Project code: ETH-35 12-2

Title of project: Two-phase flows in flexible porous media: wicking of water in micro-textiles

Principal Investigator: Jan Carmeliet

Project duration (from- to): 2013 - 2016

Abstract and goals of the original grant application

Original Abstract: Micro-textiles with higher added values, like protective clothing, sports or medical textiles are worn next to the human skin and, therefore, the interface between the fibrous materials and the skin has to be optimized. Removal of moisture produced by the skin is of primary importance for the comfort of the wearer but also in preventive medicine. Wicking of water in advanced textiles for protective clothing or performance clothing is understood as the non-saturated flow of water, or two-phase flow of water and air, in a flexible porous media, where a surface film flow occurs from a limited reservoir ahead of bulk liquid flow. Textiles show a double porosity, an intra-yarn porosity between the fibers and an inter-yarn porosity between the yarns and by applying multiple layers their specific behavior and performance may be specifically designed for. The modeling and prediction of the wicking behavior is therefore very challenging, given the complex configuration of the liquid phase within this flexible porous medium. Since continuum approaches need an unsaturated permeability as input obtained from e.g. measurements, their use as predictive tools is limited.

We propose a multi-scale framework to understand and capture the physics of the wicking process in multilayer textiles by combining advanced high resolution X-ray tomographic imaging and levelset lattice Boltzmann modeling and then to upscale this information to a continuum model validated by neutron radiography experiments. The project builds upon the recent successes in the development of the Entropic lattice Boltzmann method (ELBM) as a general novel paradigm in computational fluid dynamics, and is focused on the creation, validation and application of new ELBM models for multi-phase flows in textiles. To be able to separate the water and the textile material phases in the X-ray phase contrast results, we will apply morphometry for segmentation allowing to distinguish between air, polymer and water, followed by affine and non-affine registration to obtain the deformation of the fiber network upon wetting.

The results of the proposed project will be used to develop new technical and advanced textiles with improved moisture transport properties which will be beneficial thanks to better adapted solutions for sports, leisure activities as well as in the field of heat and cold protective clothing, and specially adapted textiles for the geriatric and paraplegic population.

Expected output as written in the original grant application

- Fundamental understanding of the material-water interactions in flexible textile structures
- Knowledge about the influence of fibers and yarns structures on the microscale water transport
- Advancement of the fluid transport visualization and image analysis
- Advanced EBLM modeling tool for two-phase flows
- Numerical and analytic tools for the development of new high-tech textiles for protective and sports applications
- Methodology for design of multilayer textiles
- Publications

Achievements and advances made during the course of the research project

The research under the ETH Research Grant ETH3512-2 was focused on establishing new computational models for multiphase flows (group Karlin) and experimental characterization of wicking in textiles (group Carmeliet).

PhD A: Predictive numerical simulations of complex multiphase flows

The research in Karlin's group carried out under the grant (doctoral student Ali Mazloomi) led to outstanding progress in the field of numerical simulation of multiphase flows. Despite enormous interest and many proposals, particularly for lattice Boltzmann models since mid of 90's, no path towards predictive simulations was established.

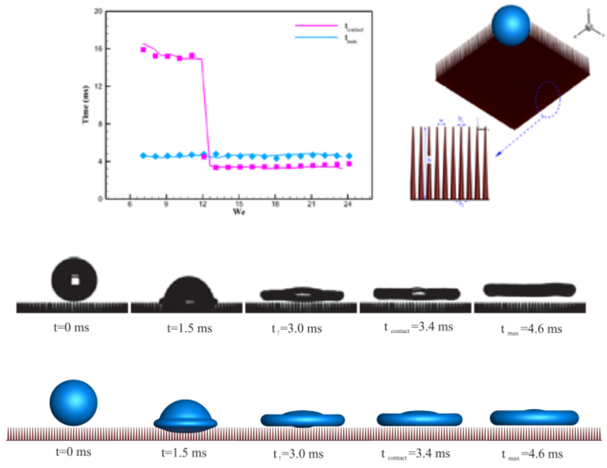

Fig. 1. Pancake bouncing on a micro-textured super-hydrophobic surface. Top right: Simulation setup with realistic geometry. Top left: Comparison of contact time and other characteristic times between experiment (line) and simulation (symbol); Bottom: Snapshots of the impact from the experiment and simulation [7].

We achieved a breakthrough by presenting a novel lattice Boltzmann model, based on the principle of entropy and thermodynamic consistency. The method was published on Physical Review Letters [1] and subsequent papers [2-4], and allowed, for the first time, to address a host of real-world phenomena through simulations. The highlights of using the new model include: Droplet impact on complex macro-textured surfaces with extreme wetting properties was studied in a collaboration with top experimental groups. With the group of Poulikakos (LTNT-ETH), we revealed the mechanism of angular momentum generation in the novel experimentally observed prompt-tumbling rebound of viscous drops from sublimating inclined surfaces [5]. Furthermore, the new model enabled quantitative understanding of a recent effect of drop bouncing off a macro-textured superhydrophobic surface (so-called pancake bouncing, where the drop rebounds in an elongated shape before recoiling) [6]. The simulations predicted a novel "egg-carton" macro-texture for contact time reduction which was then realized in the experiment by the group of Poulikakos [6]. Yet another effect, discovered by the simulations, was to reduce contact time by destroying the expanding lamella on a macro-defect to create a counter-flow in the droplet prior to recoiling, upon which the drop rebounds in a spectacular ring shape. The ring bouncing effect was observed independently, simultaneously and in quantitative agreement in the experiment of the group of Quéré (Paris) [6].

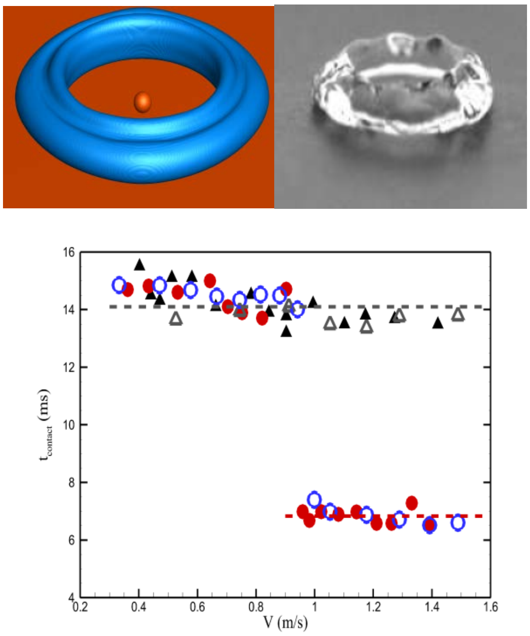

Fig. 2a: *Ring-bouncing* of a 2.6 mm water drop from a 0.4 mm spherical defect on a superhydrophobic surface. Top left: simulation, top view; Top right: Experiment (Quéré group); Bottom: Contact time vs. impact velocity. Triangle: Flat surface; Circle: Macrotexture. Open symbol: Simulation; Full symbol: Experiment. Contact time reduction is seen in both simulation and experiment.

Further results were obtained through simulation of wicking in a realistic twisted yarn geometry, in collaboration with the group of Carmeliet (ETH-EMPA) [6], joint publication is being prepared. Summarizing, the new computational model convincingly demonstrated its practical relevance in several contemporary experiments by top experimental groups. Results were presented in the ETH Doctoral Thesis of the doctorate student Ali Mazloomi (group Karlin) [6].

PhD B: Experimental characterization of wicking

The experimental investigation of wicking in textiles was realized at two scales: the yarn scale and the fabric scale. Based on a literature review of imaging techniques applied to wicking at both scales, and published in a review paper by the applicants [8], we developed more advanced imaging techniques. At the yarn scale we demonstrated the use of fast synchrotron-based phase-contrast X-ray micro tomography for obtaining three-dimensional time-resolved images of water and yarn geometry during wicking. This first full documentation of the wicking phenomenon has shown that wicking in yarns does not occur in a homogeneous single flow, but shows a core flow at the center of the yarn followed by a main flow which covers the whole yarn. These new results are now being prepared for submission.

At the fabric scale, we used neutron radiography to obtain full moisture content distribution on fabrics during wicking. The measurement was validated against conventional visible light methods and gravimetric methods. For fast wicking fabrics (cotton) we identified two wicking phenomena—intra-yarn and "hanging film" wicking—that have distinct moisture contents but were not distinguishable using conventional methods. Using the moisture profiles obtained from the moisture maps we were able to develop a dual-porosity continuum model of wicking in fabrics that accounts for these two regions in cotton fabrics. At the fabric scale, one paper regarding the experimental results is submitted [9] and one regarding the numerical model is now in preparation. Results will be presented in the ETH Doctoral Thesis of the doctorate student Marcelo Parada (group Carmeliet) to be submitted before the summer.

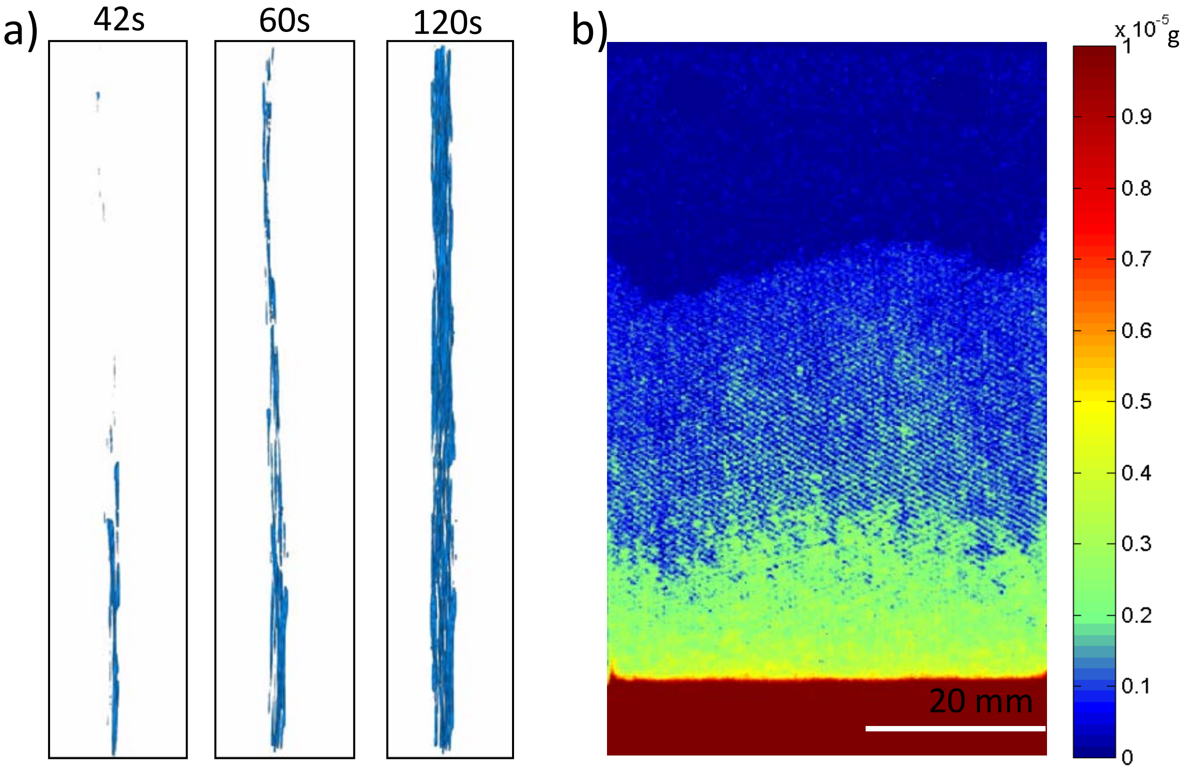

Figure 3: a) Water geometry in a PET yarn at selected time steps. Note the core flow reaching the top (5 mm) at 60 s and the final main flow at 120 s. b) Moisture content map of cotton knit during wicking. Color represent the moisture content. The bottom red region is the reservoir. The fabric in the green region is covered by a water film. In the blue region there is water only inside the yarns.

List of outputs

Publications

1. A. Mazloomi M., S. S. Chikatamarla, and I. V. Karlin, Entropic lattice Boltzmann method for multiphase flows, *Phys. Rev. Lett.* 114, 174502 (2015)
2. Ali Mazloomi M., Shyam S. Chikatamarla and Iliya V. Karlin, Entropic lattice Boltzmann method for multiphase flows: Fluid-solid interfaces, *Physical Review E* 92 (2), 023308 (2015)
3. A. Mazloomi Moqaddam, S. S. Chikatamarla and I. V. Karlin, Simulation of Droplets Collisions Using Two-Phase Entropic Lattice Boltzmann Method, *J. Stat. Phys*. 161(6), 1420-1433 (2015)
4. Ali Mazloomi Moqaddam, Shyam S. Chikatamarla and Ilya V. Karlin, Simulation of binary droplet collisions with the entropic lattice Boltzmann method, *Physics of Fluids* 28, 022106 (2016)
5. Carlo Antonini, Stefan Jung, Andreas Wetzel, Emmanuel Heer, Philippe Schoch, Ali Mazloomi Moqaddam, Shyam S. Chikatamarla, Ilya Karlin, Marco Marengo and Dimos Poulikakos, Contactless prompt tumbling rebound of drops from a sublimating slope, *Physical Review Fluids* 1, 013903 (2016)
6. Ali Mazloomi Moqaddam, Entropic Lattice Boltzmann Method for Two-Phase Flows, ETH Doctoral Thesis (2016) [Thesis defended at D-MAVT on 18 November 2016]
7. Ali Mazloomi Moqaddam, Shyam S. Chikatamarla and Ilya V. Karlin, Drops bouncing off macro-textured superhydrophbic surfaces , *Journal of Fluid Mechanics*, *submitted* (2016)
8. Marcelo Parada, Dominique Derome, René M. Rossi, Jan Carmeliet, A review on advanced imaging technologies for the quantification of wicking in textiles, *Textile Research Journal* 2017, 87: 110-132.
9. Marcelo Parada, Jan Hovind, Peter Vontobel, René M. Rossi, Dominique Derome, Jan Carmeliet, Quantification of wicking in textile with neutron radiography, *submitted* (2016)

Presentations and Posters at International Conferences

1) Marcelo Parada, Dominique Derome, René M. Rossi, Jan Carmeliet, Imaging wicking without colorants, The Fiber Society Spring 2014 Technical Conference, Liberec, 2014. (Poster)
2) Marcelo Parada, Dominique Derome, René M. Rossi, Jan Carmeliet, Imaging of wicking of water in single-layer textiles with neutron radiography, 7th International Conference on Porous Media, Padova, 2015.
3) Marcelo Parada, Dominique Derome, René M. Rossi, Jan Carmeliet, Phase-contrast synchrotron X-ray fast tomography of wicking in yarns, 2nd International Conference on Tomography of Materials and Structures, Québec, 2015.
4) Shyam Chikatamarla, Ali Mazloomi, Ilya Karlin, Contact time reduction with macro textured superhydrophobic surfaces", International Conference Mesoscopic Methods in Engineering, Hamburg, Germany, 2016
5) Ali Mazloomi M., Shyam S. Chikatamarla, and Ilya V. Karlin, Entropic lattice Boltzmann method for multiphase flows, Conference on Discrete Simulation of Fluid Dynamics, Paris, France, 2014.
6) Ali Mazloomi M., Shyam S. Chikatamarla, and Ilya V. Karlin, Free-energy based entropic lattice Boltzmann method: a new approach for two-phase flow simulations, Conference on Discrete Simulation of Fluid Dynamics, Edinburgh, Scotland, 2015.
7) Ali Mazloomi M., Shyam S. Chikatamarla, and Ilya V. Karlin, Reducing the contact time of a drop impacting on tapered surfaces, Workshop on Flowing Matter Across the Scales, Rome, Italy, 2015.