DY 7: Soft Particles in Flows I (Focus session, joint DY/CPP)

The dynamics and interactions of soft particles suspended in a flowing liquid are a physical problem of unusual complexity and of relevance in technical and biological systems, e.g. blood flow. The close connection between sophisticated numerical simulations and experiments has brought about a wealth of new insights in the recent past. The aim of the session is to review some of these recent advances, both experimental and theoretical/computational.

Organized by S. Gekle, G. Gompper, C. Wagner

Time: Monday 10:15–13:15 Location: ZEU 160

Invited Talk DY 7.1 Mon 10:15 ZEU 160

Immersed Boundary Methods for Rigid and Deformable Particles in Viscoelastic flows — •Eric Shaqfeh — Department of Chemical Engineering, Stanford University

The immersed boundary method will be used with a finite volume fluid solver to develop a unique tool to examine the properties of a viscoelastic suspension of particles. The tool will employ unstructured grids and is massively parallel, thus allowing very complex geometries to be simulated. Since the internal stress of the particles is handled using a finite element solver, nearly arbitrary stress-strain relationships for the particles can be handled and their shape can deform continuously. A number of interesting physical problems will be examined with the code including 1) Sedimentation of particles in orthogonal shear and 2) the rheology of particulate suspensions in a viscoelastic fluid under shear.

DY 7.2 Mon 10:45 ZEU 160

A new look at blood shear-thinning — Luca Lanotte[1], Johannes Mauer[2], Simon Mendez[3], Dmitry Fedosov[2], Jean-Marc Fromental[4], Viviana Claveria[1], Franck Nicoud[3], Gerhard Gompper[2], and •Manouk Abkarian[1] — [1]Centre de Biochimie Structurale, Montpellier, France — [2]Institute of Complex Systems and Institute for Advanced Simulation, Forschungszentrum Jülich, Germany — [3]Institut Montpelliérain Alexander Grothendieck, Montpellier, France — [4]Laboratooire Charles Coulomb, Montpellier, France

Blood viscosity decreases with shear stress, a property essential for an efficient perfusion of the vascular tree. Shear-thinning is intimately related to the dynamics and mutual interactions of red blood cells (RBCs), the major component of blood. Because of the lack of knowledge about their behavior under physiological conditions, the link between RBCs dynamics and blood rheology remains still unsettled. Performing experiments and simulations in microcirculatory flow conditions of viscosity, shear rates and volume fractions, our work reveals how rich RBCs dynamic morphologies govern blood shear thinning, contrary to the current paradigm assuming steady RBC orientation and membrane circulation. Our results suggest that any pathological change in RBCs* local rheology will impact the onset of these morphological transitions and should play a key role in pathological blood flow.

DY 7.3 Mon 11:00 ZEU 160

Clustering of microscopic particles in stenosed blood flow — •Christian Bächer, Lukas Schrack, and Stephan Gekle — Biofluid Simulation and Modeling, University of Bayreuth, Germany

A mixed suspension of red blood cells and microparticles flows through a cylindrical channel with a constriction mimicking a stenosed blood vessel. Our three-dimensional Lattice-Boltzmann simulations show that the red blood cells are depleted right ahead and after the constriction. For the red blood cells the axial concentration profile is very similar to that of isolated tracer particles flowing along the central axis. Most importantly, however, we find that the stiff microparticles exhibit the opposite behavior. Arriving on a marginated position near the channel wall, they can pass through the constriction only if they find a suitable gap to dip into the dense plug of red blood cells occupying the channel center. This leads to a prolonged dwell time and, as a consequence, to a pronounced increase in microparticle concentration right in front of the constriction. Similar clustering events occur for marginated particles in a cylindrical channel branching into two daughter channels.

DY 7.4 Mon 11:15 ZEU 160

Margination of blood cells — •Revaz Chachanidze[1,2], Marc Leonetti[1], and Christian Wagner[2] — [1]Institut de Recherche sur les Phénomènes Hors Equilibre (I.R.P.H.E), Aix-Marseille University, Marseille, France — [2]Saarland University, Saarbruken, Germany

In blood flow erythrocytes migrate to the centre of the vessel creating a *cell-free layer* at the edge while leucocytes, lymphocytes and platelets tend to migrate to vessel walls. This phenomenon is known as margination. Margination of leucocytes and its role in immune response as well as margination of red blood cells in cases of some diseases (such as malaria and sickle cell disease) have been subjects of research for a while. Recent advances in targeted drug delivery arouses interest to margination of micro- and nano-particles.

Our research is dedicated to better understanding of mechanical properties of particles involved in margination and to create conditions for blood flow under which particles manifest tendency to segregation. For this purposes we observe and quantify blood flow consisting of 2 populations of red blood cells * healthy and rigidified with cross-linking agent (glutaraldehyde) * in microfluidic channels in cases of different volumetric flow rate, cells concentration and etc.

15min. break

Invited Talk DY 7.5 Mon 11:45 ZEU 160

Effect of bending on the dynamics of a spherical capsule in shear flow — •Anne-Virginie Salsac — CNRS - Universite de Technologie de Compiegne, Compiegne, France

Encapsulating liquid droplets within a membrane enables to protect fragile or volatile substances and control their liberation. Typical artificial capsules are quasi*spherical at rest and present a hyperelastic membrane with mechanical and geometrical properties that are function of the fabrication process. When suspended in a simple shear flow, such capsules are elongated in the straining direction by the hydrodynamic stresses, while the membrane rotates around the deformed shape under the flow vorticity. But, for low flow strength, the capsule membrane is compressed in the equatorial region and blucking may occur. Since membrane wrinkling can cause fatigue breakup, it is important to predict it in order to avoid/provoke membrane rupture. The objective of the study is thus to study numerically an initially spherical capsule in shear flow and analyze the influence of the membrane bending rigidity on the capsule dynamics and wrinkle formation. The 3D fluid-structure interactions are modeled coupling a boundary integral method to solve for the internal and external Stokes flows with a thin shell finite element method to solve for the wall deformation [1]. For a given wall material, the capsule deformability strongly decreases when the wall thickness (or bending resistance) increases. We show that the global capsule motion and deformation can, however, be inferred from the ones obtained by a membrane model devoid of bending stiffness, as they are mainly governed by in-plane membrane tensions.

DY 7.6 Mon 12:15 ZEU 160

Hydrodynamic mechanism of shear-induced ordering in weakly confined suspensions of deformable particles — •Alexander Farutin[1,2], Zaiyi Shen[1,2], Thomas Fischer[3], Jens Harting[4,5], and Chaouqi Misbah[1,2] — [1]Univ. Grenoble Alpes, LIPHY, F-38000 Grenoble, France — [2]CNRS, LIPHY, F-38000 Grenoble, France — [3]Laboratory for Red Cell Rheology, 52134 Herzogenrath, Germany — [4]Helmholtz Institute Erlangen-Nürnberg for Renewable Energy (IEK-11), Forschungszentrum Jülich, Fürther Strasse 248, 90429, Nürnberg, Germany — [5]Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600MB Eindhoven, The Netherlands

It has been shown recently by experiments and numerical simulations that suspensions of red blood cells confined between two walls can undergo ordering when subject to shear flow. In this presentation, we propose a hydrodynamical model that explains this effect. The key ingredients of the model are (1) wall-induced migration, which keeps

the cells close to the midplane between the two walls, (2) long-range hydrodynamic interactions in the direction parallel to the walls, which cause cell pairs to align with the flow direction and to get attracted to each other and (3) short-range hydrodynamic interactions perpendicular to the walls, which cause the cells move out of the midplane in such a way that the shear flow pushes them apart. We have verified by solving our model analytically that two cells form a stable stationary pair. The intercell distance given by our model agrees with the experiments and the simulations.

DY 7.7 Mon 12:30 ZEU 160

Ultrasound-triggered margination of microbubbles for targeted drug delivery — •Achim Guckenberger and Stephan Gekle — Biofluid Simulation and Modeling, Universität Bayreuth, Germany

During circulation through the vascular system, drug delivery agents should be preferably located in the low-shear interior of the blood stream. Yet, when they are close to the pathological region, they should attain a near-wall position for the most efficient interaction with the endothelium. Using mesoscopic three-dimensional numerical simulations we show that this apparent contradiction can be resolved by using phospholipid coated microbubbles. Application of an ultrasound pulse triggers the rapid migration of the microbubbles toward the endothelial walls due to the hydrodynamic interactions with the red blood cells. The effect is caused by the oscillations of the bubbles, resulting in alternations between a soft and a stiff state, as induced by the lipid shell. We find that the effect is very robust, being triggered even if the time spent in the stiff state is three times lower than the opposing time in the soft state.

DY 7.8 Mon 12:45 ZEU 160

Inertial migration of elastic capsules in Poiseuille flow — •Christian Schaaf, Kevin Irmer, Christopher Prohm, and Holger Stark — Institut für Theoretische Physik, Technische Universität Berlin, Berlin, Germany

Deformable particles such as capsules, vesicles and red blood cells assemble at fixed equilibrium positions in a microfluidic channel under Poiseuille flow. This behavior can be used to separate particles with different mechanical properties. For example, softer cancer cells travel closer to the center than healthy ones.

Using the Lattice-Boltzmann method, we study the dynamics of single deformable particles in a microfluidic channel for intermediate Reynolds numbers.

We show that particles move to different equilibrium position depending on their size and deformability. For Reynolds numbers below 100, their equilibrium positions collapse onto a single master curve depending only on the Laplace number. By applying external forces along the channel axis, we are able to control the equilibrium distance from the channel centerline and thereby have a means to enhance the sensitivity of particle separation.

DY 7.9 Mon 13:00 ZEU 160

Migration reversal of soft particles in flows through wavy microchannels — •Matthias Laumann[1], Alexander Farutin[2], Chaouqi Misbah[2], Diego Kienle[1], and Walter Zimmermann[1] — [1]Theoretische Physik I, Universität Bayreuth, 95440 Bayreuth, Germany — [2]Laboratoire Interdisciplinaire de Physique, CNRS Universite Alpes, UMR 5588, BP 87, F-28402 Saint-Martin, d'Heres Cedex, FranceH

We study soft particles in low Reynolds number flows through microchannels with wavy boundaries. In low Reynolds number flows through microchannels with straight boundaries, soft particles often tend via cross-streamline migration to the channel center (see e.g. [1]). We show, that for wavy channel boundaries this centric motion may be reversed once the modulation amplitude exceeds a (parameter dependent) threshold, in which case the soft particles migrate to off-center trajectories. This is shown by semi-analytical and numerical results for flexible dumbbells, models for ring polymers and capsules in microflows. The distance between off-center trajectories and the center of the microchannel depends on the particle's elasticity and flow velocity as well as on the wavelength and the amplitude of the boundary modulation. Moreover, by increasing the flow velocity the migration direction may be reversed from out- to inward. Our insights can be exploited for particle separation with different properties in microchannels.

[1] B. Kaoui, G. H. Ristow, I. Cantat, C. Misbah, W. Zimmermann, Phys. Rev. E **77**, 021903 (2008).