

Mathematical model for the concentration and electric potential profiles in a solution of electrolytes under a redox reaction

Student: Agustín Escobar Blanc
Professor: Enrique Muñoz Tavera

Departamento de Física, Facultad de Física, Pontificia Universidad Católica de Chile

January 24, 2019

Contents

1	Diffusion Of Electrolytes In Solution	2
1.1	System of equations	2
2	Steady State Solution	4
2.1	Linearization of the Poisson Equation	4
2.2	Steady State Solution To The Diffusion-Reaction Problem	5
2.3	Zero order solution to Poisson's equation for the electrolyte solution	8
2.4	Charge Density At The Interface	10
2.5	Solution to the concentration at first order in the current I_0	12
2.6	Potential to first order in the current	13
2.7	Numerical Analysis	14
2.7.1	Runge-Kutta Method	15
2.7.2	The Shooting Method	17
2.7.3	Ridder's Method	17
2.7.4	Results	19
3	Dynamic Solution	22
3.1	Diffusion Only	23
3.1.1	Analytic Solution To The Diffusion-Only Problem	24
3.1.2	Numeric Solution To The Diffusion Only Equation	27
3.1.3	Numeric Solution To The Diffusion Equation With Reaction At The Interface	30
3.1.4	Analytic Solution To The Diffusion Equation With Reaction At The Interface	31
3.2	Concentration Dependent Reaction	35
3.2.1	Steady State	35
3.2.2	Dynamic Solution	36
3.3	Diffusion-Reaction Equation With Forced Current through the system.	41
3.3.1	Steady State Solution	41
3.3.2	Dynamic Solution	42

Chapter 1

Diffusion Of Electrolytes In Solution

1.1 System of equations

The system of equations we need to solve is

$$\frac{\partial C_+}{\partial t} + \nabla \cdot \mathbf{N}_+ = 0 \quad (1.1)$$

$$\frac{\partial C_-}{\partial t} + \nabla \cdot \mathbf{N}_- = 0 \quad (1.2)$$

$$\nabla^2 \phi(x) = -\frac{\rho(x)}{\epsilon} \quad (1.3)$$

Where C_s is the concentration of each species and N_s is the diffusive flux for each species. In our model, the flux is defined as

$$\begin{aligned} \mathbf{N}_+ &= -D_+ \left(\nabla C_+(x) + \frac{z_+ F}{RT} C_+(x) \nabla \phi(x) \right) \\ \mathbf{N}_- &= -D_- \left(\nabla C_-(x) + \frac{z_- F}{RT} C_-(x) \nabla \phi(x) \right) \end{aligned}$$

Therefore, the diffusion equation with electric field interaction incorporated is [Dolde2011]

$$\frac{\partial C_+}{\partial t} + \nabla \cdot \left[-D_+ \left(\nabla C_+(x) + \frac{z_+ F}{RT} C_+(x) \nabla \phi(x) \right) \right] = 0 \quad (1.4)$$

$$\frac{\partial C_-}{\partial t} + \nabla \cdot \left[-D_- \left(\nabla C_-(x) + \frac{z_- F}{RT} C_-(x) \nabla \phi(x) \right) \right] = 0 \quad (1.5)$$

where $z = |z_+| = |z_-|$ is the valence of the electrolyte, D_{\pm} are the diffusion coefficients for each chemical species and $F = 96485.33 \text{ C mol}^{-1}$ is Faraday's constant.

The reaction we are modeling is the cation reduction. In particular, we are interested in copper reduction at the surface



This chemical reaction yields the following border condition for the flux

$$\begin{aligned} \mathbf{N}_+ \cdot \hat{n}|_{\text{Surface}} &= \frac{I_0}{z_+ F A} \\ \mathbf{N}_- \cdot \hat{n}|_{\text{Surface}} &= 0. \end{aligned} \quad (1.7)$$

with A being the total area of the surface, I_0 the total electric current and \hat{n} the unit normal of the surface.

Chapter 2

Steady State Solution

2.1 Linearization of the Poisson Equation

As a first approach to solving the equilibrium system (that is, system when there is no current at all), we can simplify the Poisson-Boltzmann Equation by linearizing the Boltzmann term in the Debye-Huckel theory to first order in the potential. The Poisson-Boltzmann equation is

$$-\frac{d^2\phi(x)}{dx^2} = \frac{1}{\epsilon} \sum_s z_s F C_{b,s} e^{\frac{z_s F \phi(x)}{RT}},$$

which by expanding the exponential for $\left| \frac{z_s F \phi(x)}{RT} \right| < 1$ we get

$$-\frac{d^2\phi(x)}{dx^2} = \frac{1}{\epsilon} \sum_s z_s F C_s \left(1 - \frac{z_s F \phi(x)}{RT} \right)$$

Due to electro-neutrality in the bulk solution, the first term in the right hand side is zero. Therefore,

$$\frac{d^2\phi(x)}{dx^2} = \kappa^2 \phi(x)$$

where we have defined

$$\kappa = \sqrt{\frac{\sum_s C_{b,s} z_s^2 F^2}{\epsilon RT}}$$

Given the boundary conditions $\phi(0) = V_0$, and considering the reference zero at $\phi(\delta) = \phi_b = 0$, the solution is trivially found to be

$$\phi(x) = V_0 e^{-\kappa x},$$

This gives the potential in a static situation, in which the electrolytes move to an equilibrium position and the configuration as a hole is static.

This results gives a good physical sense of how the potential should look like in a context of electrolyte solutions at equilibrium. We are interested in the dynamics of the system, though, so it makes sense to try to incorporate the current into Eq. 2.1. In the next section we shall incorporate the current flowing through the interface as a border condition of Eq. 2.1.

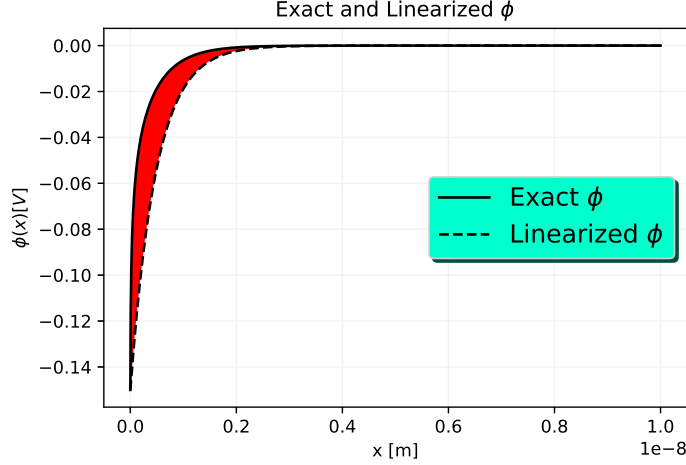


Figure 2.1: Comparison of the linearized PB solution with the analytical solution. The region in red is the error committed in this approximation

2.2 Steady State Solution To The Diffusion-Reaction Problem

In what follows, we shall assume that the system presents concentration gradients and potential gradients along a single dimension x . This is equivalent to considering the interface infinitely large. Therefore, $\mathbf{N}_+ = \hat{x}N_+$ and $\mathbf{N}_- = \hat{x}N_-$.

In the steady state solution the concentration distribution of each electrolyte throughout the system should not change in time, thus

$$\frac{\partial C_+}{\partial t} = \frac{\partial C_-}{\partial t} = 0$$

This yields the following results

$$\nabla \cdot \mathbf{N}_+ = \frac{\partial N_+}{\partial x} = 0$$

$$\nabla \cdot \mathbf{N}_- = \frac{\partial N_-}{\partial x} = 0$$

Therefore, we have

$$N_+ = A_1$$

$$N_- = A_2$$

where A_1 and A_2 are constants determined by border conditions. Since the anion does not interact with the interface, we get after Eq.(1.7) $N_- = 0$. On the other hand, the flux due to the cation reaction with the interface ($Cu^{+2} \rightarrow Cu^0$) gives the boundary condition for N_+ ,

$$N_+ = \frac{I_0}{Az_+F}$$

The complete system of equations to be solved is

$$N_-(x) = 0$$

$$N_+(x) = \frac{I_0}{Aze}$$

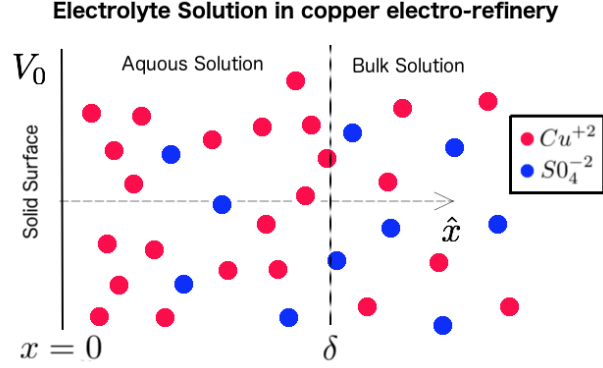


Figure 2.2: Geometry of the problem. $x < \delta$ is the region of laminar. $x > \delta$ is the bulk of the solution. This image is for a value of $V_0 < 0$, such that the positive electrolytes distribute closer to the surface.

According to Fig. 2.2, for an interface area large compared to the laminar flux region we get the following equations

$$\frac{\partial C_+}{\partial x} - \frac{zF}{RT} C_+ \frac{\partial \phi}{\partial x} = -\frac{I_0}{D_+ A z_+ F} \quad (2.1)$$

$$\frac{\partial C_-}{\partial x} + \frac{zF}{RT} C_- \frac{\partial \phi}{\partial x} = 0 \quad (2.2)$$

$$\frac{\partial^2 \phi}{\partial x^2} = -\frac{1}{\epsilon} \sum_{s=\pm} z_s F C_s(x) \quad (2.3)$$

where A is the area of the interface electrode.

To solve this system of partial differential equations, we will expand the concentration and the potential as a series in powers of $r = \frac{I_0}{D_+ A z_+ F}$. We have

$$C_s(x) = \sum_{n=0}^{\infty} r^n C_s^{(n)}(x) \quad (2.4)$$

$$\phi(x) = \sum_{n=0}^{\infty} r^n \phi^{(n)}(x) \quad (2.5)$$

Truncating the series at first order in r , we obtain the following system of equations to

order zero in the current

$$\frac{\partial C_+^{(0)}}{\partial x} - \frac{zF}{RT} C_+^{(0)}(x) \frac{\partial \phi^{(0)}}{\partial x} = 0 \quad (2.6)$$

$$\frac{\partial C_-^{(0)}}{\partial x} + \frac{zF}{RT} C_-^{(0)}(x) \frac{\partial \phi^{(0)}}{\partial x} = 0 \quad (2.7)$$

$$\frac{\partial^2 \phi^{(0)}}{\partial x^2} = -\frac{1}{\epsilon} \sum_{s=\pm} szFC_s^{(0)}(x) \quad (2.8)$$

and to first order in the current

$$\frac{\partial C_+^{(1)}}{\partial x} - \frac{zF}{RT} \left(C_+^{(1)}(x) \frac{\partial \phi^{(0)}}{\partial x} + C_+^{(0)}(x) \frac{\partial \phi^{(1)}}{\partial x} \right) = -1, \quad (2.9)$$

$$\frac{\partial C_-^{(1)}}{\partial x} + \frac{zF}{RT} \left(C_-^{(1)}(x) \frac{\partial \phi^{(0)}}{\partial x} + C_-^{(0)}(x) \frac{\partial \phi^{(1)}}{\partial x} \right) = 0, \quad (2.10)$$

$$\frac{\partial^2 \phi^{(1)}}{\partial x^2} = -\frac{1}{\epsilon} \sum_{s=\pm} szFC_s^{(1)}(x). \quad (2.11)$$

2.3 Zero order solution to Poisson's equation for the electrolyte solution

We want to work with the dimensionless potential

$$\Phi(x) = \frac{zF}{RT}\phi(x).$$

The zero order system can thus be written as

$$C_+^{(0)}(x)' - C_+^{(0)}(x)\Phi^{(0)}(x)' = 0 \quad (2.12)$$

$$C_-^{(0)}(x)' + C_-^{(0)}(x)\Phi^{(0)}(x)' = 0 \quad (2.13)$$

$$\Phi^{(0)}(x)'' = -\frac{(zF)^2}{RT\epsilon}(C_+^{(0)}(x) - C_-^{(0)}(x)) \quad (2.14)$$

In this section we will solve equations 2.10 and 2.11.

From Eq. 2.12,

$$\frac{\partial C_s^{(0)}}{\partial x} - sC_s^{(0)}\Phi^{(0)}(x) = 0$$

which yields

$$\int_{C_{b,s}}^{C_s^{(0)}(x)} \frac{dC_s^{(0)}}{C_s^{(0)}} = s \int_{\phi_b}^{\phi^{(0)}} d\Phi^{(0)}$$

where $\Phi_b = \Phi(\delta)$ is the potential at the bulk, which we will consider as the reference zero, $\phi_b = 0$. $C_{b,s}$ is the bulk concentration of each species in solution.

$$C_s^{(0)}(x) = C_{b,s}e^{s\Phi^{(0)}(x)}$$

Notice that

$$C_s^{(0)}(\delta) = C_{b,s}e^{\frac{zF}{RT}\phi_b} = C_{b,s}. \quad (2.15)$$

Consider the bulk values of the concentration, $C_{s,b}$. In the bulk, the solution should be electrically neutral due to conservation of charge. Therefore, for a two electrolyte salt at the bulk

$$\sum_{s=\pm} C_{s,b}szF = 0 \quad (2.16)$$

where z is the valence of the electrolytes and $s = \pm$ is the sign of the charge of the electrolyte. $F = eN_A$ is the Faraday constant. From 2.16 we get,

$$\begin{aligned} C_{b,+}Fz - C_{b,-}Fz &= 0 \\ \rightarrow \frac{C_{b,+}}{C_{b,-}} &= 1 \end{aligned} \quad (2.17)$$

$$C_{b,+}Fz - C_{b,-}Fz = 0$$

$$\rightarrow \frac{C_{b,+}}{C_{b,-}} = 1$$

In the case of a symmetric salt, $q_s = -q_{-s}$ (since in our notation $s = \pm$). Poisson's equation can be written (to zero order in the current) as

$$\frac{\partial^2 \Phi^{(0)}}{\partial x^2} = -\frac{zF}{\epsilon} \left(C_{b,+} e^{\Phi^{(0)}(x)} - C_{b,-} e^{-\Phi^{(0)}(x)} \right) \quad (2.18)$$

where $z = |z_-| = |z_+|$. From equations 2.15 and 2.17 we have $C_{b,+} = C_{b,-} = C_b$. Equation 2.18 can be written in terms of the hyperbolic sine,

$$\frac{\partial^2 \Phi^{(0)}}{\partial x^2} = 2 \frac{(zF)^2 C_b}{RT\epsilon} \sinh(\Phi^{(0)}(x)) \quad (2.19)$$

We define the quantity

$$\kappa^2 = \frac{(zF)^2 C_b}{RT\epsilon}$$

$$\frac{\partial^2 \Phi^{(0)}}{\partial x^2} = 2\kappa \sinh(\Phi^{(0)}(x)) \quad (2.20)$$

We want to change variables to the dimensionless quantity κx ,

$$x \rightarrow \xi = \kappa x$$

$$d\xi = \kappa dx$$

Thus, we write,

$$\Phi^{(0)}(\xi)'' = 2 \sinh(\Phi^{(0)}(\xi)) \quad (2.21)$$

Multiplying by $\Phi'^{(0)}$ and integrating the equation over the interval $[\xi, \delta]$ we get,

$$\Phi^{(0)}(\kappa\delta)^2 - \Phi^{(0)}(\xi)^2 = 2(\cosh(\phi(\kappa\delta)) - \cosh(\phi(\xi))) \quad (2.22)$$

The border condition for the potential yields,

$$\Phi^{(0)}(\xi)' \rightarrow 0.$$

Therefore

$$\Phi^{(0)}(\xi)^2 = 2(\cosh(\phi(\xi)) - 1), \quad (2.23)$$

$$= 4\sinh^2(\phi(\xi)), \quad (2.24)$$

$$\rightarrow \Phi^{(0)} = \pm 2 \sinh(\phi(\xi)). \quad (2.25)$$

The border conditions for the potential are $\Phi^{(0)}(0) = \bar{V}_0 < 0$ and $\Phi^{(0)}(\kappa\delta) = 0$, the slope of $\Phi^{(0)}$ must be positive and decreasing. This yields the positive solution to equation 2.25

$$\Phi^{(0)} = 2\sqrt{\sinh(\phi(\xi))}. \quad (2.26)$$

This is a separable equation which can be integrated directly, yielding

$$\log \left(\frac{1 - e^{\Phi^{(0)}/2}}{1 + e^{\Phi^{(0)}/2}} \right) = -\xi + C, \quad (2.27)$$

$$\rightarrow \frac{1 - e^{\Phi^{(0)}/2}}{1 + e^{\Phi^{(0)}/2}} = Ae^{-\xi}. \quad (2.28)$$

It can be found using the border condition $\Phi^{(0)}(0) = \bar{V}_0$

$$A = \tanh(\bar{V}_0/4) \quad (2.29)$$

Solving for $\Phi^{(0)}$,

$$\Phi^{(0)}(\xi) = 2 \log \left(\tanh \left(\frac{\xi - \xi_0}{2} \right) \right), \quad (2.30)$$

where we have defined

The minus sign in the previous definition is due to the fact that $\bar{V}_0 < 0$ for our case.

2.4 Charge Density At The Interface

From equation 2.31 we can obtain the electric field, which in terms of x has the form

$$E(x) = \frac{2\kappa}{\beta q} \csc(\kappa(x - x_0)), \quad (2.31)$$

where

$$e^{\xi_0} = -\tanh \left(\frac{\bar{V}_0}{4} \right). \quad (2.32)$$

From electrostatics we know that the border condition for the electric field at a conductors interface is

$$E(x)|_{interface} = \frac{\sigma}{\epsilon}. \quad (2.33)$$

We thus obtain the surface charge in terms of the voltage at the interface

$$\sigma = -\frac{2\epsilon\kappa}{\beta q} \csc(kz_0), \quad (2.34)$$

which using Eq. 2.32 can be written as

$$\sigma(V_0) = -\frac{2\epsilon\kappa}{\beta q} \frac{\tanh\left(\frac{q\beta V_0}{4}\right)}{\tanh\left(\frac{q\beta V_0}{4}\right) - 1} \quad (2.35)$$

This equation can be solved for V_0 in terms of the surface charge density σ

$$V_0 = \tanh^{-1} \left(-\frac{8\epsilon\kappa}{(q\beta)^2\sigma} \left(1 \pm \frac{1}{2} \sqrt{1 + \frac{\beta^2 q^2 \sigma^2}{\epsilon^2 \kappa^2}} \right) \right) \quad (2.36)$$

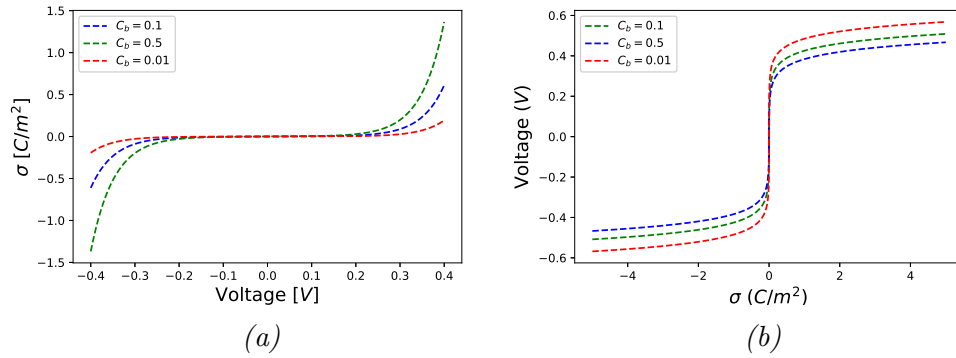


Figure 2.3: **(a)** Surface charge density in terms of the potential border condition. **(b)** Inverse of (a)

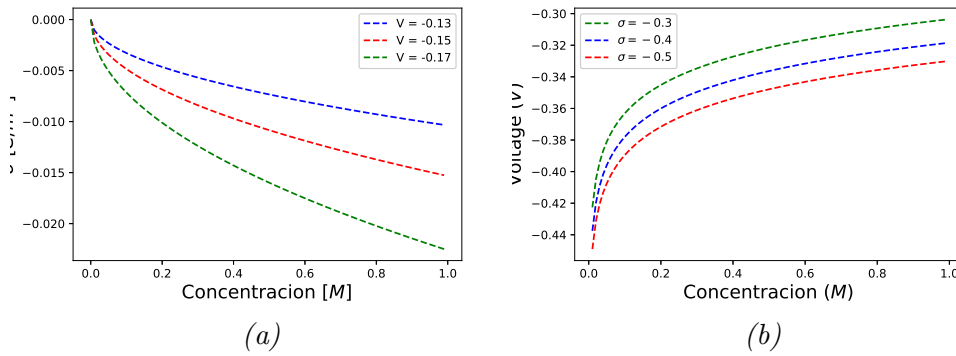


Figure 2.4: **(a)** Surface charge density in terms of the bulk concentration. **(b)** Voltage at the interface in terms of the bulk concentration (a)

2.5 Solution to the concentration at first order in the current I_0

Now we solve Equation 2.1 at first order in the current I_0 . From Eq. 2.11, we consider the term proportional to $\frac{\partial \phi^{(1)}}{\partial x}$ such that

$$\left| \frac{\partial \phi^{(1)}}{\partial x} \right| \ll \frac{\kappa V_0}{r}, \quad (2.37)$$

since the gradient of the correction to the potential should be negligible compared to the gradient of the zero order contribution. This will be shown later in a numerical analysis. With this approximation, the system to first order in r becomes

$$\frac{\partial C_+^{(1)}}{\partial \xi} - C_+^{(1)}(\xi) \frac{\partial \Phi^{(0)}}{\partial \xi} = -\frac{1}{\kappa} \quad (2.38)$$

$$\frac{\partial C_-^{(1)}}{\partial \xi} + C_-^{(1)}(\xi) \frac{\partial \Phi^{(0)}}{\partial \xi} = 0 \quad (2.39)$$

$$\frac{\partial^2 \phi^{(1)}}{\partial \xi^2} = -(C_+^{(1)}(\xi) - C_-^{(1)}(\xi)) \quad (2.40)$$

In Eq. 2.39, we obtain

$$\frac{\partial C_+^{(1)}}{\partial \xi} - C_+^{(1)} \frac{\partial \Phi^{(0)}}{\partial \xi} = -\frac{1}{\kappa}$$

Using an integrating factor of the form

$$\mu(\xi) = e^{-\int_{\kappa\delta}^{\xi} \frac{zF}{RT} \frac{d\phi^{(0)}}{d\xi'} d\xi'} = e^{-(\Phi^{(0)}(\xi) - \phi_b)} = e^{-\Phi^{(0)}(\xi)}$$

We can write 2.39 as

$$\frac{d}{d\xi} \left(C_+^{(1)}(\xi) \mu(\xi) \right) = -\frac{\mu(\xi)}{\kappa},$$

where $z = |z_{\pm}|$. Integrating over x and considering that $C_+^{(1)}(\xi) \mu(\xi) \big|_{\xi \rightarrow \infty} = C_{+,b}^{(1)} = 0$ due to border conditions, we get

$$C_+^{(1)}(\xi) = \frac{1}{\kappa \mu(\xi)} \int_0^{\xi} \mu(\xi') d\xi'$$

Eq. 2.40 can be integrated by separation of variables, and the solution is

$$C_-^{(1)}(\xi) = C_{b,-}^{(1)} e^{\phi^{(0)}(\xi)}.$$

Since our border condition yields $C_{b,-}^{(1)} = 0$, the contribution to first order of the negative ion concentration is zero.

Computing the integral, we find to first order in the current the following solutions for the concentrations.

$$C_+^{(1)}(\xi) = -\frac{1}{\kappa} \left(\xi_\delta - \xi - \frac{2}{\gamma} \right) \tanh^2 \left(\frac{\xi - \xi_0}{2} \right) + 2 \tanh \left(\frac{\xi - \xi_0}{2} \right) \quad (2.41)$$

$$C_-^{(1)}(\xi) = 0 \quad (2.42)$$

2.6 Potential to first order in the current

Now we need to solve Eq. 2.40

$$\frac{\partial^2 \Phi^{(1)}}{\partial \xi^2} = -(C_+^{(1)}(\xi) - C_-^{(1)}(\xi)). \quad (2.43)$$

Expanding, we have

$$\begin{aligned} \frac{\partial^2 \Phi^{(1)}}{\partial \xi^2} &= -C_+^{(1)}(\xi) \\ &= -\frac{1}{\kappa} \left(\xi_\delta - \xi - \frac{2}{\gamma} \right) \tanh^2 \left(\frac{\xi - \xi_0}{2} \right) + 2 \tanh \left(\frac{\xi - \xi_0}{2} \right) \end{aligned} \quad (2.44)$$

Integrating twice and using the fact that $\Psi'^{(1)} = 0$, $\Psi^{(1)} = 0$ we obtain

$$\Phi'^{(1)}(\xi) = \frac{1}{\kappa} \left(A + B\xi + C\xi^2 + D \tanh \frac{\xi - \xi_0}{2} + E\xi \tanh \frac{\xi - \xi_0}{2} \right) \quad (2.45)$$

And

$$\Phi^{(1)}(\xi) = -\frac{1}{\kappa} \left(A(\xi_\delta - \xi) + \frac{B}{2}(\xi_\delta^2 - \xi^2) + \frac{C}{3}(\xi_\delta^3 - \xi^3) + \right. \quad (2.46)$$

$$\left. D \log \left| \frac{\cosh \frac{\xi_\delta - \xi}{2}}{\cosh \frac{\xi - \xi_0}{2}} \right| + E \left(\xi_\delta \log \left| \cosh \left(\frac{\xi_\delta - \xi_0}{2} \right) \right| - \xi \log \left| \cosh \left(\frac{\xi - \xi_0}{2} \right) \right| \right) - EI_\delta(\xi) \right) \quad (2.47)$$

where

$$A = 2\gamma\xi_\delta - \frac{2\xi_\delta}{\gamma} - 2\gamma - \frac{\xi_\delta^2}{2},$$

$$B = -\left(\xi_\delta - \frac{2}{\gamma} \right),$$

$$C = \frac{3}{2}$$

$$D = -2\left(\xi_\delta - \frac{2}{\gamma} \right),$$

$$E = 2,$$

$$\gamma = \tanh \left(\frac{\xi_0}{2} \right),$$

and

$$I_\delta(\xi) = \int_\xi^{\xi_\delta} \log \left| \cosh \left(\frac{\xi - \xi_0}{2} \right) \right| d\xi. \quad (2.48)$$

This integral must be evaluated numerically for each value of ξ . In order to do this, we use the Simpson Rule. Fig. 2.5 shows the potential to first order in the current alongside with the zero order potential.

Analytic Solution

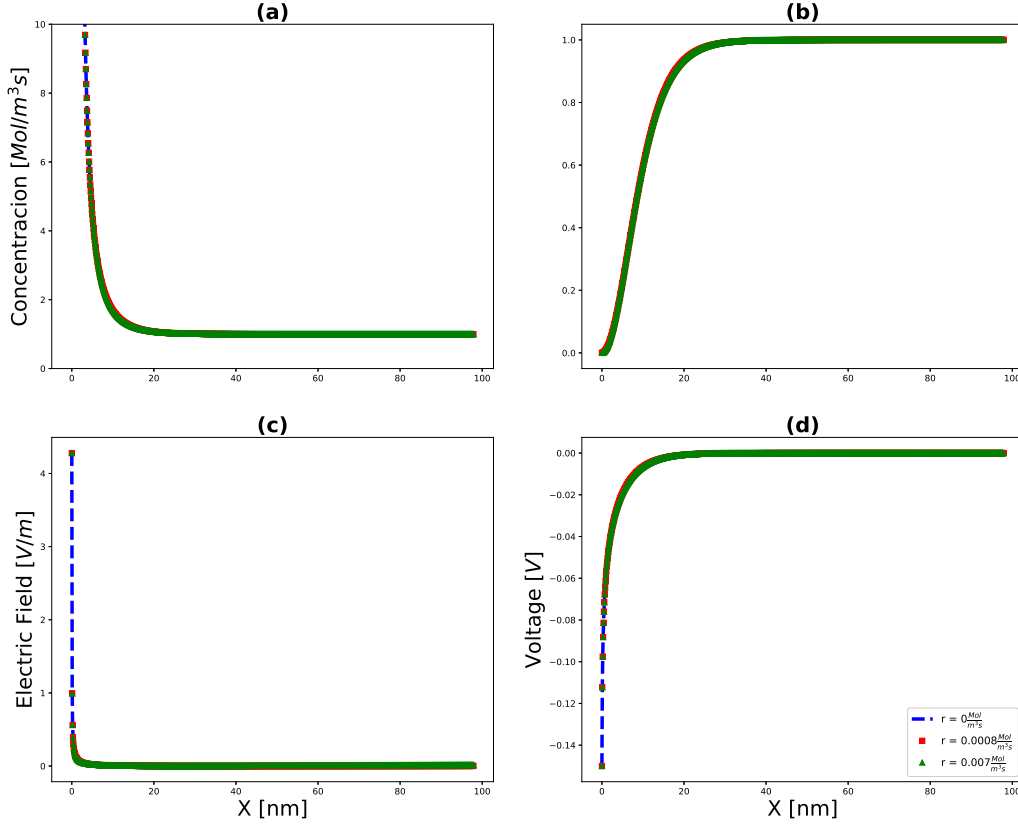


Figure 2.5: Analytic results. (a), (b) are the concentrations of each species of electrolytes. (c) is the electric potential and (d) the electric potential. Each plot is compared for 3 different values of the reaction rate.

2.7 Numerical Analysis

In order to validate the approximations made in previous sections, we solve system 2.1 numerically. In order to do so, we use the Runge-Kutta Method of order 4 along with the

Shooting Method to solve the two point boundary value (reference to Numerical Methods in python).

The complexity of the problem lies exactly in the two point boundary feature of the problem, where the concentrations are known in the bulk, but the potential is known at the interface(see Fig. 2.2).

The approach used in these type of problems is transforming the second order system 2.1 into a first order one,

$$C'_+(x) - \frac{zF}{RT}E(x)C_+(x) = -r, \quad (2.49)$$

$$C'_-(x) + \frac{zF}{RT}E(x)C_-(x) = 0, \quad (2.50)$$

$$E'(x) = \frac{zF}{\epsilon}(C_+(x) - C_-(x)), \quad (2.51)$$

$$\phi'(x) = -E(x). \quad (2.52)$$

subject to the border conditions

$$C_+(\delta) = C_b \quad (2.53)$$

$$C_-(\delta) = C_b \quad (2.54)$$

$$\phi(\delta) = 0 \quad (2.55)$$

$$\phi(0) = V_0 \quad (2.56)$$

Here the primes denote derivatives with respect to x . Once the system is in the form of Eqn. 2.56, we can apply the Runge-Kutta Method with the shooting method to obtain the numerical solutions.

2.7.1 Runge-Kutta Method

The Runge-Kutta Method is used to determine the numerical value of a system of differential equations to which we know the boundary conditions. Let

$$\vec{y}' = \vec{F}(x, \vec{y})$$

$$\vec{y}(x_0) = \vec{y}_0$$

be the system of equations we want to solve with the method. We approximate the derivative by

$$\frac{\vec{y}(x+h) - \vec{y}(x)}{h} = \vec{F}(x+h, \vec{y} + \vec{y}(x+h))$$

We want to approximate the left hand side with a series expansion to arbitrary order in h . We obtain thus an expression for $y(x+h)$,

$$\vec{y}(x+h) = \vec{y}(x) + h\vec{F}(x+h, \vec{y} + \vec{y}(x+h)).$$

In this work we use the Runge-Kutta of fifth order in the integration step h . The expression for the increment at this order of precision is

$$\vec{y}_5(x+h) = \vec{y}(x) + \sum_{i=0}^6 C_i K_i,$$

and

$$K_0 = hF(x, y),$$

$$K_i = hF\left(x + A_i h, y + \sum_{j=0}^{i-1} B_{ij} K_j\right)$$

where $i = 1, 2, 3, \dots, 6$.

We also need the fourth order Runge-Kutta method in order to obtain the error in the integration. This is given by

$$\vec{y}_4(x+h) = \vec{y}(x) + \sum_{i=0}^6 D_i K_i,$$

The error is given by

$$\vec{E}(h) = \vec{y}_5(x+h) - \vec{y}_4(x+h). \quad (2.57)$$

Of this expression, we can take the root mean square of the components of $\vec{E}(h)$,

$$e(h) = \sqrt{\frac{1}{n} \sum_{i=0}^{n-1} E_i^2(h)} \quad (2.58)$$

This way we obtain a scalar measure of the error.

If h_1 and h_2 are two consecutive steps in the integration of the differential equation, then it can be shown that

$$\frac{e(h_1)}{e(h_2)} \approx \left(\frac{h_1}{h_2}\right)^5 \quad (2.59)$$

We don't know what the error of the next step will be, but we can define a tolerance $\epsilon > 0$ such that the error of the next step is at most ϵ . Thus, the following step can be computed from Eq. 2.60 by letting $e(h_2) = \epsilon$

$$h_2 = h_1 \left(\frac{\epsilon}{e(h_1)}\right)^{1/5} \quad (2.60)$$

This method is good for our purposes since the curves we are trying to analyze are flat at the beginning but have sharp slopes towards the interface (see Fig. ?? and ??).

2.7.2 The Shooting Method

The method described in section 2.7.1 can solve the system of equations if the border conditions are all known at a given value of $x = x_0$. Nevertheless, as it can be seen from 3.109, that we have boundary conditions at $x = 0$ (the interface) and at $x = \delta$ the bulk solution (see Fig. 2.2). This is a complication which can be overcome by using the shooting method. The idea is to transform the problem with boundary conditions

$$\begin{aligned} C_+(\delta) &= C_-(\delta) = C_b \\ \phi(\delta) &= 0 \\ \phi(0) &= V_0 \end{aligned}$$

into the problem

$$\begin{aligned} C_+(\delta) &= C_-(\delta) = C_b \\ \phi(\delta) &= 0 \\ E(\delta) &= u, \end{aligned}$$

where u is a constant yet to be determined. To determine u , we define a residual function

$$r(u) = \phi(0) - V_0.$$

which is zero when the value of $\phi(0)$ (given an appropriate u) is the original boundary condition. Therefore, the two-point boundary problem is transformed into a root finding problem. First, we need to find two values of u , u_1 and u_2 such that $r(u_1) < 0$ and $r(u_2) > 0$. Once we have that, we can use Ridder's method to find the root.

2.7.3 Ridder's Method

In this method it is assumed that the root is bracketed within two values. We define an auxiliary function

$$G(x) = F(x)e^{(x-x_1)Q}$$

where Q is determined by imposing that the points $(x_1, G(x_1))$, $(x_2, G(x_2))$ and $(x_3, G(x_3))$ be in a straight line. That is, if $x_1 - x_2 = 2h$ and $x_1 - x_3 = h = x_3 - x_2$ we should get

$$G(x_3) = \frac{G(x_1) - G(x_2)}{2}. \quad (2.61)$$

Using equation 2.61, we obtain that

$$e^{hQ} = \frac{f(x_1) + f(x_2)e^{2hQ}}{2} \quad (2.62)$$

Which is a quadratic equation on e^{hQ} . Solving for this quantity we obtain

$$e^{hQ} = \frac{f(x_3) \pm \sqrt{f(x_3)^2 - f(x_2)f(x_1)}}{f(x_2)} \quad (2.63)$$

Now that we have determined completely our function $G(x)$, we can do linear interpolation on it to get a better estimation of the root of $f(x)$. Let x_r be it. Then

$$x_r^\pm = x_3 \pm (x_3 - x_1) \frac{f(x_3)}{\sqrt{f^2(x_3) - f(x_1)f(x_2)}}$$

It can be show that

- If $f(x_1) - f(x_2) < 0$, we should pick the x_r^- solution
- If $f(x_1) - f(x_2) > 0$, we should pick the x_r^+ solution

When we have our solution, we make $x_3 = x_r^s$ ($s+$, $-$, for every case) and find a new correction to x_r . We stop when $x_r^+ - x_r^-$ is below the define tolerance.

To test convergence, our method assumes the function we are passing on is of the form

$$f(x) = g(x) - g_0,$$

where we are trying to find x_0 such that $g(x_0) = g_0$. This means that when the root is found, we should get

$$f(x_0) \in [-\epsilon, +\epsilon],$$

where $\epsilon > 0$ is a predefined tolerance.

2.7.4 Results

Fig. 2.6 show the results obtained. The solution of the steady state at different values of the reaction rate do not defer much closest to the surface of the electrode ($x = 0$). Also, from Fig. 2.6 (c) and (d) we can see that the approximation of the electric field and the electric potential is fairly

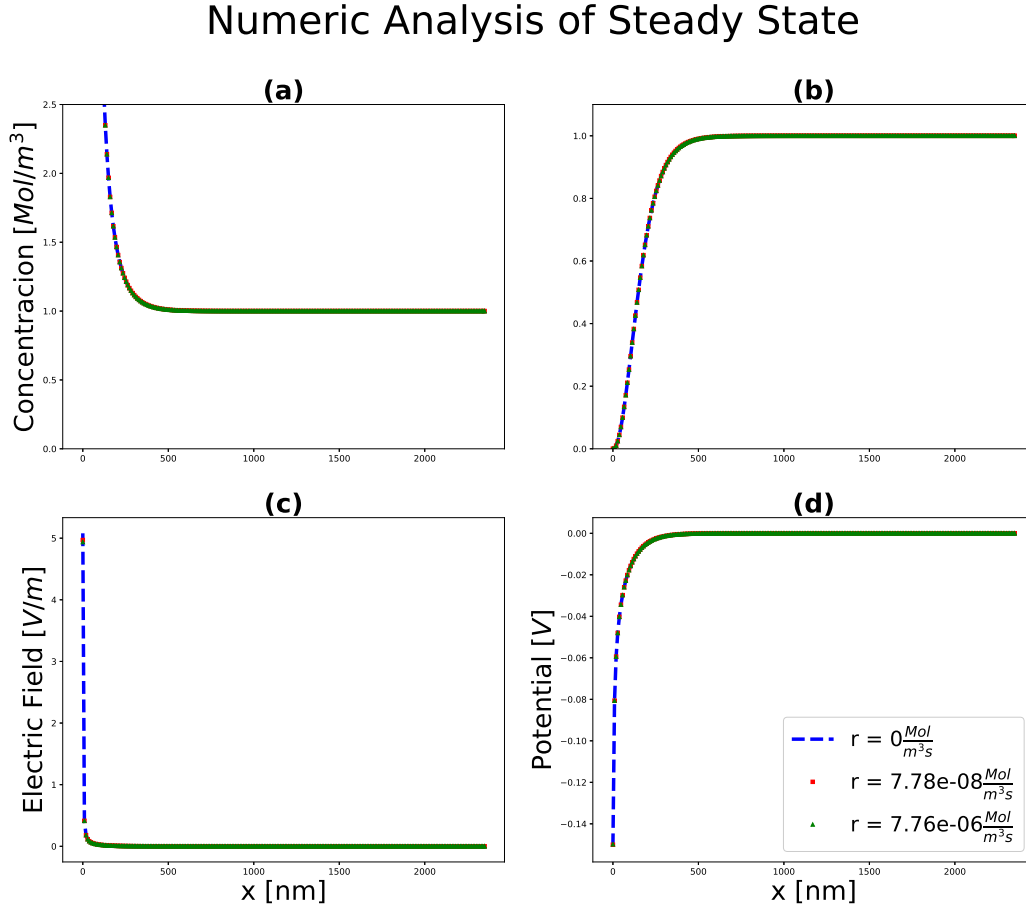


Figure 2.6: The numerical and the analytic solution to the potential to first order in the current.

Dealing with the equations as presented in Eq. 2.1 is extremely difficult when doing a numerical analysis. This is due to the fact that the natural units of the system (x which is measured in meters) are too small for the computer to handle. Also, non-linearity gives extreme fluctuations of the concentration of the positive ion near the surface. Since we were using the shooting method, we needed to change the values of the electric field at the bulk, such that the boundary condition for the electric potential is correct, but this induced such strong concentrations at the interface sometimes, that the computer could not handle the numbers resulting from Runge-Kutta method. We had to make a little adaptation in order to be able to find the correct boundary condition for the electric field with the shooting method.

As it can be seen in figures ??, ??, the electric field and potential approach zero when the start moving into the bulk of the solution, as expected. The further away from the interface

we go, the better the border conditions for the electric field are met. For our particular case, we cut the integration range when we reached a tolerance of $E_{bulk} < 1 \times 10^{-3}$, where E_{bulk} is the border condition of the dimensionless electric field at the bulk.

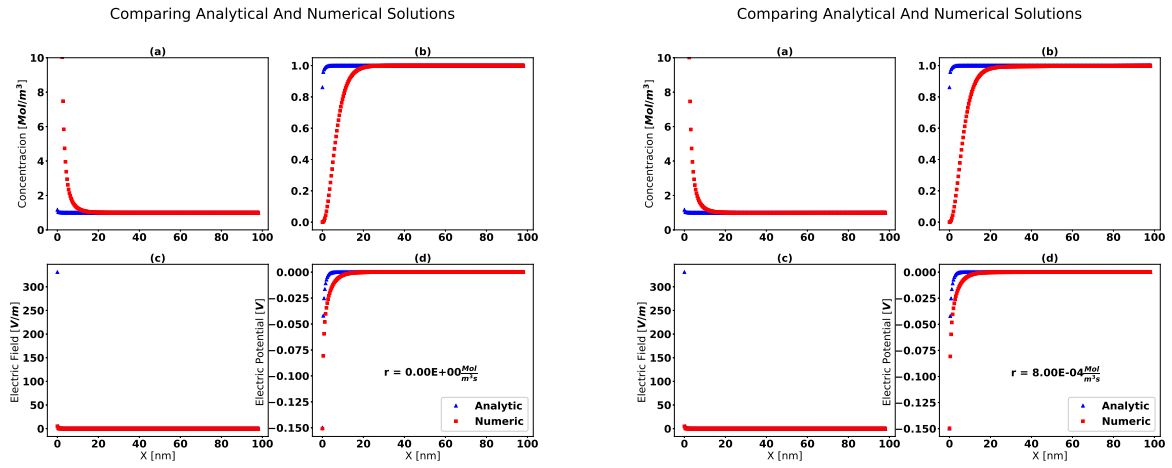
A similar analysis can be done for the concentrations (Fig. ??), but this time the value of both concentrations at the bulk is C_b , as defined by the border conditions for the system 2.1.

Another difficulty is that, since we used the adaptive Runge-Kutta method, the concentrations change so abruptly that the adaptive step h becomes incredibly small. The problem with this is that the number of iterations needed with a step of the order of $h \approx 10^{-29}$. In order to reach the full length of integration is too big and therefore, we obtain only a part of the integration interval and not as close to the interface as we should like.

To avoid such difficulties, we have worked with the adimensional potential in a scale of adimensional length $\xi = \kappa x$. We have integrated on the interval $[0, 20\kappa\delta]$.

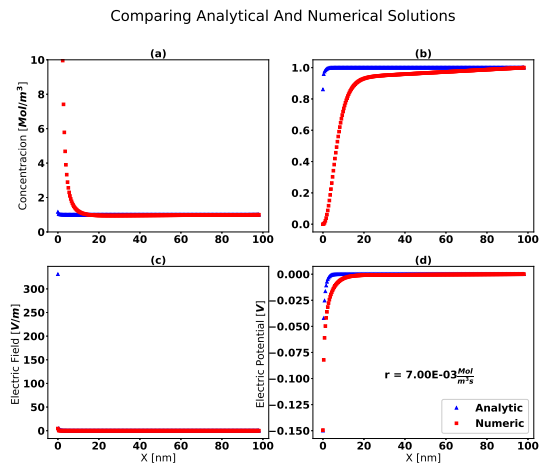
Comparing Numeric An Analytic Results

Fig. ?? shows the comparison between the numeric and analytic results.



(a)

(b)



(c)

Figure 2.7: Three subfigures

Chapter 3

Dynamic Solution

To study the dynamics of the system, we need to consider the complete diffusion equation, along with the time dependent electric potential equation.

We consider

$$\frac{\partial C_+}{\partial t} = D_+ [\nabla^2 C_+ - \nabla(C_+ \nabla \Psi)] , \quad (3.1)$$

$$\frac{\partial C_-}{\partial t} = D_- [\nabla^2 C_- + \nabla(C_- \nabla \Psi)] , \quad (3.2)$$

$$\nabla^2 \Psi = -\kappa^2 (C_+ - C_-) . \quad (3.3)$$

subject to the border condition

$$C_+(0, x) = 0 \quad (3.4)$$

$$C_-(0, x) = 0 \quad (3.5)$$

$$\Phi(0, x) = 0. \quad (3.6)$$

where the super-script *SS* indicates the steady state solution (See Ch. 2)

3.1 Diffusion Only

As a first approach to our problem, we evaluate the simpler diffusion-only problem

$$\frac{\partial C_+}{\partial t} = D_+ \nabla^2 C_+, \quad (3.7)$$

$$\frac{\partial C_-}{\partial t} = D_- \nabla^2 C_-, \quad (3.8)$$

which in our limit (infinite plate) we can write as

$$\frac{\partial C_s}{\partial t} = D_s \frac{\partial^2 C_s}{\partial x^2}, \quad (3.9)$$

$$(3.10)$$

with $s = \pm$. The equation is subject to the following boundary conditions

$$C_s(\delta, t) = C_b, \quad (3.11)$$

$$J_s(0, t) = D_s \frac{\partial C_s}{\partial x} \Big|_{x=0} = r \delta_{+,s}, \quad (3.12)$$

where $J_s(x, t)$ is the flux for each species, which is non-zero at the interface only for the interacting species (copper, in our case). The initial condition for our system is

$$C_s(x, 0) = 0. \quad (3.13)$$

3.1.1 Analytic Solution To The Diffusion-Only Problem

First, we solve for $s = -$. Let

$$\rho_-(x, t) = \frac{C_-(x, t) - C_b}{C_b}, \quad (3.14)$$

which yields the equation

$$\frac{\partial \rho_-}{\partial t} = D_- \frac{\partial^2 \rho_-}{\partial x^2}, \quad (3.15)$$

$$(3.16)$$

The border conditions for the new function 3.14 are

$$\rho(\delta, t) = -C_b, \quad (3.17)$$

$$C_b D_- \frac{\partial \rho_-}{\partial x} \Big|_{x=0} = J_-(0, t) = 0. \quad (3.18)$$

We will solve this equation using the method of separation of variables. Let

$$\rho_-(x, t) = g_-(t) f_-(x) \quad (3.19)$$

We get the following two equations for $g_-(t)$ and $f_-(x)$

$$g'_-(t) + \lambda g_-(t) = 0, \quad (3.20)$$

$$f''_-(x) + \frac{\lambda}{D_-} f_-(x) = 0. \quad (3.21)$$

λ is a positive constant, due to border conditions. The solution to these equations are

$$g_-(t) = g_-(0) e^{-\lambda t}, \quad (3.22)$$

$$f_-(x) = F_{-, \lambda}^1 \cos \left(\sqrt{\frac{\lambda}{D_-}} x \right) + F_{-, \lambda}^2 \sin \left(\sqrt{\frac{\lambda}{D_-}} x \right), \quad (3.23)$$

where $F_{-, \lambda}^1$, $F_{-, \lambda}^2$ and $G_{-, 0}$ are constants dependent on the parameter λ , which is yet to be determined. Border conditions 3.16 yield $B_{-, \lambda} = 0$. We get the general solution,

$$\rho_-(x, t) = \sum_{\lambda} A_{\lambda} e^{-\lambda t} \cos \left(\frac{\lambda}{D_-} x \right), \quad (3.24)$$

where $A_{-, \lambda} = g_-(0) F_{-, \lambda}^1$. is a constant. Considering the border condition at $x = \delta$, we can determine the value of λ ,

$$\rho_-(x = \delta, t) = \sum_{\lambda} A_{\lambda} e^{-\lambda t} \cos\left(\frac{\lambda}{D_-} \delta\right) = 0. \quad (3.25)$$

The only way (unless $A_{-, \lambda} = 0$, in which case we get the trivial solution) for equation 3.28 to be zero is if we get

$$\cos\left(\sqrt{\frac{\lambda}{D_-}} \delta\right) = 0$$

$$\sqrt{\frac{\lambda}{D_-}} \delta = \frac{(2n+1)\pi}{2}. \quad (3.26)$$

Solving for λ ,

$$\lambda = \left(\frac{(2n+1)\pi}{2\delta}\right)^2 D_-. \quad (3.27)$$

Replacing 3.27 into the general expression ??,

$$\rho_-(x, t) = \sum_n A_n e^{-\left(\frac{(2n+1)\pi}{2}\right)^2 \frac{D_- t}{\delta^2}} \cos\left(\frac{(2n+1)\pi}{2\delta} x\right) \quad (3.28)$$

From initial condition 3.28, we have $\rho_-(x, 0) = -C_b$, which in turn yields

$$-C_b = \sum_n A_n \cos\left(\frac{(2n+1)\pi}{2\delta} x\right). \quad (3.29)$$

Multiplying 3.29 by $\cos\left(\frac{(2m+1)\pi}{2\delta} x\right)$ and integrating over the domain,

$$-C_b \int_0^{\delta} \cos\left(\frac{(2m+1)\pi}{2\delta} x\right) dx = \sum_n A_n \int_0^{\delta} \cos\left(\frac{(2m+1)\pi}{2\delta} x\right) \cos\left(\frac{(2n+1)\pi}{2\delta} x\right) dx. \quad (3.30)$$

The integral on the LHS is simply

$$\int_0^{\delta} \cos\left(\frac{(2m+1)\pi}{2\delta} x\right) dx = \left(\frac{2\delta}{(2m+1)\pi}\right) \left(\sin\left(\frac{(2m+1)\pi}{2}\right) - \sin(0)\right). \quad (3.31)$$

Notice that

$$\sin\left(\frac{(2m+1)\pi}{2}\right) = (-1)^m. \quad (3.32)$$

Therefore,

$$\int_0^\delta \cos\left(\frac{(2m+1)\pi}{2\delta}x\right) dx = \frac{2\delta(-1)^m}{(2m+1)\pi}. \quad (3.33)$$

On the other hand,

$$\int_0^\delta \cos\left(\frac{(2m+1)\pi}{2\delta}x\right) \cos\left(\frac{(2n+1)\pi}{2\delta}x\right) dx = \frac{\delta}{2} \delta_{m,n}. \quad (3.34)$$

The Fourier coefficients are thus

$$A_m = -\frac{4C_b}{\pi} \frac{(-1)^m}{(2m+1)}. \quad (3.35)$$

Plugging these coefficients into expression 3.29

$$\rho_-(x, 0) = -\frac{4C_b}{\pi} \sum_n \frac{(-1)^m}{(2m+1)} \cos\left(\frac{(2m+1)\pi}{2\delta}x\right), \quad (3.36)$$

which in turn yields the concentration profile at time t=0

$$C_-(x, 0) = C_b \left(1 - \frac{4}{\pi} \sum_n \frac{(-1)^m}{(2m+1)} \cos\left(\frac{(2m+1)\pi}{2\delta}x\right) \right). \quad (3.37)$$

From 3.29, the time dependent solution for the concentration is

$$C_-(x, t) = C_b \left(1 - \frac{4}{\pi} \sum_n \frac{(-1)^m}{(2m+1)} \exp\left[-\left(\frac{(2n+1)\pi}{2}\right)^2 \frac{D_-t}{\delta^2}\right] \cos\left(\frac{(2m+1)\pi}{2} \frac{x}{\delta}\right) \right). \quad (3.38)$$

We define the dimensionless parameters $\tau = \frac{D_-t}{\delta^2}$ and $\xi = \frac{x}{\delta}$. In terms of this parameters the concentration is

$$C_-(\xi, \tau) = C_b \left(1 - \frac{4}{\pi} \sum_n \frac{(-1)^m}{(2m+1)} \exp\left[-\left(\frac{(2n+1)\pi}{2}\right)^2 \tau\right] \cos\left(\frac{(2m+1)\pi}{2} \xi\right) \right). \quad (3.39)$$

3.1.2 Numeric Solution To The Diffusion Only Equation

As a first approach to the problem, we will use an implicit scheme to find the numerical solution. This means that, in approaching the finite difference method, we will compute the spacial derivative at time step $n + 1$. Just as in the analytic case, we define

$$\rho(x, t) = \frac{C(x, t) - C_b}{C_b}, \quad (3.40)$$

which will make the numerical computations converge faster.
Consider the one dimensional diffusion equation

$$\frac{\partial \rho}{\partial t} = D \frac{\partial^2 \rho}{\partial x^2}. \quad (3.41)$$

We will define $x = \delta \xi$ where δ is the width of the laminar flow sheet.

$$\frac{\partial \rho}{\partial t} = \frac{D}{\delta^2} \frac{\partial^2 \rho}{\partial \xi^2}, \quad (3.42)$$

$$\frac{\partial \rho}{\partial \tau} = \frac{\partial^2 \rho}{\partial \xi^2}, \quad (3.43)$$

where we have defined $\tau = Dt/\delta^2$, which follows the modified border and initial conditions,

$$\rho(\xi = 1, \tau) = 0, \quad (3.44)$$

$$D \frac{\partial \rho}{\partial \xi}(\xi = 0, \tau) = 0, \quad (3.45)$$

$$\rho(\xi, \tau = 0) = -1. \quad (3.46)$$

We will discretize the derivative as follows,

$$\frac{\partial \rho^{n+1,k}}{\partial \tau} = \frac{C^{n+1,k} - \rho^{n,k}}{\Delta \tau}, \quad (3.47)$$

$$\frac{\partial^2 \rho^{n+1,k}}{\partial \xi^2} = \frac{\rho^{n+1,k-1} - 2\rho^{n,k} + \rho^{n+1,k+1}}{\Delta \xi^2}. \quad (3.48)$$

Replacing these approximations into equation 3.41 we get

$$-\alpha \rho^{n+1,k-1} + (1 + 2\alpha) \rho^{n+1,k} - \alpha \rho^{n+1,k+1} = \rho^{n,k} \quad (3.49)$$

$$k \in [1, \dots, m-1] \quad (3.50)$$

In particular, for a given n value, the equations for $k = 1$ and $k = m - 1$ (which include the border conditions) are

$$-\alpha\rho^{n+1,0} + (1 + 2\alpha)\rho^{n+1,1} - \alpha\rho^{n+1,2} = \rho^{n,1}, \quad (3.51)$$

$$-\alpha\rho^{n+1,m-2} + (1 + 2\alpha)\rho^{n+1,m-1} - \alpha\rho^{n+1,m} = \rho^{n,m-1}. \quad (3.52)$$

The border conditions for our system (in discretized form) are

$$\rho^{n,0} = \rho^{n,1}, \quad (3.53)$$

$$\rho^{n,m-1} = 0. \quad (3.54)$$

Therefore, equations 3.52 yield

$$(1 + \alpha)\rho^{n+1,1} - \alpha\rho^{n+1,2} = \rho^{n,1}, \quad (3.55)$$

$$-\alpha\rho^{n+1,m-2} + (1 + 2\alpha)\rho^{n+1,m-1} = \rho^{n,m-1}. \quad (3.56)$$

We want to put these equations in matrix form. Let

$$\rho^{\mathbf{n}} = \begin{bmatrix} \rho^{n,0} \\ \rho^{n,1} \\ \vdots \\ \rho^{n,m-1} \\ \rho^{n,m} \end{bmatrix}, \quad (3.57)$$

and

$$\underline{\mathbf{A}} = \begin{bmatrix} (1 + \alpha) & -\alpha & 0 & 0 & \cdots & 0 \\ -\alpha & (1 + 2\alpha) & -\alpha & \cdots & 0 & 0 \\ \vdots & \cdots & \ddots & \ddots & \ddots & \\ \vdots & \cdots & 0 & -\alpha & (1 + 2\alpha) & -\alpha \\ 0 & \cdots & 0 & 0 & -\alpha & (1 + 2\alpha) \end{bmatrix}. \quad (3.58)$$

Equations 3.50 can be expressed as

$$\underline{\mathbf{A}}\rho^{\mathbf{n}+1} = \rho^{\mathbf{n}}. \quad (3.59)$$

Considering the initial conditions ??, we get

$$\rho^{0,k} = -\mathbf{C}_b, \quad (3.60)$$

$$k \in [1, \dots, M - 1]. \quad (3.61)$$

This means that the shape of $\underline{\mathbf{A}}$ is $M - 2 \times M - 2$ and the numerical solution is solved in the interval $k \in [0, \dots, M]$, leaving $k = 0$ and $k = M$ as the overflow terms to push the

boundary conditions. Nevertheless, these terms must be included in order to get the full solution (otherwise we should start from $k = 1$ and end at $k = M - 1$ and not include the border conditions in the plot of our numeric result).

Now we are ready to start iterating this matrix equation to get the time evolution.

We will use the parameters $\xi = x/\delta$ and $\tau = t/\delta^2$ as the parameters of the equation. The comparison between numeric and analytic results is shown in figure]refdiffusion-comparison.

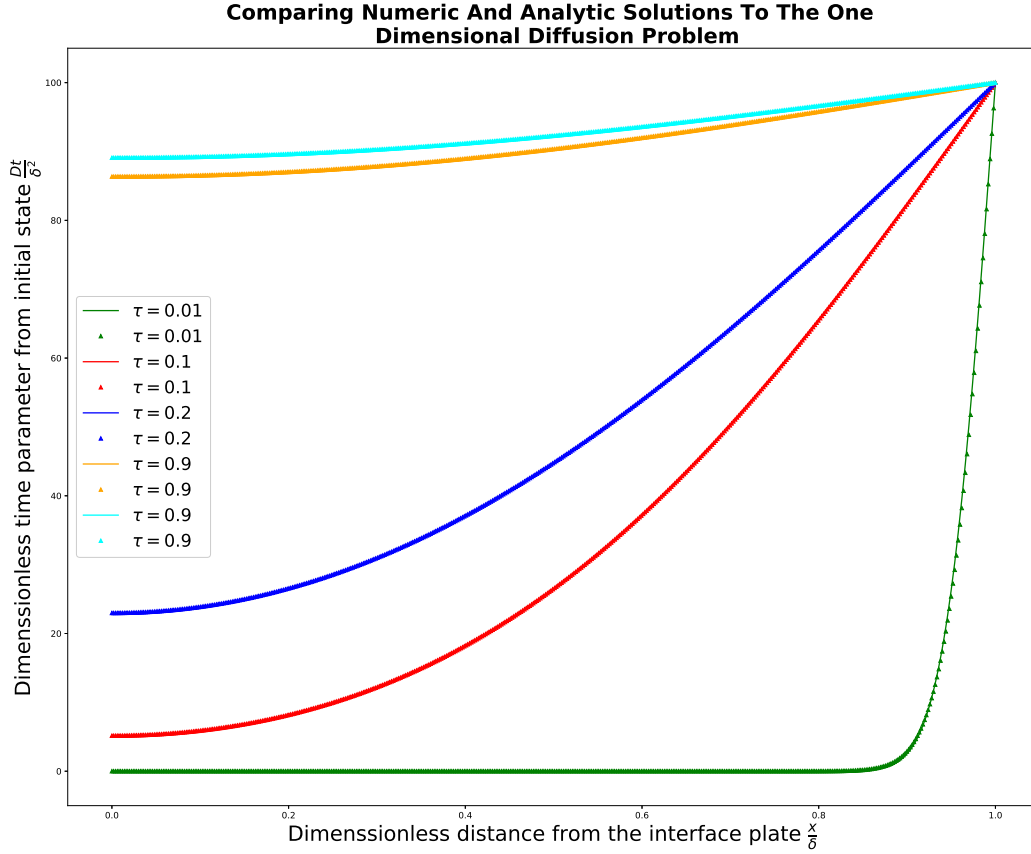


Figure 3.1

3.1.3 Numeric Solution To The Diffusion Equation With Reaction At The Interface

For this case (s=+), we have the same equation, but border conditions at the interface change a little. We have

$$\rho_+(\xi = 1, \tau) = 0, \quad (3.62)$$

$$D \frac{\partial \rho_+}{\partial \xi}(\xi = 0, \tau) = \frac{\delta r}{C_b}, \quad (3.63)$$

$$\rho_+(\xi, \tau = 0) = -1. \quad (3.64)$$

Here, we have used the adimensional parameters

$$\tau = \frac{Dt}{\delta^2}, \quad (3.65)$$

$$\xi = \delta x \quad (3.66)$$

The approach in discretizing is exactly the same as in the previous case, with the exception of the first equation (k = 1) in which we get the following border condition

$$\frac{D}{\delta} \frac{\partial \rho_+}{\partial \xi} = \frac{r}{C_b}. \quad (3.67)$$

In discretized form

$$\frac{D}{\delta} \frac{(\rho_+^{n,1} - \rho_+^{n,0})}{\Delta \xi} = \frac{r}{C_b}, \quad (3.68)$$

where r is the reaction rate. In discretized form, this border condition can be written as

$$\rho_+^{n,0} = \rho_+^{n,1} - \frac{r\delta}{DC_b} \Delta \xi. \quad (3.69)$$

This means that the discrete equations are (in matrix form)

$$\underline{\mathbf{A}} \rho_+^{n+1} = \rho_+^n + \mathbf{b}, \quad (3.70)$$

where $\underline{\mathbf{A}}$ is the same as the diffusion-only case and

$$\mathbf{b} = \begin{bmatrix} -\alpha \frac{r\delta}{DC_b} \Delta \xi \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad (3.71)$$

On the other hand,

$$r = \left. \frac{\partial C_s}{\partial t} \right|_{\xi=0} = \left. \frac{\partial z F C_s}{\partial t} \frac{1}{zF} \right|_{\xi=0} = \left. \frac{\partial Q_s}{\partial t} \frac{1}{zF} \right|_{\xi=0} = \frac{i_0}{zF}. \quad (3.72)$$

3.1.4 Analytic Solution To The Diffusion Equation With Reaction At The Interface

In this section we compute the analytic solution to the diffusion equation, subject to a chemical reaction at the interface ($x = 0$). We need to solve the equation

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2}, \quad (3.73)$$

which must meet the border conditions

$$C(x = \delta, t) = C_b, \quad (3.74)$$

$$-D \frac{\partial C(x = 0, t)}{\partial x} = -r, \quad (3.75)$$

and the initial condition

$$C(x, t = 0) = 0. \quad (3.76)$$

First, we will compute the steady state solution, that is

$$\frac{\partial C_{ss}}{\partial t} = 0. \quad (3.77)$$

Which, from ?? takes the form

$$C_{ss}(x) = Ax + B, \quad (3.78)$$

where A and B are constants to be determined. From border conditions ??,

$$A = \frac{r}{D}, \quad (3.79)$$

$$B = C_b - \frac{r\delta}{D} \quad (3.80)$$

Also, we want to take our system to the dimensionless parameters $\xi = x/\delta$ and $\tau = Dt/\delta^2$, thus

$$C_{ss}(x) = C_b - \frac{r\delta}{D}(1 - \xi). \quad (3.81)$$

The complete system including time difference can be easily treated making the non-homogenous border condition at $x = 0$ homogenous. Consider the following function

$$\rho(\xi, \tau) = \frac{C(\xi, \tau) - C_{ss}(\xi, \tau)}{C_b}. \quad (3.82)$$

Since border conditions are met for all time, we get that

$$\rho(\xi = 1, \tau) = \frac{C(\xi = 1, \tau) - C_{SS}(\xi = 1, \tau)}{C_b} = \frac{C_b - C_b}{C_b} = 0, \quad (3.83)$$

$$-D \frac{\partial \rho(\xi = 0, \tau)}{\partial x} = \frac{-D \frac{\partial C(\xi=0, \tau)}{\partial x} + D \frac{\partial C_{SS}(\xi=1, \tau)}{\partial x}}{C_b} = \frac{-r + r}{C_b} = 0. \quad (3.84)$$

$$(3.85)$$

Thus we need to solve a system with homogenous border conditions,

$$\frac{\partial \rho}{\partial \tau} = D \frac{\partial^2 \rho}{\partial \xi^2}, \quad (3.86)$$

$$\rho(\xi = 1, \tau) = 0, \quad (3.87)$$

$$\frac{\partial \rho(\xi = 0, \tau)}{\partial \tau} = 0, \quad (3.88)$$

$$\rho(\xi, \tau = 0) = -\frac{\partial C_{SS}(x)}{C_b}. \quad (3.89)$$

This system is solve on a similar fashion as 3.16: using separation of variables to obtain the solution as a Fourier series. The general solution is of the form

$$\rho(\xi, \tau) = \sum_{n=0}^{\infty} G_n \exp \left[- \left(\frac{2n+1}{2} \pi \right)^2 \tau \right] \cos \left(\frac{2n+1}{2} \pi \xi \right) \quad (3.90)$$

where G_n are the Fourier coefficients, which need to be determined according to the initial condition 3.89. We have

$$\rho(\xi, \tau = 0) = \sum_{n=0}^{\infty} G_n \cos \left(\frac{2n+1}{2} \pi \xi \right) = -\frac{C_{SS}}{C_b} \quad (3.91)$$

In a similar procedure as in the case of 3.30,

$$\sum_{n=0}^{\infty} G_n \int_0^1 \cos \left(\frac{2n+1}{2} \pi \xi \right) \cos \left(\frac{2m+1}{2} \pi \xi \right) d\xi = - \int_0^1 \frac{C_{SS}}{C_b} \cos \left(\frac{2n+1}{2} \pi \xi \right) d\xi \quad (3.92)$$

We have already computed the integral on the LHS 3.31. On the RHS we need to compute the following types of integrals

$$\int_0^1 \cos \left(\frac{2m+1}{2} \pi \xi \right) d\xi = \frac{2}{2m+1} \frac{(-1)^m}{\pi} \quad (3.93)$$

$$\int_0^1 \xi \cos \left(\frac{2m+1}{2} \pi \xi \right) d\xi = \frac{2}{(2m+1)\pi} \left((-1)^m - \frac{2}{(2m+1)\pi} \right). \quad (3.94)$$

This yields the following Fourier coefficients

$$G_m = -\frac{4}{\pi} \frac{(-1)^m}{(2m+1)} + \frac{8r\delta}{DC_b\pi^2} \frac{1}{(2m+1)^2} \quad (3.95)$$

The complete solution to the diffusion equation with a reaction at the interface is

$$C(\xi, \tau) = C_{SS}(\xi) + C_b\rho(\xi, \tau)$$

or explicitly

$$\begin{aligned} C_-(x, 0) = C_b \left(1 - \frac{4}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n+1)} \exp \left[- \left(\frac{(2n+1)\pi}{2} \right)^2 \frac{D_- t}{\delta^2} \right] \cos \left(\frac{(2n+1)\pi x}{2\delta} \right) \right) \\ - \frac{r\delta}{D} \left(1 - \xi - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \left[- \left(\frac{(2n+1)\pi}{2} \right)^2 \frac{D_- t}{\delta^2} \right] \cos \left(\frac{(2n+1)\pi x}{2\delta} \right) \right). \end{aligned} \quad (3.96)$$

In order to compare the numeric and analytic solution, we compute the numeric solution for $r = \frac{150 \times 10}{2.96485.3329} \frac{A}{m^2 C} = 7.77 \times 10^{-4}$.

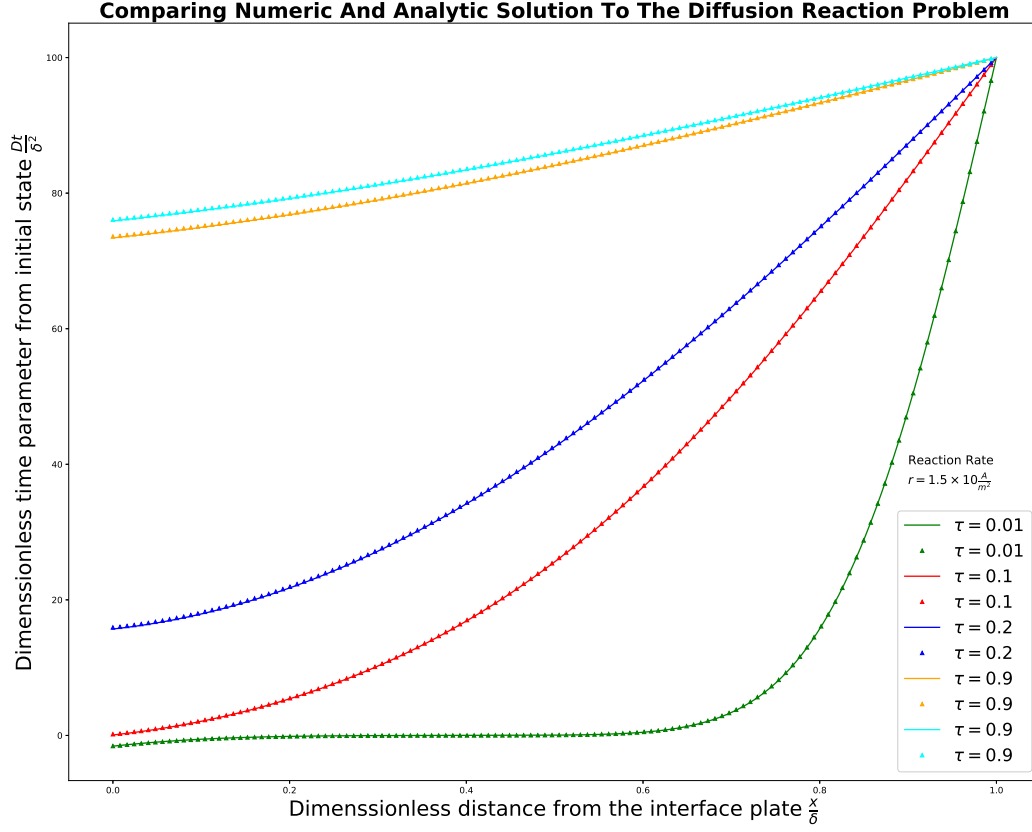


Figure 3.2

3.2 Concentration Dependent Reaction

In this section we consider the reaction as a concentration dependent quantity. This is

$$J_{x=0} = -D \frac{\partial C}{\partial x} \Big|_{x=0} = -R, \quad (3.97)$$

where R is given by the Langmuir absorption model

$$R = \frac{kC(0, t)}{K + C(0, t)}, \quad (3.98)$$

where k is and K

If $C \ll K$, we can expand this into what is known as the Freundlich formula,

$$R \approx k_f C(0, t), \quad (3.99)$$

with $k_f = k/K$. For this case, we get the following boundary condition for the flux

$$J_{x=0} = -k_f C(0^+, t), \quad (3.100)$$

which yields a Robin type of boundary condition for our system

$$\frac{\partial C}{\partial x} \Big|_{x=0} - \frac{k_f}{D} C(0^+, t) = 0. \quad (3.101)$$

Thus, we need to solve the following system

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} \quad (3.102)$$

$$C(x = \delta, t) = C_b \quad (3.103)$$

$$\frac{\partial C}{\partial x} \Big|_{x=0} - \frac{k_f}{D} C(0^+, t) = 0 \quad (3.104)$$

$$C(x, t = 0) = 0 \quad (3.105)$$

3.2.1 Steady State

First, we will solve the steady state solution of this equation,

$$\frac{\partial C_{SS}}{\partial t} = D \frac{\partial^2 C_{SS}}{\partial x^2} = 0 \quad (3.106)$$

$$C(\delta, t) = C_b \quad (3.107)$$

$$\frac{\partial C}{\partial x} \Big|_{x=0} - \frac{k_f}{D} C(0^+, t) = 0 \quad (3.108)$$

$$(3.109)$$

From 3.106, we get

$$C_{ss}(x) = Ax + B \quad (3.110)$$

Boundary conditions 3.109 yield

$$A\delta + B = C_b \quad (3.111)$$

$$A - \frac{k_f}{D} B = 0. \quad (3.112)$$

From which we get

$$A = \frac{C_b}{1 + \frac{k_f \delta}{D}} \frac{k_f}{D}, \quad (3.113)$$

$$B = \frac{C_b}{1 + \frac{k_f \delta}{D}}. \quad (3.114)$$

Therefore,

$$C_{ss} = \frac{C_b}{1 + \frac{k_f \delta}{D}} \left(\frac{k_f x}{D} + 1 \right) \quad (3.115)$$

3.2.2 Dynamic Solution

Now we consider the complete system 3.122. To solve this system we define the dimensionless fluctuations with respect to the steady state as

$$\rho(x, t) = \frac{C(x, t) - C_{ss}(x)}{C_b} \quad (3.116)$$

which hold the following boundary conditions, which are derived from 3.105

$$\rho(\delta, t) = 0 \quad (3.117)$$

$$\frac{\partial \rho}{\partial x} \Big|_{x=0} - \frac{k_f}{D} \rho(0^+, t) = 0 \quad (3.118)$$

$$\rho(x, t = 0) = - \frac{C_{ss}(x)}{C_b} \quad (3.119)$$

First, we will change variables

$$\xi = \frac{x}{\delta}, \quad (3.120)$$

$$\tau = \frac{Dt}{\delta^2}. \quad (3.121)$$

The dimensionless system is

$$\frac{\partial \rho}{\partial \tau} = \frac{\partial^2 \rho}{\partial \xi^2} \quad (3.122)$$

$$\rho(\xi = 1, \tau) = 0 \quad (3.123)$$

$$\left. \frac{\partial \rho}{\partial \xi} \right|_{\xi=0} - \frac{k_f \delta}{D} \rho(0^+, \tau) = 0 \quad (3.124)$$

$$\rho(x, t = 0) = - \frac{C_{SS}(x)}{C_b} \quad (3.125)$$

We use separation of variables. Let

$$\rho(\xi, \tau) = G(\tau)F(\xi). \quad (3.126)$$

In a similar procedure as in section 3.1.4 we get the following two equations

$$F''(\xi) = -\lambda^2 F(\xi), \quad (3.127)$$

$$G'(\tau) = -\lambda^2 G(\tau). \quad (3.128)$$

Note that boundary conditions can be rearrange as

$$F(\xi = 1) = 0 \quad (3.129)$$

$$\left(\left. \frac{dF(\xi)}{d\xi} \right|_{\xi=0} - \frac{k_f \delta}{D} F(0^+) \right) = 0 \quad (3.130)$$

The solution to equation 3.128 is

$$G(\tau) = G(0)e^{-\lambda^2 \tau} \quad (3.131)$$

A particular solution to equation 3.127 is

$$F(\xi) = A_\lambda \cos(\lambda \xi) + B_\lambda \sin(\lambda \xi) \quad (3.132)$$

Boundary conditions yield

$$B\lambda - \frac{k_f\delta}{D}A = 0, \quad (3.133)$$

$$A \cos(\lambda) + B \sin(\lambda) = 0. \quad (3.134)$$

From these we obtain that the eigenvalues of the Sturm-Liouville problem λ satisfy the following transcendent equation

$$\frac{\tan \lambda}{\lambda} = -\frac{D}{k_f\delta}. \quad (3.135)$$

The general solution is then,

$$\rho(\xi, \tau) = \sum_{\lambda} G(0) e^{-\lambda^2 \tau} (A_{\lambda} \cos(\lambda \xi) + B_{\lambda} \sin(\lambda \xi)) \quad (3.136)$$

From 3.133 we get

$$\rho(\xi, \tau) = \sum_{\lambda} A_{\lambda} e^{-\lambda^2 \tau} \left(\cos(\lambda \xi) + \frac{k_f\delta}{D\lambda} \sin(\lambda \xi) \right) \quad (3.137)$$

or equivalently

$$\rho(\xi, \tau) = \sum_{\lambda} A_{\lambda} e^{-\lambda^2 \tau} (\cos(\lambda \xi) - \cot(\lambda) \sin(\lambda \xi)) \quad (3.138)$$

In appendix ?? we show that the functions

$$P_{\lambda}(\xi) = \cos(\lambda \xi) - \cot(\lambda) \sin(\lambda \xi), \quad (3.139)$$

are orthogonal such that,

$$\langle P_{\lambda}, P_{\lambda'} \rangle = 0, \quad (3.140)$$

$$\langle P_{\lambda}, P_{\lambda'} \rangle = -\frac{(\cot(\lambda) - \lambda \csc^2(\lambda))}{2\lambda}. \quad (3.141)$$

Thus, the Fourier coefficients can be obtained from the initial condition,

$$\rho(\xi, \tau = 0) = \sum_{\lambda} A_{\lambda} (\cos(\lambda \xi) - \cot(\lambda) \sin(\lambda \xi)) = -\frac{C_{ss}(\xi)}{C_b} \quad (3.142)$$

Using ,

$$\sum_{\lambda'} A_{\lambda'} \delta_{\lambda, \lambda'} \left(-\frac{(\cot(\lambda) - \lambda \csc^2(\lambda))}{2\lambda} \right) = -\int_0^1 \frac{C_{SS}(\xi)}{C_b} (\cos(\lambda\xi) - \cot(\lambda) \sin(\lambda\xi)) d\xi. \quad (3.143)$$

Substituting 3.115 we get

$$A_\lambda = \frac{2\lambda}{(\cot(\lambda) - \lambda \csc^2(\lambda))} \int_0^1 \left(\frac{1 + \frac{k_f \delta}{D} \xi}{1 + \frac{k_f \delta}{D}} \right) (\cos(\lambda\xi) - \cot(\lambda) \sin(\lambda\xi)) d\xi, \quad (3.144)$$

$$= \frac{2\lambda}{(\cot(\lambda) - \lambda \csc^2(\lambda))} I. \quad (3.145)$$

The integral I can be computed to yield (using equation 3.135)

$$I = \int_0^1 \left(\frac{1 + \frac{k_f \delta}{D} \xi}{1 + \frac{k_f \delta}{D}} \right) (\cos(\lambda\xi) - \cot(\lambda) \sin(\lambda\xi)) d\xi, \quad (3.146)$$

$$= \int_0^1 \left(\frac{1 - \lambda \cot(\lambda) \xi}{1 - \lambda \cot(\lambda)} \right) (\cos(\lambda\xi) - \cot(\lambda) \sin(\lambda\xi)) d\xi, \quad (3.147)$$

$$= \frac{1}{\lambda \sin(\lambda)} \quad (3.148)$$

we obtain,

$$A_\lambda = \frac{2\lambda}{\lambda \sin(\lambda) (\cot(\lambda) - \lambda \csc^2(\lambda))} \quad (3.149)$$

or equivalently

$$A_\lambda = \frac{2 \sin(\lambda)}{\sin(\lambda) \cos(\lambda) - \lambda} \quad (3.150)$$

Therefore the general solution for this case is

$$\rho(\xi, \tau) = \sum_{\lambda} \frac{2 \sin(\lambda) e^{-\lambda^2 \tau}}{\sin(\lambda) \cos(\lambda) - \lambda} (\cos(\lambda\xi) - \cot(\lambda) \sin(\lambda\xi)) \quad (3.151)$$

With

$$\tan(\lambda) = -\frac{D\lambda}{k_f \delta} \quad (3.152)$$

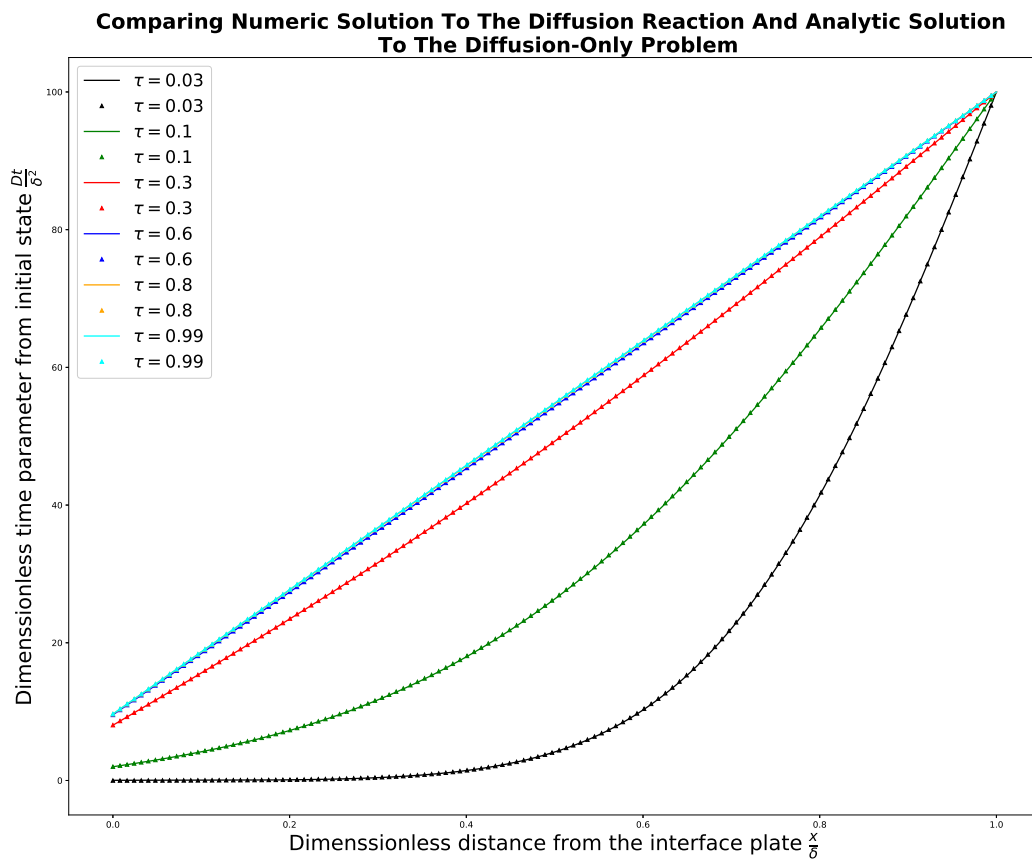


Figure 3.3

3.3 Diffusion-Reaction Equation With Forced Current through the system.

We consider the same system as above

$$\frac{\partial C}{\partial t} = \frac{\partial^2 C}{\partial x^2}, \quad (3.153)$$

with a slight change in border conditions. We want to impose the current on the system, which should be proportional to the reaction rate at the interface.

$$R = k_f C(0^+, t) \quad (3.154)$$

$$= \frac{i_0}{\mathcal{F}}. \quad (3.155)$$

This yields the following border and initial conditions for the problem

$$C(\delta, t) = C_b, \quad (3.156)$$

$$C(0^+, t) = \frac{R}{k_f}, \quad (3.157)$$

$$C(x, 0) = 0. \quad (3.158)$$

or equivalently

$$C(\delta, t) = C_b, \quad (3.159)$$

$$C(0^+, t) = \frac{i_0}{\mathcal{F}k_f}, \quad (3.160)$$

$$C(x, 0) = 0. \quad (3.161)$$

3.3.1 Steady State Solution

As always, first we compute the steady state solution.

$$\frac{d^2 C}{dx^2} = 0. \quad (3.162)$$

The solution is of the form

$$C_{SS}(x) = A + Bx. \quad (3.163)$$

Border conditions yield,

$$C_{SS}(\delta) = A + B\delta \quad (3.164)$$

$$= C_b, \quad (3.165)$$

and

$$C_{SS}(0) = A \quad (3.166)$$

$$= \frac{i_0}{\mathcal{F}k_f}. \quad (3.167)$$

Therefore,

$$C_{SS}(x) = \frac{i_0}{\mathcal{F}k_f} + \left(C_b - \frac{i_0}{\mathcal{F}k_f} \right) \frac{x}{\delta} \quad (3.168)$$

3.3.2 Dynamic Solution

To solve the dynamic solution, we consider the following change of variable

$$\rho(x, t) = \frac{C(x, t) - C_{SS}(x)}{C_b}. \quad (3.169)$$

As in previous sections, we define the dimensionless parameters $\tau = \frac{\mathcal{D}t}{\delta^2}$, $\xi = \frac{x}{\delta}$. This leads to the equation

$$\frac{\partial \rho}{\partial \tau} = \frac{\partial^2 \rho}{\partial \xi^2}. \quad (3.170)$$

Let $\rho(\xi, \tau)$ be of the form

$$\rho(\xi, \tau) = F(\xi)G(\tau). \quad (3.171)$$

Separation of variables leads to the Sturm-Liouville problem

$$\frac{dG}{d\tau} + \lambda^2 G(\tau) = 0, \quad (3.172)$$

$$\frac{d^2 F}{d\xi^2} + \lambda^2 F(\xi) = 0. \quad (3.173)$$

The solution of 3.172 is

$$G(\tau) = G(0)e^{-\lambda^2 \tau}, \quad (3.174)$$

whereas for 3.173 we get the particular solution,

$$F(\xi) = A_\lambda \sin(\lambda\xi) + B_\lambda \cos(\lambda\xi) \quad (3.175)$$

Border conditions yield

$$B = 0, \quad (3.176)$$

$$\lambda = n\pi. \quad (3.177)$$

where n is an integer number. We let $A_n = G(0)A_\lambda$ and the general solution for ρ is

$$\rho(\xi, \tau) = \sum_n A_n e^{-n^2 \pi^2 \tau} \sin(n\pi\xi) \quad (3.178)$$

Consider the following integral

$$J_{n,m} = \int_0^1 \sin(n\pi\xi) \sin(m\pi\xi) d\xi. \quad (3.179)$$

It can be shown that

$$J_{n,m} = \frac{1}{2} \delta_{n,m}. \quad (3.180)$$

Using 3.180, we can compute the value of A_n using the initial condition,

$$\rho(\xi, 0) = \sum_n A_n \sin(n\pi\xi) \quad (3.181)$$

$$= -\frac{C_{SS}(\xi)}{C_b}. \quad (3.182)$$

or equivalently,

$$A_n = -\frac{2}{C_b} \int_0^1 C_{SS}(\xi) \sin(n\pi\xi) d\xi \quad (3.183)$$

Computing the integral and using 3.106 we get

$$A_n = -\frac{2}{n\pi C_b} \left(\frac{i_0}{k_f \mathcal{F}} - (-1)^n C_b \right). \quad (3.184)$$

Therefore,

$$\rho(\xi, \tau) = \sum_n \frac{2}{n\pi C_b} \left((-1)^n C_b - \frac{i_0}{k_f \mathcal{F}} \right) e^{-n^2 \pi^2 \tau} \sin(n\pi \xi) \quad (3.185)$$

Therefore,

$$C(\xi, \tau) = \frac{i_0}{\mathcal{F} k_f} + \left(C_b - \frac{i_0}{\mathcal{F} k_f} \right) \xi + \frac{2}{\pi} \sum_n \left((-1)^n C_b - \frac{i_0}{k_f \mathcal{F}} \right) \frac{e^{-n^2 \pi^2 \tau}}{n} \sin(n\pi \xi) \quad (3.186)$$

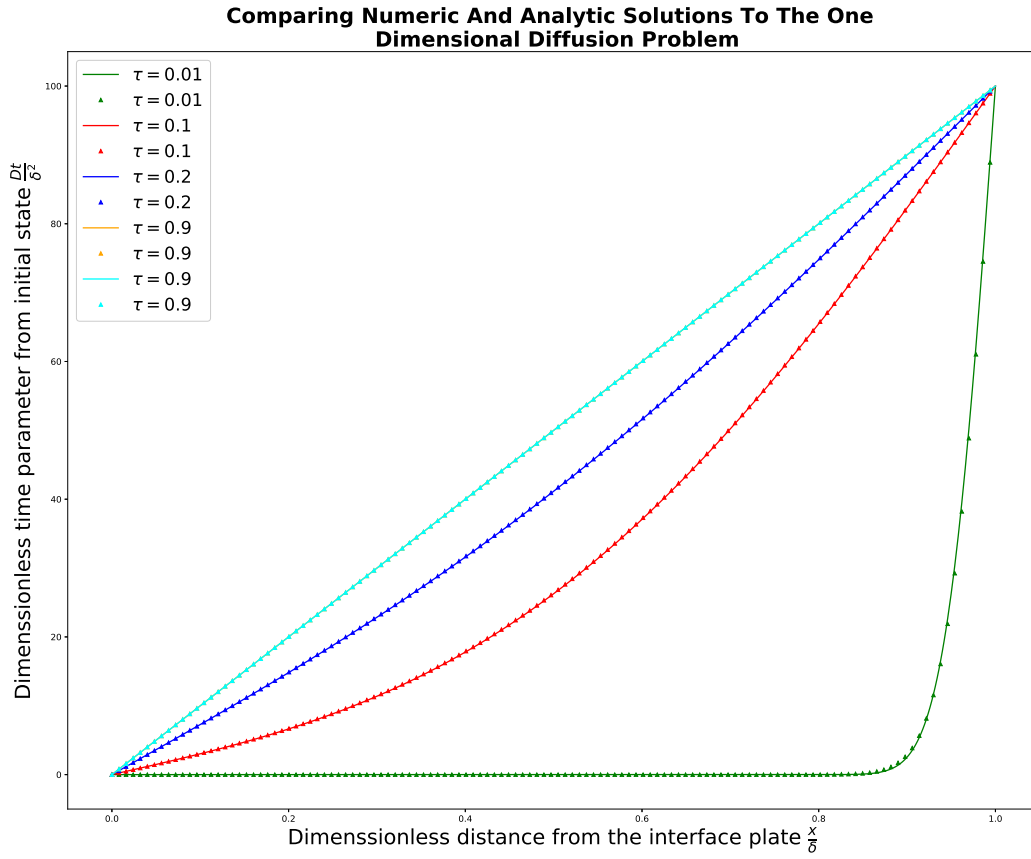


Figure 3.4