Multiphase Flow Simulations in Inclined Tubes with Lattice Boltzmann Method on GPU*

Khramtsov D.P., Nekrasov D.A., Pokusaev B.G.

Department of Thermodynamics, Thermal Engineering and Energy Saving Technologies, Moscow State University of Mechanical Engineering, Moscow, Russia

`dmitry@khramtsov.net, nekrasov55@yandex.ru, pokusaev2005@yandex.ru`

Abstract. *Multiphase flows are widely used in many practical applications in industry, such as oil industry, chemical and thermal engineering, bioengineering and medicine. Especially flows in tubes with granular layer. Multiphase flows in inclined tubes are poorly studied. Numerical study of multiphase flows in inclined tubes was performed. Cases of clear tube and tube with granular layer were examined. Simulation model was based on lattice Boltzmann method. Parallel algorithm was programmed in CUDA C. For numerical simulations graphical processor nVidia Tesla C2075 was used. Bubble flow in inclined tubes with different inclination angles and diameters of beads were studied. Simulation results are in agreement with the experimental studies. Flow pattern of air bubble was examined.*

Keywords

Lattice Boltzmann method, CUDA, GPU, nVidia Tesla, computational fluid dynamics, multiphase flow.

1 Introduction

Multiphase flows have many applications in industry, especially slug flows in tubes. Slug flows represent the gas bubble rising in liquid. Such bubbles can have different forms that called flow patterns. This pattern depends on liquid and gas type. Also angle of tube inclination play an important role. Maximum speeds are differs for clear tube and tube with granular layer. Flow pattern effects the speed of bubble rising, while this speed have an influence on heat and mass transfer. It is critical in such systems as reactor cooling systems. In modern cooling systems coated fuel particles are packed directly in cooling tubes. So, it is become actual to study multiphase flows in granular layer. Detailed experimental studies of flow patterns are quite difficult, especially in case of slug flow in granular layer. Numerical simulations can provide a comprehensive approach for studying of such systems.

Numerical simulation model can be based on finite-difference or finite-element method. These methods are widely studied. For multiphase problems with compound boundary conditions such methods lead to complex mathematical formulation. Simulations based on such complex models have lack of performance due to difficulties with effective parallelization. Particularly it becomes noticeable for large-scale tree-dimensional problems.

Alternative approach is to use methods based on cellular automata theory. In cellular automata scheme fluid flow is modeling by moving particles from one node of lattice to another. This approach is very simple but not accurate enough. As evolution of cellular automata methods lattice Boltzmann method was proposed.

2 Related Works

Lattice Boltzmann method was successfully applied to two-phase flows with large density differences, like water and air [1]. Simulations results were close to theoretical calculations. Numerical study of bubble rising dynamics in a vertical and inclined square channel was performed with Lattice Boltzmann approach [2]. GPU implementation and scalability

---

* Work was funded by RFBR grants (11-08-00368, 12-08-00734, 12-08-31243) and The Ministry of Education and Science of the Russian Federation grant 7.7787.2013.

of Lattice Boltzmann solver was discussed in [3]. Three-dimensional numerical simulation of liquid-vapor systems based on Lattice Boltzmann method was described in [4]. Numerical study results for slug flow in vertical tubes was obtained in [5], but finite-element scheme was used.

3 Algorithm design and numerical simulations

3.1 Lattice Boltzmann method

The main idea of the lattice Boltzmann method is to solve statistical equations that describe the dynamics of mean particle population, instead of directly solving Navier-Stokes equation. Particles distributions are described by Maxwell-Boltzmann distribution. The basis of lattice Boltzmann method is discrete kinetic equation, which describes collisions and streaming of particles (Equation 1).

$$f_i(\vec{x} + \vec{e_i}\Delta t, t + \Delta t) = f_i(\vec{x}, t) + \Omega_i(f(\vec{x}, t)), i = 0, 1...N - 1 \tag{1}$$

where f_i is a function, that describes discrete distribution of particle velocity for each direction i, Δt and Δx define steps in time and space accordingly, e_i is a velocity vector, Ω_i is a collision operator. For collisions approximation Bhatnagar-Gross-Krook operator was used (Equation 2).

$$\Omega_i = \frac{1}{\tau}(f_i^{eq} - f_i) \tag{2}$$

where τ is a relaxation time and f_i^{eq} is an equilibrium distribution function, which obtained as expansion of Maxwell-Boltzmann distribution in Taylor series up to second order (3). Such order is chosen, because Navier-Stokes equation has the second order nonlinearity [7].

$$f_i^{eq}(\vec{x}) = \omega_i \rho(\vec{x}) \left[1 + 3\frac{\vec{e_i} \cdot \vec{u}}{c^2} + \frac{9}{2}\frac{(\vec{e_i} \cdot \vec{u})^2}{c^4} - \frac{3}{2}\frac{\vec{u}^2}{c^2}\right], i = 0, 1...N - 1 \tag{3}$$

Propagation speed is defined by c. It is an analog of sound speed, measured in lattice units. Weight coefficients ω_i depends on lattice type. In this work D3Q19 model was used. This model has 19 velocity vectors in 3 dimensions (Figure 1).

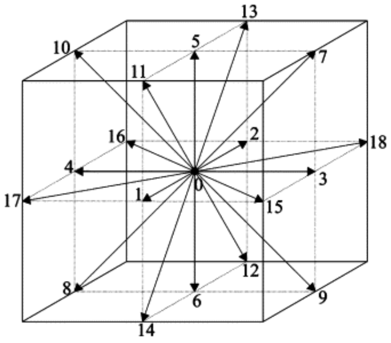

Figure 1. Lattice Boltzmann three-dimensional 19 velocity lattice (D3Q19).

Density and velocity are calculated for each node via equations $\rho = \sum_N^{i=0} f_i$ and $\vec{u} = \frac{1}{\rho} \sum_N^{i=0} f_i \vec{e_i}$ respectively. It makes possible to perform this operations in parallel.

Interaction between gas and liquid phases were modeled with method, proposed by Shan X., Chen H. [6]. This method exclude density gap between gas and liquid and allow treating both phases in a same way. This approach helps to simplify description of simulation model.

Bounce-back rule [7] was used to implement interaction between solids and gas-liquid flow. This rule is extremely simple, but accurate. Using this rule give the ability to define complex boundary conditions much easier.

3.2 Parallel algorithm implementation

Algorithm was programmed in CUDA C. Simulations were performed on laboratory computer using general purpose graphical processor nVidia Tesla C2075 with peak performance of 1,03 TFLOPS. Main advantage of using GPU for parallel computations is number of cores compared to CPU. In table 1 comparison of computing units that was available in laboratory is presented.

Table 1. Comparison of cores number for different computing units.

Device	Number of cores
Intel Core i5	4
Intel Xeon E5-1620	8
nVidia Tesla C2075	448

GPGPU was chosen for simulations instead of GPU because there is no lack of performance on double precision operations for general purpose graphical units.

Geometry of tube and phases distribution were specified as tree-dimensional array. For every element of array a number was assigned, that define the density of substance. Solid particles were coded as zero, because solid phase is processed separately form gas and liquid phases. Computational grid had $12{\cdot}10^6$ nodes. Granular layer consists of spherical solid particles. These particles were generated by subprogram. This subprogram assigns zero for each node that represents solid phase. These nodes should form the geometry of packed spherical particles. Input data for subprogram are diameter of particles and type of packing. Array, that store data about density, is modified during the process of simulation. At each step of simulation array with data about velocity field for each node is formed. Through every specified step intermediate simulation results were saved to hard disk in VTK format. This format allows to postrpocess simulation data with specialized visualization software ParaView.

Arrays with data about simulation parameters were stored in global memory of graphical processor. So, each multiprocessor could access the data. Global memory also was used to transfer results to host. Local variables for each thread were stored in registers.

Some components were run on CPU. These components provide the ability to transfer data from GPU and control threads via CUDA driver. Also there was an error control module. If error occurred, this module wrote information about error into a log file. Developed software is represented schematically on Figure 2.

As each node of lattice can be treated independently, potentially all nodes can be processed in parallel. But usually size of tree-dimensional lattice is much greater than maximum number of threads avaliable on GPU. To solve this problem thread pool design pattern was used.

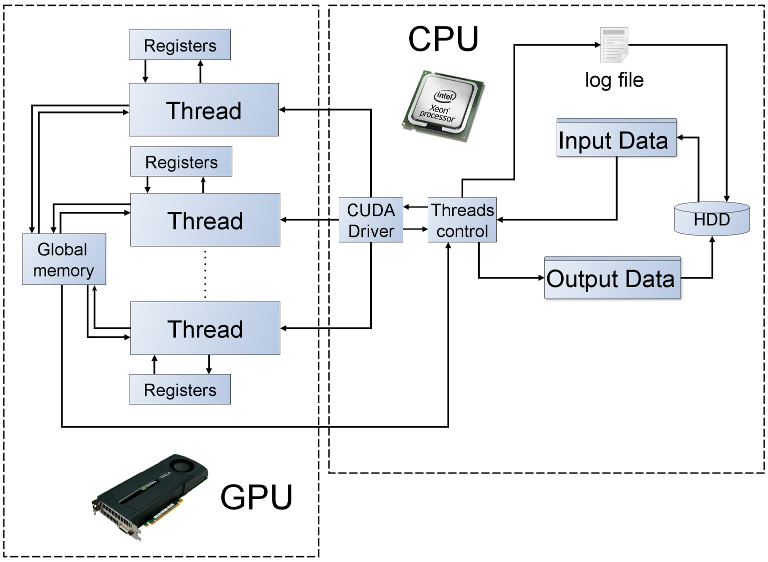

Figure 2. Functional scheme of developed software for parallel computations.

All operations, that needed to be performed for each node, were realized as CUDA kernel function. As input argument, this function takes pointer to array element, that stores all data about particular node and then apply to it all lattice Boltzmann procedures.

3.3 Simulation results

Three-dimensional simulations of air bubble dynamics in water were performed for two-phase liquid-gas and tree-phase liquid-gas-solids systems. Results of air bubble simulation is shown on Figure 3 and Figure 4.

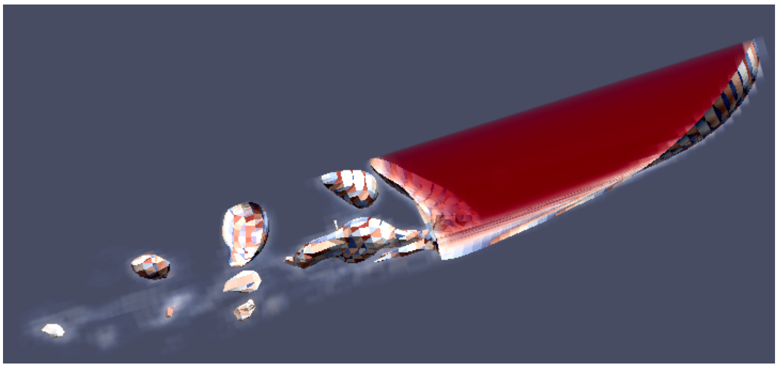

Figure 3. Result of tree-dimensional simulation of air bubble in an inclined tube.

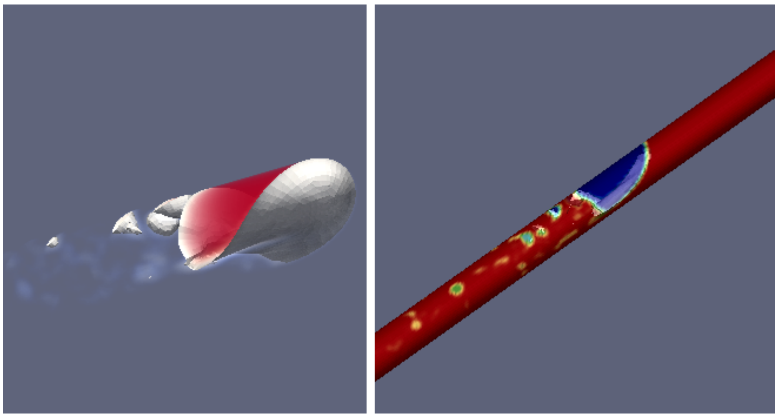

Figure 4. Visualization of air bubble flow in the tube with inclination angle 40 °.

Diameter of granular layer beads was varied from 4 to 20 mm with 0.5 mm step. Angle of tube inclination was varied from 10 ° to 90 ° with 10 ° step. Numerical results were also obtained for beads with diameters of 4, 4.25, 4.5 and 4.75 mm. It was not possible to realize in physical experiment due to absence of beads with proper diameters. Computer simulation results showed that air bubble speed decreases when beads with diameter less than 5 mm were used.

Experimental data for maximum bubble rising speed and bubble speed vs tube inclination angle were obtained previously in [8]. Simulation results are in agreement with experimental data. Simulation results confirm that maximum speed of air bubble in water is achieved with 5 mm beads. Experimental and numerical results for dependence of maximum speed of air bubble vs diameter of bead is shown on Figure 5.

4 Conclusion

Simulation model, based on lattice Boltzmann method, was developed. Parallel algorithm was performed on high performance graphical processor. Model based on lattice Boltzmann method showed high potential to parallelization which makes possible to implement this method not only on local machine, but also use cloud computing services like Amazon EC2 or Hadoop based distributed computer clusters. Lattice Boltzmann method can speed-up computations, especially

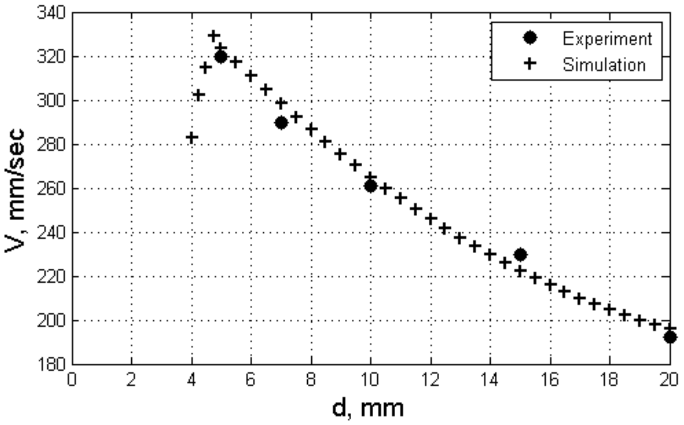

Figure 5. Comparison of numerical simulation results with experimental data.

for tree-dimensional problems. Bounce-back rule simplify the process of interacting between solid boundaries and multiphase flow. Simulation results are in agreement with the experimental studies. Performed simulations made possible to make detailed study of air bubble flow pattern. Optimal regimes of slug flow were defined.

5 Acknowledgments

This work was partially supported by The Russian Foundation for Basic Research (grants 11-08-00368, 12-08-00734, 12-08-31243) and The Ministry of Education and Science of the Russian Federation (grant 7.7787.2013).

References

[1] T. Inamuro, T. Ogata, S. Tajima, N. Konishi: A lattice Boltzmann method for incompressible two-phase flows with large density differences. *Journal of Computational Physics*, 2(198): 628-644, 2004.

[2] L. Amaya-Bower, T. Lee: Numerical simulation of single bubble rising in vertical and inclined square channel using lattice Boltzmann method. *Chemical Engineering Science*, 5(66): 935-952, 2011.

[3] C. Obrechta, F. Kuznik, B. Tourancheaud, J. Rouxb: Scalable lattice Boltzmann solvers for CUDA GPU clusters. *Parallel Computing*, 6(37): 259-270, 2013.

[4] A. L. Kupershtokh : Three-dimensional simulations of two-phase liquid-vapor systems on GPU using the lattice Boltzmann method. *Modern Science*, 2(4): 56-63, 2010.

[5] T. Taha, Z. Cui: CFD modelling of slug flow in vertical tubes. *Chem. Eng. Sci.* , 2(61): 676-687, 2005.

[6] X. Shan, H. Chen: Simulation of nonideal gases and liquid-gas phase transitions by the lattice Boltzmann equation. *Phys. Rev. E.*, 4(49): 2941-2948, 1994.

[7] S. Chen, G. Doolen: Lattice Boltzmann method for fluid flows. *Annu. Rev. Fluid Mech.*, 30: 329-364, 1998.

[8] B. G. Pokusaev, D. A. Kazenin, S. P. Karlov, et al.: Motion of a Gas Slug in Inclined Tubes. *Theor. Found. Chem. Eng.* , 5(45): 640-645, 2011.