CYLINDRICAL MICROPARTICLE TRANSPORT AND DEPOSITION FROM ELECTROKINETIC MICROFLOW IN A 90 DEGREE BEND

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Abstract- Cylindrical microparticle transport and deposition from electrokinetic microflow in a 90 degree bend have been numerically simulated. Under the effect of dielectrohporetic force, gravity and stokes force, it's found that microparticles with larger size deposit on the lower region of the bend's outer wall. An exponential curve of deposition efficiency versus the product of stokes number and shape factor is fitted based on large number of numerical results.

Keywords- Deposition Efficiency, Dielectrophoresis, Cylindrical Particle

1. INTRODUCTION

Microfluidic systems are being increasingly used in analytical and bioanalytical applications over the past decade, and have also been developed as the tools for fundamental research. Miniaturization of fluidic processes in microfluidic systems holds great potential for biochemical analysis systems [1]. Electrokinetic flow is often used in microfluidic systems as it is considered as an efficient and effective transport mechanism that does not involve the intervention of moving parts and offers good control over sample handling [2]. Deposition of colloids, macromolecules, and bioparticles onto a solid surface is also of great significance to many technological processes such as separation of particle [3][4] and the assembly of carbon nanotube [5], etc. In these technological processes, most of colloids, which are usually nonspherical which can usually be seen as cylindrical particle, need to be extracted and delivered to the specified position with specified orientation accurately for counting and assembly. To design and control these systems with high efficiency, an in-depth study is necessary to understand the underlying mechanisms of particle deposition in electro;kinetic microfluidic systems, which is mostly controlled by the combined influence of electrical, hydrodynamic interactions.

With regard to particle deposition from fluid flow, even though numerous theoretical and experimental studies have been reported [6], focusing on analyzing the surface blocking effect in pressure-driven or shear flow of quiescent and flowing dispersions, and some experiments [7] showed the weak dependence of the curvature ratio on the deposition efficiency and the strong dependence of the flow Reynolds number on the same parameter. There are still few studies on the particle deposition from electrokinetic microfluidic flow have been attempted, especially for cylindrical particle, to the best of our knowledge. In electrokinetic microchannel flow, electroosmosis, refers to liquid flow induced by an applied external electrical field along

electro-statically charged surface, is being utilized extensively, and geometry induced DC-DEP is vital to particle transport [8][9]. Harikrishnan [10] studied the kinetics of electrokinetic transport and deposition of colloidal particles in a parallel-plate microchannel; Lettieri et al. [11] studied the transport and trapping of particles in microfluidic recirculatory flows generated by a combination of electroosmosis and applied pressure. However, the particle in these aforementioned studies is spherical, cylindrical microparticle deposition from electrokinetic microflow in 90 degree bend is the problem we wish to study, and the impetus for the present study comes from our interest in understanding the mechanics of the assembly of carbon nanotube within a compact area of microchip.
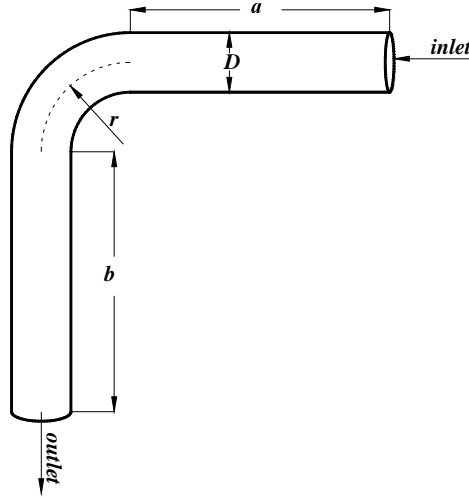
2. DEFINITION OF THE PROBLEM

Fig. 1 The schematic of 90° bend pipe

In this study, the pipe's hydraulic diameter (D) is 100μm, and radius of curvature (r) is 300μm, and a=700μm, b=700μm.

1.1 Flow field Modelling

Assuming the flow is incompressible and steady, and the flow is driven by electroosmosis, the momentum equation of flow is given as:

$$\rho(\boldsymbol{V}.\nabla)\boldsymbol{V} = -\nabla p + \mu\nabla^2\boldsymbol{V} + 2n_\infty ze\sinh(ze\varphi/k_bT)\nabla\phi \qquad (1)$$

where $\boldsymbol{V}$ is velocity vector, p is pressure, ρ and μ denote the density and the viscosity of the solution, respectively. ρ_e is the charge density. The relation between ρ_e and the EDL potential φ is shown as

$$\nabla^2\varphi = -\rho_e/\varepsilon\varepsilon_0, \nabla^2\phi = 0, \rho_e = -2n_\infty ze\sinh(ze\varphi/k_bT) \qquad (2)$$

where ε is the dielectric constant of the electrolyte solution and ε_0 is the permittivity of vacuum. z is the valence of ions, e is the fundamental electric charge, n_∞ is the ionic number concentration in the bulk solution, T is the absolute temperature of the solution and k_b is Boltzmann's constant. The above equations use the following boundary conditions:

For fluid flow, a constant pressure (atmospheric pressure) is specified at the inlet and outlet of the microchannel, no slip boundary condition is imposed on the walls; for externally applied electric potential, a fixed value at the inlet and outlet is specified, and its normal-differential value on the wall is zero; for *EDL* potential, a fixed value on the wall is specified, and its normal-differential value on the inlet and outlet is zero. The control-volume-based method was used to solve these equations, and specified discretization method was used to get secondary accuracy. Eqs. (2) was solved firstly to get the distribution of surface potential and externally applied electric filed in the microchannel, then Eqs.(1) was solved to get the electrokinetic flow field.

1.2 Particle Transport Modelling

For a low volume fraction of dispersed phase (particles), the Lagrangian approach with one-way coupling was used, the governing equation can be written as:

$$du_i^p/dt = F_D + F_g + F_{DEP} \tag{3}$$

where F_D is the drag force per unit particle mass taking the form of Stokes' drag law defined as, $F_D = 18\mu C_D Re(u_f - u_p)/24d_p^2\rho_p$, and u_f is the fluid phase velocity, u_p is the particle velocity, μ is the molecular viscosity of the fluid, ρ is the fluid density, ρ_p is the density of the particle, and d_p is the particle diameter. Re is the relative Reynolds number, which is defined as $Re=\rho d_p|u_f-u_p|/\mu$, which is in the range of 6.32e-3 to 0.125 in this study. The drag coefficient, C_D, can be taken from

$$C_D = \frac{24}{Re_p}\left(1 + aRe_p^b\right) + \frac{cRe_p}{d + Re_{p,}} \tag{4}$$

$$a = \exp(2.3288 - 6.4581\beta + 2.4486\beta^2), \quad b = 0.0964 + 0.5565\beta$$

Where $c = \exp(4.905 - 13.8944\beta + 18.4222\beta^2 - 10.2599\beta^3)$ \hfill (5)

$$d = \exp(1.4681 + 12.2584\beta - 20.7322\beta^2 + 15.8855\beta^3)$$

The shape factor, β, is defined as $\beta=A_s/A_p$, where A_s is the surface area of a sphere having the same volume as the particle, and A_p is the actual surface area of the particle. The particle Reynolds number Re_p is computed with the diameter of a sphere having the same volume.

The gravity force can be expressed as $F_g=g(\rho_p-\rho_g)/\rho_p$, and ρ_p and ρ_g denotes the density of particle and media, respectively. The dielectrophoretic force, F_{DEP}, acting on a cylindrical, is given by $F_{DEP}=\pi r_p^2 l\varepsilon_m Re[K(w)]\nabla E^2/2m_p$, where r_p is the particle radius, l represents the length of the cylindrical structure, m_p is the particle mass, ε_m is the permittivity of the suspending medium, ∇ is the Del vector (gradient) operator, E is the rms electric field and $Re[K(w)]$ the real part of the Clausius-Mossotti factor, given by $K(w=0) = (\sigma_p-\sigma_m)/ (\sigma_p+2\sigma_m)$ with σ_p and σ_m the conductivity of particle and medium, respectively, and w the angular frequency of the applied electric field. To treat fluid flow and particle transport in a general way, the dimensionless parameter such as stokes number (St) was used here. Stokes number is defined as the ratio of the stopping distance of a particle to a characteristic dimension of the obstacle and given as $St =$

$C_c\rho_p d_p{}^2 U_0/9\mu D$, where U_0 is the mean axial velocity in the bend, D is the tube radius, and C_c is the slip correction factor.

3. RESULTS AND DISCUSSION

To ensure statistical independence, mesh convergence as well as particle number independence tests were performed. Particle number 10,000 and mesh 84,915, respectively, could produce particle number and mesh independent results and hence was used for all simulation runs. In this study, the electric voltage drop between pipe's ends is in the range of 30~300V. The cross section diameter of particle injected is $40\mu m$, and its shape factor is in the range of 0.17~0.20.
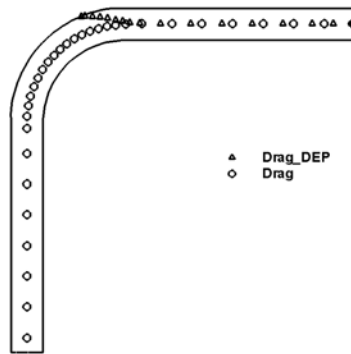

Fig. 2 Schematic of trajectories of microparticle injected from the centroid of inlet under drag force ("O"), both drag, gravity and DEP force("Δ")

Referring to Fig. 2, when single particle is injected from the inlet of the bend, it will move under those forces listed in eq. (3). Among them, stokes force is induced by the relative velocity between the fluid and particle, and it is almost parallel to the wall of bend pipe, under only stokes force, microparticle far from the wall has little chance to deposit on it; Under both DEP and drag force, it can be found that DEP force can bring particle to the close region of outer wall gradually and particle is trapped by the wall in the end.

In order to get the statistical deposition efficiency of large number of microparticles in some region, the deposition efficiency (*DE*) for region i can be expressed as $DE_i=N_{id}/N_{io}$, here N_{i0} and N_{id} are the number of particles entering and depositing in the *i* th region respectively.

Fig. 3(a) shows the number and position of microparticle deposited in the bend, from that it can be seen qualitatively that microparticle transported under DEP, gravity and stokes force mostly deposited in the outer bend for the inertial effect. Next, the statistical method is used to the get the contour of deposition efficiency as shown in Fig. 3(b), from which it can be found that the downstream of the outer bend has the maximum deposition efficiency.

When DEP, gravity and drag force are considered, large number of the numerical simulations about the deposition efficiency of particles with different diameters under variant electric fields is carried out, and these data are labeled with scatters in Fig. 4, from which it can be found that *DE* increases exponentially with the increase of χ and it reaches 1 when χ is about 1.0e-3, and χ can be expressed as $\chi=St*\beta$. Here, *St* is a dimensionless number corresponding to the behavior of particles suspended in a fluid

flow. In general, for $St \gg 1$, particles will continue in a straight line as the fluid turns around the obstacle therefore impacting on the obstacle. For $St \ll 1$, particles will follow the fluid streamlines closely. St varies from 4.4e-7 to 1.25e-2 in this study. β is shape factor, which describes the degree of similarity between sphere and other shapes, for sphere, it has the value of 1, and it's in the range of 0.17 to 0.20. In addition, it can be concluded that it's more difficult for particle with larger stokes number or shape factor to follow the fluid flow and it's easier to colloid with the wall and deposits there.

(a)   (b)

Fig. 3 Regional deposition patterns of microparticles with cross section diameter 40μm under drop voltage 50V, with drag force, DEP force in consideration
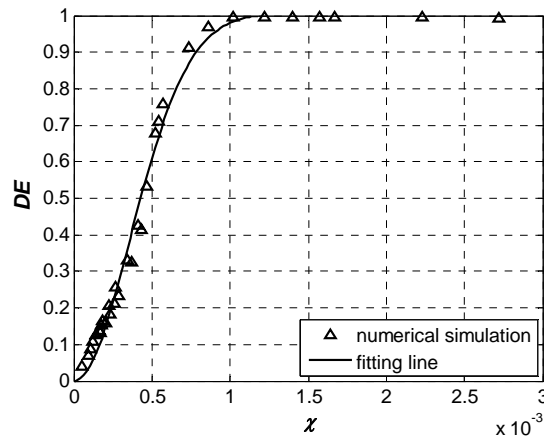

Fig. 4 The fit of the non-spherical microparticle deposition efficiency in the 90 degree bend with consideration of DEP and hydrodynamic force

In order to get the unified theory of cylindrical microparticle deposition from electrokinetic microflow in 90 degree bend, an exponential function about χ is used here, which embodies the effect fluid, electric field and particle's physical property, and can be expressed as

$$DE = c(1.0 - 10^{(a*\chi^b)}) \qquad\qquad (6)$$

Here a, b and c represent constant coefficients. After the post processing of the numerical data shown in Fig. 4, the coefficient in this equation can be derived as

$$a = -1.2325e+006, \quad b = 1.9640, \quad c = 1.0 \qquad\qquad (7)$$

4. CONCLUSIONS

This study reports a theoretical and numerical study on the irreversible deposition of cylindrical particles from electrokinetic microfluidic flow in 90 degree bend. The flow and electric field are numerically simulated with finite volume method first, then large number of microparticles are injected and traced with one-way coupling stochastic Langevin equation, incorporating the electrical, hydrodynamic on colloidal particles. Under the effect of DEP force, it's found that larger sized microparticles are repelled to close to and deposit on the lower region of the outer wall. Furthermore, it's concluded that microparticle deposition efficiency has specified exponential relation with the product of particle stokes number and shape factor.

5. ACKNOWLEDGEMENTS

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