GPU-Enabled Large-Scale DNS of Gas-Solid Flows

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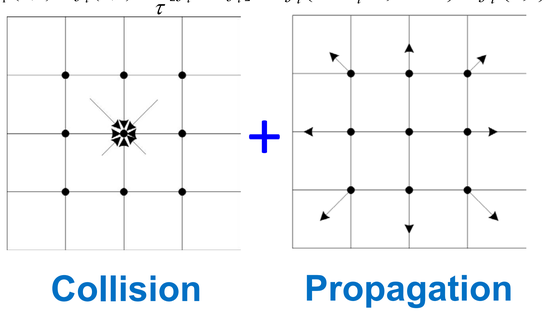
Abstract: Large-scale direct numerical simulation (**DNS**) of gas-solid suspension flows is traditionally limited for its huge demand of compute resource, but urgently needed to study the interaction between gas and solid particle. Usually, empirical formulas are employed to estimate the interaction, and Wen & Yu equation is the most frequently used one. However, with the acceleration of **GPU**, large-scale DNS of gas-solid flows is feasible, so that we can expect to obtain the full knowledge of the interaction between gas and solid particle. In this study, lattice Boltzmann method (**LBM**) is adopted to solver the gas for its inherent parallelism, discrete element method (**DEM**) deals with particle collision, and immersed moving boundary (**IMB**) for the coupling of gas and solid.

Keyword: GPU Acceleration, DNS, LBM, CFD

Model: LBM+DEM+IMB

LBM as Gas Solver

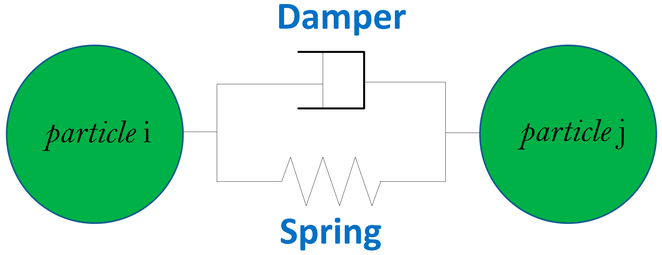
$$f_i^{'}(\mathbf{x},t)=f_i(\mathbf{x},t)+\frac{1}{\tau}[f_i^{eq}-f_i] \qquad f_i(\mathbf{x}+e_i\Delta t,t+\Delta t)=f_i^{'}(\mathbf{x},t)$$



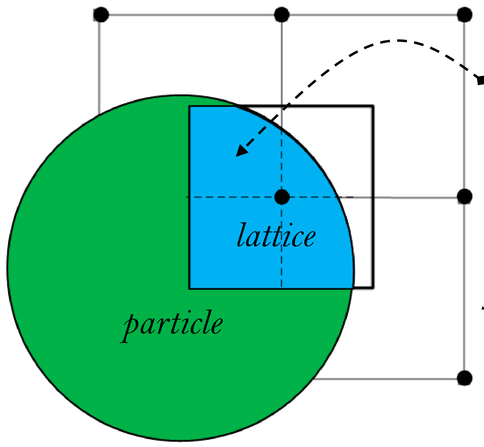
Collision + Propagation

Navier-Stokes Equations

DEM Modelling Particle Collision



IBM for Gas-Solid Coupling



$$\varepsilon_s=\frac{area\ overlapped}{area\ of\ lattice}$$

$$\beta(\varepsilon_s,\tau)=\frac{\varepsilon_s(\tau-0.5)}{(1-\varepsilon_s)+(\tau-0.5)}.$$

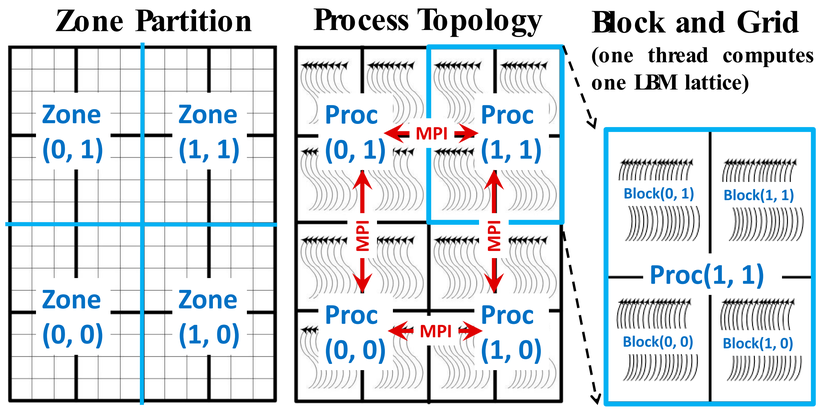
$$\Omega_i^s=f_{-i}(\mathbf{x},t)-f_i(\mathbf{x},t)+f_i^{eq}(\rho,\mathbf{V}_s)-f_{-i}^{eq}(\rho,\mathbf{v})$$

Additional Source Term

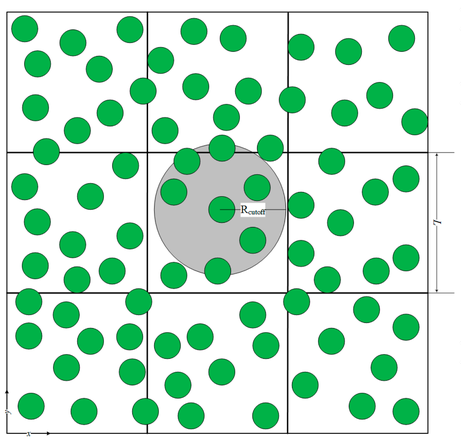
Resulting LBM to following form

$$f_i(\mathbf{x}+1,t+1)=f_i(\mathbf{x},t)+(1-\beta(\varepsilon_s,\tau))\frac{1}{\tau}(f_i^{eq}(\rho,\mathbf{v})-f_i(\mathbf{x},t))+\beta(\varepsilon_s,\tau)\Omega_i^s$$

Implementation on GPU (2D for example)



Searching of collision pairs: neighbor list



- Neighbor cell: length of L, larger than R_{cutoff}
- Building neighbor list for each particle by searching neighbor cell

neighbor list for particle i

id1	*id2*	···	*idk*	···	*idn*		

neighbor list for particle j

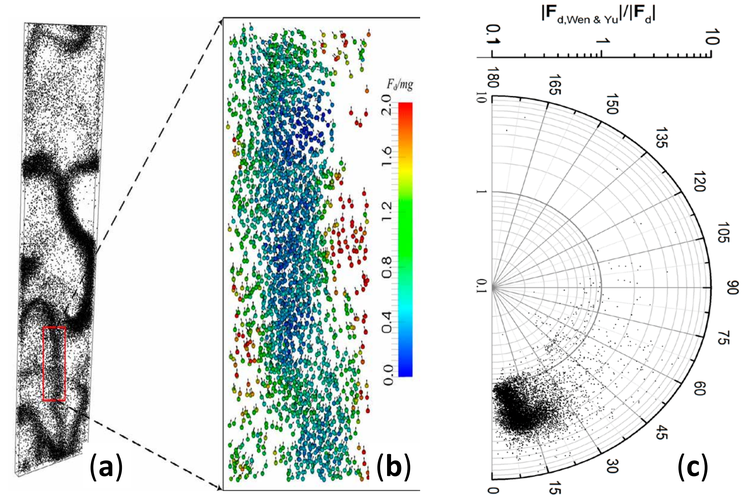
id1'	*id2'*	···	*idk'*	···	*idn'*	*idn'+1*

- Each thread deals with one particle's interaction with all its neighbors

Simulation and Result

Physical properties of gas and particle and simulation settings for 3D DNS (**Up to 196 GPUs are used**)

Properties of gas and particle			Simulation settings		
ρ_f	gas density	1.3 kg/m^3	Δx	space step	3.75×10^{-6} m
v	kinetic viscosity	1.385×10^{-5}m^2/s	Δt	time step	5.08×10^{-8} s
ρ_p	particle density	1500 kg/m^3	τ	relaxation time	0.65
d_p	particle diameter	7.5×10^{-5}m	Lx	domain thickness	0.024 cm
g	gravity	9.80 m/s^2	Ly	domain width	0.576 cm
κ_n	stiffness coefficient	1.0×10^3 N/m	Lz	domain height	2.304 cm
e	coefficient of restitution	0. 80	ϕ	solid volume fraction	0.100



(**a**): A snapshot of particle distribution. Particles display significant heterogeneity in gas-solid suspension flows.
(**b**): Distribution of force exerted on particles in a local zone, which also exhibits heterogeneity.
(**c**): Quantitative comparison with Wen & Yu equation. 90% of the samples show over-prediction with Wen & Yu equation, although 95% of the angle less than 30˚.

Conclusions

- A GPU-accelerated DNS program has been developed for gas-solid flows.
- Detailed dynamics can be extracted with the DNS program. Hoping to construct accurate correlations.
- Related achievements has been published on **CES** (**Volume 116, 6 Sep 2014, Pages9-22**).