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Size Selective Capturing of Biomolecules and Nanoparticles by Combined Dielectrophoresis and Surface Tension

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ABSTRACT

Electric field has become one of the most widely used tools for manipulating cells, biomolecules, and nanoscale particles in microfluidic devices. This work presents the theory, modeling, and experimental efforts on manipulation of nano- and biomaterials by using an electric field and surface tension. The separation of a specific bio-nano molecule out of a mixture is important for biomedical applications such as disease diagnostics from nucleic acids circulating in body fluids. The challenge lies in the separation of the circulating DNA from cells and other biomolecules. A nano-structured needle is proposed to concentrate nucleic acids in a sample solution onto the needle in a size-selective manner by using dielectrophoresis (DEP) and capillary action. A nanoneedle is fabricated with a single-walled carbon nanotubes tip attached to a SiC nanowire. With application of an AC electric field, the dielectrophoretic force attracts DNA and other biomolecules in the vicinity of a nanoneedle. As the needle is withdrawn from the solution, DNA molecules are captured by dielectrophoresis while other larger bioparticles including cells remain due to capillary action generated between the solution and the needle. Whether particles of a specific size are captured is determined by the surface tension acting on the particles during pulling process.

Numerical simulations are used to explore the size selective capturing mechanism and to determine optimal operating parameters of DNA capturing under various conditions. The immersed electrokinetic finite element method (IEFEM), which couples fluid-structure interaction problem with electrokinetics, is proposed for modeling the electrokinetic-induced mechanical motion of particles in a fluid domain under an applied electric field. In this method, independent solid meshes move in a fixed background field mesh that models the fluid and electric field. The dynamic attraction process of biomolecules and nanoparticles toward the tip under electric field is simulated through IEFEM method. The surface tension acting on a spherical particle attached to the tip during pulling is calculated. In a series of simulations with particles of different sizes, it is found that the relative diameter ratio between the particle and the tip largely impacts the final breakup of the liquid bridge between the tip and the solution.

For a particle with a diameter significantly smaller than tip diameter, the liquid bridge breakup happens at a wetting perimeter below the center plane of the sphere. Thus, the small particle remains inside the separated drop and gets pulled out of the solution. For a particle with a diameter close to tip diameter, however, the breakup happens at a wetting perimeter above the center plane, leading to a large surface tension that retracts the particle back to the solution. As a result, a nanoneedle, whose diameter is around 500nm, can attract DNA molecules, but cannot capture cells whose diameter is larger than 2μm. The particle size dependent pulling process predicted from the simulation agrees quite well with experimental observations. The various dynamic capturing processes and captured molecule patterns are also explored.

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