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Numerical Simulation of Melting with Natural Convection Based on Lattice Boltzmann Method and Performed with CUDA Enabled GPU

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Abstract. A new solver is developed to numerically simulate the melting phase change with natural convection. This solver was implemented on a single Nvidia GPU based on the CUDA technology in order to simulate the melting phase change in a 2D rectangular enclosure. The Rayleigh number is of the order of magnitude of 10^8 and Prandlt is 50. The hybrid thermal lattice Boltzmann method (HTLBM) is employed to simulate the natural convection in the liquid phase, and the enthalpy formulation is used to simulate the phase change aspect. The model is validated by experimental data and published analytic results. The simulation results manifest a strong convection in the melted phase and a different flow pattern from the reference results with low Rayleigh number. In addition, the computational performance is estimated for single precision arithmetic, and this solver yields 703.31 MLUPS and 61.89 GB/s device to device data throughput on a Nvidia Tesla C2050 GPU.

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Key words: LBM, GPU, phase change, natural convection, numerical simulation, experimental study.

1 Introduction

Heat storage technologies now are widely used as an effective means to manage the energy availability and decrease the temperature fluctuations in various practical applications, such as in the electronics industry [1], the automotive industry [2,3] and building design [4,5]. Compared to the sensible heat storage [6], the latent heat storage has a significant advantage as it uses less storage volume to achieve a specified amount of heat

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load. Furthermore, in general, latent heat storage process is a constant temperature process.

One of the most important physical phenomenon of latent heat storage is the solid-liquid phase change, which is also a very critical process for many other applications such as in the metal casting industry. To better understand solid-liquid phase change, we need to know the temperature distribution in both solid and liquid phases, the flow characteristics in liquid phase, the heat transfer characteristics and the transient interface location. However, the solid-liquid phase change phenomenon is a complex process which couples the natural convection in the liquid phase, the shifting of the solid-liquid boundary and a heat transfer process. Due to these reasons, the solid-liquid phase change is a strong non-linear process, difficult to analyse except for simple and ideal test cases.

The traditional way to simulate numerically the solid-liquid phase change by solving the Navier-Stokes equations is an effective method [8, 9]. The key aspect being the switching of the advection term on and off during the phase change. In addition, the dynamic position of the solid-liquid interface must be computed at each time step and the corresponding boundary conditions for the LBM must be chosen accordingly.

In the past two decades the lattice Boltzmann method (LBM) matured as a promising approach for CFD due to its intrinsic parallelism and good numerical stability along with favourable numerical dissipation properties [24, 25]. All of those advantages make LBM a promising complementary approach to the direct solution of the Navier-Stokes (NS) equations [26]. In relatively recent studies, some researchers have begun to choose LBM to simulate phase change [10–14].

In order to make the most of the inherent parallelism of LBM, numerous efforts have been devoted to harness the calculation power of graphic processing units (GPU) [15–18]. A GPU is characterised by its highly parallel, manycore structure, which is especially suited for data intensive calculations. Because more transistors are used to perform data operations, a GPU performs considerably more float-point operations per time unit and has a large memory bandwidth than a CPU counterpart [29]. Since GPUs were initially used to render graphics, using them for a general purpose calculation remains complex and prevents an easy implementation.

In this study, an approach is presented to numerically simulate the melting process in combination with natural convection. We developed a highly efficient solver, running on a graphic processing unit, for the liquid-solid melting phase change. The hybrid thermal lattice Boltzmann method is employed to simulate the natural convection in the liquid phase. For phase change, the enthalpy formulation is used. Because the total latent heat of each grid node is a function of temperature and can embody the status of the material, it is used as the key parameter to locate the interface. The simulation program is optimized for parallel computing. Besides, experiments are also carried out, in order to validate the present numerical simulation.