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ESTIMATION OF FILLING TIME OF BLOOD AND WATER IN MICROCHANNELS

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INTRODUCTION

Blood samples are a critical component of Point-of-Care clinical diagnosis [1]. These blood samples are analyzed in Lab-on-a-Chip devices, which monitor important parameters such as glucose and lactate levels. For these systems to work, the blood sample must be introduced to an empty capillary microchannel that guides the sample to an on-chip sensor. Thus the filling characteristic of an empty microchannel is an important aspect of study. The equation (eq 1)for the capillary-induced rise of a Newtonian liquid as a function of time in a circular tube was derived by Washburn:

$$X = \sqrt{\frac{\gamma_{LV} R \cos\theta_t}{2\eta}}\sqrt{t} \qquad (1)$$

where x is the distance of liquid penetration, R is the radius, θ_t is the contact angle, η is the viscosity, γ is the surface tension, and t is time [2].

In this paper, numerical simulations for both Newtonian and non-Newtonian fluids have been conducted and the results have been compared with theoretical analysis based on Washburn's equation. The effect of channel radius on filling distance was investigated. The liquid penetration and withdrawal in microchannel was also studied.

METHODOLOGY

The computations were run using the finite volume method. Volume of fluid (VOF) and an axi-symmetric model were used for the simulations, which used 144×10^3 nodes. The Navier-Stoke equations are solved for the fluid motion, and equations 2 and 3 are used for the interface tracking of the fluid:

$$\frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q) = 0 \qquad (2)$$

$$\sum_{q=1}^{n} \alpha_q = 1 \qquad (3)$$

where α_q, ρ_q, v_q denotes volume fraction, density and velocity of the q^{th} phase respectively.

The implicit formulation was used in the transient solver for this simulation. Figure 1 shows the mesh and simulated flow of water through the capillary. The contact angle between the fluid and the channel wall is shown.

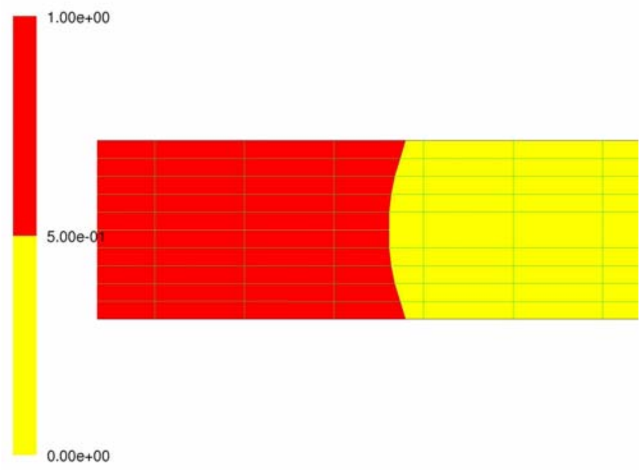

Figure 1. Simulation mesh showing water in microchannel at t = 0.0581 seconds.

For the first set of simulations, water was used as the liquid entering three different microchannels with radius 25, 50, and 100 µm. The inlet to the channel contained water with viscosity 1 cP, density 1000 kg/m^3, surface tension 0.073 N/m, and no mass flow rate. The outlet of the channel was open to atmospheric pressure. The flow was transient with a contact angle of 61° between the liquid and the channel wall. Next, the Carreau model was employed to simulate blood entering the microchannel with density 1050 kg/m^3, contact angle of 92°, surface tension 0.056 N/m. The time constant was 3.313 sec with zero shear viscosity of 0.56 kg/m-s and infinite shear viscosity of 0.0345 kg/m-s [3]. Finally, a Power-Law non-Newtonian model was used to verify the blood simulation results. The Power-Law Index was 0.2, and minimum and maximum viscosity limit was 0.0345 kg/m-s and 0.56 kg/m-s respectively. The consistency index was 0.42 $kg\text{-}s^{n-2}/m$.

RESULTS

The results of the simulations of water entering the capillary microchannels with radius 25, 50, and 100 µm are shown in Figure 2, with the theoretical validation based on Washburn's equation.

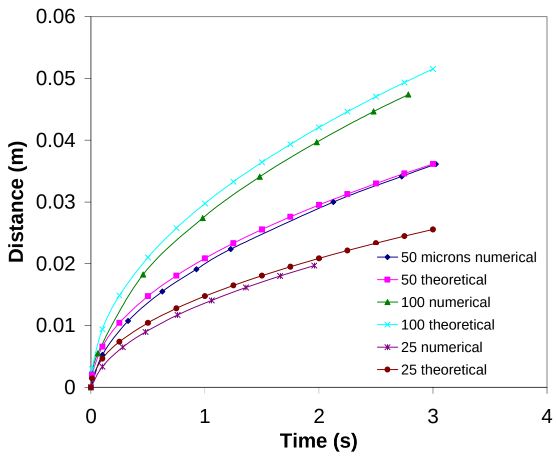

Figure 2. Simulation results for water in 25, 50, and 100 µm channels.

The difference between the theoretical prediction and the simulated results was 5.8%, 1.6%, and 6% for the 25, 50, and 100 µm channels respectively. As expected, the liquid penetration distance increased with increasing channel width. After 2 seconds, the liquid had penetrated 42% farther in the 100 µm channel than in the 50 µm channel, and 41% farther in the 50 µm channel than in the 25 µm channel.

Figure 3 shows the distance of blood penetration and withdrawal using the Carreau model for 25 µm and 50 µm capillaries. The penetration and withdrawal of blood in the capillary microchannels can be observed, which confirms the conclusions of Turian [4]. The blood in the 25µm channel penetrated 155 µm and withdrew 58% to 65 µm, whereas the blood in the 50 µm channel penetrated 400 µm and withdrew 68% to 125 µm. The result of the Power-Law non-Newtonian model for 100µm channel is plotted in Figure 4. After entering the channel, very little withdrawal of blood was observed.

CONCLUSIONS

Numerical computations of microchannel capillary flow were performed and compared with analytical models. Theoretical predictions and simulations agree for several channel geometries. The filling distance increases with increasing channel radius. The Carreau model showed large withdrawal of blood after initial penetration, whereas the Power-Law model showed very little withdrawal.

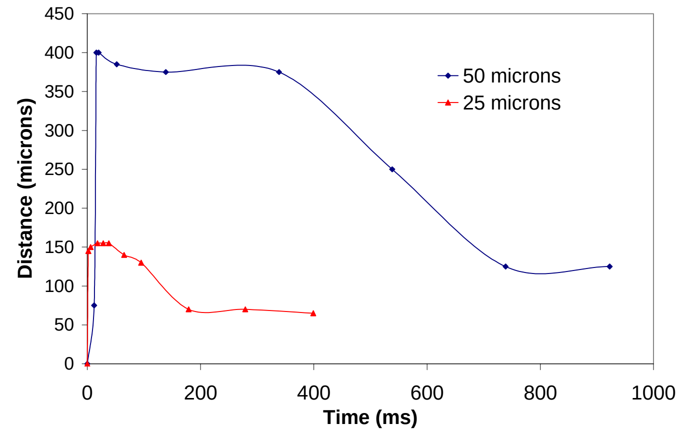

Figure 3. Results from simulation using Carreau model.

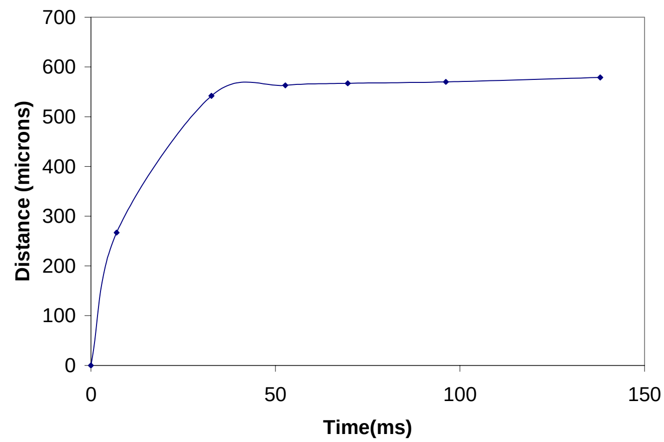

Figure 4. Results from Power-Law non-Newtonian model.

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