Role of Electrokinetics in the Cleaning-Efficiency of a Dialyzer: Toward an Artificial-Kidney

A. Nastasia Allred, Samantha Blanton, J. Robby Sanders, and Pedro E. Arce
Chemical Engineering Department, Tennessee Technological University

Introduction/Motivation

1 in 10 have some form of chronic kidney disease worldwide.

CKD has no cure, kidney transplants are accompanied by long wait times and the possibility of tissue rejection, while dialysis provides a poor quality of life.

The goal of this work is to analyze the blood at the microscopic level (dialysis level) and then downscale to a size ideal for potentially designing an artificial kidney. Artificial kidney -> better quality of life.

As the system is downscaled the importance of electrokinetics comes into question in a more detailed manner.

The “H” is representative of a glomerular capillary.

Continuum mechanics approaches are used to analyze the system.

Methods

A single capillary of a cylindrical geometry is used as a potential domain for a “neprin”, the most crucial element of the kidney filtration. Continuum mechanics approaches are used to analyze the system.

Solute Portion

\[ \frac{\partial C}{\partial t} + \mathbf{v} \cdot \nabla C = D \nabla^2 C \]

Boundary Conditions

\[ C = C_0 \]

Dimensionless Variables

\[ \beta = \frac{\varepsilon_0 \sigma \mathbf{E}}{\mu} \]

\[ \beta > 1 \]

\[ \beta < 1 \]

\[ \beta = 1 \]

The electrostatic forces are dominating and the net flow is in the direction of the pressure gradient.

The hydraulic forces are dominating and the net flow is reverse.

The electrostatic and hydraulic forces are equal. We have a balance of flow reversal towards the wall and forward flow in the center.

Methods (Cont.)

Figure 1: Layers of Glomerular Capillary - A glomerular capillary has three main layers of which have various characteristics that determine their function due to size and charge. Image credit - A. Nastasia Allred

Figure 2: System Description - This image shows the system we are describing using our mathematical model and is representative of a glomerular capillary. Image Credit - A. Nastasia Allred

Figure 3: Taxonomy of Electrokinetic application - The "H" is representative of the three main components of Electrokinetic Hydrodynamics. It also shows how the connection of these components results in multiple conservation principles and phenomena. Image credit - A. Nastasia Allred

Figure 4: Electrostatic Potential in Capillary - This plot shows how the electrostatic potential as a function of non-dimensional radius is affected by changing the kappal parameter which is the inverse Debye length. Image credit - A. Nastasia Allred

Figure 5: Electrostatic Effect on Hydrodynamic Velocity Profiles - This image shows how the hydraulic velocity profiles within the capillary are affected by electrical forces. The beta parameter is indicative of the ratio of electrical forces to hydraulic forces. Image credit - A. Nastasia Allred

Discussions

1. Assumptions

- Fully developed laminar flow
- Steady state
- Isothermal
- Incompressible fluid
- Non-dimensionalization

2. Model Development

From Navier-Stokes with Electrostatics:

\[ \frac{d}{dt} \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla P + \frac{\varepsilon_0 \sigma \mathbf{E}}{\mu} \]

Poisson-Boltzmann Equation:

\[ \nabla \cdot \mathbf{u} = 0 \]

Solution:

\[ \mathbf{u} = \frac{\mathbf{E}}{\varepsilon_0 \sigma} \nabla \phi \]

Non-dimensionalized Profile:

\[ \mathbf{u} = \frac{\mathbf{E}}{\varepsilon_0 \sigma} \nabla \phi \]

Dimensionless Numbers

\[ \beta = \frac{\varepsilon_0 \sigma \mathbf{E}}{\mu} \]

\[ \varepsilon_0 = \frac{n e^2}{m} \]

\[ \mathbf{E} = \frac{\varepsilon_0 \sigma \mathbf{E}}{\mu} \]

\[ \delta = \frac{\lambda_D}{L} \]

\[ \beta = \frac{\varepsilon_0 \sigma \mathbf{E}}{\mu} \]

\[ \beta > 1 \]

\[ \beta < 1 \]

\[ \beta = 1 \]

Results

The electrostatic forces are dominating and flow reversal is the result.

The hydraulic forces are dominating and the net flow is in the direction of the pressure gradient.

The electrostatic and hydraulic forces are equal. We have a balance of flow reversal towards the wall and forward flow in the center.

Conclusions/Future Work

Currently, progress has been made toward developing a model to depict the electrowetting effects on filtration in the glomerular capillary. The electrosorption profile has been developed, and the electrowetting effects have been illustrated. These parameters can be used to increase separation efficiency of the capillary. The next step of this research is to develop an asymptotic solution for the concentration profile. The model has been set up, but due to complex functions (such as Bessel functions), computational software including Matlab and Maple will be incorporated.

• Use Maple to solve Global BC for integration constants C_0, C_1, C_2
• Put constants into asymptotic solution

• Plots will then be developed using Maple and/or Matlab software
• Parameters (x and y) will be varied in order to optimize the filtration in the capillary.

Validation

• Feasibility regions will be determined for this solution
• Values will be tested for feasibility.

References


Acknowledgements

I would like to thank Dr. Pedro Arce, Samantha Blanton, and Dr. Robby Sanders for their help and guidance throughout this project.

I would also like to give thanks to the College of Engineering and the Department of Chemical Engineering for funding this research.