



Computational Study on Urea Concentration Profiles in Hemodialysis Hollow Fiber Membranes Under Different Blood Flow Conditions

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Abstract

Kidney failure severely impairs vital bodily functions, resulting in dangerous accumulations of urea. When renal function declines below 75%, hemodialysis becomes a critical therapeutic intervention. This process involves circulating a patient's blood outside the body through a specialized device called a dialyzer. The current investigation focuses on a hollow fiber dialyzer, characterized by a shell-side compartment for dialysate flow, a porous membrane, and internal tubes facilitating blood flow. The primary objective of this research was to develop a theoretical model to describe mass transfer within these hollow fiber membranes during hemodialysis. The study specifically aimed to analyze the impact of blood flow rate on urea concentration distributions across the tube, membrane, and shell regions in both axial and radial dimensions. Furthermore, it explored how membrane length influences urea clearance and assessed the effect of dialysate flow rate on this clearance. The findings indicated that increased blood flow rates led to higher urea concentrations at the tube outlet, implying reduced diffusion into the shell compartment. Conversely, extending the membrane length was associated with improved urea clearance rates. Interestingly, the research revealed that the dialysate flow rate had no significant impact on urea clearance. Specifically, with a fixed dialysate flow rate of 500 mL/min and a membrane length of 27 cm, the measured urea clearances for blood flow rates of 200, 300, 400, and 500 mL/min were 21.95%, 17.06%, 14.31%, and 12.52%, respectively. Among the conditions studied, the highest urea clearance of 62.60 mL/min was achieved at a blood flow rate of 500 mL/min, with a dialysate flow rate of 500 mL/min and a membrane length of 27 cm. Additionally, the unsteady-state simulation results showed that most urea removal occurred in the first 60–80 seconds, providing insight into early-phase clearance dynamics. This understanding can support the future development of more time-efficient or portable dialysis systems by optimizing initial urea extraction.

Keywords: Clearance; Concentration; Flowrate; Hemodialysis; Hollow fiber

Nomenclature

T	temperature
r_1	membrane inner radius
r_2	membrane outer radius
r_3	effective radius of shell
R	module inner radius
n	number of hollow fibers
L	length of hollow fibers
$D_{B,urea}$	urea-blood diffusivity coefficient
$D_{D,urea}$	urea-dialysate diffusivity coefficient
C_{urea}	the initial concentration of urea
MW_{urea}	molecular weight of urea
m_{urea}	urea-blood and urea-dialysate equilibrium constant
C_A	urea concentration
Q_b	blood flow rate
Q_d	dialysate flow rate

1. Introduction

The kidneys are an important organ in the body that can filter around 120 – 150 liters of blood daily and remove metabolic waste, namely urea, creatinine, and foreign chemicals, through urine. Apart from that, the kidneys also secrete renin and stimulate the production of red blood cells. Failure of the kidneys to carry out these important functions causes a condition called uremia. Uremia is a condition where the urea level in the body is so high that it can be toxic to the body [1]. Based on WHO data, Chronic Kidney Failure (CKD) causes the deaths of 850,000 people every year and is ranked 12th with the highest death rate [2]. In Indonesia, in 2018, as many as 713,783 people, or 0.38% of the total population, suffered from Chronic Kidney Failure (CKD). Therefore, this disease is the 10th cause of death with a death toll of more than 42 thousand per year [3].

If the kidneys are no longer functioning above 75%, then dialysis or hemodialysis is something that helps the sufferer to prolong life, but cannot cure it [4]. Hemodialysis is a medical procedure where blood is drawn from the body and circulated through an external system containing a device known as a dialyzer. Within the dialyzer, metabolic waste products, including urea, and excess water are filtered from the blood as they pass across a semi-permeable membrane into a dialysis solution. The purified blood is then returned to the patient, and this cycle continues to cleanse the blood of accumulated metabolic toxins. The dialyzer itself is central to the dialysis machine's function, as it is where the actual blood purification occurs. Inside the dialyzer, blood and dialysate flow in opposing directions on either side of the semi-permeable membrane, facilitating the removal of waste [5].

Many factors influence the efficiency of the hemodialysis process, one of which is the blood flow rate. Therefore, in this study, we will discuss the effect of blood flow rate on urea concentration along the membrane. The research was carried out by reviewing one hollow fiber membrane using the continuity equation and Fick's law, which was solved using the explicit method of the central difference approach. By understanding how urea concentration changes along the membrane with variations in blood flow rate, this research can help in optimizing the efficiency of removing toxic substances from the patient's blood.

2. Method

2.1. Modelling

A hollow fiber membrane consists of three main components: a shell, a porous membrane, and an inner tube. Blood flows through the tube, while dialysate circulates through the surrounding shell in a countercurrent manner. Each of these regions—the blood side, the dialysate side, and the membrane itself—possesses distinct porosity characteristics. As illustrated in Figure 1, blood enters the interior of the hollow fiber, while dialysate flows along its exterior. Within this porous membrane, mass transfer primarily occurs through two mechanisms: diffusion and ultrafiltration. Diffusion refers to the movement of small solutes across the dialysis membrane, driven by concentration differences between the blood and dialysate. Specifically, urea migrates from the blood into the dialysate. Assuming other factors are constant, this process is fundamentally dependent on the concentration gradient between the two fluids and is significantly influenced by the velocities of blood and dialysate flow, as well as the countercurrent flow distribution within their respective compartments. Diffusion takes place both axially (along the z -axis from $z = 0$ to $z = L$) and radially (along the r -axis from $r = 0$ to $r = r_3$) within the hollow fiber membranes. (See Figure 1 for further clarification). During ultrafiltration, dissolved substances are carried along with the fluid through solvent drag (convection), which actively pulls the solution and its solutes across the membrane. For effective hemodialysis, urea particles, which are approximately 9.16 ± 4 nm in size, must move from the blood into the dialysate. Consequently, an ultrafiltration membrane with an average pore diameter typically ranging from 10-1000 Å (1-100 nm) is essential for the hemodialysis process [6], [7].

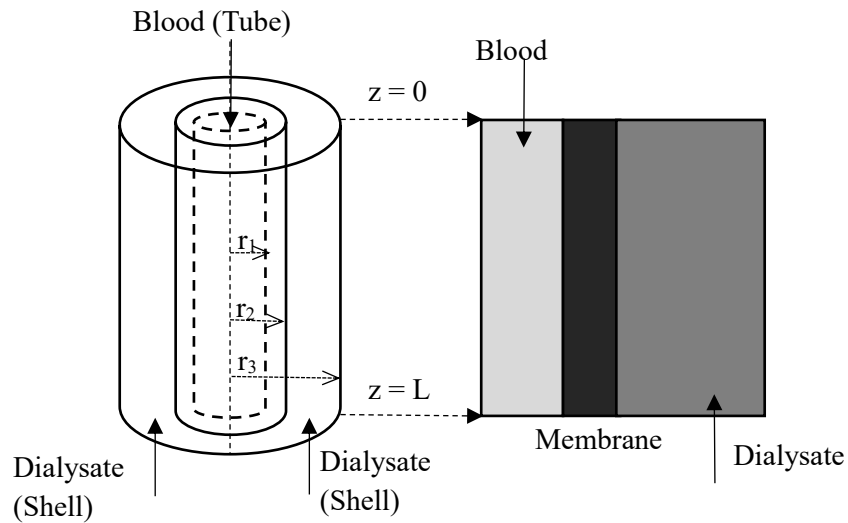


Figure 1. Single Hollow Fiber Scheme

Table 1. Value of the Parameter for the Model.

Parameter	Value	Unit	Reference
T	37	°C	Standard human body temperature
r_1	0.1	mm	[8]
r_2	0.14	mm	[8]
R	2.5	cm	[8]
n	500	-	Estimated
L	24.4	cm	[9]
$D_{B,urea}$	1.4×10^{-9}	m^2/s	[8]
$D_{D,urea}$	1.5×10^{-9}	m^2/s	[8]
C_{A-i}	1	mg/mL	[10]
m_{urea}	0.7	-	[8]
Qb	200, 300, 400, 500	mL/min	[11]
Qd	500	mL/min	[11]

2.2. Initial conditions and boundary conditions

The initial conditions used in this research are that the urea concentration in the tube is 1 mg/mL and the urea concentration in the shell is zero. The boundary conditions used in this research are listed in Table 2.

Table 2. Boundary conditions.

Section	z	r	Conditions
Tube	L	-	$C_{A-tube} = C_{A-i}$
	-	0	$\frac{\partial C_{A-tube}}{\partial r} = 0$
	-	r_1	$C_{A-tube} = \frac{C_{A-membrane}}{m_{urea}}$
Membrane	-	r_1	$C_{A-membrane} = m_{urea} \times C_{A-tube}$
	-	r_2	$C_{A-membrane} = C_{A-shell}$
Shell	0	-	$C_{A-shell} = 0$

$$\begin{array}{ccc} - & r_2 & C_{A-shell} = C_{A-membrane} \\ & r_3 & \frac{\partial C_{A-shell}}{\partial r} = 0 \end{array}$$

2.3. Assumptions

The assumptions used in this research are listed in Table 3.

Table 3. Model assumptions.

Assumptions	Description
Blood and dialysate flow regime	Laminar
Density of blood and dialysate	Constant
Model of blood viscosity	Newtonian
Model of dialysate viscosity	Newtonian
Diffusion coefficient of urea	Constant
Diffusion in the tube and shell side	Radial and axial
Liquid velocity profile on the tube side	Fully developed parabolic

2.4. Material Balance for Steady State Condition

To construct a two-dimensional mathematical model of the membrane contactor system, a mass balance is essential. This specific model was designed for a single hollow fiber, where blood flows with a fully developed laminar parabolic velocity profile. The fiber is encompassed by a laminar, counter-directional flow of dialysate. Based on Happel's free surface model, only a segment of the fluid surrounding the fiber is approximated as having a circular cross-section.

For the tube side, the steady-state continuity equation, accounting for simultaneous mass transfer of each component within the system, can be stated as follows:

$$\frac{\partial C_A}{\partial t} = -\nabla \cdot N_A \quad (1)$$

Where C_A is the concentration of component A in mol/m³ and N_A is the flux of component A. The mass balance for urea transfer in the tube section will be given by the following equation. The left side of the equation above shows diffusion, while the right side of the equation shows convection.

$$D_{A-tube} \left[\frac{\partial^2 C_{A-tube}}{\partial r^2} + \frac{1}{r} \frac{\partial C_{A-tube}}{\partial r} + \frac{\partial^2 C_{A-tube}}{\partial z^2} \right] = V_{z-tube} \frac{\partial C_{A-tube}}{\partial z} \quad (2)$$

$$V_{z-tube} = 2\bar{V}_{tube} \left[1 - \left(\frac{r}{r_1} \right)^2 \right] \quad (3)$$

$$\bar{V}_{tube} = \frac{Qb}{n\pi r_1^2} \quad (4)$$

Where Qb is the blood flow rate, n is the number of hollow fibers, $\bar{V}_{tube}$ is the average flow rate in the tube section, and r_1 is the inner radius of the hollow fiber [8].

In the membrane side, the movement of urea that occurs in the pores of the membrane contactor is assumed to be due to diffusion only. The steady-state continuity equation for urea transport in the membrane can be written as follows.

$$D_{A-membrane} \left[\frac{\partial^2 C_{A-membrane}}{\partial r^2} + \frac{1}{r} \frac{\partial C_{A-membrane}}{\partial r} \right] = 0 \quad (5)$$

The membrane diffusion coefficient, $D_{A-membrane}$, is influenced by membrane porosity and tortuosity, which can be written with the following equation.

$$D_{A-membrane} = \frac{D_{A-tube} \times \varepsilon}{\tau} \quad (6)$$

Where ε is the membrane porosity value and τ is the membrane tortuosity value [8].

On the shell side, Fick's law is used to estimate the continuity equation for mass transfer of urea on the shell side of the hollow fiber membrane.

$$D_{A-shell} \left[\frac{\partial^2 C_{A-shell}}{\partial r^2} + \frac{1}{r} \frac{\partial C_{A-shell}}{\partial r} \right] = V_{z-shell} \frac{\partial C_{A-shell}}{\partial z} \quad (7)$$

The axial velocity equation obtained from Happel's free surface theory is as follows.

$$V_{z-shell} = 2\bar{V}_{shell} \left[1 - \left(\frac{r_2}{r_3} \right)^2 \right] x \left[\frac{\left(\frac{r}{r_3} \right)^2 - \left(\frac{r_2}{r_3} \right)^2 + 2 \ln \left(\frac{r_2}{r} \right)}{3 + \left(\frac{r_2}{r_3} \right)^4 - 4 \left(\frac{r_2}{r_3} \right)^2 + 4 \ln \left(\frac{r_2}{r_3} \right)} \right] \quad (8)$$

$$\bar{V}_{shell} = \frac{Qd}{\pi R^2 - n\pi r_2^2} \quad (9)$$

$$r_3 = \left(\frac{1}{1 - \phi} \right)^{\frac{1}{2}} r_2 \quad (10)$$

$$1 - \phi = \frac{nr_2^2}{R^2} \quad (11)$$

Where $\bar{V}_{shell}$ is the average flow rate in the shell, Qd is the dialysate flow rate, r_2 is the outer radius of the hollow fiber, r_3 is the effective radius of the shell, ϕ is the volume fraction of the void, and R is the module inner radius [12].

2.5. Material Balance for Unsteady State Condition

The material balance for the membrane contactor system is calculated using the finite difference method to represent blood flow in the simulation. This method was selected due to its simplicity and effectiveness in converting differential equations into a form suitable for computation. It allows complex, continuous behavior to be represented in a manageable, discrete framework. By accounting for both spatial and temporal changes, the finite difference method enables accurate modeling of fluid flow and mass transfer within the system. The Navier-Stokes equations were employed to model the fluid flow dynamics within the channel, offering a detailed description of velocity, pressure, and shear stress. To represent flow through the porous membrane, Darcy's law was applied to account for the influence of permeability and porosity on fluid transport. Combined, these methods provide a comprehensive and balanced framework for simulating fluid-porous medium interactions with both computational efficiency and accuracy. Equations (8) – (11) for calculating the concentrations of urea in unsteady state conditions [13].

$$\frac{\partial C}{\partial t} = \frac{C_i^{n+1} - C_i^n}{\Delta t} \quad (12)$$

$$\frac{\partial^2 C}{\partial x^2} = \frac{C_{i+1}^n - 2C_i^n + C_{i-1}^n}{(\Delta x)^2} \quad (13)$$

$$\frac{\partial C}{\partial x} = \frac{C_{i+1}^n - C_{i-1}^n}{2\Delta x} \quad (14)$$

$$C_i^{n+1} = C_i^n - \Delta t \cdot V_i^n \frac{C_{i+1}^n - C_{i-1}^n}{2\Delta x} + \Delta t \cdot D \frac{C_{i+1}^n - 2C_i^n + C_{i-1}^n}{(\Delta x)^2} \quad (15)$$

2.6. Clearance

The clearance of urea is a critical parameter used to evaluate the performance of hemodialysis membranes in removing waste solutes from the blood. In this study, the percentage of urea clearance is calculated using Equation (12), as adopted from reference [17]. The formula expresses as:

$$\% \text{Clearance} = \frac{C_{A-i} - C_{A-o}}{C_{A-i}} \times 100\% \quad (16)$$

where C_{A-i} and C_{A-o} represent the urea concentrations at the inlet and outlet of the membrane module, respectively. This equation quantifies the efficiency of urea removal, with a higher clearance value indicating more effective solute transport across the membrane.

2.7. Numerical Solution

The mathematical model that has been prepared forms a system of partial differential equations, which is then solved numerically. The equations used for numerical solutions are mass balance on the tube side, membrane side, and shell side, with boundary conditions. Then, a trial was carried out on the concentration of urea coming out of the shell until it met the total mass balance equation. The use of software to complete the mathematical model that has been prepared is made in the MATLAB software program version R2023b.

3. Results and Discussion

3.1. Effect of Blood Flow Rate on Urea Concentration Radially

Figure 2 illustrates the influence of blood flow rate on urea concentration radially in the tube, membrane, and shell sections. The flow rates of the blood (Q_b) used were 200, 300, 400, and 500 mL/min. In Figure 2 (a), the influence of blood flow rate on urea concentration in the tube section is depicted, ranging from $r = 0$ to $r = r_1$ (0.1 mm). It was found that as the blood flow rate decreases, the urea concentration increases in the radius range $r = 0$ to $r = r_1$. For more detailed data, please refer to Table 4. With a lower blood flow rate, the transfer of substances from the tube section towards the membrane becomes slower, resulting in fewer urea particles diffusing through the membrane. Consequently, a significant amount of urea particles remains in the tube (blood). Additionally, it was observed that the urea concentration decreases with an increase in radius. As the radius expands, the surface area for diffusion enlarges, allowing more urea to diffuse towards the membrane [14]. With this increase in radius, the blood has an extended contact time with the membrane. This elongation in diffusion time for urea from the blood to the dialysis solution leads to a decrease in urea concentration in the blood due to a greater amount of urea being dialyzed out.

Table 4. Urea concentration in the tube section.

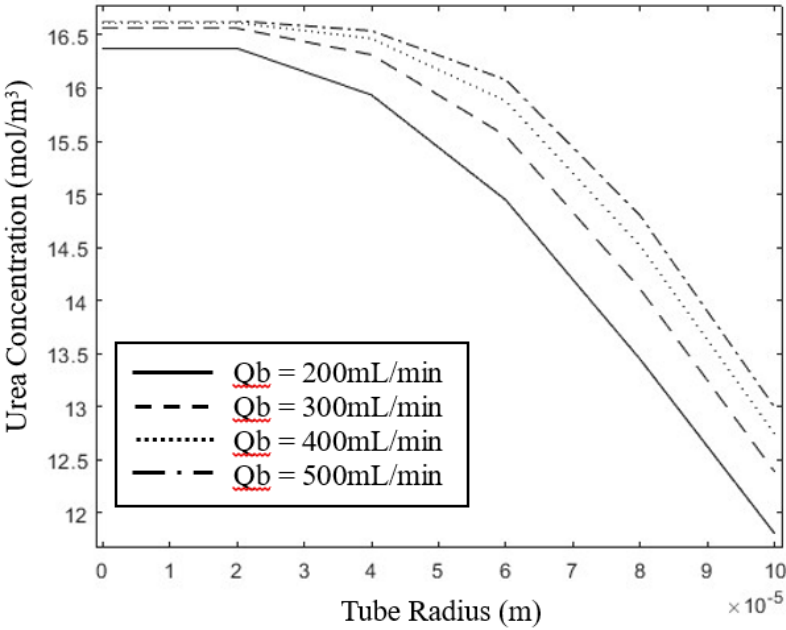
Blood Flow Rate [mL/min]	Radius [mm]					
	0	0.02	0.04	0.06	0.08	0.1
Concentration of Urea [mol/m ³]						
200	16.3742	16.3742	15.9353	14.9449	13.4445	11.8043
300	16.5627	16.5627	16.3140	15.5501	14.1065	12.3855
400	16.6146	16.6146	16.4667	15.8778	14.5137	12.7430
500	16.6331	16.6331	16.5395	16.0779	14.7985	12.9930

Figure 2 (b) illustrates the influence of blood flow rate on urea concentration in the membrane section, ranging from radius $r = r_1$ (0.1 mm) to $r = r_2$ (0.14 mm). It was found that the lower the blood flow rate, the lower the urea concentration in the membrane section. More detailed data can be found in Table 5. This contrasts with the effect of blood flow rate on urea concentration in the tube section. When the blood flow rate decreases, there is less urea diffusing into the membrane, resulting in a significant amount remaining in the tube. The influence of radius on urea concentration in the membrane is like the tube section. As the radius of the membrane increases, the urea concentration decreases. With an extended membrane radius, there's a greater distance from the tube containing urea-rich blood, hence reducing the urea concentration. Furthermore, this occurs due to the law of diffusion, which states that solutes move from areas of higher concentration to areas of lower concentration until equilibrium is reached. Initially, the urea

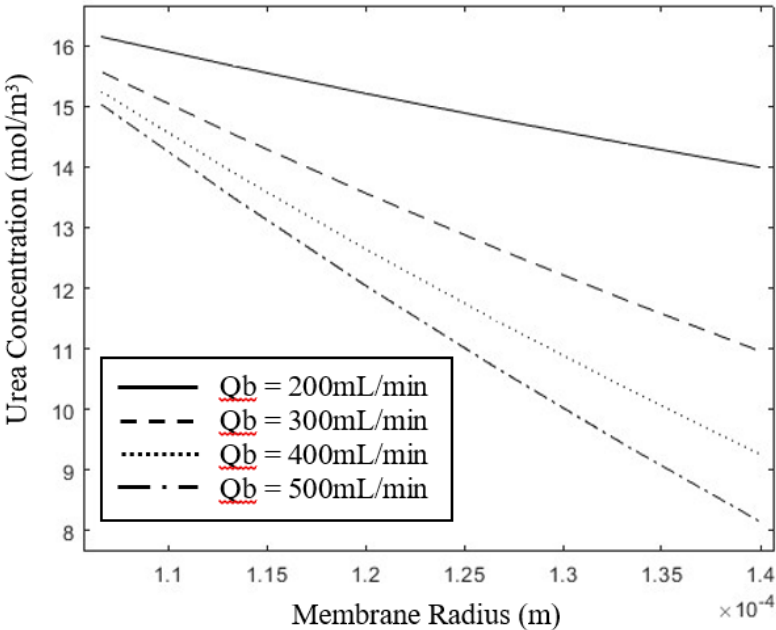
concentration tends to be higher on the blood side. As diffusion begins, urea moves across the membrane toward the dialysis solution with a lower concentration.

Table 5. Urea concentration in the membrane section.

Blood Flow Rate [mL/min]	Radius [mm]					
	0.107	0.113	0.120	0.127	0.133	0.140
Concentration of Urea [mol/m ³]						
200	16.1398	15.6605	15.2087	14.7812	14.3757	13.9900
300	15.5586	14.5334	13.5668	12.6525	11.7851	10.9600
400	15.2325	13.9010	12.6456	11.4582	10.3316	9.2600
500	15.0196	13.4881	12.0442	10.6783	9.3826	8.1500



(a)



(b)

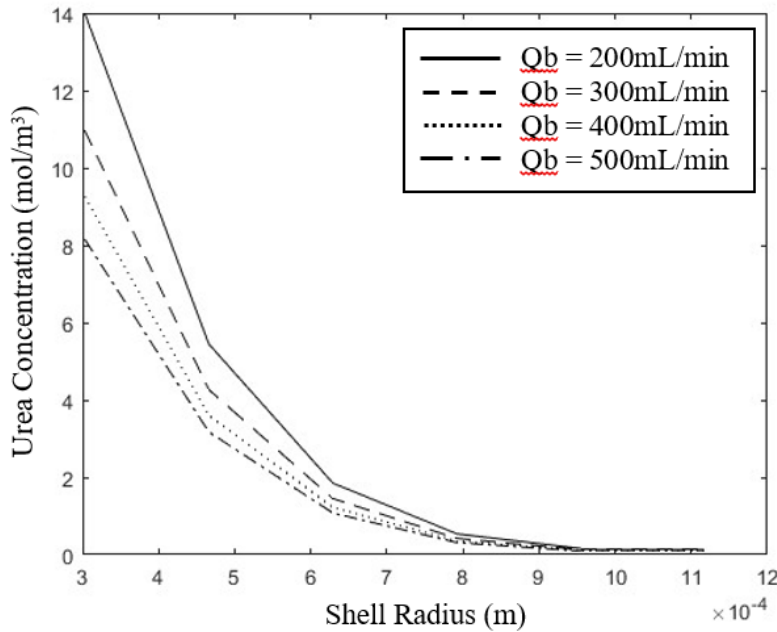


Figure 1. (a) Effect of blood flow rate on urea concentration in the tube side; (b) Effect of blood flow rate on urea concentration in the membrane side; (c) Effect of blood flow rate on urea concentration in the shell side.

Figure 2 (c) illustrates the influence of blood flow rate on urea concentration in the shell section, specifically at radius $r = r_2$ (0.14 mm) up to $r = r_3$ (1.118 mm). The value of r_3 is obtained from equations (10) and (11). Where r_3 represents the shell effective radius ϕ represents the volume fraction of the void, R and n denote the inner module radius and the number of fibers, respectively [15]. It is observed that the smaller the blood flow rate, the lower the urea concentration in the shell section. However, in Figure 2 (c), the variation in urea concentration at $r > 0.9$ mm is not significant for each change in blood flow rate. For more detailed data, refer to Table 6. The effect of radius on urea concentration in the shell region is like that in the tube and membrane. A longer shell radius results in a lower urea concentration. The decrease in urea concentration in the shell section, akin to the tube, forms a non-linear curve. However, in the membrane section, the decrease in urea concentration is linear. This difference arises because mass transfer in the membrane occurs solely via diffusion, while in the tube and shell regions, mass transfer occurs via both diffusion and convection. Convection happens due to the blood flow in the tube and the dialysate flow in the shell.

The radial profiles of urea concentration shown in Figure 4 are consistent with findings reported by Cancillia et al. [11], who demonstrated that urea clearance increases with increasing radius in a hollow fiber membrane system. This implies a corresponding decrease in urea concentration along the radial direction, as more solute is removed across the membrane. Our simulation results exhibit the same behavior, where urea concentration decreases from the center of the tube (Figure 4a) through the membrane (Figure 4b) and into the shell region (Figure 4c). At higher blood flow rates, the radial gradient becomes less steep due to reduced residence time, yet the overall decreasing trend remains. This agreement with literature findings validates the model's ability to represent radial mass transfer in hemodialysis accurately.

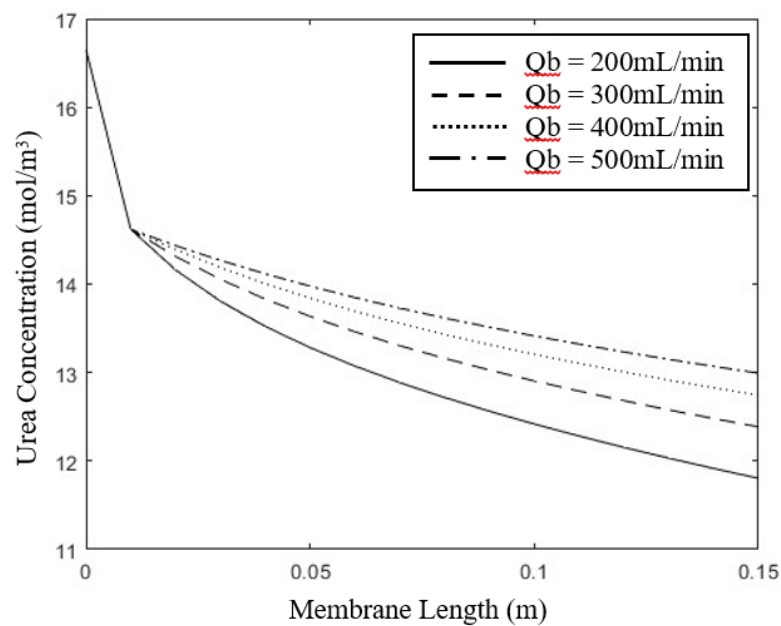
3.2. Effect of Blood Flow Rate on Urea Concentration Axially

Figure 3 (a) illustrates the impact of blood flow rate on urea concentration at $r = r_1$ axially. Blood enters the tube at $z = 0$ and exits at $z = L$ ($z = 0.25$ m). Therefore, at $z = 0$, the urea concentration remains constant for all flow rate variations, specifically at 16.65 mol/m^3 . The consistent decrease in concentration is observed across all flow rates up to $z = 0.018$ m. Subsequently, a higher flow rate corresponds to a greater urea concentration exiting the tube. In essence, the urea concentration within the tube section decreases from $z = 0$ to $z = L$ for all variations in flow rate.

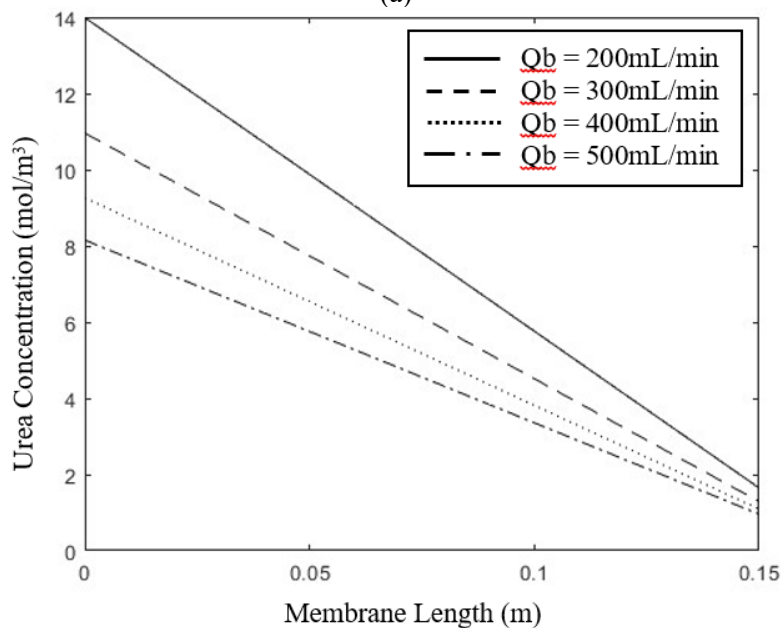
The impact of blood flow rate on the axial concentration of urea in the membrane ($r = r_2$) is depicted in Figure 3 (b). The correlation between blood flow rate and urea concentration in the membrane section mirrors that of the shell

section: higher flow rates correspond to lower urea concentrations. In summary, the urea concentration in the membrane section decreased overall from $z = 0$ to $z = L$ across all variations in flow rate. In Figure 3 (c), the influence of blood flow rate on the axial concentration of urea in the shell section ($r = r_3$) is depicted. The dialysate enters the shell section at $z = L$ ($z = 0.25$ m), maintaining a urea concentration of 0 mol/m^3 across all flow rate variations. Subsequently, the dialysate exits at $z = 0$. It's observed that with decreasing flow rate, the urea concentration exiting the dialysate increases. This aligns with the earlier statement: higher blood flow rates result in higher urea concentrations exiting the tube, thereby reducing the concentration of urea exiting the shell.

The trend observed in Figure 3, where urea concentration decreases along the membrane length, is consistent with experimental and theoretical findings reported by Cancilla et al.[9] . Their study demonstrated that as blood flows through the dialyzer, urea progressively diffuses across the membrane, resulting in a monotonic decline in concentration along the axial direction. This behavior is accurately captured in our simulation results across all examined blood flow rates. In particular, the urea concentration in the tube side ($r = r_1$) exhibits a steeper decline at lower flow rates due to longer residence time, while higher flow rates result in a more gradual decrease. This agreement confirms that the model reliably reflects the axial mass transfer behavior described in previous literature, supporting the validity of the simulation framework.



(a)



(b)

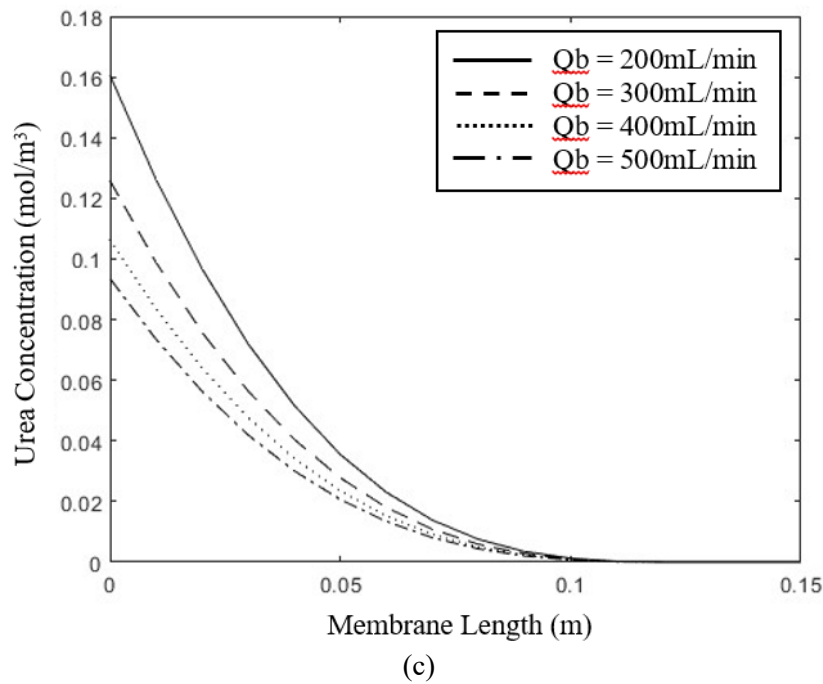


Figure 3. (a) Effect of blood flow rate on urea concentration in the tube side ($r = r_1$) (b) Effect of blood flow rate on urea concentration in the membrane side ($r = r_2$) (c) Effect of blood flow rate on urea concentration in the shell side ($r = r_3$)

3.3. Effect of Membrane Length on Clearance

Figure 4 illustrates the effect of membrane length on the clearance of urea with variations in blood flow rate. The clearance percentage is obtained from equation (16). The longer the membrane is used, the greater the urea clearance. A longer membrane provides a larger surface area for the diffusion process and the removal of urea from the blood. However, with increased length, a longer duration is required for substances to diffuse. Consequently, despite the larger surface area, the longer contact time between the blood and the membrane retains a greater amount of urea in the blood, resulting in a smaller clearance.

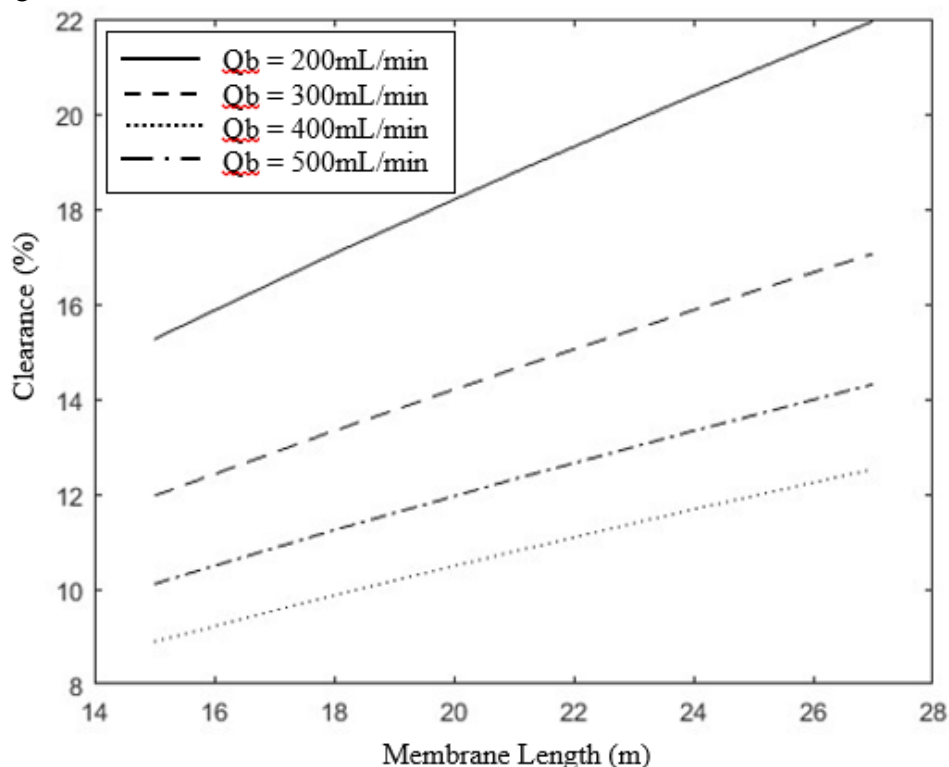


Figure 2. Effect of membrane length on urea clearance at varying blood flow rates

3.4. Effect of Blood Flow Rate on Clearance

Based on Table 6, the greater the blood flow rate, the smaller the clearance value. By increasing the blood flow rate, blood flows faster through the dialysis membrane, resulting in a shorter contact time between the blood and the dialysis membrane. Therefore, less urea diffuses into the shell, resulting in a smaller clearance. So, it can be said that the greater the blood flow rate, the smaller the clearance value. In this simulation, the clearance varies around 44 to 63 mL/min. For healthy individuals, blood urea clearance typically ranges from 22 to 64 mL/min. However, for patients requiring hemodialysis multiple times weekly, the target blood urea clearance must be significantly higher, reaching 200 to 300 mL/min [16], [17], [18].

Table 7. Effect of blood flow rate on clearance

Blood Flow Rate (mL/min)	Inlet Urea Concentration (mol/m ³)	Outlet Urea Concentration (mol/m ³)	Clearance (%)	Clearance (mL/min)
200	16.65	12.9947	21.95%	43.90
300	16.65	13.8097	17.06%	51.18
400	16.65	14.2667	14.31%	57.24
500	16.65	14.5653	12.52%	62.60

The simulation results were validated by comparing the trend of blood flow rate and clearance with experimental observations reported in the literature. Specifically, Yu et al. [19] demonstrated that an increase in blood flow rate leads to a corresponding increase in urea clearance, due to enhanced convective transport and improved mass transfer across the dialysis membrane. This finding aligns with the current study, where simulated clearance values rose from 43.90 mL/min at 200 mL/min blood flow to 62.60 mL/min at 500 mL/min. Although the percentage clearance decreases with flow rate due to shorter contact time, the absolute clearance in mL/min increases, a trend consistent with Yu et al.'s findings. This agreement supports the validity of the model in capturing the interplay between flow dynamics and solute removal in hemodialysis systems.

3.5. Effect of Blood Flow Rate on Concentration of Urea in Unsteady State Conditions

Figure 5 illustrates the effect of blood flow rate on the urea concentration at the tube outlet. The blood flow rates (Q_b) investigated were 200, 300, 400, and 500 mL/min. It was observed that a higher blood flow rate resulted in a higher urea concentration at the tube outlet. This suggests that less urea diffused into the dialysate section and was subsequently removed via the shell section. This outcome is attributed to the fact that an increased blood flow rate reduces the contact time between the blood and the membrane. At all tested flow rates, the axial urea concentration in the tube showed a rapid initial decline, gradually tapering off until it stabilized at a plateau. This behavior indicates that most of the urea removal occurs during the early phase of operation, particularly within the first 60–80 seconds. However, despite this apparent rapid clearance in the simulation, it is important to consider that in clinical hemodialysis, the typical treatment duration is around four hours. This extended time frame accounts for the redistribution of urea from interstitial and intracellular compartments back into the bloodstream, which cannot be captured in a short-duration simulation. Furthermore, prolonged dialysis ensures gradual and safe removal of solutes and fluids, minimizing the risk of complications such as dialysis disequilibrium syndrome or hypotension. Therefore, while the model demonstrates efficient early-stage urea removal, effective and clinically safe hemodialysis requires longer treatment to fully clear urea from the entire body and maintain patient stability [20].

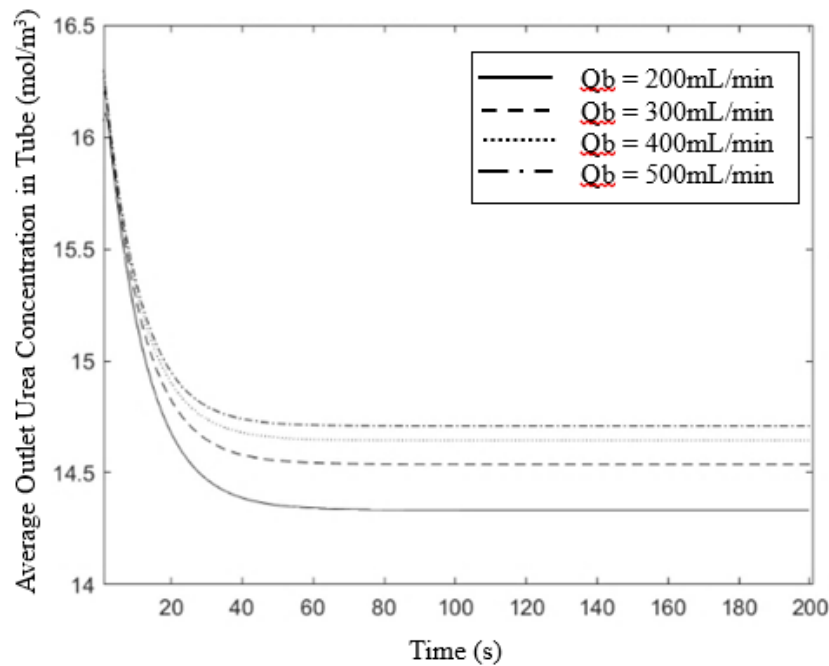


Figure 5. Effect of blood flow rate on urea concentration in unsteady state conditions.

4. Conclusions

The simulation results demonstrate that urea concentration consistently decreases both axially and radially across the tube, membrane, and shell regions. Blood flow rate plays a crucial role in influencing urea transport during hemodialysis. Although higher blood flow rates lead to reduced clearance percentages due to shorter contact time, they result in greater absolute clearance values. Among the conditions studied, the highest urea clearance of 62.60 mL/min was achieved at a blood flow rate of 500 mL/min, with a dialysate flow rate of 500 mL/min and a membrane length of 27 cm. These findings highlight the importance of optimizing flow conditions to enhance dialysis performance. Additionally, the unsteady-state simulation results showed that most urea removal occurred within the first 60–80 seconds, providing valuable insight into early-phase clearance dynamics.

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