A\Delta p)$ of the hollow fiber membrane was determined to be $L_p = (3.28 \pm 0.02) \times 10^{-12}$ m/s/Pa, consistent with values obtained from measurements on this type of membrane material [22].