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# Fully coupled Lattice Boltzmann simulation of fiber reinforced self compacting concrete flow

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## Abstract

To correctly predict the casting process of a fiber reinforced self compacting concrete on a structural level is a challenging task since the distribution and orientation of fibers influence the global flow pattern and vice versa. In this contribution, a modeling approach capable to represent accurately the most important phenomena is introduced. A conventional Lattice Boltzmann method has been chosen as a fluid dynamics solver of the non-Newtonian fluid. A Mass Tracking Algorithm has been implemented to correctly represent a free surface and a modified Immersed Boundary Method (IBM) with direct forcing is used to explicitly represent individual fibers in the fluid. A novel variable time sub-stepping algorithm for dynamics of immersed rigid particles ensuring stability of simulations has been developed which, together with the IBM, provides an efficient, yet accurate way to simulate flow of suspensions.

In the following, the developed model is used to simulate flow of the fiber reinforced self compacting concrete. Fibers are modeled as slender rigid cylinders using the previously developed correction for particles of a sub-grid size. A lubrication force correction term and collisions with Coulomb friction between fibers and between fibers and boundary conditions are introduced. Several simulation scenarios are presented and compared to experimental data to validate the proposed approach. Further an extension of the model to the structural scale is discussed and demonstrated on an example modeling the final dispersion and orientation of fibers during a real casting process.

*Keywords: fluid mechanics, concrete, multiscale problem, numerical analysis, structural mechanics*

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## 1. Introduction

Self compacting concrete (SCC) is a promising material in the civil engineering industry. One of the benefits of the SCC is a fast and simplified casting followed by decreased labor costs. The SCC as any other type of concrete has a significantly lower tensile and shear strength in comparison to the compression strength and, therefore, needs to be reinforced. Fiber reinforced concrete is an alternative to traditional stirrups reinforcement leading to lowered labor costs. To be able to access mechanical properties of the fiber reinforced concrete, knowledge of the final spread and orientation of fibers is necessary. Computational fluid dynamics (CFD) comes to play at this stage since the final spread and fiber orientation are dependent on the flow patterns in the fresh material. Formulation of a possible CFD model that is able to solve multi-phase and multi-component non-Newtonian flow with complex boundary conditions and fiber suspension and preferably in reasonable time constitutes a very challenging task.

A proposed model is presented in Section 2 whereas a possible application of the model is shown in Section 3. Section 2.1 deals with a fluid dynamics solver of the model, Section 2.2 presents a simple free surface method and Sections 2.3, 2.4, 2.5 and 2.6 are devoted to solid particles representation, movement of the particles and interaction of the particles respectively.

## 2. Model

### 2.1. Fluid Dynamics Solver

A Lattice Boltzmann Method (LBM) [6] is used as a fluid dynamics solver of the non-Newtonian flow. Traditional CFD tools

formulate the problem in a form of macroscopic quantities such as pressure and velocity fields. The LBM on the other hand, with its roots in a kinetic theory of gases and cellular automata, treats the fluid as mesoscopic particle distributions where the microscopic particles can be seen as e.g. molecules. The LBM provides rules for mutual collisions and propagation of the particle distributions as well as for the computation of the macroscopic quantities.

Contrary to other methods, the LBM is very simple to implement and reason about. The lid-driven cavity problem, for example, fits into approx. 50 lines of Matlab code (see [www.lbmmethod.org](http://www.lbmmethod.org)). Due to the simplicity of the code and locality of the LBM, the code is relatively easily parallelized.

### 2.2. Free Surface

A free surface has been implemented in the form of a Mass Tracking Algorithm (MTA) [3]. In the framework of the MTA, fluid, gas and interface phases are present. The LBM computations are conducted in the fluid and interface phases only. Interface cells separate fluid phase and gas phase and are therefore responsible for mass conservation. Interface cells are moreover the only place where the MTA comes into play in the form of local mass tracking and reconstruction of missing information from the gas phase.

Although the method theoretically conserves the mass exactly, small oscillations due to numerical errors are observed in the range of  $10^{-3}$  % which after several thousand iterations can lead to a complete loss of the mass. Correction of the total mass is therefore suggested.

The MTA is despite of the correction a very simple and fast algorithm which contrary to other methods theoretically con-

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serves mass precisely.

### 2.3. Immersed Particles Representation

The Immersed Boundary Method with direct forcing (IBM) [2] is used to explicitly represent rigid or deformable solid particles immersed in the fluid in the form of a force field. A traditional approach of modeling particles in the field of the LBM would be to use a Standard Bounce Back rule (SBB) [1]. Shape and boundary movement of the particles are stepwise in the framework of SBB which restricts the minimum discretized size of the particles to approx. 5 lattice units to obtain reasonable results. Using the IBM, particle shapes are represented in a diffuse form using a Dirac delta function leading to satisfactory results for particles down to approx. 2 lattice units. In the framework of IBM, the movement of particle boundaries is smooth.

The limiting dimension of particles with high aspect ratio such as fibers, i.e. the diameter, is restricted to a minimum size of approx. 2 lattice units. The discretized length of the particles therefore reaches a range of 100 lattice units which makes it impossible to simulate the casting process on a structural level in a reasonable amount of time and with a reasonable computational power. A correction term has been proposed to overcome the approx. 2 lattice units restriction.

### 2.4. Correction Term

The problematics has been studied in [5] and, as a conclusion, a correction term of the direct forcing,  $F_{cor} = CF_{IBM}$ , has been proposed by fitting for the case of fibers to overcome the limit of 2 lattice units as

$$C = 1.8d^{-1.2}, \quad d < 1.5 \quad (1)$$

$$1, \quad d > 1.5, \quad (2)$$

where  $d$  stands for the diameter of fibers. The correction term allows to reduce the minimum dimension of the particle down to 0.3 lattice units without any significant loss in accuracy. Fiber diameter of 0.3 lattice units instead of 2 lattice units results in approx. 1000 times shorter computational time.

### 2.5. Variable Sub-Step Time

Movement of the immersed particles is driven by the Newton's second law discretized with the explicit forward Euler method. When the acceleration varies significantly during one lattice time step, the method might become unstable. A variable sub-stepping has been proposed by [4] to address the problem. The limiting time step is computed analytically by restricting a maximum change in the forces exerted on the particle by the surrounding fluid.

Particles move and interact with each other and with the boundary conditions on the sub-step level whereas the fluid remains frozen during the sub-stepping procedure.

### 2.6. Interaction Forces

Due to discretization, the LBM is not capable to properly catch the flow and especially the pressure field between two solid particles when the distance between them falls below 1 lattice units. For sub-grid particles, the problem is even more pronounced. Lubrication forces correction [7] between fibers and between fibers and boundary conditions were therefore added to the model.

A simple collision model with Coulomb friction based on a force impulse is introduced in the model as well.

## 3. Application

Several simulations and an experimental work is presented to validate the proposed set of tools. As an example, a 3D fiber re-

inforced SCC slump test has been simulated and different time snaps are shown in the Figure 1.

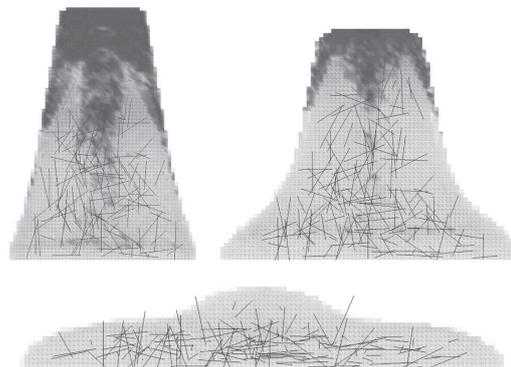


Figure 1: Sections of a 3D slump test at different time snaps. Dark region represents high viscosity

## 4. Conclusion

The Lattice Boltzmann method together with other ingredients such as the corrected Immersed Boundary Method, variable time sub-stepping or the Mass Tracking Algorithm has been presented in this contribution. The developed model has been used to simulate a non-Newtonian liquid together with particle inclusions with a focus on steel fiber reinforced self compacting concrete.

The presented model is based on well established methods and provides an efficient tool that can be applied to a range of engineering problems on different length scales yielding results matching favorably theoretical and experimental results.

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