NUMERICAL STUDY OF MAGNETIC MICRO-BEADS STEER BY MAGNETIC RESONANCE NAVIGATION IN TUMOR EMBOLIZATION

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Introduction

Magnetic resonance navigation (MRN) of medicinal substances is gaining popularity in the treatment of liver cancer. This method relies on a cluster of particles formed by dipole-dipole interaction; the latter originates from the magnetic moments generated by the MRI scanner static magnetic field. These aggregates are then injected into the controlled blood flow where they are steered into the target branch by the combination of the magnetic gradient force and gravity.

The success of the MRN procedure depends on the aggregates shape, which determines their mobility and stability. To evaluate the latter we deploy a computational model. Prior research has only examined a few particle forces [1,3] or employed drag approximation models [1,2,3], both of which are unsuitable for clusters formed by the MRN approach.

This study focuses on the issue of stability of the aggregates, which is determined by the interplay between the drag force applied on individual particles and dipole-dipole interaction.

Methods

Using the point-particle approach, a modified version of the Maxey-Riley equation [4] is used to model particle trajectories (p=particle, f=flow, m=mass, u=velocity, $\boldsymbol{\xi}$=drag tensor):

$$m_p \frac{d\boldsymbol{u}_p}{dt} = \boldsymbol{\xi}(\boldsymbol{u}_f - \boldsymbol{u}_p) + m_f \frac{D\boldsymbol{u}_f}{Dt} + m_f \left[\frac{D\boldsymbol{u}_f}{Dt} - \frac{d\boldsymbol{u}_p}{dt}\right] - (m_p - m_f)\boldsymbol{g} \quad (1)$$

Where the terms on the right-hand side (RHS) represent in order drag, pressure gradient, virtual mass, gravity, and buoyancy forces. Additional forces such as gradient magnetic force, dipole-dipole interaction, and collision force also contribute to the RHS.

The dipole-dipole interaction force describes the interaction of magnetized particles and is responsible for their clustering. Dipole-dipole forces are opposed to shear forces generated by the non-uniform drag distribution across particles within the aggregate. To investigate the stability of the aggregates, the hydrodynamic forces on individual particles in the aggregate has to be thoroughly investigated, here by means of the immersed boundary method (IBM).

Results

The investigation starts with an a-priori simple case representing a chain of spherical particles oriented parallel or perpendicular to the flow direction. In fact, it represents an already challenging computational case for the IBM. The total drag is validated against experimental data and the bead-chain drag model (BDM) [5]. Fig.1(a) illustrates that even though the IBM results follow the trend of the experimental and BDM results, the IBM displays an error of ~10%. The distribution of the drag was then computed across individual particles (fig.1(b)), which demonstrates that the largest force is applied to the outermost particles, while the applied drag on other particles is much smaller. This indicates that the outermost particles of the aggregate are the loosest part of the chain.

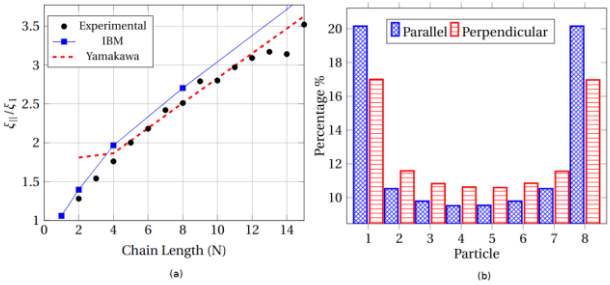

Figure 1: (a) Comparison of experimental, BDM theoretical [5] and IBM drag coefficient values for bead-chains parallel to flow. (b) Distribution of drag force across a chain of 8 particles, parallel and perpendicular to flow.

Discussion

Preliminary results show that the immersed boundary method is suitable for determining the drag as its results are in a good agreement with the bead drag model and the experiments reported in the literature. However as the bead drag model is limited to a rigid chain of spherical particles, additional research is required to generalize the effect of the hydrodynamic force on aggregates of different shapes in a realistic arterial blood flow field.

References

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