A Novel Design And Analysis Of Dialysate Flow For Temperature Control

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Abstract: Dialysis and kidney transplantation transformed medical care for patients with kidney failure, but these therapies are not widely available to most patients who need them worldwide. Moreover, Intradialytic hypotension (IDH) remains a frequent problem in routine outpatient hemodialysis, which affects the patient's quality of life. Additionally the dialysate system on hemodialysis has got higher potential to minimize the IDH episodes, yet there are not many studies conducted in this area in the recent years. In this paper, a novel dialysate flow design was proposed and their behavior was analyzed using COMSOL Multiphysics®. The non-isothermal flow of dialysate fluid was carefully analyzed with a set of boundary conditions. However, this design provides various sets of temperatures at the outlet without altering its outlet flow rate, which is vital for this application. But, the temperature profile is found to be imprecise as expected, yet these discrepancies can be adapted at the implementation phase. In future, implementing this design to control the temperature using a controller would benefit the patient's quality of life.

Keywords:COMSOL Multiphysics, dialysate biofeedback systems,fuzzy control, hemodialysis

I. INTRODUCTION

Chronic kidney disease (CKD) was ranked 27th leading cause of death worldwide in 1990, but has now risen to 18th deadliest disease in the world[1]. In Malaysia, there was an exponential growth in the incidence of CKD and the number of those patients on dialysis treatment [2]. This rapid rise is mainly due to the increase in the incidence of diabetes and hypertension disease following the urbanization and changes in lifestyle[3], [4]. Dialysis and kidney transplantation transformed medical care for patients with kidney failure, but these therapies are unavailable to most patients who need them worldwide. Most of these patients of preventable death fell on low-income and middle-income countries[5].

Over many years, Hemodialysis (HD) had improved the survival rate of patients with end-stage renal disease. Intradialytic hypotension (IDH) is the most adverse effect of HD, occurring up to 20% to 30% of dialysis sessions, which is responsible for various symptoms such as vomiting, dizziness, fatigue, etc., [6]. Such episodes predispose the patients to leave the dialysis unit and if it is repetitive, it can lead to inadequate clearance of solutes. IDH is one of the most significant and independent risk factors affecting mortality in dialysis patients[7].

With the help of technological development, particularly in the last 20 years, complications have reduced to a great extent. Major technological developments have made possible the detection of subclinical predictors of hemodynamic instability, for example relative blood volume variations, in order to prevent hypotension. With instantaneous measurement of these specific parameters during HD, actions can be implemented to correct the monitored parameters towards a desired target, with the aim of preventing hypotension. These actions are automated and regulated by a closed feedback loop, known by biofeedback control system. At the present time, biofeedback systems are available for different parameters: relative blood volume, temperature, and plasma conductivity[8].

It can be said that studies on temperature biofeedback control system in recent years are quite sparse[8]. Also, it was shown that these control system has higher potential to reduce IDH during hemodialysis[9]. Thus, these facts serve as a motivation factor to initiate the research on the dialysate temperature control system. In this paper, the dialysate flow through tubing was carefully simulated with the help of COMSOL Multiphysics® software. The valuable information from this study can be used in designing a control system to link with the body temperature. The main aim of this COMSOL study was to find the best design with acceptable temperature and flow rate at the end of outlet, as it is essential for this application.

II. DESIGN AND METHODOLOGY

In this study, a 2D model was developed to investigate the influence of two-dimensional effects on the flow and heat transfer in dialysate fluid. Primarily, the model was constructed using Geometry tools of COMSOL Multiphysics®, and it has used several tools to achieve the proposed 2D dialysate fluid model as shown in Fig.1. The overall measurement of this design was limited to 220mm in length, while the tubing diameter is 10mm. Also, the design consists of smooth curvature on the edges to minimize the effect of pressure and velocity. Meanwhile, water is the main component of dialysate fluid, so the material library was used for the definition of properties of water. This 2D model was chosen to depict the tubing the fluid was flowing through. The type of physics to be applied was then added. The physics used was laminar fluid flow and then non-isothermal flow was chosen. This allowed for definition for not only the fluid parameters but also the heat transfer of the constant wall temperature to the fluid. For fluid flow, the inlet flow rates were defined within a pre-defined range in order to get the outlet flow rate as suitable for this application. But, the temperatures of the dialysate flowing at the inlets were defined with two different constant values. The table (Table I) below shows the further initial boundary conditions of the model in COMSOL Multiphysics®.

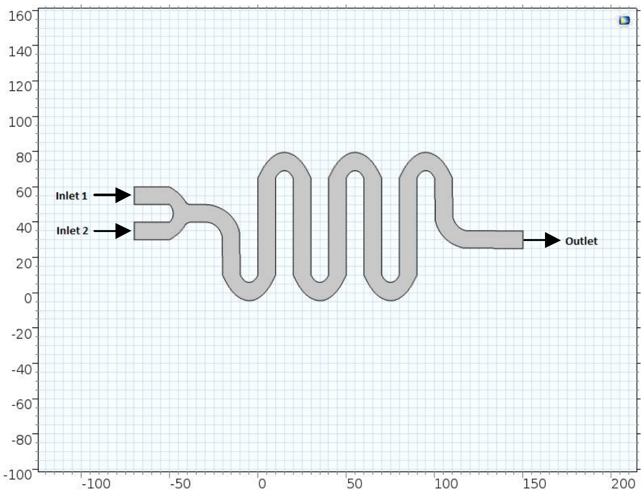

Fig 1 – Dialysate flow model created using COMSOL Multiphysics®

The general approach for describing fluid flow relies on the Navier-Stokes equation, which is based on Newton's second law through a combination of terms describing the acceleration of the fluid and forces acting on the fluid. An expression of this equation for stationary and incompressible flow is:

$$\rho(u\cdot\nabla)u = \nabla\cdot[-pI + \mu(\nabla u + (\nabla u)^T)] + F \qquad (1)$$

Where u is the fluid velocity (m/s), p is the fluid pressure (Pa), ρ is the fluid density (kg/m3), μ is the dynamic viscosity (Pa.s), and F is the external forces applied to the fluid. These equations are always solved together with the continuity equation:

$$\nabla\cdot(\rho u) = 0 \qquad (2)$$

In both equations, the symbol ∇ denotes to a partial gradient with respect to the spatial variables (x, y for a two-dimensional model) or vector differential operator.

For heat transfer in fluids, the governing equation is heat equation, which is based on the energy conservation equation. The heat equation is revised for steady state problem is

$$\rho C_p u\cdot\nabla T = \nabla\cdot(k\nabla T) + Q \qquad (3)$$

Where C_p is the heat capacity at constant pressure (J/kg.K), k is the thermal conductivity (W/m.K), T is the temperature (K) and Q is the heat source term. The fluid velocity, u is the velocity field comes from the Navier-Stokes equation.

Table I – Shows the initial boundary conditions for this model.

Settings	Boundaries			
Boundary Type	Inlet 1	Inlet 2	Outlet	Walls
Boundary Condition	Laminar Inflow, Temperature	Laminar Inflow, Temperature	Suppress backflow	No slip, Thermally insulated
Flow Rate [ml/min]	Q_in1	Q_in2	-	-
Pressure [atm]	1	1	0	-
External Temperature [°C]	35	37	-	-

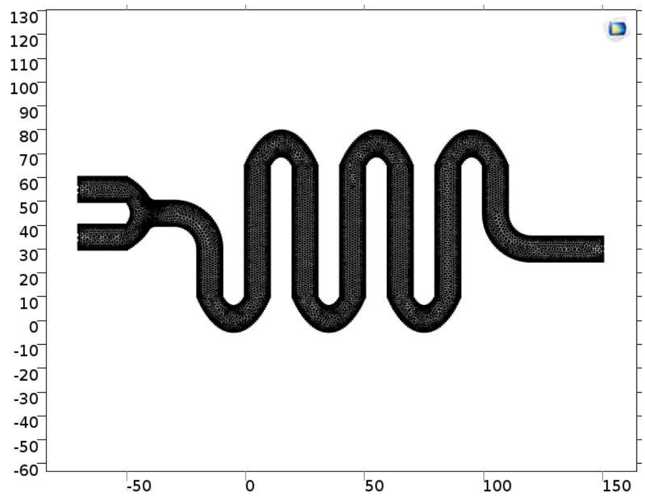

Fig 2 - Mesh diagram of Dialysate flow model

In this simulation, a total of 14851 mesh elements (finer) were built to provide sufficient spatial resolution as shown in Fig. 2. The coupled temperature and fluid flow of dialysate fluid are then solved using COMSOL until a converged solution is obtained.

III. Results and Discussion

In this model, a parametric sweep study was carried out in order to find the solution to a sequence of stationary problems that arise when varying inlet flow rates within a defined range. The inlet flow rates used in this model varied from 50 ml/min to 450 ml/min. Generally, the dialysate flow rate to the dialyzer was found to be 500 ml/min, while it affects dialyzer performance when exceeds this limit [10]. Hence, the inlet flow rates were assigned in such a combination to get the required flow rate at the outlet.

The simulated results showing the temperature surface with the variations are shown in the Fig.3. The mixing of two different temperature fluids with varying flow rate was made possible with the curved and smooth edge designs in this model. Moreover, these curved paths and smooth edges reduce the effect of velocity of fluid. Therefore, the temperatures of two fluids were mixed effectively to attain the constant temperature. Nonetheless, the velocity and temperature along the selected arc length of outlet were selected in order to study its precise relationship.

The velocity graph for this model shows an inverted parabolic shape as shown in Fig. 4. The inverted parabolic shape strongly agrees with the fluid dynamics theory, that is fluid velocity magnitude is higher at the center of the tubing while the velocity is lower at the boundary walls. It also agrees that the outlet velocity is identical for all the combinations of inlet flow rates, which is much needed to attain high efficiency for dialyzer.

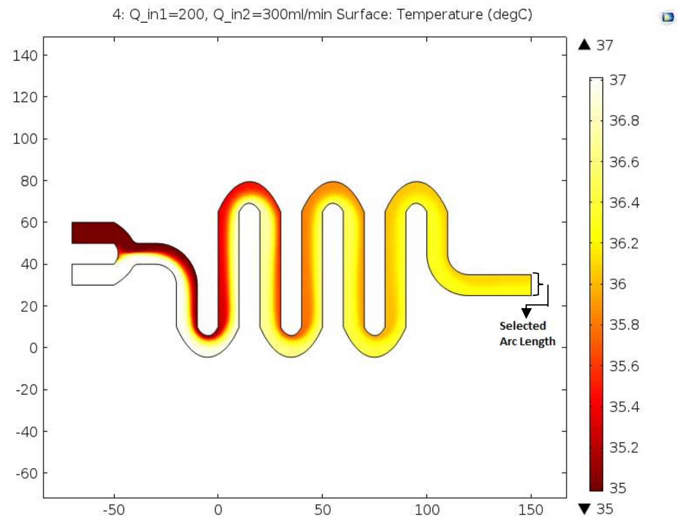

Fig 3 - Temperature surface for the model with flow rates 200 ml/min and 300 ml/min respectively.

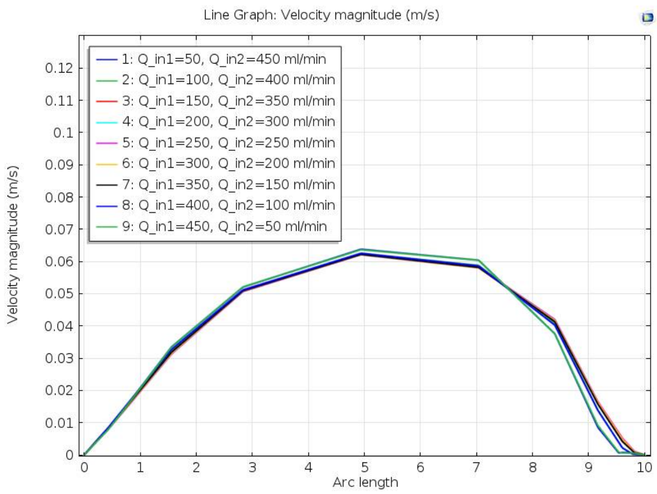

Fig 4 - Velocity graph along the arc length of outlet for various inlet flow rates.

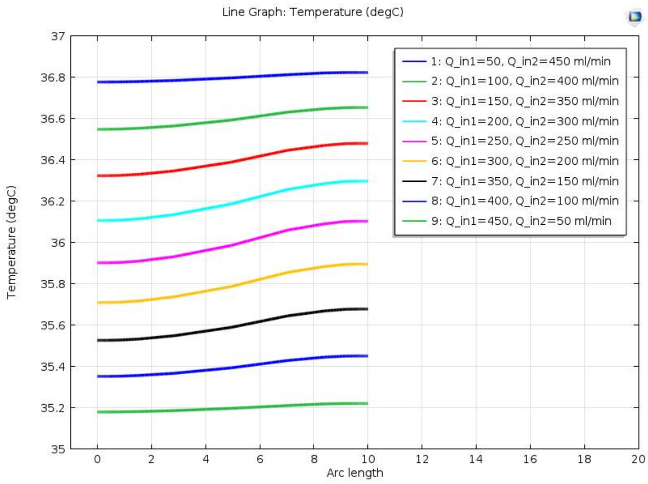

Fig 5 - Temperature graph along the arc length of outlet for various inlet flow rates

The model provides outlet temperature ranges from 35°C to 37°C, which is acceptable range of dialysate fluid during hemodialysis. The outlet temperature along its arc length was found to be inconsistent for some combinations of flow rates as shown in Fig. 5. Even though, these imprecise dialysate temperatures are slightly minor, this can be eliminated using a controller in further studies. Nowadays, more studies have been done using different dialysate temperatures, which depends on the patient's condition [11]. Thereby, the results show that active regulation of dialysate temperature is required to maintain stable body temperature for the patients. Hence, this simulation would be useful in designing an optimum controller to maintain temperature at constant level.

IV. Conclusion

The dialysate fluid behavior was carefully analyzed with the help of COMSOL Multiphysics® software. The study on dialysate temperature control has got higher potential to maintain hemodynamic stability for hemodialysis patients. Also, simulation shows the variation of inlet temperature for corresponding temperatures without comprising its dialysate outlet flow rate, which has to be steady for this application. So, this valuable information would be beneficial for further design and implementation of an adaptive controller. Thereby, it has higher potential to minimize these intradialytic complications during hemodialysis.

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