Theoretical and Experimental Study of Microchannel Blockage Phenomena

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Summary Microchannel blockage by hard, spherical particles have been investigated. The experiments on taking statistical data, and the visualization of the particles dynamics in the channel, were performed over a particle-to-channel diameter ratio of $0.14<R<0.65$. The experimentally obtained critical particle concentrations of the blockage (ϕ_c) are surprisingly low. The modified flocculation theory failed to explain the strong relation between ϕ_c and share rate (G), although it predicted the dependency of ϕ_c and R well.

Recent developments in fabrication techniques for micro-fluidic systems and in methods for the study of micro-fluid dynamics allow engineers to design integrated, complicated micro-fluidic devices, such as lab-on-chip total analysis systems and implant-type medical monitoring systems. The device usually consists of series of closed microchannels having cross-sectional dimension less than 1 *mm* and greater than 1 μm to transport materials with or without having chemical or biological reactions. In real applications, micro-fluidic devices are often used to transport a variety of particle-laden liquids at various flow speeds. Blockage of micro-channel by the particles may limit the life expectancy or usage of the micro-fluidic devices. Although, great number of potential applications for bioengineering and chemical analysis devices could be found, few experimental and theoretical studies about a mechanics of particle-laden liquids at large Peclet number (*Pe*) have been done. It is crucial to know when, or how often, blockages occur in each channel of a particle bearing micro-fluidic system. Also, operations to remove a blockage or replace a channel in a micro scale device involve numerous technical complexities.

Sharp (2001)[1] and Sharp and Adrian (2001)[2] have proposed shear induced arching (also called hydrokinetic arching) as the main mechanism causing a blockage based on observation of final blockage geometrical configurations. The explanation is based on the likelihood of particles colliding when placed in a non-uniform laminar flow velocity profile, followed by the formation of "arches", much like the arching phenomena in dry granular flows. It indicates that sufficient large number of particle must be in close distance prior to the arch formation. Assuming that the particles are uniformly dispersed at the inlet of channel, some mechanisms must bring the particles together in the channel. Study of flocculation of particles in the microchannels could gives us some insight of the mechanism about how the particle come together to form the arches.

The original work on orthokinetic flocculation theory (particle aggregation cause by fluid motion, $Pe>>1$) was that of Smoluchowski (1917), who described the collision rate of spherical particles, travelling along parallel streamlines. Gregory (1981)[4] simplified it for the case of mono dispersed suspension of uniform radius spheres,

$$-\frac{dn}{dt}=\frac{4\alpha\phi Gn}{\pi}$$

where n is number of aggregates in unit volume, ϕ is the volumetric concentration of particles, G is the local shear rate and α is a dimensionless collision efficiency factor which indicates number percentage of collision of particles could result aggregate over total number of collision. The theory is based on the assumption that form of aggregate is spherical. For example, colliding two particles merge into one sphere having double volume. The possibility that shear force or the effect of repulsion force can separate the doublet is neglected. Brownian diffusion has also been neglected. Further simplification was done by applying the cylindrical straight channel with laminar flow. Then it was integrated to give;

$$J=\frac{n_0}{n_{tot}}=\exp(\frac{128}{9\pi}\beta R^3 N)$$

where J is mean number of particles per aggregate, N is number of individual particles in the volume of the tube, R is diameter ratio of particle and tube, β is modified collision efficiency factor for a large aggregate. The equation nicely predicts the particle collision rate in early stage of flocculation process (doublet forming rate). It should be noted that the equation over estimates the growth rate of larger aggregate.

It can be inferred that the tube should be blocked when the mean aggregate diameter becomes larger than the tube diameter (D). Therefore to avoid the blockage in the tube, $N_B(R)>J$ must be satisfied, where $N_B(R)$ is the number of particles in the aggregate of diameter D. The number of particles in the aggregate having diameter equal to D is determined only by R. The solution of $N_B(R)$ can be generalised as the problem of finding a number of small spheres that can be packed inside of a lager sphere, the so-called spheres in a sphere problem. The general, exact solution for the dense packing is still unknown. Simple numerical cord has been written to approximate the solution. The obtained results have agreed very well with the results calculated by the algorithm from Boll and Donovan (1998)[5,6].

Now, at critical particle number $N=N_c$, J can be replaced by $N_B(R)$. Then the equation can be solved for N_c to obtain following final form.

$$N_c=\frac{9\pi}{128\beta}\ln(N_B(R))\frac{1}{R^3}$$

Experiments were performed in the micro-fluidic apparatus described in Figure 1. Due to technical limitations, the experiments can be repeated limited number of times with limited experimental time length. The following conditions have been set to determine the experimental N_c from the limited number of data. (i) Each experiment is stopped after *10 minutes* (*0.5 ml* of injection) or when the monitoring system detects a blockage. (ii) The 'critical' point N_c was decided after four consecutive experiments that were finished without the blockage, including at least one experiment at slightly lower concentration.

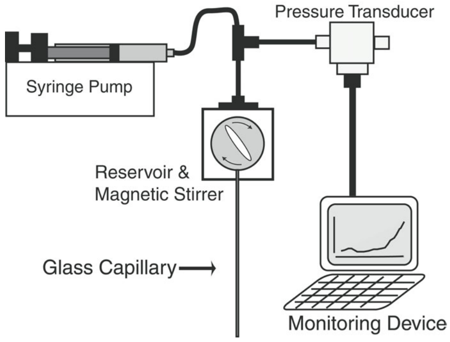

Figure 1: Setup for the blockage experiment

Figure 2 shows the experimental results (dots) and theoretical predictions (lines). The equation predicts relationship between R and N_c well, however the experimental results are classified by average share rate ($\overline{G}$). β = 0.1 is determined to match the experimental data at average share rate $\overline{G} = 5440.8s^{-1}$ (D = 100 μm). Values of β for the other $\overline{G}$ are also determined to fit the experimental results. Figure 3 shows how $\overline{G}$ affects on the blockage data. In the figure, $\overline{G}$ is only variable changed throughout the experiment. It clearly indicates that shear (averaged shear) rate increases the blockage probability at all stages. It shifts the probability distribution curve. This could not be predicted by the theory.

As it is stated above, the modified flocculation theory is an extension of the collision frequency between the particles. It does not provide sufficient information to predict the blockage at large *Pe* for two possible reasons. First of all, it ignores the possibility that the large aggregate having size to occupy the channel could slip though the channel without interrupting the flow. Another theoretical possibility is that the arch can be formed with enough number of single particles if they are located at collect geometry simultaneously. It does not require single large aggregation to fill the channel. In fact, Figure 3 is indicating that forming of the large aggregation may not be necessary for the blockage.

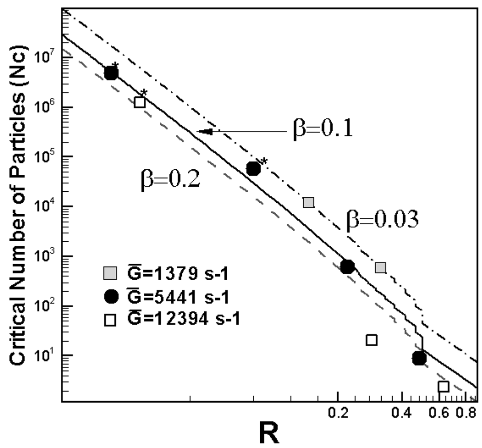

Figure 2: Theoretical predictions (lines) and experimental data (dots). Data with * were based on the blockage data taken by Sharp (2001). Their critical values were decided by the author.

The effect of flocculation must be distinguished from the effect of following arching formation to evaluate the effect of share on the blockage formation. Visual information regarding formation of arches and the following blockage forming process could provide hints to understand the mechanisms of the above possibilities, however due to the complexity of the analysis, the experiment setting and device is still under development. Also, the current experimental setting is insufficient to evaluate whether or not the blockage depends on some other parameters or initial configurations. Further discussion for this probability distribution requires further data collection with much more accurate experiment setting.

The work is in progress. The presentation will discuss comparison of theoretical prediction based on the flocculation theory and experimental results in a limited range of $0.14<R<0.65$. It will show how the preceding step to the arching will form and whether or not understanding of the complex arching mechanism is required to establish a reliable prediction of the blockage.

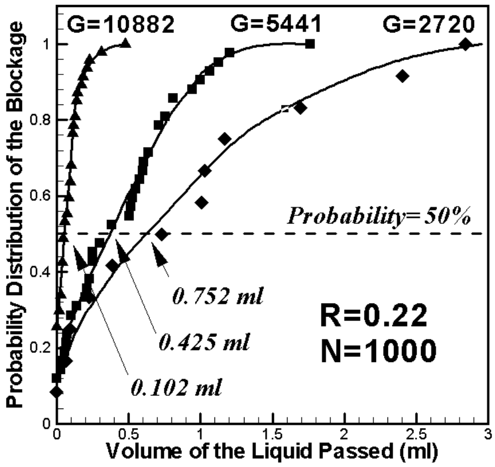

Figure 3: Probability distribution at various G. The probability of the blockage increases with average shear rate.

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