Microfluidic Flow Multiscale Model for Bio-Diagnostic Lab-Chip Device

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Abstract - **Recent advances in of microfluidic Lab-Chip technologies brings new approach to modelling techniques, called multiscale modelling. Its key issue is coupling of the molecular and continuum scale models, which can bring better understanding of the fluid dynamics in case of multi-phase flows and allow further improving of the Lab-Chip designs.**

Keywords – **Microfluidic Flow, Multiscale Model, Lab-Chip, Bio-Diagnostics.**

I. Introduction

Modern microfluidic technology is an area of science & technology, where appropriate devices manipulate with fluids in micro or nano litter range. Such devices, generally called as Lab-Chip systems, had received great interest due to its impact on a wide range of biochemical and medical applications. Lab-Chip devices involve fluid flow, convection, diffusion and chemical reactions within the microfluidic chambers and channels. The interaction between these complex phenomena must be well understood to enable its adequate implementation in Lab-Chip systems [1].

Average length scales of some biological objects, which can be applied in microfluidic Lab-Chip diagnostic devices:

- Ø of glucose molecule	1 nm
- Ø of insulin molecule	5 nm
- Ø of typical virus	75 nm
- Ø of the smallest bacterium	200 nm
- Ø of red blood cell	8.4 mkm
- Ø of average cell in human body	10 mkm
- Ø of the typical animal oocyte	100 mkm
- Ø of the largest bacterium	750 mkm

II. Modern Lab-Chip Flow Modelling Issues

Transport phenomena (pressure, electrical, capillary, thermal, etc.) in continuous-flow diagnostic Lab-Chips devices have several important aspects. The main one is distribution of flow components and/or biological objects (living cells) through microchannels or microchambers. There have been many different methods developed to control microfluidic flows, which are based on: 1) differential pressure between the inlet and outlet of the channel network by pumping [2], or 2) electrokinetic flow, which can be induced by electric field across a channel [3]. The bio-sample's spatial distribution within the system can be collectively represented by a scalar value concentration. Such continuous-flow Lab-Chip devices have been actively investigated in a variety of fields.

It is always a challenge to control the complex biological fluid flows in microchannels/microchambers, because each new Lab-Chip device has unique design with its flow specifics, which is not well understood and can't be easily described. Any changes in microchannel/microchamber geometry significantly affect the trajectory of fluid flow, as well as the distribution of microfluidic components and supplying biological material, like living cells. Fluid flow in microdevices remains like at macro scale, but some of its effects - surface tension, viscosity, electrical charges can significantly affect the fluid behaviour (because of the surface-to-volume ratio). By incorporating the complexities of cell and chamber geometry, fluid flow patterns and bio-cell mechanics into overall numerical model, the behaviour of whole Lab-Chip system can be accurately predicted.

In addition, most of microfluidic Lab-Chip flows, dedicated to biochemical diagnostics, are multiphase in principle (two or more immiscible fluids are introduced and manipulated). The immiscible fluids can appear, because of different chemical compositions – liquid/liquid, or in different physical states – gas/liquid, solid/liquid or gas/solid/liquid [4]. When different phases mixed together in microchannel, the flow patterns change between droplet-based flows and stratified flows depending on the physicochemical properties of fluids and channel surfaces, which adds specific influence to this movement. Modelling of such fluids is much more complicated than in unconfined systems or single-phase systems and multi-scale approach is a solution for these cases.

III. Multiscale Modelling and Simulation

The motion of the mixture of microfluidic substance and biochemical particles usually can be obtained by applying a pressure difference to a microchannel or by applying an electric field along the channel. Pressure-driven flow usually has parabolic flow profile, which influence on mixing efficiency. Another type: electrokinetic forces generate flow, which is insensitive to channel sizes. In microchannels with characteristic length (100nm .. 100μm) (in case $Kn<0,1$) the liquid flows can still be described with continuum Navier–Stokes equations. Further decrease of length scale makes surface force and electrokinetic effects more important then regular inertial force.

There are four main differences between fluid mechanics at micro- and macro- scales: Low Reynolds number effects, Surface-dominated effects, Non-continuum effects, Multiscale multiphase effects.

The small length scale cause very small Reynolds number with high velocity gradient and high viscous force, which cannot be achieved at macro scales. Thus, the hypothesis of continuum mechanics may become unacceptable. Some of these effects can be simulated with relatively simple modifications of the standard CFD procedures, but other requires new approaches, like multiscale modelling.

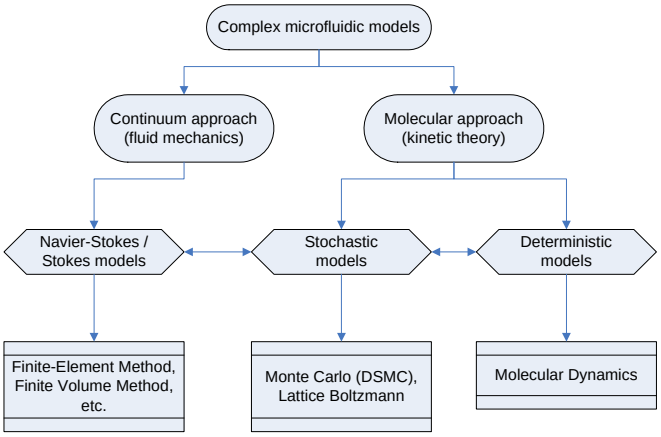

Fig.1 Classification of microfluidic models and methods

There are two basic modelling approaches for simulating microfluidic flow mixture:

1) general continuum Navier-Stokes (NS) equations

$$\begin{cases} \rho\left(\partial_t u + \nabla \cdot \left(u \otimes u\right)\right) - \nabla_x \cdot \tau = 0 \\ \nabla \cdot u = 0 \end{cases}, , \qquad (1)$$

where ρ – fluid density, u – field velocity, τ – stress tensor, x ϵ Ω – bounded domain.

2) general molecular dynamics (MD) equations

$$\begin{cases} m_i \cdot \ddot{r}_i = f_i \\ i = \overline{1..N} \end{cases}, \qquad (2)$$

where m_i – particle mass , r_i – particle position, f_i – atomistic force on the i-th particle.

The continuum model is in a form of Navier–Stokes equations, which describes the regular microfluidic flow with the channel sizes in a micrometer range. As the length scale decreases or/and bioparticles appear in flow, the continuum approach breaks and molecular models should be applied to the discrete particles. Although, the molecular dynamics model can't simulate the whole Lab-Chip device due to its extremely high computational cost. These limitations in applying different microfluidic models cause CFD scientists to use hybrid multi-scale simulation techniques. The reason is to combine both molecular-continuum scales in one model. One of two coupling schemes can be usually used: direct flux exchange or domain decomposition method (NS model and MD model are calculated in different domains simultaneously).

The general strategy for the seamless multiscale methods was shown in [5]. According to this, both models - the macroscale (1) and the microscale (2) can be linked together through the stress tensor τ by the Irving-Kirkwood equation, which calculates the this tensor through microscale variables. Here, the macroscale stress tensor at $\tau(x,t)$ will be evaluated from MD model in the corresponding microchannel point at the time t. Thus, multiscale model contain two disparate time scales: a macro scale associated with the hydrodynamics, and a micro scale associated with the fast molecular motions.

Practical computational experiments confirm that Lab-Chip simulation on multiscale models fits experiments much better. Nevertheless, for complex flows and general non-Newtonian fluids, it is still difficult to agree calculated results with the experiments. So, it is necessary to analyze this problem from the modelling and simulating viewpoints in order to improve the model. This work is planned to be conducted within the developed multiscale approach and method of coupling the micro-macro models.

IV. Conclusion

The modelling of complex micro/nanoscale fluid behaviour in bio-diagnostic Lab-Chips is very important for the further development of these devices. The complex nature of multi-phase mixture together with micro- and nano-effects at these scales raises many new challenges. The interest to the microscale approach rises because it is based on a clear understanding of the physics of microfluidics processes, but it requires much computational efforts. Thus, multi-scale modelling and simulation technique is a perspective approach for designing and analysing new Lab-Chip devices for diagnostic purposes.

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