Computational fluid dynamics approach for modeling a non-Newtonian blood flow in a split and recombine micromixer

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Abstract— **In this work, the blood flow in a passive planar micromixer is analyzed in order to provide a case study for the use of different models of the blood dynamic viscosity in COMSOL Multiphysics. Regarding the Newtonian or non-Newtonian behavior, the blood is best approximated with a non-Newtonian model since its viscosity changes with dependence on the shear rate. The usual Newtonian model of blood viscosity, as well as two non-Newtonian models including Carreau model and the Power law model are used to study the wall shear stress. For the models study, a passive planar micromixer with ellipse-liked micropillars is proposed to operate in the laminar flow regime for high mixing efficiency.**

Keywords— **Micromixer, passive mixing, splitting and recombination, computational fluid dynamics, non-Newtonian fluid model.**

I. INTRODUCTION

In recent years, the development of an advanced technology named microfluidic has drawn more attention, which allows miniaturization and integration of microfluidic devices into a system for the widespread use in the chemical and biological fields. Compared with traditional analytical methods, microfluidic devices have many practical advantages, including a shorter analysis time, a lower sample and reagent consumption, and the potential for integration with other miniaturized devices.

Since Reynolds number is generally low at the microscopic scale because of the small feature size and low flow velocity in the microchannel. Thus, the turbulent fluctuations are absent and the diffusion mechanism plays a significant role in homogenous fluid mixing. In addition, a passive micromixer based on the splitting and recombination (SAR) concept can be employed to decrease the diffusion distance of the fluids [1], the space usage for micromixer in integrated microfluidic systems is also minimized.

In this study, we focus on species mixing performance of micromixers with ellipse-liked micropillars according to numerical study. Three blood models, two non-Newtonian (the Power law and the Carreau) and one Newtonian model were used to evaluate the flow over the geometry of the ellipse-liked micropillars, using COMSOL Multiphysics 4.3 and its Chemical Engineering module. The governing Navier-Stokes equation and convection-diffusion equation are solved in order to identify the flow characteristics of a fluid with properties similar with that of the blood.

II. MATERIAL AND METHODS

A. Theory of the numerical model

To study the behavior of the blood flow in the micromixer, blood can be assumed an incompressible fluid which is governed by the Navier–Stokes equation and the continuity equation as shown in Eqs. (1) and (2), respectively.

$$\frac{\partial u}{\partial t} + u.\nabla u = -\frac{1}{\rho}\nabla p + v\nabla^2 u \quad (1)$$

$$\nabla \cdot u = 0 \quad (2)$$

where u is the velocity, ρ is the density of the fluid, p is the pressure, and v is the kinematic viscosity of the fluid.

To investigate mixing in the micromixer, the convection-diffusion equation can be used and described with Eq. (3)

$$\frac{\partial c}{\partial t} + (u \cdot \nabla)c = D\nabla^2 c \quad (3)$$

where c and D are concentration and diffusion constant of the species, respectively.

The blood dynamic viscosity μ is modeled as a function of the strain rate $\dot{\gamma}$ in the three blood models with the similar parameters used in Ref. 2. The three models are as follows:

a) Newtonian model:

$$\mu = 0.00345 \text{ Pa.s} \quad (4)$$

b) Non-Newtonian Power law model:

$$\mu = m(\dot{\gamma})^{n-1} \quad (5)$$

where fluid consistency coefficient m = 0.035 [kg/m.s], flow behavior index n = 0.6.

c) Non-Newtonian Carreau model:

$$\mu = \mu_\infty + (\mu_0 - \mu_\infty)[1 + (\lambda\dot{\gamma})^2]^{(n-1)/2} \quad (6)$$

where zero shear rate viscosity μ_0 = 0.056 Pa.s, infinite shear rate viscosity μ_∞ = 0.00345 Pa.s, model parameter λ = 3.313s, n = 0.3568.

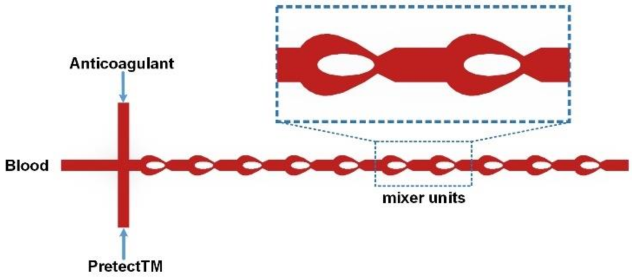

Fig. 1 SAR micromixer for blood mixing

B. Structure design of the micromixer

Fig.1 shows the design of the SAR micromixer with ellipse-liked micropillars base on the splitting and recombination concept. The term ellipse-liked micropillar is an element having the shape of an ellipse [3]. The micropillar structures result in the split of the main stream at the beginning of the micropillars and the reduction of the diffusion distance of two fluids. Besides, the mixing strength is increased at the end of the micropillars with the impingement effects when one stream is injected into the other. The contact interface of fluids is increased throughout each ellipse-liked micropillar so that the mixing effect is enhanced.

SAR micromixer with ellipse-liked micropillars for blood mixing includes 3 inlet channels (blood sample, anticoagulant solution, Pretect^{TM} solution (PreTect AS, Klokkarstua, Norway)), one outlet channel, and some mixing units.

C. Modeling and setting

Multiphysics simulation software (COMSOL 4.3) was used to examine the mixing performance of the SAR micromixer with ellipse-liked micropillars. During simulation, the incompressible steady flow condition was assumed. The physical properties of blood were applied, the fluid density and the average diffusion coefficient are 1060 kg/m^3 and 7.5x10^{-10}m^2/s [4], respectively. No-slip boundary condition is applied to the boundary on the wall. The velocity boundary condition is used for the inlets with the flow rate being varied from 0.005ml/min to 0.05ml/min. The boundary condition for the outlet is zero pressure. The normalized molar concentration of the species was set 1 for the inlet of blood, 0 for the inlet of anticoagulant and Pretect^{TM} solution. The governing equations are solved with a mesh consists of 428679 domain elements, 47228 boundary elements, and 3685 edge elements.

III. RESULTS AND DISCUSSION

A. Velocity field

Fig. 2 shows the flow field (streamline visualization) for the non-Newtonian Power law model with the inlet flow rate of 0.015ml/min. Since the cross-section area at the beginning of the micropillar is larger than the cross-section area at the end of micropillar, the local velocity at the end of micropillar will be larger than the local velocity at the beginning of micropillar. This phenomenon improves the mixing efficiency when the fluids from separated channels injected into the other with high velocity.

Similarly, the flow fields have also obtained for the Newtonian and non-Newtonian Carreau model in order to compare the velocity profile at the outlet between the different models. While the Newtonian model exhibits the characteristic parabolic profile, the non-Newtonian Power law model shows the profiles that are flatter in the center and larger velocity gradient towards the wall of micromixer for all the inlet speeds (see Fig. 3). This phenomenon can be a consequence of the shear thinning property of blood. On the other hand,

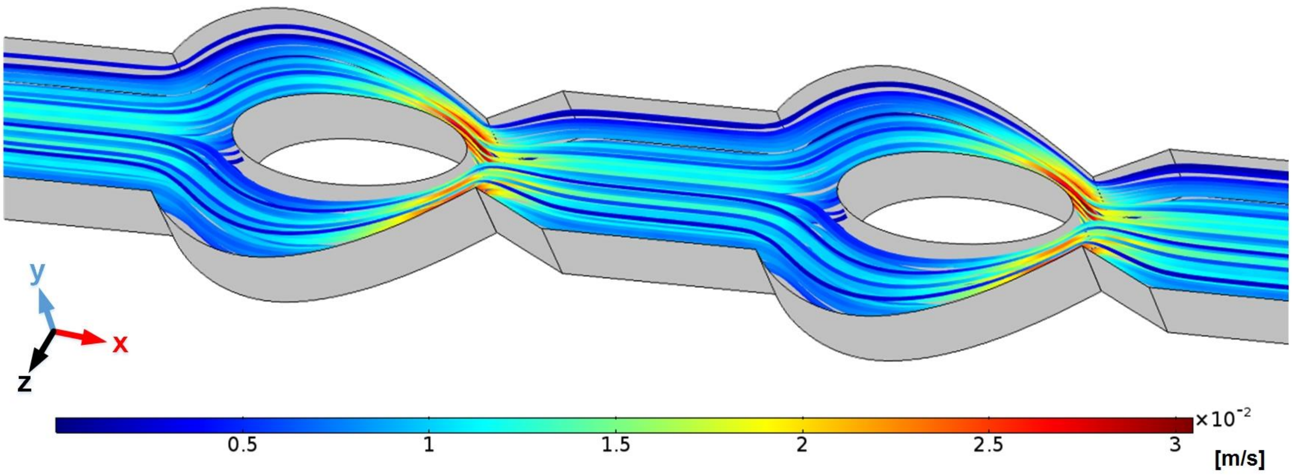

Fig. 2 Velocity field for the non-Newtonian Power law model with the inlet flow rate of 0.015ml/min

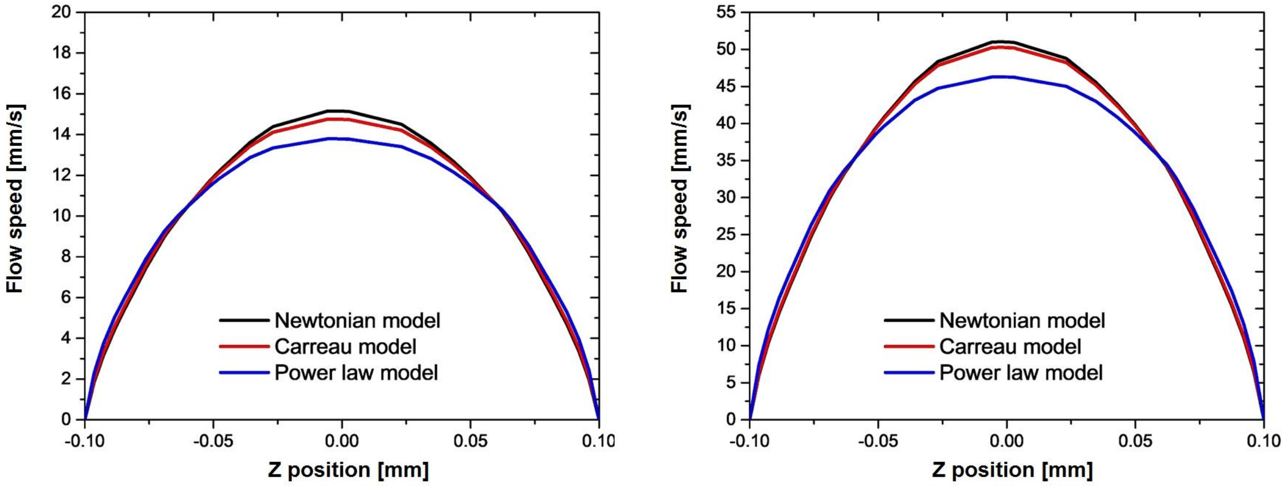

Fig. 3 Comparison between the velocity profiles at the outlet for the Newtonian, Carreau and Power law models: (left) inlet speed = 0.015ml/min; (right) inlet speed = 0.05ml/min.

the velocity profiles at the outlet for the Newtonian model and non-Newtonian Carreau model are almost overlapping. It's due to the convergence of the non-Newtonian Carreau model to the usual Newtonian model. The average viscosity in non-Newtonian Carreau model becomes closer to the viscosity in the Newtonian model.

B. Mixing field

Fig. 4 shows the mixing process of the blood (red color) with anticoagulant and Pretect^{TM} (blue color) in SAR mixer at the inlet speed of 0.015ml/min. The concentration field was normalized such that the concentration of blood denoted a value 1; the concentration of anticoagulant and Pretect^{TM} denoted a value 0. The color of the fluids clearly varied with the increase in mixing distance. We defined that the mixing region having a concentration between 0.23 and 0.43. The lower and upper limit for the mixing region are defined by Z1 and Z2 along the z-axis. The larger of (Z2-Z1) is the better mixing of fluids.

Concentration profiles at the outlet for the Newtonian model and non-Newtonian models are presented in the Fig.5. The mixing region for the lower inlet speed (0.015ml/min) is larger than the mixing region for the higher inlet speed (0.05ml/min) (see Table 1, Table 2, Fig. 5).

Table 1 Mixing region for the inlet speed of 0.015ml/min

Model	Z1	Z2
Newtonian	-0.06649	0.06514
Carreau	-0.06510	0.06382
Power law	-0.06040	0.05964

Table 2 Mixing region for the inlet speed of 0.05ml/min

Model	Z1	Z2
Newtonian	-0.05422	0.05396
Carreau	-0.05363	0.05346
Power law	-0.04794	0.04820

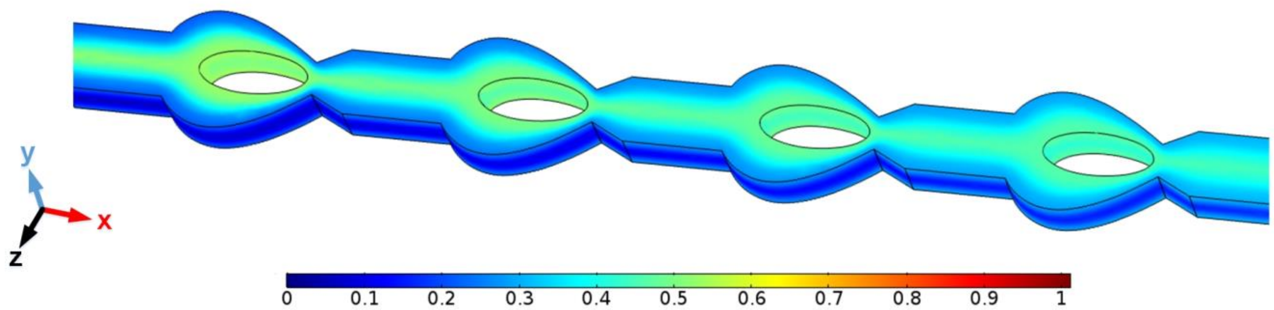

Fig. 4 Visualization of fluid mixing in SAR mixer.

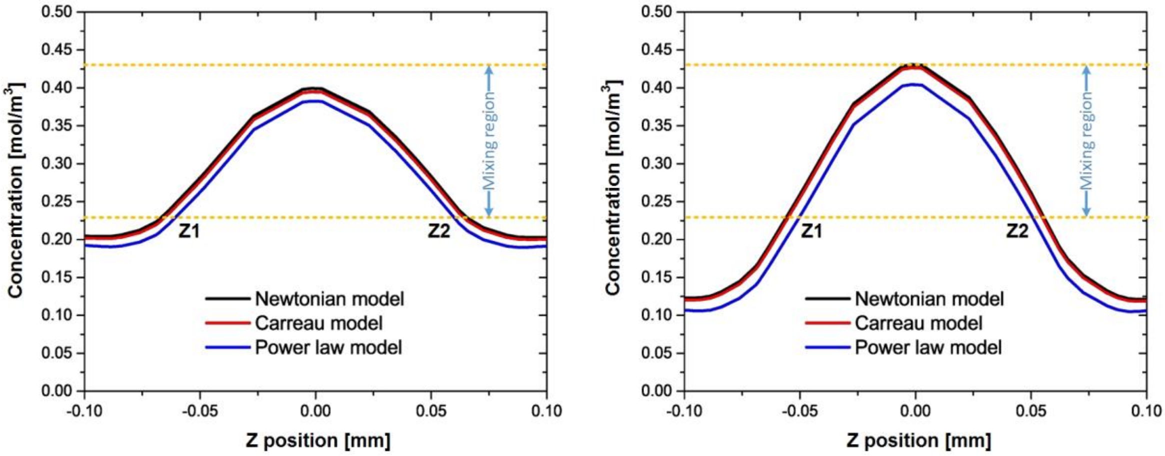

Fig. 5 Comparison between the concentration profiles at the outlet for the Newtonian, Carreau and Power law models: (left) inlet speed = 0.015ml/min; (right) inlet speed = 0.05ml/min.

During the transport of fluids along the x-axis, the fluids are also diffused to the sidewall (along the z-axis). Thus, mixing process along the z-axis decreases at the higher inlet speed. With these analyses, the operation condition of SAR micromixer can be known in order to get the perfect mixing performance.

IV. Conclusions

The COMSOL Multiphysics 4.3 was used successfully for the calculation and visualization of the flow fields and mixing field of a fluid with similar properties to those of blood. The solution to governing equations is obtained by using different model including usual Newtonian model and non-Newtonian model (Carreau model and Power law model). The steady state solution indicates that the differences in velocity profiles between the different models are reduced at the large flow speeds, especially for models such as the Carreau model. The better mixing performance in the microscale can be achieved at the lower flow speeds.

Acknowledgment

This research work is supported by the Research Council of Norway. The Research Council of Norway is acknowledged for the support through the Industrial Ph.D. scheme [grant number 214860/O30] and the Personal Post-doctoral Research Fellowships (HAVBRUK 2) [grant number 254862].

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