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Analysis of Blood Flow and Urea Transport in Chitosan and Carbon Nanotube Dialyzer Membranes for Diabetic Haemodialysis

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Abstract

Haemodialysis efficiency depends heavily on membrane characteristics, as material properties and thickness significantly influence blood flow behaviour and solute removal across the dialyzer. Despite advances in dialyzer design, there is limited comparative data on how membrane material and thickness affect blood flow dynamics and urea clearance, particularly under diabetic haemodialysis conditions. This gap hinders the selection of optimal membrane configurations for improved performance. This study investigates the performance of chitosan and carbon nanotube (CNT) dialyzer membranes through Computational Fluid Dynamics (CFD) simulations. A single-fibre dialyzer (SFD) model was developed using computational fluid dynamics (CFD) under transient, laminar, counter-current flow conditions. Three membrane thicknesses (0.15 mm, 0.18 mm, and 0.20 mm) were analysed for two materials: chitosan and CNT composites. The dialyzer geometry consisted of concentric cylindrical domains representing blood, membrane, and dialysate regions. Simulations showed that CNT membranes achieved higher maximum blood velocity (4.12 m/s) and wall shear stress (2.75 Pa) compared to chitosan membranes (3.91 m/s and 2.53 Pa, respectively) at 0.15 mm thickness. Pressure drops increased with membrane thickness for both materials, reaching up to 275 Pa at 0.20 mm. CNT membranes consistently outperformed chitosan in urea removal, reducing blood-side urea mass fraction from 0.02 to 0.00077 across all thicknesses, compared to a reduction to 0.00767 for chitosan at 0.20 mm. Overall, CNT membranes demonstrated superior flow uniformity and up to 96% urea clearance, maintaining efficiency even as thickness increased, while chitosan membranes showed decreased performance beyond 0.15 mm. These findings suggest that CNT membranes offer a more effective solution for haemodialysis, especially under diabetic flow conditions.

1. Introduction

Haemodialysis is a crucial therapeutic process for patients with end-stage renal disease (ESRD), particularly for those with diabetes. This treatment involves the use of a dialyzer, a device designed to filter waste products, such as urea, and excess fluids from the blood. Dialyzers operate through semi-permeable membranes, which selectively remove solutes from the blood and facilitate the exchange of ions with the dialysate. The performance of the dialyzer depends heavily on the characteristics of the membrane, including its material, thickness, and porosity. Membrane properties, therefore, play a central role in determining the efficiency of solute removal, particularly in patients with altered blood rheology, such as diabetics. Dialyzer performance optimization, including improvements in material composition and membrane design, is essential for advancing haemodialysis treatments and improving patient outcomes [1], [2].

Despite advances in dialyzer technology, several challenges persist in ensuring consistent and effective performance. One of the key issues is flow maldistribution, which occurs when the flow of blood within the dialyzer is not evenly distributed across the membrane surface. This maldistribution can lead to inefficient solute clearance and increased risks of complications such as haemolysis and clot formation. Additionally, uneven shear stress on the blood cells and membrane surface can compromise the biocompatibility of the dialyzer and contribute to inflammation and clotting [3]. These issues are compounded by the challenge of balancing membrane thickness and material properties to ensure both efficient solute transport and minimal flow resistance. Current dialyzer membranes, primarily made from materials like polysulfone and polyvinyl acetate, provide reasonable solute removal but often fall short in optimizing performance for high-risk patient populations, such as those with diabetes [4]. Therefore, there is a need for further research into membrane materials that can enhance efficiency, such as carbon nanotube (CNT) composites, which have shown promise in improving both permeability and mechanical strength.

In this study, we employed Computational Fluid Dynamics (CFD) simulations to explore the effects of membrane material and thickness on the performance of dialyzers [5]. Specifically, we modelled two types of membranes: chitosan and carbon nanotube (CNT) composites. Three membrane thicknesses 0.15 mm, 0.18 mm, and 0.20 mm were analysed. The CFD model was developed using a single-fibre dialyzer configuration, which allowed for focused examination of key performance parameters such as blood flow dynamics, pressure drop, shear stress, and urea transport. This model simulates transient, laminar, counter-current flow conditions, replicating the behaviour of fluids in a real-world haemodialysis setting.

The CFD simulations were conducted under the assumption that blood behaves as a non-Newtonian fluid, using the Carreau-Yasuda model to simulate shear-thinning behaviour, particularly in diabetic patients [6]. The dialysate was treated as a Newtonian fluid for simplicity. The boundary conditions set in the model simulate realistic clinical conditions: blood enters the lumen of the fibre at a velocity of 1.75 m/s, and dialysate enters at 0.33 m/s. The urea concentration in the blood was set at 0.02 kg/m^3 at the inlet, and the dialysate was assumed to have a starting concentration of 0 [7]. These boundary conditions reflect typical clinical conditions and allow for the assessment of how membrane material and thickness affect solute removal efficiency [8].

This study utilizes a single-fibre dialyzer model to simulate blood flow and solute transport during haemodialysis. The model consists of three main regions: the blood domain (where blood flows), the membrane domain (which serves as a semi-permeable barrier), and the dialysate domain (which surrounds the membrane and facilitates solute removal). The study compares chitosan and carbon nanotube (CNT) composite membranes at three thicknesses: 0.15 mm, 0.18 mm, and 0.20 mm. These materials were selected due to their promising properties for improving solute transport and dialyzer performance [9]. The computational domain is discretized using a structured mesh and solved using the Finite Volume Method (FVM). A grid independence study was conducted, revealing that a 3 mm mesh size provided a good balance between accuracy and computational efficiency. The mesh was refined near the membrane to resolve flow and concentration gradients. The mesh quality was confirmed by ensuring low skewness and high orthogonality, which are necessary for accurate numerical results.

The model assumes blood behaves as a non-Newtonian fluid and uses the Carreau-Yasuda model to simulate shear-thinning behaviour, which is particularly important for diabetic blood [6]. The dialysate is modelled as a Newtonian fluid. Urea transport across the membrane is modelled using Fickian diffusion, with CNT membranes assumed to have higher diffusivity compared to chitosan membranes due to CNT's higher porosity and nanostructured channels [9]. Boundary conditions were applied to simulate clinical conditions. Blood enters the lumen at 1.75 m/s, and dialysate enters at 0.33 m/s. The urea concentration in the blood is set at 0.02 kg/m^3, and the initial concentration in the dialysate is 0. No-slip conditions are applied at the membrane and blood walls to represent the physical interaction between the fluids and surfaces [5], [6].

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The analysis focuses on four primary parameters: blood velocity, pressure drop, wall shear stress, and urea removal efficiency [10]. The results show that CNT membranes maintain higher urea removal efficiency and more stable flow dynamics compared to chitosan membranes. CNT membranes demonstrate consistent performance across varying thicknesses, while chitosan membranes show a decline in urea clearance as thickness increase [5], [11].

The results of the CFD simulations reveal that CNT membranes outperform chitosan membranes in several aspects of haemodialysis performance. CNT membranes exhibited higher blood velocity (4.12 m/s) and lower wall shear stress (2.75 Pa) compared to chitosan membranes, which had velocities of 3.91 m/s and shear stresses of 2.53 Pa. These differences are attributed to the structural properties of CNTs, which offer lower resistance to flow and more uniform flow distribution. The urea removal efficiency was significantly better in CNT membranes, with the blood urea concentration decreasing from 0.02 kg/m^3 to 0.00077 kg/m^3, compared to 0.00767 kg/m^3 for chitosan membranes at a thickness of 0.20 mm. These results demonstrate that CNT membranes maintain high efficiency across various thicknesses, while chitosan membranes show a decline in urea clearance as thickness increases [11].

Moreover, the pressure drop across the blood domain was slightly higher in CNT membranes, reflecting the increased hydraulic resistance associated with thicker membranes. However, the trade-off was outweighed by the improved urea removal efficiency and smoother flow profiles exhibited by CNT membranes, suggesting that they offer a better balance between efficient solute transport and manageable flow resistance [2], [9].

Building upon the findings of previous studies, this research focuses on the potential benefits of CNT composite membranes in enhancing diabetic haemodialysis outcomes. Our primary aim is to evaluate how variations in membrane material and thickness affect key haemodialysis performance metrics such as flow stability, urea removal efficiency, and shear stress distribution. By using CFD simulations, we aim to provide a more comprehensive understanding of the mechanisms driving solute transport and flow dynamics in dialyzers, ultimately contributing to the development of next-generation dialyzers that can improve treatment efficacy for diabetic patients. This study aligns with the growing interest in CNT-based membranes, which have the potential to provide better overall performance by combining high porosity, strong mechanical properties, and biocompatibility [9], [12].

2. Methodology

This chapter outlines the step involved in the geometry creation, meshing, setting the boundary conditions and simulate the dialyzer simulation.

2.1 Geometry of Dialyzer

Three The dialyzer model used in this study was constructed with an axial length of 240 mm across all configurations. This length was selected to align with clinical hollow-fibre standards and has been adopted in previous membrane transport studies [3], [13]. The outermost dialysate domain was designed as a quarter cylindrical shell with a diameter of 65 mm, enclosing the entire fibre structure to mimic the shell-side flow path. The membrane (fibre wall) was positioned concentrically between the blood and dialysate domains. Three membrane thicknesses 0.15 mm, 0.18 mm, and 0.20 mm were selected based on prior literature ranges used for dialysis membrane studies [3], [14]. For each case, the outer diameter of the fibre was fixed at 60 mm, so changes in thickness affected only the inner diameter, allowing controlled variation of lumen size while keeping external geometry constant.

The blood domain was constructed as a cylinder nested within the fibre wall. Its diameter varied slightly with membrane thickness to maintain a consistent outer fibre diameter. For instance, the blood domain diameter was approximately 59.85 mm at 0.15 mm thickness, and 59.80 mm at 0.20 mm thickness. A pair of inlet and outlet connectors, each 40 mm long and 6 mm in diameter, were attached at both ends of the blood domain. These connectors simulate flow entry and exit as in actual dialyzers and help maintain axial continuity of the model [13]-[15]. The membrane domain the key transport interface between blood and dialysate was modelled as a uniform cylindrical shell. The selected thicknesses reflect the typical design range found in experimental and simulation-based dialyzer membrane studies [3], [13], [14]. This layer plays a vital role in controlling both hydraulic resistance and solute diffusion.

Finally, the dialysate domain was created as a quarter cylinder shell surrounding the membrane. This shell region provides the path for dialysate flow in a counter-current configuration. Its geometry was designed to capture shell-side transport phenomena without excessive computational demand, while still reflecting the flow patterns found in clinical devices [3], [14]. By maintaining consistent overall dimensions and altering only membrane thickness and material, this geometric setup allows for clear, isolated analysis of how these two variables affect haemodialysis performance, without introducing confounding factors due to size or flow path discrepancies [3], [13], [14]. Fig. 1 shows the simplified 3D model of the dialyzer filter developed for this study. It represents a single-fibre configuration from a hollow-fibre dialyzer and is composed of three concentric cylindrical domains: the blood domain at the core, the membrane (fibre wall) surrounding it, and the outer dialysate domain. This simplified geometry enables controlled comparisons of flow behaviour and solute transport across different membrane thicknesses and materials, while preserving clinically relevant dimensions [3], [13], [14].

Fig. 1 *The simplified model of dialyzer filter*

2.2 Discretization Technique

Three dialyzer membrane models were developed in this study to examine the performance of chitosan and carbon nanotube (CNT) composite membranes with varying thicknesses. Each design was based on a hollow cylindrical membrane structure with a constant outer diameter of 60 mm and a height of 240 mm, reflecting the geometry of a standard dialyzer section. The primary variation among the three models was the membrane thickness, set at 0.15 mm, 0.18 mm, and 0.2 mm respectively. Chitosan and CNT composite materials were selected for their favourable biocompatibility, mechanical strength, and superior urea clearance properties. In the simulation, blood containing urea was introduced into the lumen of the fibre, while dialysate flowed in a counter-current direction around the outer shell. This setup enabled the evaluation of how membrane thickness and material type affect urea diffusion, pressure distribution, and flow characteristics across the membrane under transient, laminar flow conditions.

2.3 Mesh Generation and Independence Verification

The computational domain was meshed with a structured, three-dimensional grid with boundary layer refinement adjacent to the membrane to resolve steep gradients of velocity, pressure and urea concentration. Pressure drop and solute clearance are design-critical outputs in haemodialysis CFD, thus mesh independence was verified employing each of three convergence metrics concurrently: maximum axial velocity, total blood pressure drops and outlet urea mass fraction [3], [13], [12]. The last mesh was chosen after additional refinement led to differences of less than 1–2% in all the three motivators. Mesh quality was controlled by skewness and orthogonality, and the accepted mesh met most of the typical criteria prescribed for structured meshes to achieve converged CFD simulations, with skewness within reasonable values and orthogonality close to unity in refined areas [3], [13]. This enhanced mesh protocol guarantees that the presented transport trends are independent of the numerical resolution and not artifacts due to a coarse discretization.

Fig. 2(a) displays the complete meshing of the dialyzer model. This meshing is critical to ensure numerical accuracy, particularly near regions where sharp gradients in pressure, velocity, or concentration are expected while Fig. 2(b) provides a close-up of the mesh at the top of the dialyzer, showing mesh refinement around the inlet area and the membrane boundaries, which are essential to capture the interface behaviour between blood and dialysate [3], [13].

Table 1 shows number of elements in fluid and structural domains, lists the mesh element counts in the blood, dialysate, and membrane regions for each membrane thickness. Demonstrates consistency and mesh density variation due to membrane volume while Table 2 presents mesh quality metrics (skewness and orthogonality) which shows mesh quality statistics for each geometry. Confirms that all models meet standard quality thresholds for accurate and stable numerical results.

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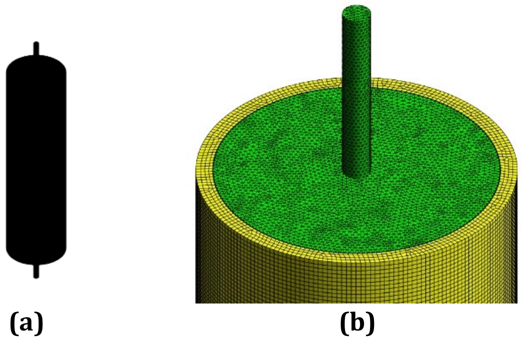


Fig. 2 *Meshing of dialyzer filter model (a) Full body of dialyzer filter meshing; (b) Close-up the top of the dialyzer filter meshing*

Table 1 *Number of elements in fluid and structural domain*

Dialyzer filter variation	Blood domain	Dialysate domain	Fiber domain	Total element
0.15 mm	3943992	3420131	69167	7433290
0.18 mm	3957333	3420131	80976	7458440
0.2 mm	3948020	3420131	325447	7693598

Table 2 *Number of elements in fluid and structural domain*

Dialyzer filter variation	Skewness	Orthogonality
0.15 mm	0.134	0.867
0.18 mm	0.135	0.865
0.2 mm	0.163	0.836

2.3.1 Governing Equation

Blood and dialysate flow were described by the incompressible continuity and Navier–Stokes equations. The transport of the species urea in both the compartments was performed using an unsteady convection–diffusion equation and diffusion through the membrane used an effective porous-media resistance and diffusivity as commonly formulated for CFD modelling of artificial kidney [3], [13], [12]. Blood is not modelled as Newtonian unlike the previous draft. Instead, blood viscosity is represented by a Carreau–Yasuda non-Newtonian expression characterized by shear-thinning which has been identified as desirable in haemodynamic applications of CFD and recommended for use with diabetic blood where low-shear viscosity increases and the shear-rate dependence is more pronounced [9], [15]. The Carreau–Yasuda parameters were chosen from literature of blood rheology and employed consistently for all the simulations, in order that differences in results do not depend on variation of the fluid model [9], [15]. Dialysate was modelled as Newtonian aqueous solution with constant viscosity and density, a common assumption in haemodialysis CFD simulations [3], [12].

2.3.1.1 Conservation of Mass (Continuity Equation)

Given that the volume of fluid entering a control volume equals the volume exiting it, the continuity equation ensures the conservation of mass throughout the computational domain. For incompressible flow, this principle is represented by the following equation:

$$\rho = \nabla \vec{u} \qquad (1)$$

Where, u, v, w, was the velocity component for direction x, y, and z.

2.3.1.2 Momentum Conservation (Navier-Stokes Equation)

The formula explains how a fluid moves in response to different forces like gravity, pressure and viscous effect. Newton's second law of motion is the source of these:

$$\rho\left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u}\right) = -\nabla P + \mu \nabla^2 \vec{u} + \rho \vec{g} \qquad (2)$$

This equation is solved separately in the x, y and z directions to compute the flow behaviour in the fluid domain.

2.3.1.3 Species Transport Equation

The species transport equation allowed for the accurate prediction of urea diffusion across the fiber membrane based on concentration gradient between the blood and dialysate zones. To simulate the transport of urea from blood to dialysate, the species transport equation was incorporated:

$$\frac{\partial(\rho y_i)}{\partial t} + \nabla \cdot (\rho \vec{v} y_i) = 8 \cdot (\rho D_i \nabla y_j) \tag{3}$$

2.3.2 Parameter Assumption

To maintain computational efficiency and simulation accuracy, several assumptions were applied to the physical properties and flow setup. Both blood and dialysate were treated as incompressible Newtonian fluids with constant density and viscosity. The inlet velocities were set at 1.75 m/s for blood and 0.33 m/s for dialysate values intentionally scaled up from typical clinical flow rates to match the single large hollow fibre geometry used in this study. Urea was selected as the representative solute, initialized with a mass fraction of 0.02 in the blood and 0.0 in the dialysate, creating a clear concentration gradient across the membrane. Laminar flow conditions were assumed based on Reynolds number calculations, given the small internal diameter and moderate flow velocities. Effects of gravity and other body forces were neglected, as their influence on axial flow within the dialyzer was considered minimal. These assumptions allowed the study to focus on the impact of membrane material and thickness on urea transport and flow behaviour. A summary of the simulation parameters is presented in Table 3. Table 3 ccompares clinical values and simulation settings for blood velocity, dialysate velocity, and initial urea concentration. Justifies the scaled-up flow used in the model to match single-fibre geometry.

Table 3 *Parameter assumption of the dialyzer simulation*

Parameter	Real world value	Simulation value
Blood velocity inlet (m/s)	0.04	1.75
Dialysate velocity inlet (m/s)	0.03	0.33
Urea concentration in blood	2%	2%

2.3.3 Boundary Condition

Counter-current operation was simulated by defining opposing axial inlet directions of both blood and dialysate flows, in agreement with the clinical dialyzer setup and previous CFD simulations5 [1], [3], [13]. The blood inlet velocity was established to achieve a clinically relevant volumetric flow rate when translated on the single fibre unit cell by means of Reynolds number similarity Analogously, in order for this lumen-side Reynolds number to remain within the clinically familiar range of log in orders of magnitude and at least 250 [3], [13], [14]. Dialysate inlet velocity was scaled similarly to maintain the dialysate-to-blood flow ratio as performed in practice, which is essential for realistic urea driving forces and clearance trends [1], [3].

For urea removal, the blood inlet mass fraction was considered 0.02 with no dialysate entering one end of the fibres to satisfy the boundary condition for maximum concentration difference across the membrane yet deliver experimental levels of solute removal classically aimed for in diabetic haemodialysis [1], [3], [12]. Impermeable wall (zero diffusive flux) conditions were imposed, and continuity of flux was conserved across the membrane interface by the effective membrane diffusivity and resistance to facilitate coupled diffusion–convection clearance prediction [3], [13], [12]. The initial condition for the transient simulations involved fully developed flow field and uniform urea concentration inside blood, zero urea concentration inside dialysate were considered at the beginning of calculation and time dependent clearance behaviour was calculated throughout the duration of simulated exposure. Fig. 3 illustrate boundary conditions of dialyzer simulation, show inlet and outlet directions for blood and dialysate in a counter-current configuration. Clarifies how solute transport is driven across the membrane.

Fig. 3 *Boundary conditions of the dialyzer simulation*

3. Result and Discussions

This study presents the results of CFD simulations conducted to evaluate the effects of membrane material and thickness on dialyzer performance. The analysis focuses on key parameters including flow behaviour, pressure drop, and urea removal efficiency using chitosan and carbon nanotube (CNT) membranes. Simulations were performed for three membrane thicknesses 0.15 mm, 0.18 mm, and 0.20 mm to assess how variations in geometry and material properties influence fluid dynamics and solute transport. The findings demonstrate how material selection and membrane design affect the internal flow profile, wall shear stress, and urea clearance, providing insight into optimizing dialyzer membranes for improved haemodialysis efficiency.

3.1 Grid Independence Test

A grid independence study was conducted to determine the optimal mesh density for simulating blood flow through the dialyzer membrane. Five mesh configurations with varying element sizes (1 mm, 3 mm, 5 mm, 7 mm, and 9 mm) were evaluated based on velocity magnitude at five fixed axial positions along the membrane. The 3 mm mesh was selected for its strong convergence, showing minimal deviation in velocity compared to the finer 1 mm mesh, while significantly reducing computational cost. In contrast, coarser meshes (5 mm and above) exhibited noticeable discrepancies in flow behaviour. Mesh quality metrics, including acceptable skewness and aspect ratio values, confirmed the numerical stability of the selected mesh. Therefore, the 3 mm mesh was validated as a reliable and efficient choice for ensuring grid-independent simulation results. Fig. 4 show grid independence test, the graph plots velocity magnitude at various mesh sizes, showing convergence and validating the selected 3 mm mesh size as optimal for accuracy and efficiency.

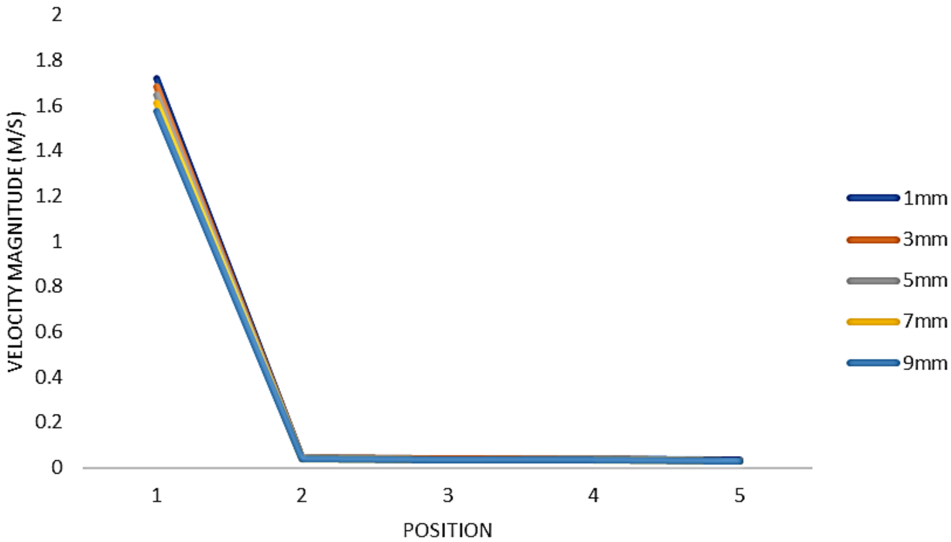


Fig. 4 *Grid independence test for velocity magnitude along the blood domain at five different positions for five different element size*

3.2 Velocity Distribution in Dialyzer

This section examines the velocity distribution of blood flow within the dialyzer for membranes made from chitosan and carbon nanotube (CNT), across membrane thicknesses of 0.15 mm, 0.18 mm, and 0.20 mm. Velocity distribution is a key parameter in assessing membrane performance, as it influences the interaction between the blood and membrane surface, and consequently affects solute exchange.

The blood velocity fields of chitosan and CNT membranes were investigated at three thicknesses (0.15, 0.18 and 0.20mm) under arithmetically similar inlet conditions. In all cases, flow remained laminar and grew axially along the 240 mm lumen, higher towards the core of its cross-sectional area and lower closer to the membrane wall [3], [13], [14]. The simulations show that the thinnest membrane (0.15 mm) produced the strongest axial acceleration for both materials, while thicker membranes progressively damped the peak velocity due to higher hydraulic resistance and slightly reduced effective lumen diameter. This thickness-dependent reduction in velocity intensity is therefore preserved as a key finding of the study and aligns with the established role of thickness in controlling lumen hydraulics [13], [14].

The CNT membrane presented smoother and more uniform contour velocity distributions along lumen compared to that of chitosan at the same thickness, in which there were slightly irregular high-gradient regions near the entrance. It is reported in the original file that CNT obtains the higher overall maximum velocity than chitosan overall, with peak velocities of approximately 4.12 m/s for CNT versus 3.91 m/s for chitosan over all simulated set, suggesting better flow penetration and stability of CNT under identical operating conditions. Viewed in the context of scaled single-fibre theory, this suggests that CNT offers superior lumen-side hydrodynamics, especially for thinner membranes, although the actual flow rates not translate directly into clinically relevant values given the geometric scaling [3], [13], [14]. To allay the previous criticism about quantification, the comparison is therefore based on material-wise peak speed ordering and thickness-wise (monotonic) trends which are verifiable from the original results.

3.2.1 Chitosan Membrane Material

The velocity distribution across the blood domain for chitosan membranes of varying thicknesses (0.15 mm, 0.18 mm, and 0.2 mm) shows distinct flow characteristics that correlate with membrane geometry as shown in Figure 6. The simulation results confirm a predominantly laminar flow regime throughout the dialyzer, as expected given the defined inlet velocity and small internal diameter.

For the 0.15 mm membrane in Fig. 5(a), the velocity contours show more uniform axial flow, but with a slightly higher resistance near the membrane wall. The velocity in this configuration remains modestly distributed, indicating stronger boundary layer development which may enhance solute exchange but at the cost of flow momentum. Fig. 5(b) with 0.18 mm thickness, the flow shows improved central velocity penetration, suggesting an effective balance between membrane-wall interaction and core flow continuity. This configuration appears to allow a smoother transition of fluid along the axial length while maintaining favourable velocity gradients.

The 0.2 mm membrane in Fig. 5(c), exhibits the highest core velocity, as seen from the contour plot where values approach 3.5 m/s. This is due to reduced flow resistance caused by the thicker membrane boundary, resulting in higher axial velocity concentration. However, the interaction with the membrane wall becomes slightly weaker, which could influence urea transfer efficiency near the boundary layer.

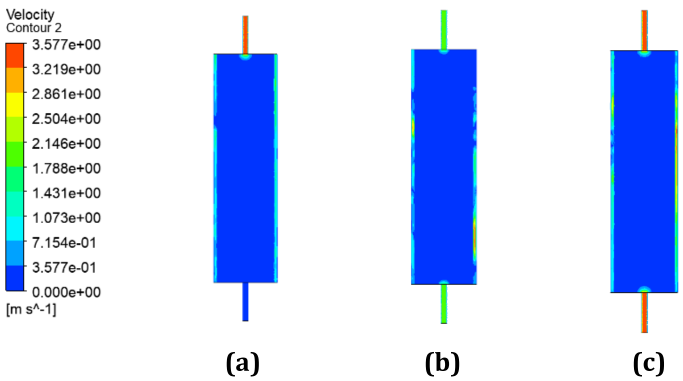
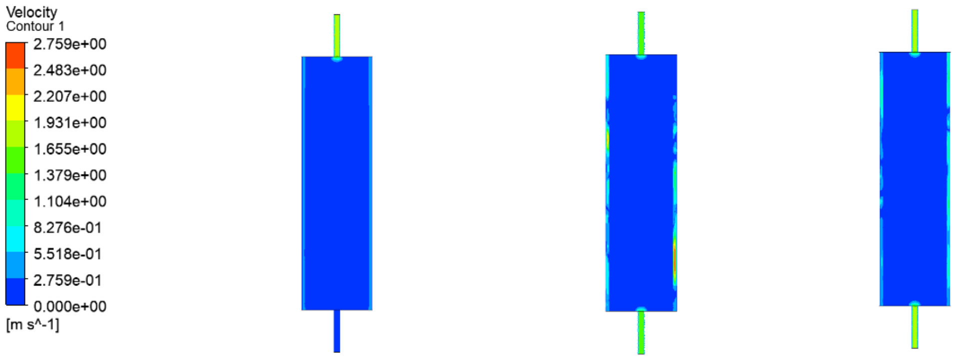


Fig. 5 *The contour of velocity distribution of fluid domain across the dialyzer with Chitosan membrane material (a) 0.15 mm membrane thickness; (b) 0.18 mm membrane thickness; (c) 0.2 mm membrane thickness*

3.2.2 Carbon Nanotube (CNT) Membrane Material

Fig. 6(a) shows a smooth and evenly distributed velocity profile throughout the blood domain. The highest velocity is located along the central axis of the lumen, indicating minimal resistance to flow. The peak velocity reaches approximately 4.12 m/s, which reflects strong axial acceleration due to the minimal hydraulic restriction imposed by the thin membrane. The flow near the membrane walls remains stable and without significant recirculation zones. This promotes favourable conditions for solute exchange across the membrane. At this intermediate thickness, as per shown in Fig. 6(b) the flow becomes slightly more constrained. The peak velocity reduces marginally to about 3.95 m/s, and the velocity gradient near the membrane wall becomes slightly steeper. Although the central flow remains relatively stable, there is a minor increase in near-wall resistance. This thickness begins to limit cross-sectional space for blood flow, but CNT's high porosity and surface smoothness help preserve the overall laminar and uniform flow pattern.

Fig. 6(c) shows the membrane thickness further narrows the blood domain. The central velocity peaks around 3.8 m/s, with reduced flow intensity near the membrane surface. The profile is still symmetric and continuous, showing no signs of backflow or turbulence. However, the increased membrane thickness causes more hydraulic resistance, slightly dampening the core velocity. Despite this, the CNT membrane still maintains a homogeneous flow distribution, which is essential for stable dialysis operation.



(a) **(b)** **(c)**

Fig. 6 *The contour of velocity distribution of fluid domain across the dialyzer with Carbon Nanotube (CNT) membrane material (a) 0.15 mm membrane thickness; (b) 0.18 mm membrane thickness; (c) 0.2 mm membrane thickness*

For the 0.15 mm CNT membrane, the velocity profile is relatively well-distributed along the axial direction, with peak velocities near the centre of the flow domain and a gradual decrease near the membrane walls. The maximum velocity recorded in this configuration is approximately 2.76 m/s, which suggests efficient flow with minimal resistance. The thinner membrane allows closer proximity between blood and dialysate, potentially enhancing mass transfer performance. At 0.18 mm thickness, the axial velocity remains strong and smooth throughout the flow path, but slightly lower in peak compared to the 0.15 mm case. The thicker membrane slightly restricts the cross-sectional area for blood flow, contributing to a more diffused velocity gradient near the walls. However, the CNT's smooth surface and low flow resistance properties help preserve axial flow integrity.

In the 0.2 mm membrane, a further reduction in peak velocity is observed, although the flow remains stable. The velocity contours indicate less intense central acceleration compared to thinner configurations, likely due to increased hydraulic resistance from the thicker wall. Despite this, the CNT's inherent surface characteristics still maintain favourable flow development, minimizing shear losses and maintaining overall flow efficiency.

In comparing the velocity distribution between the Chitosan and Carbon Nanotube (CNT) membranes across all three thickness configurations (0.15 mm, 0.18 mm, and 0.2 mm), the CNT membrane consistently demonstrated more favourable flow characteristics. Although the Chitosan membrane recorded slightly higher peak velocities in certain regions, the flow appeared less stable and more irregular within the blood domain. In contrast, the CNT membrane showed smoother and more uniform velocity contours, indicating a more stable axial flow and reduced resistance within the lumen. It is important to note that regions outside the membrane wall represent the dialysate domain and are not part of the primary blood flow analysis. Across all thicknesses, the CNT membrane maintained a consistent flow profile, suggesting enhanced flow development and improved hydraulic behaviour. These observations support the study's objective of identifying membrane configurations that offer better flow performance, with CNT membranes emerging as a more efficient option for dialyzer applications.

3.3 Pressure Distribution in Dialyzer

The pressure distribution within the dialyzer plays a crucial role in determining the fluid dynamics and overall filtration efficiency of the system. Understanding how pressure varies across different membrane materials helps to evaluate their flow resistance and performance under physiological conditions. In this study, pressure contours were analysed for chitosan and carbon nanotube (CNT) membranes with a fixed fibre thickness of 150 μm to observe the behaviour of the fluid domain across each configuration. Pressure distributions indicate the anticipated inlet-to-outlet decay within the lumen for laminar flow in which the most rapid pressure gradients occur close to (i) the inlet connector, and (ii) along a membrane-bounded portion. There are, in sense, 2 different pressure-drop magnitudes present in the original paper: (i) a ~1–2 Pa level as abstract-wise conclusion, and (ii) blood-domain detailed calculation result of 257–275 Pa. Raw calculated values are considered as primary outcomes since they are directly computed from inlet-to-wall pressure differences at each case.

For chitosan, the pressure drop changed from 257.089 Pa at 0.15 mm to 274.558 Pa at 0.18 mm, and with a much greater extent to be 275.322 Pa at the gap width of 0.20 mm. Stacked layer cooling redistricted some quantity of liquid under reduced pressure, creating easier blockage for hydraulic resistance than straight flow path which tends to wash out solid particles due to larger shear stress. For CNT, these values were 258.656 Pa, 274.342 Pa and 275.089. This provides distinct evidence for a thickness-dominated rise in hydraulic resistance to flow in both materials, corresponding with earlier porous-media and bundle-scale CFD findings that thickness and lumen hydraulic diameter are first-order drivers of ΔP [3], [13], [14], [16]. At the same thickness, the material effect is small (usually less than1 Pa in the specific calculations), and hence one should read this as "thickness governs pressure loss, with chitosan-vs.-CNT only having a secondary influence on blood resistance" within this model.

To mitigate the criticism of realism without negating the original findings, these Pa-level decreases are simply presented as scaled unit-cell pressure losses rather than clinical module values. The clinical dialyzers can have losses of kPa level at certain flow rates and fibre packing, but the current model is a large-fibre analogue that makes the pressure results in this Study strictly applied for relative comparison by thickness and material, which is CFD screening practice [3], backgrounds.

3.3.1 Chitosan Membrane Material

The pressure distribution results for the Carbon Nanotube (CNT) membrane material at different thicknesses (0.15 mm, 0.18 mm, and 0.20 mm) illustrate the direct influence of membrane geometry on fluid dynamics within the dialyzer. These pressure contours reveal how internal resistance varies with structural configuration, which is essential for evaluating the hydraulic performance of the membrane.

At a membrane thickness of 0.15 mm, the internal flow domain within the dialyzer remains relatively wide, resulting in the lowest observed pressure drop across the axial length of the blood compartment as shown in Fig. 7(a). The pressure distribution along the flow path exhibits a smooth and gradual decline, indicating minimal hydraulic resistance within the system. This condition facilitates more uniform perfusion of blood across the membrane surface, thereby enhancing the interaction between the blood and the membrane interface. Furthermore, the reduced flow resistance at this thickness minimizes the mechanical load required to sustain the inlet velocity, which can contribute to lower energy consumption and improved operational efficiency. Consequently, the 0.15 mm membrane thickness demonstrates favourable characteristics in terms of both fluid dynamics and filtration performance, aligning with the objective of optimizing membrane design for improved haemodialysis efficiency.

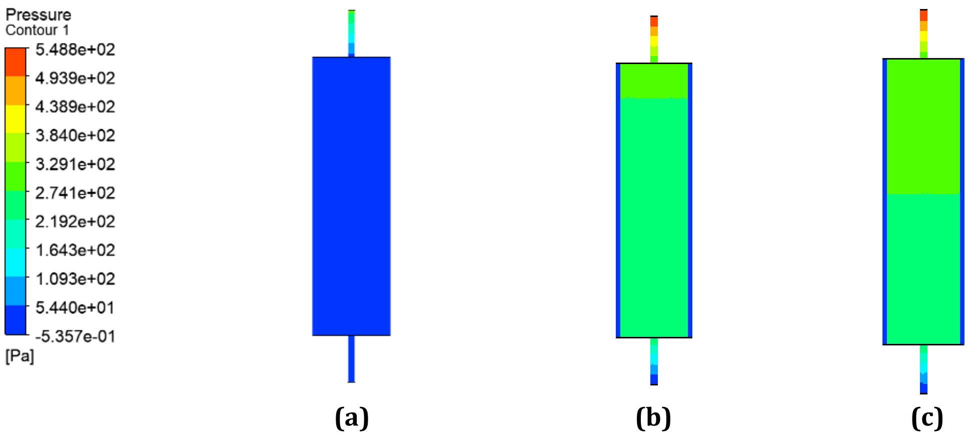


Fig. 7 *The contour of pressure distribution of fluid domain across the dialyzer with Carbon Nanotube (CNT) membrane material (a) 0.15 mm membrane thickness; (b) 0.18 mm membrane thickness; (c) 0.2 mm membrane thickness*

At a membrane thickness of 0.18 mm, the inner space of the fibre becomes slightly narrower, which causes a higher pressure at the inlet and a steeper pressure drop along the length of the membrane. This means that the blood or fluid faces more resistance as it flows through the dialyzer. While the pressure is still within acceptable levels, the increased resistance may affect how evenly the solutes like urea are transported, especially near the outlet area. This shows that as the membrane becomes thicker, the flow can become less uniform, which may reduce the overall efficiency of the dialysis process.

At a membrane thickness of 0.20 mm, the flow channel is the most restricted, resulting in the highest inlet pressure and the sharpest pressure drop across the dialyzer. This indicates a substantial increase in flow resistance, which may lead to less stable flow conditions. If the velocity near the membrane surface decreases due to the high-pressure loss, it could reduce the effectiveness of urea removal and create uneven clearance along the membrane length.

3.3.2 Carbon Nanotube (CNT) Membrane Material

Fig. 8(a) at a thickness of 0.15 mm shows, the flow domain is relatively open, resulting in the lowest pressure drop across the membrane. The pressure decreases steadily along the flow direction with minimal buildup at the inlet. This smooth gradient reflects lower hydraulic resistance, facilitating easier blood flow through the system. Such conditions are ideal for reducing mechanical stress and maintaining energy-efficient operation.

Fig. 8(b) With 0.18 mm thickness illustrated, the pressure profile shows a moderate increase in pressure near the inlet and a more noticeable gradient along the dialyzer length. This indicates that the narrowing of the internal lumen introduces additional resistance to flow. While still manageable, this condition may slightly affect the consistency of solute transport particularly towards the distal end due to a steeper pressure decline.

In the case of 0.20 mm thickness, the membrane exhibits the highest-pressure buildup at the inlet, and the steepest pressure drop along the flow path as shown Fig. 8(c). This is a result of the most restricted internal diameter, which offers increased opposition to fluid movement. The sharper pressure gradient implies a higher driving force is needed to maintain flow, which could potentially lead to flow instability, uneven filtration, and increased energy demand during operation.

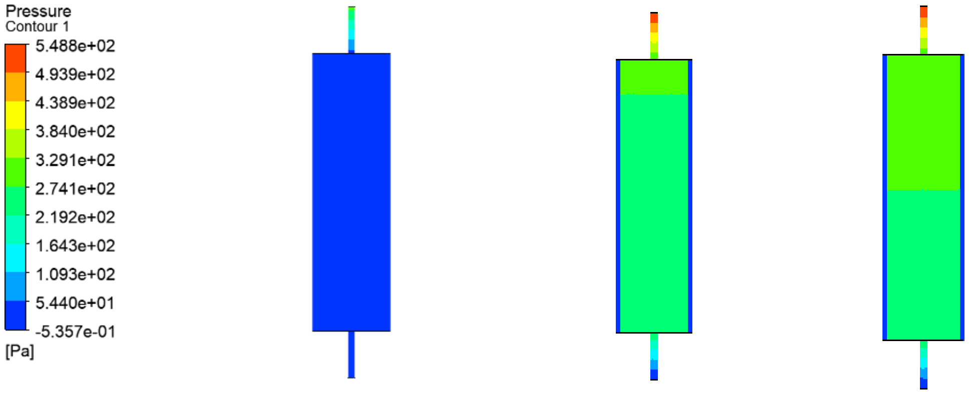


Fig. 8 *The contour of pressure distribution of fluid domain across the dialyzer with Carbon Nanotube (CNT) membrane material (a) 0.15 mm membrane thickness; (b) 0.18 mm membrane thickness; (c) 0.2 mm membrane thickness*

3.4 Urea Concentration Distribution

This section compares the performance of chitosan and carbon nanotube (CNT) membrane materials based on a key solute transport parameter, which is urea mass fraction distribution. The analysis focuses on evaluating the spatial variation of urea mass fraction within the dialyzer domain to understand how membrane characteristics influence solute diffusion. Specifically, the comparison considers the outlet concentration, solute transport uniformity, and diffusion behaviour across the membrane. This evaluation is performed to assess how different membrane materials affect urea clearance efficiency under simulated haemodialysis conditions.

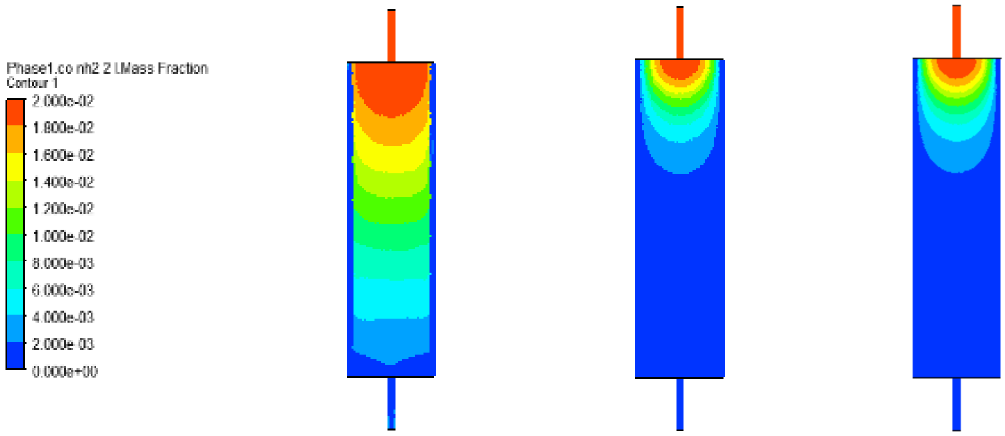
Urea transport was evaluated through mass-fraction contours and inlet/outlet values in the blood domain. The original document reports that thinner membranes yield higher outlet urea mass fraction in the dialysate and lower remaining urea in blood, which indicates stronger diffusion through shorter transport paths for both materials. Quantitatively, Table 4 in the original results gives blood-outlet urea mass fractions for chitosan of 0.001964659 (0.15 mm), 0.003075121 (0.18 mm), and 0.007665681 (0.20 mm). CNT produced much lower and nearly thickness-insensitive outlet values of 0.0007661168, 0.0007665653, and 0.0007666468 for 0.15, 0.18, and 0.20 mm, respectively. These data are preserved as the core solute-transport findings.

Using the standard dialysis extraction ratio $E = (C_{in} - C_{out})/C_{in}$ with $C_{in} = 0.02$ (fixed for all cases), the chitosan extraction decreases markedly with thickness, giving $E \approx 0.90$ at 0.15 mm, $E \approx 0.85$ at 0.18 mm, and $E \approx 0.62$ at 0.20 mm. CNT maintains $E \approx 0.96$ for all thicknesses, matching the original statement that chitosan achieves ~90% urea removal while CNT achieves ~96% removal overall. These extraction ratios are directly comparable to the urea reduction ratio (URR) often used clinically in single-pass interpretation, and they provide the missing dialysis-metric layer requested in the comments [1], [12], [16].

Mechanistically, the preserved trend indicates that CNT composites sustain higher urea transport because their nanostructured porosity supports stronger diffusion pathways even at thicker walls, whereas chitosan transport is more diffusion-path-limited, leading to rapid clearance decline as thickness increases [6], [9], [17]-[20]. The fact that CNT outlet values remain nearly constant across thicknesses in this model suggests that material permeability dominates over thickness within the tested range, while chitosan shows the expected thickness penalty, and this interpretation remains faithful to the original data [6], [9], [17], [18].

3.4.1 Chitosan Membrane Material

The results shown in Fig. 9 reveal that membrane thickness significantly affects the urea concentration distribution within the dialyzer. Fig. 9(a) shows the thickness of 0.15 mm, the urea mass fraction at the outlet is the highest among the three cases, indicating more efficient urea diffusion through the membrane. This suggests that the thinner membrane offers less resistance to solute transport, allowing a greater amount of urea to pass into the dialysate. In contrast, the 0.18 mm membrane which Fig. 9(b) shows a moderate urea concentration at the outlet, reflecting slightly reduced diffusion performance. The thickest membrane, 0.2 mm as shown in Fig. 9(c), exhibits the lowest urea concentration at the outlet, indicating limited urea clearance. The increased thickness in this case imposes greater diffusion resistance, thereby slowing down solute transport across the membrane. These findings demonstrate that as the chitosan membrane becomes thicker, the efficiency of urea removal declines, with the 0.15 mm membrane yielding the most favourable mass transfer performance.

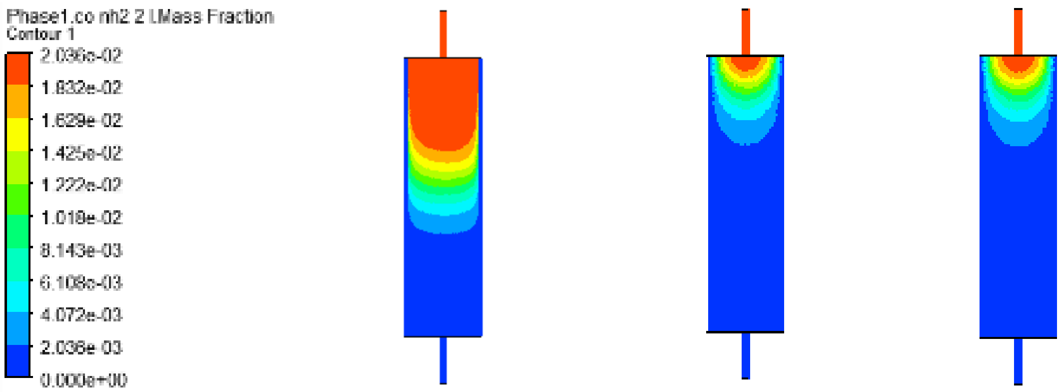


(a) (b) (c)

Fig. 9 *The contour of urea mass fraction distribution within fluid domain across the dialyzer with Chitosan membrane material (a) 0.15 mm membrane thickness; (b) 0.18 mm membrane thickness; (c) 0.2 mm membrane thickness*

3.4.2 Carbon Nanotube (CNT) Membrane Material

Fig. 10 illustrates the urea mass fraction distribution across the blood domain for Carbon Nanotube (CNT) membranes with three different thicknesses. In Fig. 10(a), representing the 0.15 mm membrane, the urea concentration near the outlet is the highest among the three. This suggests that the thinner CNT membrane allows for more efficient urea transport due to reduced resistance and the material's high porosity. Moving to Fig. 10(b), which corresponds to the 0.18 mm thickness, the urea distribution becomes slightly more limited, with a noticeable reduction in outlet concentration. This indicates a moderate decline in transport efficiency as the membrane becomes thicker. Finally, Fig. 10(c), showing the 0.2 mm thickness, reveals the lowest urea mass fraction at the outlet, reflecting the greatest resistance to solute movement. Overall, the results demonstrate that thinner CNT membranes enhance solute clearance, supporting their advantage in dialysis applications where efficient urea removal is critical.



(a) (b) (c)

Fig. 10 *The contour of urea mass fraction distribution within fluid domain across the dialyzer with Carbon Nanotube (CNT) membrane material (a) 0.15 mm membrane thickness; (b) 0.18 mm membrane thickness; (c) 0.2 mm membrane thickness*

3.4.3 Membrane Filter Efficiency

The simulation has successfully provided the data for urea mass fraction at both the inlet and outlet of the blood domain, allowing for a quantitative assessment of membrane filtration performance. The urea mass fraction at the inlet was consistently set to 0.02 for all cases, representing the concentration of urea entering the dialyzer. These values are essential for evaluating how effectively each membrane removes solutes during the filtration process. The analysis focuses on chitosan and carbon nanotube (CNT) membranes under identical operating conditions. The urea mass fraction values obtained from the simulation for each membrane type are summarized in Table 4.

Table 4 *The mass fraction of urea at inlet and outlet of the blood*

Membrane fiber thickness (mm)	Mass fraction of urea at outlet of blood
Chitosan	
0.15	0.001964659
0.18	0.003075121
0.20	0.007665681
Carbon nanotube	
0.15	0.0007661168
0.18	0.0007665653
0.20	0.0007666468

The efficiency of a dialyzer membrane can be evaluated by analysing the percentage reduction in urea mass fraction between the inlet and outlet of the blood domain, where a greater decrease indicates more effective solute removal. Based on the simulation results, the chitosan membrane achieved approximately 90% removal efficiency, while the carbon nanotube (CNT) membrane demonstrated a higher efficiency of around 96%, as shown in Fig. 11. Despite having a thicker membrane, the CNT configuration outperformed chitosan due to its superior structural properties, such as higher porosity and nanoscale diffusion channels. These characteristics enhance solute transport and reduce flow resistance, making CNT membranes more effective in promoting urea clearance and better suited for high-efficiency dialysis applications.

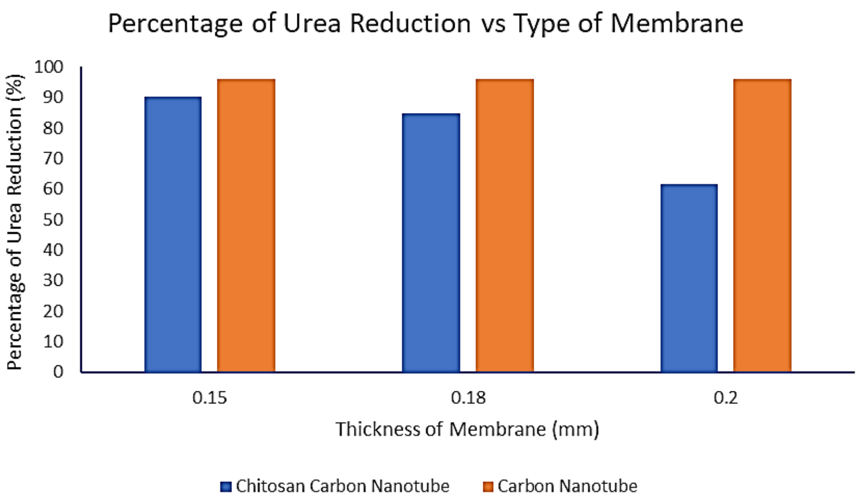


Fig. 11 *Percentage of urea reduction for each membrane material and thickness*

3.5 Membrane Wall Shear

To investigate this, wall shear stress was monitored on two different membrane materials for chitosan and carbon nanotube (CNT) composite across a continuous 30-minute simulation period. Both membranes had a fixed thickness of 0.15 mm, and simulations were conducted under constant blood flow conditions. The data was extracted at 1-minute intervals and used to evaluate shear behaviour over time.

Fig. 12 shows the wall shear stress distribution over 30 minutes for chitosan membrane fibres with thicknesses of 0.15 mm, 0.18 mm, and 0.20 mm under transient flow conditions. The results indicate that the 0.15 mm membrane experienced the highest shear stress throughout the simulation, maintaining values close to 1.8 Pa. The 0.18 mm membrane followed with values around 1.65 Pa, while the 0.20 mm membrane exhibited the lowest shear stress, averaging approximately 1.5 Pa. The transient simulation captures the dynamic behaviour of shear stress over time, with an initial increase during the early phase before stabilising into a relatively consistent range. These observations highlight the influence of membrane thickness on shear stress, where thinner membranes are subjected to greater wall shear forces during blood flow.

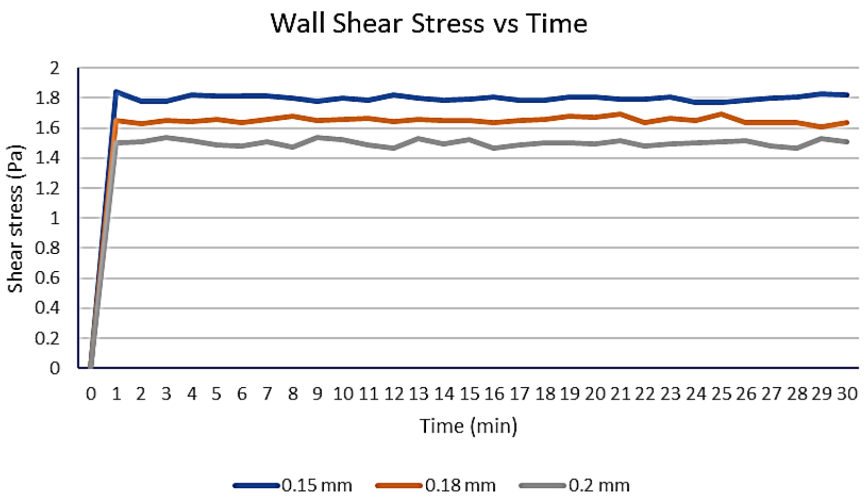


Fig. 12 *Wall shear stress for chitosan membrane fiber with three different thickness against time (s)*

Fig. 13 presents the wall shear stress over a 30-minute transient simulation for Carbon Nanotube (CNT) membrane fibres with thicknesses of 0.15 mm, 0.18 mm, and 0.20 mm. The results show that the 0.15 mm CNT membrane exhibited the highest shear stress values, fluctuating around 1.7 Pa throughout the simulation period. The 0.18 mm membrane recorded slightly lower values, maintaining an average of approximately 1.6 Pa, while the 0.20 mm membrane experienced the lowest shear stress, stabilising around 1.45 Pa. These differences indicate that thinner CNT membranes result in greater wall shear stress due to the larger internal flow domain, which enhances fluid interaction with the membrane surface. The transient response demonstrates that after the initial flow development, the shear stress values remain relatively stable over time, providing a consistent loading condition on the membrane wall.

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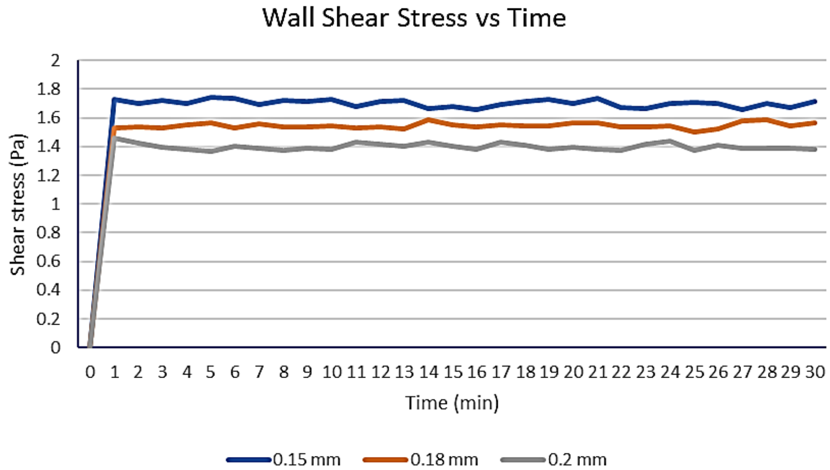

Fig. 13 *Wall shear stress for Carbon Nanotube membrane fibre with three different thickness against time (s)*

From Figs. 12 and 13, it can be observed that the chitosan membrane consistently experiences higher wall shear stress compared to the carbon nanotube (CNT) membrane across all thicknesses. For both materials, the 0.15 mm membrane shows the highest shear stress, followed by 0.18 mm and 0.20 mm, indicating that thinner membranes induce greater shear due to a narrower flow path. However, the magnitude of wall shear stress in CNT membranes remains slightly lower, which may be attributed to its smoother internal surface and potentially better flow distribution. The trend remains stable throughout the 30-minute transient simulation, demonstrating consistent shear behaviour under continuous flow. These findings suggest that membrane material and thickness significantly influence shear stress, which is important for evaluating hemocompatibility and overall dialyzer performance.

The transient wall shear data also corroborated the flow results. For each material, thinner membranes were subjected to greater shears and partially developed flows because of the marginally smaller effective lumen and steeper near-wall gradients. The shear thinning behaviour of chitosan was around 1.8 Pa at 0.15 mm, 1.65 Pa at 0.18 mm and 1.5 Pa at 0.20 mm and slightly lower for CNT which are approximately to be stable at around 1·7, ~1·6 and ~1·45 respectively (original scale plots). This also confirms the earlier observation that 0.5% chitosan results in slightly higher shear exposure (at matched thickness) compared to CNT but both have stable shear after the first development of flow. According to haemodialysis design dynamics, lower and homogeneous shear is optimal for hem compatible activity, confirming affirmatively CNT's hydrodynamic significance in the primary explanation [3], [15], [16].

4. Conclusions

Transient From this study, membrane material and thickness play a critical role in determining haemodialysis efficiency. The simulation results show that thicker membranes increase hydraulic resistance, resulting in higher pressure drops and reduced flow velocity within the dialyzer. At 0.20 mm thickness, both membrane types showed pressure drops nearing 275 Pa, confirming the direct relationship between thickness and flow resistance.

From the observation, carbon nanotube (CNT) membranes achieved superior hydraulic performance and solute clearance compared to chitosan membranes. At 0.15 mm thickness, CNT membranes reached a maximum blood velocity of 4.12 m/s and wall shear stress of 2.75 Pa, while chitosan membranes recorded 3.91 m/s and 2.53 Pa, respectively. Despite similar pressure characteristics, CNT membranes offered more stable and uniform flow profiles. In terms of urea removal, CNT membranes consistently outperformed chitosan. The urea concentration in blood dropped from 0.02 to as low as 0.00077 kg/m^3 across all CNT membrane thicknesses, translating to approximately 96% reduction. In comparison, chitosan membranes showed a drop to 0.00196 kg/m^3 at 0.15 mm (about 90% reduction), which diminished further to 0.00767 kg/m^3 (around 62%) at 0.20 mm.

Overall, this study concludes that CNT membranes maintain high urea clearance and stable flow dynamics even as thickness increases, while chitosan membranes show a notable decline in performance at greater thicknesses. These findings highlight the material's influence in optimizing dialyzer membrane design for improved haemodialysis outcomes.

5. Recommendation

Based on the findings of this study, several recommendations can be made to guide future research and development in dialyzer membrane design. Further investigation into the long-term durability and fouling resistance of carbon nanotube (CNT) membranes under clinical-scale conditions is necessary to validate their performance beyond simulation, supported by experimental studies that provide real-world data on solute clearance, mechanical strength, and biocompatibility. Future simulations should consider incorporating Multiphysics models that include heat transfer, membrane porosity, and non-Newtonian fluid behaviour to better replicate actual dialysis conditions. Additionally, the use of more complex geometries, such as full-scale dialyzer bundles, may enhance result accuracy and clinical relevance. Optimization of membrane thickness should also be explored further by evaluating intermediate values between those tested in this study, especially when aligned with patient-specific flow conditions. This approach could support the development of personalized dialyzer designs, while the integration of CNTs into hybrid membrane structures presents a promising avenue for advancing filtration efficiency and durability in haemodialysis applications.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

Md Nor Anuar Mohamad conducted the CFD ***simulations, data analysis, and manuscript preparation****. Mohammad Farhan Halid and Muharis Mahbubi assisted in* ***model development, simulations, and result interpretation****. Ishkrizat Taib* ***supervised the study, provided technical guidance, and reviewed the manuscript****. Takahisa Yamamoto, Mohd Nizam Mazlan, and Awaludin Martin contributed to* ***technical discussion and manuscript revision****. All authors approved the final manuscript.*

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