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Eulerian-Lagrangian and Eulerian-Eulerian approaches for the simulation of particle-laden free surface flow

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This paper studies the Eulerian-Lagrangian and Eulerian-Eulerian approaches for the simulation of free surface flow with particles. The study of free surface flows with immersed particles is of high importance across various fields in industry, such as hydraulic, ocean, environmental engineering or casting, which this work is focused on. In the casting manufacturing process, the design of the casting mould is essential. Based on the geometry of the mould, inlets and outlets need to be positioned such that the molten material fills in the mould completely. Computational modelling becomes an efficient tool for predicting the casting process, where also fillers are embedded in molten material for the improvement of its mechanical properties.

To computationally resolve the free surface flow with immersed particles within a thin casting mould cavity, a computational grid with numerous cells is often required. Thus, the numerical simulation becomes expensive in terms of computational time and memory demands. In order to address these issues, the lattice Boltzmann method (LBM) has been chosen, as it is well suited for massive parallelization on various architectures while its algorithm is very efficient.

For the free surface tracking in simulations, a method similar to Volume of Fluid (VOF) method is employed. VOF is widely used in Navier-Stokes solvers and a very influential paper concerning VOF LBM is, e.g., [3, 5]. In our applications, the effect of the gaseous phase is negligible. For these reasons, the gaseous phase is ignored in this study.

For fluid-particle interaction, the particulate immersed boundary method (PIBM) [1] is adopted. It is similar to the traditional immersed boundary method (IBM), which only assumes the mesh resolution much smaller than the particle size and imposes velocity boundary condition on the particle surface. However, many applications including casting with fillers involve numerous tiny particles. Therefore, the PIBM, allows particles to be much smaller than grid resolution and the fluid-particle interaction behaviour is corrected by introducing the fluid-particle slip velocity.

In general, particles submerged in a fluid can be described using the Lagrangian or the Eulerian approach. In the Lagrangian approach, each of the particles has its own coordinates and its own equations of motion. In the case of the Eulerian approach, the particles are described statistically by a function of particle concentration, the time evolution of which is described by a convection-diffusion equation, see [4]. In Fig. 1, as an example of a comparative test case, the results obtained by Eulerian-Lagrangian and Eulerian-Eulerian LB schemes and the results taken from [2] are shown next to each other. The Reynolds number in this simulation is set to 1 000 and 5 000 particles are randomly distributed inside the three-dimensional cavity. The results are in very good agreement, but the Eulerian-Eulerian approach has one big advantage. The computational complexity does not depend on the number of simulated particles. In contrast, the computational complexity increases with the number of modelled particles in case of

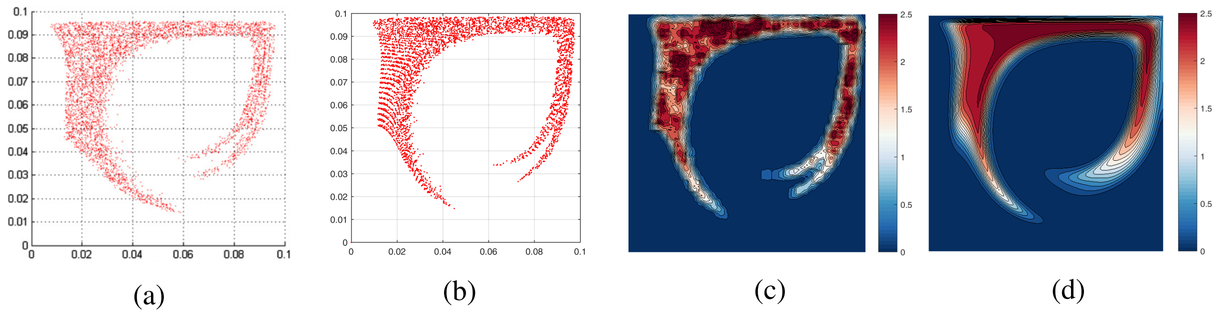

Fig. 1. Distribution of particles within 3D cavity. Individual particles (a) are shown for the results taken from [2]. Both individual particles (b) and concentration (c) are shown for results by the Eulerian-Lagrangian LB scheme. Only concentration (d) is show in the case of the Eulerian-Eulerian LB scheme. In both cases, concentration is summed along the z-axis

the Eulerian-Lagrangian approach. This fact is important for simulations with many particles such as gravity casting with fillers.

A test case concentrating on more practical problems similar to those encountered in gravity casting with fillers is presented in Fig. 2. Here, the free surface is modelled as well. The reservoir on the top of the mould is filled by fluid with density $\varrho = 1000\,\mathrm{kg\,m^{-3}}$ and the kinematic viscosity $\nu = 10^{-4}\,\mathrm{m^2\,s^{-1}}$ and partially filled by evenly distributed particles (red color) with diameter $d_p = 2 \times 10^{-4}\,\mathrm{m}$ and density $\varrho_p = 5000\,\mathrm{kg\,m^{-3}}$. At time $t = 0$, the gate is removed and the fluid with the dispersed particles fills the mould as it is pulled by gravity downwards.

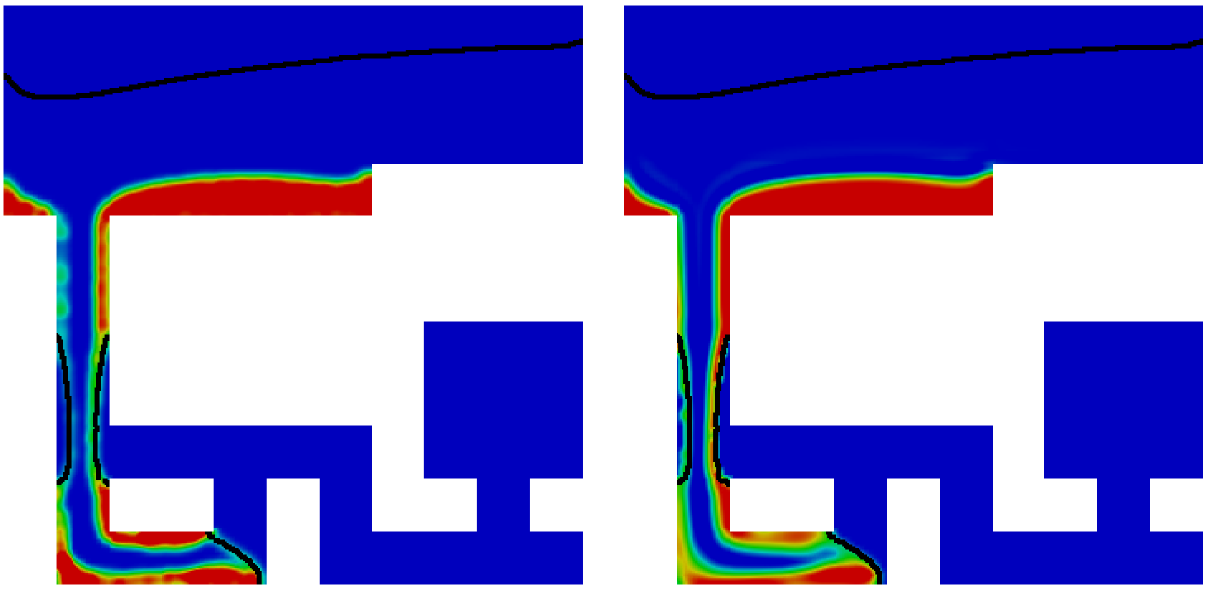

Fig. 2. Particle concentration obtained by the Eulerian-Lagrangian (*left*) and Eulerian-Eulerian (*right*) schemes at simulation time $t = 0.5\,\mathrm{s}$

In this work, Eulerian-Lagrangian and Eulerian-Eulerian lattice Boltzmann (LB) schemes were developed and compared. The main target of this work is to validate the Eulerian-Eulerian approach developed for the solution of the free surface flows with dispersed particles against the Eulerian-Lagrangian approach, considered as a reference solution. The solutions by the fully Eulerian LB scheme is more smeared but the agreement is more than satisfactory.

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