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Technologies and Applications of Moving Particle Simulation

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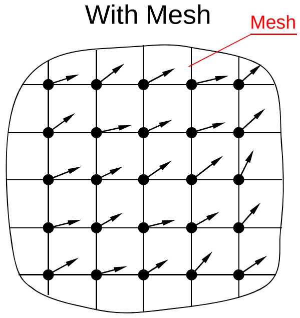
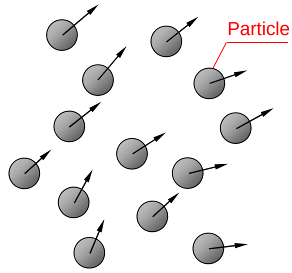
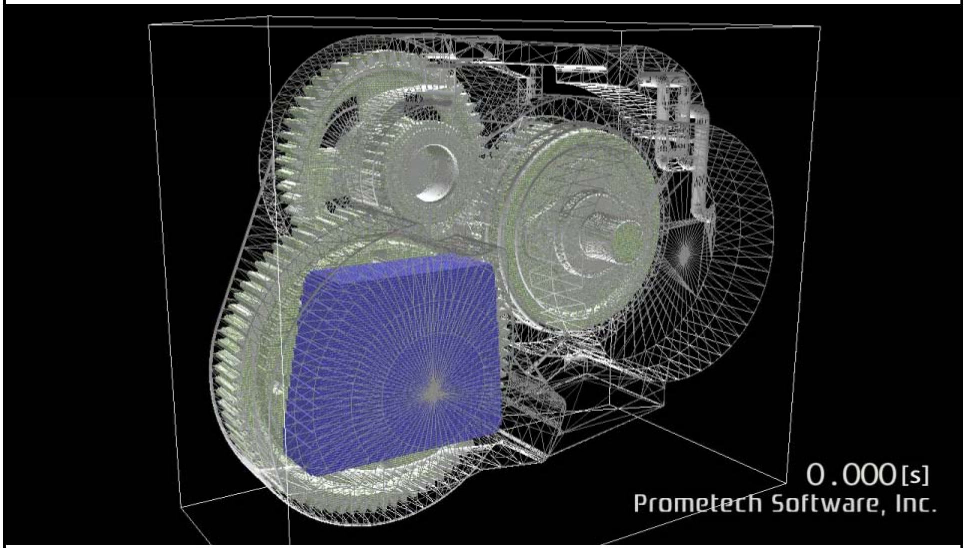
Introduction

SPH and MPS

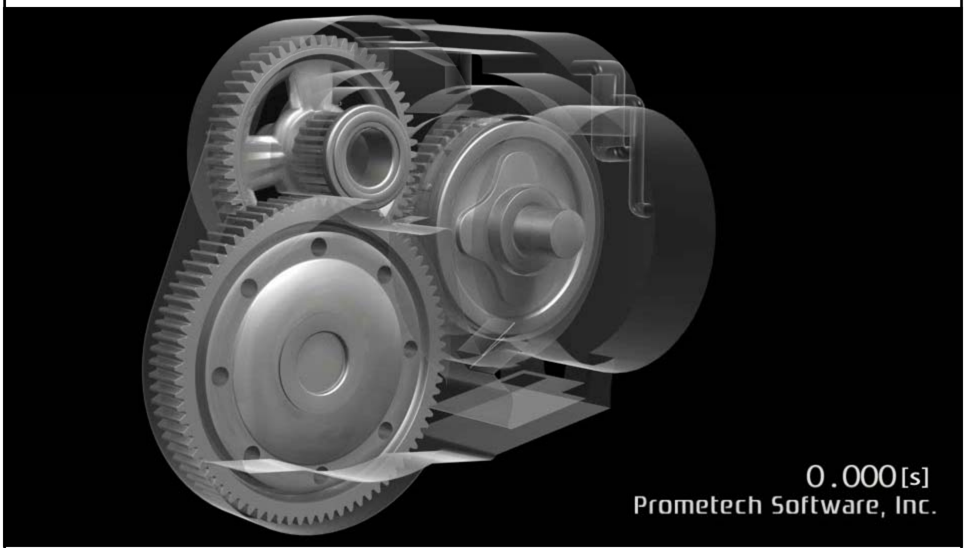
Particle Method

Mesh Methods	Particle Methods
FVM／FEM	
With Mesh 	Without Mesh 

Oil flow in automobile gear box



Oil flow in automobile gear box (photo-realistic CG)



Advantages of Particle Simulation

- Lagrangian description
  - – no convection terms, no numerical diffusion
- No mesh
  - – no mesh tangling
  - – less labor for mesh generation
- Simple formulation
  - – multi-physics simulation
  - – parallel computing on GPU

Particle Methods for Fluid Dynamics

PAF (Particle-and-Force): Daly et al., *LA-3144* (1965)
Concept of particle simulation

SPH (Smoothed Particle Hydrodynamics):
Lucy, *Astron. J.* (1977)
Gingold and Monaghan, *MNRAS* (1977)
Compressible, Explicit, Non-viscous, Astrophysics

MPS (Moving Particle Semi-implicit):
Koshizuka and Oka, *Nucl. Sci. Eng.* (1996)
Incompressible, Semi-implicit, Viscous, Engineering

Spatial Discretization

SPH

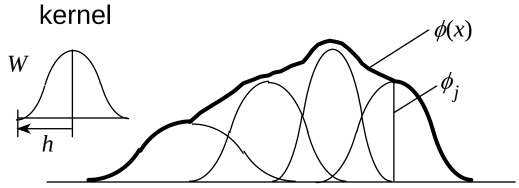
Distribution: superposition of kernels

$$\langle \phi(\mathbf{x})\rangle = \sum_j \phi_j w(|\mathbf{x}-\mathbf{r}_j|,h)\frac{m_j}{\rho_j}$$

Derivative: superposition of derivatives of kernels

$$\langle \nabla\phi(\mathbf{x})\rangle = \sum_j \phi_j \nabla w(|\mathbf{x}-\mathbf{r}_j|,h)\frac{m_j}{\rho_j}$$

kernel



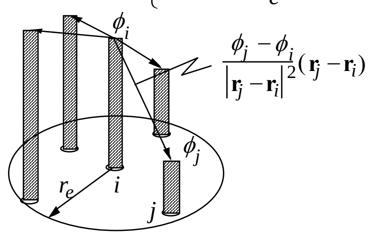
MPS

Derivative: weighted average of differences

$$\langle\nabla\phi\rangle_i = \frac{d}{n^0}\sum_{j\neq i}\left[\frac{\phi_j-\phi_i}{|\mathbf{r}_j-\mathbf{r}_i|^2}(\mathbf{r}_j-\mathbf{r}_i)\,w(|\mathbf{r}_j-\mathbf{r}_i|)\right]$$

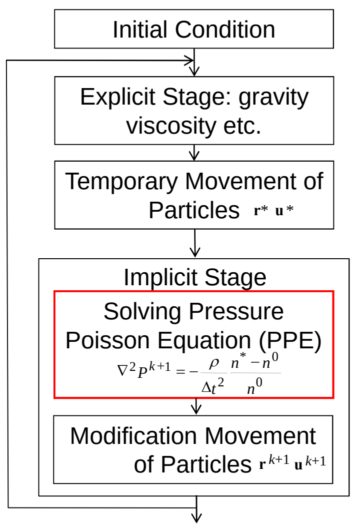
weight function

$$w(r) = \begin{cases} \frac{r_e}{r} - 1 & 0 \le r < r_e \\ 0 & r_e \le r \end{cases}$$



$$\frac{\phi_j-\phi_i}{|\mathbf{r}_j-\mathbf{r}_i|^2}(\mathbf{r}_j-\mathbf{r}_i)$$

Semi-implicit Algorithm



- Poisson equation of pressure is solved.
- The source term is deviation of particle number density from the constant value.

ISPH

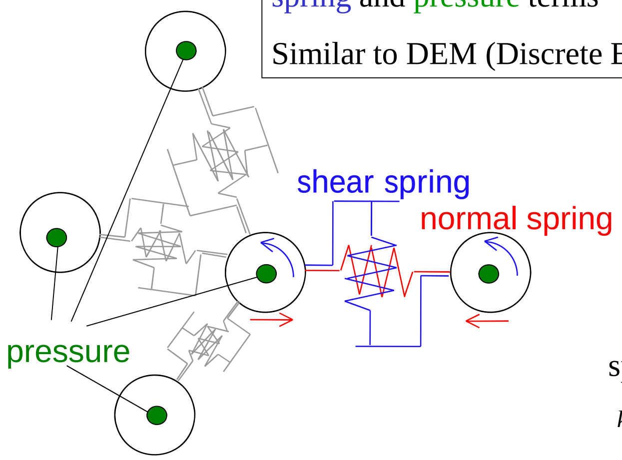
Cummins and Rudman, *JCP* (1999)

Shao and Lo, *Advances Water Res.* (2003)

Elastic Solids Using MPS

Discretized to 3 terms: normal spring, shear spring and pressure terms

Similar to DEM (Discrete Element Method)



spring constant

$$k_{ij} = \frac{m}{\rho}\frac{2d}{n^0}\frac{2\mu}{r_{ij}^2}w(r_{ij})$$

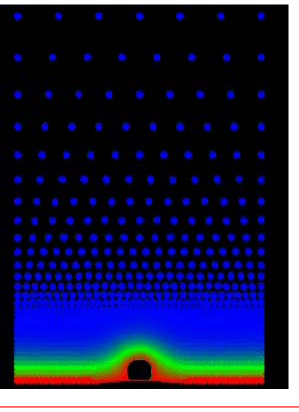
Technology Development

Development of Numerical Methods in MPS

Numerical Methods in MPS (1)

- Basic Algorithms
  - **Semi-implicit** algorithm for incompressible flow: Koshizuka and Oka, *Nucl. Sci. Eng.* (1996)
  - **Arbitrary Lagrangian-Eulerian** (ALE): Yoon et al., Int. *J. Numer. Methods in Fluids* (1999)
  - **Symplectic** scheme (RATTLE): Suzuki et al., *Comput. Methods Appl. Mech. Engrg.* (2007)
  - **Compressible-incompressible unified** algorithm: Arai and Koshizuka, *J. Power and Energy Systems* (2009)
  - Explicit algorithm (**pseudo-compressible**): Shakibaeinia and Jin, *Int. J. Num. Methods Fluids* (2009)

Simulation of Nucleate Boiling



Fluid : water
Pressure : atomospheric
Bottom wall temp. ∶ 110℃
Bulk water temp. ∶ 96℃

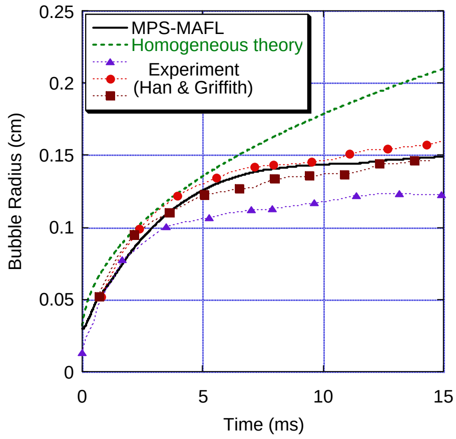
Initial bubble radius ∶ 0.3 mm
Contact angle ∶ 45°

red ∶ hot, blue ∶ cold

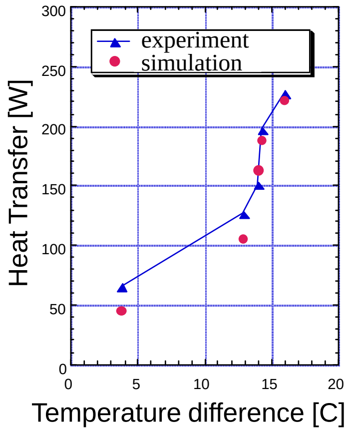
Quantitative direct simulation was successful.

Exp: Han-Griffith (1965)

Bubble Radius



Heat Transfer



H. Y. Yoon, S. Koshizuka and Y. Oka, *Int. J. Multiphase Flow* **27**, 277-298 (2001)
S. Heo, S. Koshizuka and Y. Oka, *Int. J. Heat Mass Transfer* **45**, 2633-2642 (2002)

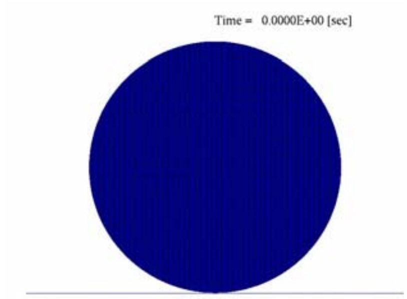
Liquid Droplet Impingement (2D)

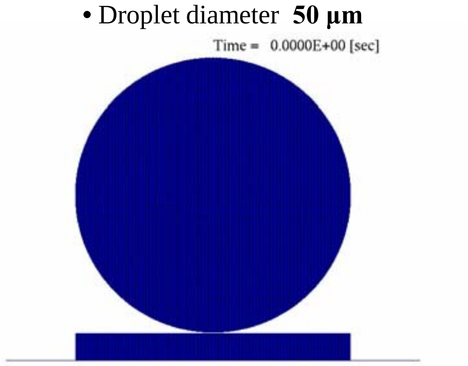
- evaluation of pipe inner wall thinning -

Dry wall
- Impact velocity **200m/s**
- Droplet diameter **50 μm**

Equation of state: Tait equation

Wet wall
- Water film thickness: **5 μm**
- Impact velocity **200m/s**
- Droplet diameter **50 μm**

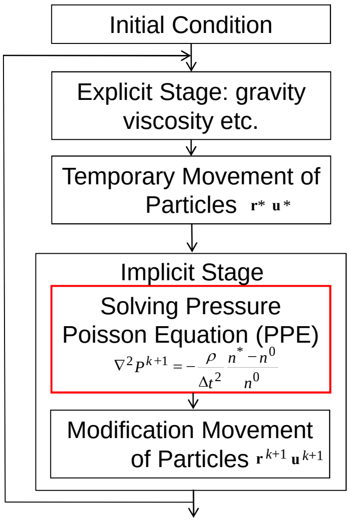




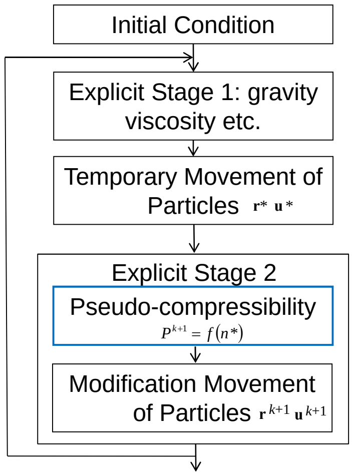
J. Xiong, S. Koshizuka and M. Sakai, *J. Nucl. Sci. Eng.* **47**, 314-321 (2010)

Semi-implicit and Explicit Algorithms

Semi-implicit



Explicit (pseudo-compressible)



MPS-explicit Algorithm

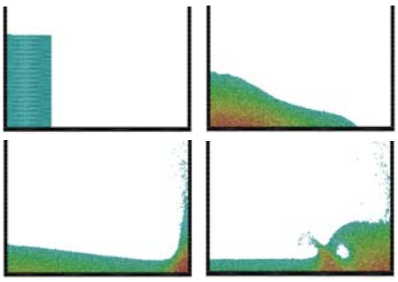
Oochi et al., *Trans. JSCES* (2010) (in Japanese)

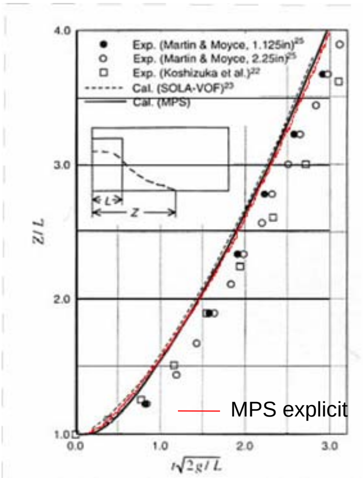
Pressure Function

$$P^{k+1} = \frac{c^2}{n^0}\left(n^{k+1} - n^0\right)$$

c : sound speed

Δt limitation
velocity Courant number C_u =0.2
Mach number: M=0.2



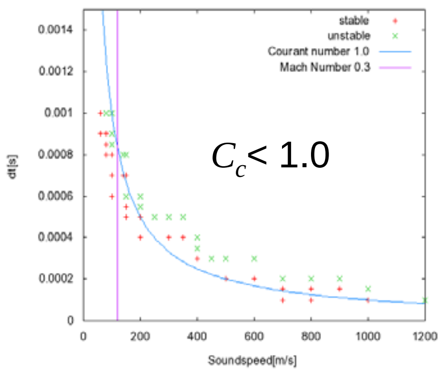


Leading edge position

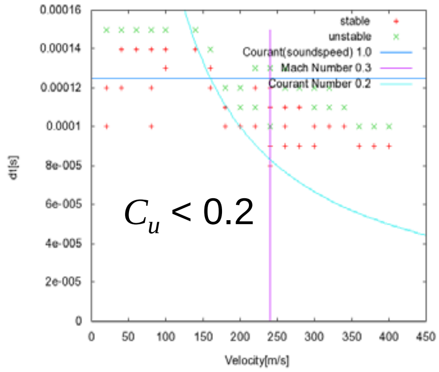
Numerical Stability

l_0 : particle spacing
c : sound speed
u : flow velocity

$$C_c = \frac{\Delta t c}{l_0} \qquad C_u = \frac{\Delta t u}{l_0}$$



Limitation of sound speed
(flow velocity fixed to 40m/s)

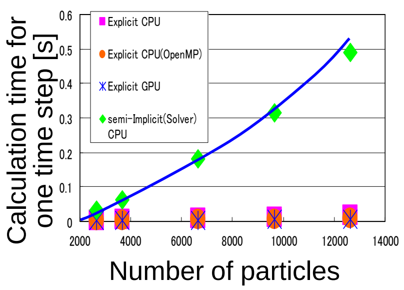


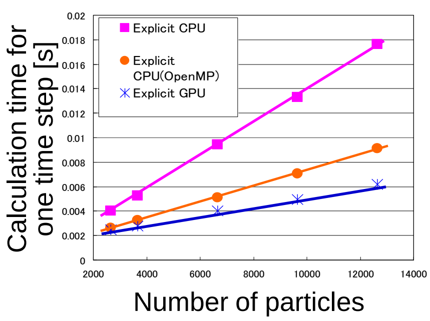
Limitation of flow velocity
(sound speed fixed to 800m/s)

When $M(=u/c)$ is 0.2, $C_c = C_u$. → Optimum

Calculation Time of One Time Step

OS : Windows XP x64 SP2, Memory : 12GB
Intel Core i7 920 (4Cores,8Threads)
NVIDIA Tesla C1060(240 Cores)
CUDA Version 2.3
Intel C++ Compiler 11.0



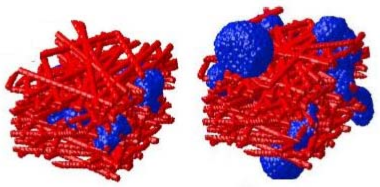


Explicit algorithm is much faster.
Scaling of explicit algorithm is $O(N^{1.0})$.
Good accelerations are obtained using multi-core CPU and GPU.

Numerical Methods in MPS (2)

- Surface Tension Model
  - **Continuum Surface Force (CSF)** model: Nomura et al., *J. Nucl. Sci. Technol.* (2001)
  - **Potential** force model: Shirakawa et al., *J. Nucl. Sci. Technol.* (2001)
  - **Theoretical potential** force: Kondo et al., *Trans. JSCES* (2007) (in Japanese)
- Wettability Model
  - **CSF**: Liu et al., *J. Comput. Phys.* (2005)
  - **Theoretical Potential** force: Kondo et al., *Trans. JSCES* (2007) (in Japanese)

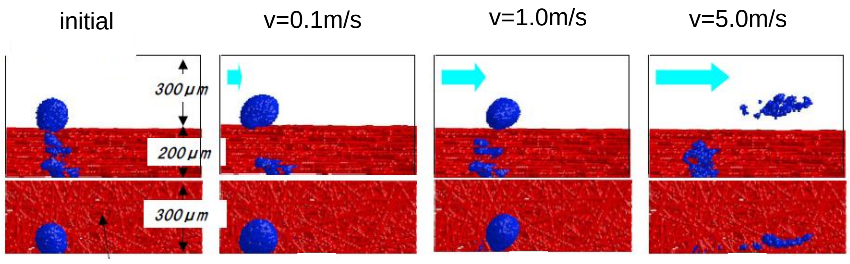
Simulation in GDL by MPS



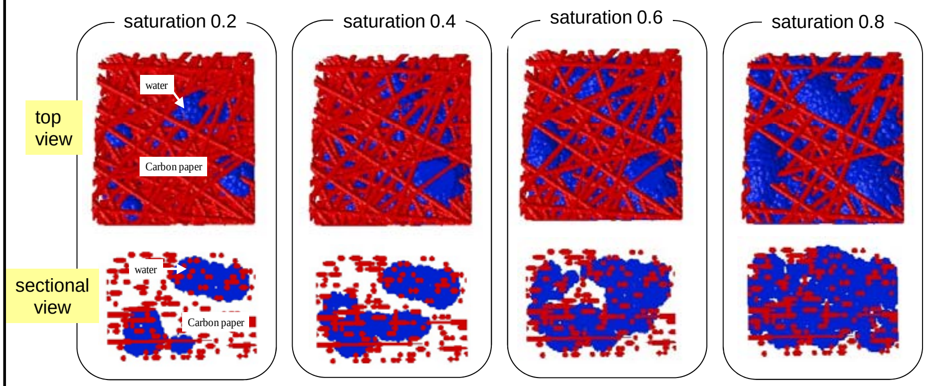
GDL is porous media made by carbon paper.

fiber diameter = 10μm

Micro Flow : Surface tension is relatively strong



◆ Micro flow analysis in Polymer Electrolyte Fuel Cell



Gas : channel -> GDL (Gas Diffusion Layer) -> electrode

Water : electrode -> GDL -> channel

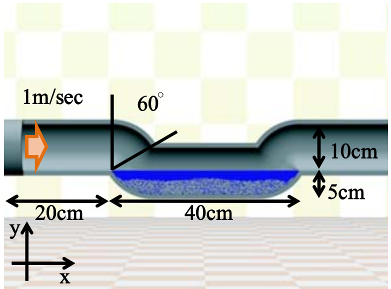
Kondo et al. ASME-FEDSM 2007

Numerical Methods in MPS (3)

- Solid-Liquid Phase Change Model
  - **Latent Heat** model: Koshizuka and Oka, *CFD J.* (2001)
  - **Continuous** model: Nagata and Koshizuka, *Proc. JSCES Conf.* (2008) (in Japanese)
- Liquid-Gas Phase Change Model
  - **New particle generation** in boiling: Koshizuka et al., *Nucl. Eng. Des.* (1999)
- Dispersed Solid-Liquid Two-Phase Flow
  - **DEM-MPS** coupling: Gotoh et al., *Annual J. Coastal Eng., JSCE* (2003) (in Japanese)
  - **DEM-MPS** coupling with coarse grain model: Sakai et al., *J. Soc. Powder Technology Japan* (2008) (in Japanese)

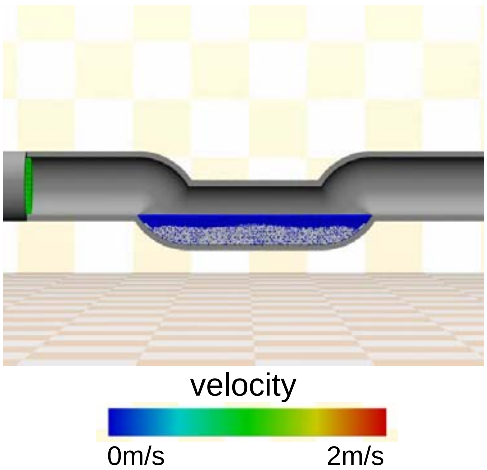
Solid-Liquid Two-Phase Flow in a Pipe

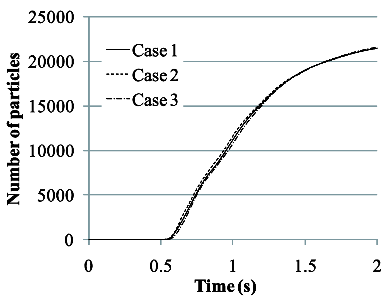
Liquid Phase	
Number of particles	38728
Particle distance	3mm
Density	1000kg/m^3
Kinematic viscosity	1.0×10^{-5}m^2/s
Solid Phase	
Number of particles	28154
Particle diameter	3mm
Density	2500kg/m^3
Spring constant	100N/m
Restitution coeff.	0.8
Friction coeff.	0.3



DEM-MPS Coupled Analysis

Case 3: c=15m/s, explicit algorithm





outflow solid particles

Numerical Methods in MPS (4)

- Turbulence
  - **LES** model: Gotoh et al., *CFD J.* (2001)
  - LES model **+ wall function**: Arai and Koshizuka, *Proc. JSME Mechanical Eng. Cong.* (2007) (in Japanese)
- Suppression of Pressure Oscillations (by source term)
  - Kondo and Koshizuka, *Trans. JSCES* (2008) (in Japanese)
  - Tanaka and Masunaga, *J. Comput. Phys.* (2010)
- Variable Resolution
  - Tanaka et al., *Trans. JSCES* (2009) (in Japanese)
- Polygon Wall Boundary
  - Harada et al., *Trans. JSCES* (2008) (in Japanese)

Numerical Methods in MPS (5)

- Neighboring Search
  - **Two Tables**: Koshizuka et al., *Int. J. Numer. Meth. Fluids* (1998)
  - **Bucket**: Gotoh et al., *J. Hydraul. Coastal Environ. Eng.* (2003) (in Japanese)
  - **Renumbering**: Iribe et al., *Coastal Eng. J.* (2010)
- Graphics Processing Unit (GPU)
  - **Multiphysics**: Harada, GPU Gem3 Chapter 29 (2008)
  - **Semi-implicit MPS**: Gotoh et al., JSCE *J. Hydraulic Coastal Env. Eng.* (2010) (in Japanese)
  - **Explicit MPS**: Oochi et al., *Trans. JSCES* (2010) (in Japanese)

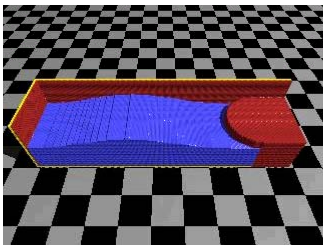
Applications

with high quality computer graphics
(physics-based computer graphics)

Shipping Water on Ship Deck

experiment in NMRI

particle simulation



Particles

Marching cubes

Movie "252 Seizonsha Ari" (2008.12)

海猿3 (Umizaru 3)
Movie released in 2010.9

oil eruption onto a platform: particle simulation, rendering

oil eruption close-up: particle simulation, rendering

storm: particle simulation, scene

platform sinking: 1 2

Octave Engine - Casual

- 2D real-time multiphysics simulation

Game for portable phone

Developed by Prometech and Hudson (2008)

youtube.com

Concluding Remarks

- Moving Particle Simulation (MPS) technologies have been developed to analyze complicated continuum mechanics: basic algorithm, surface tension, multi-phase flow with phase change and GPU acceleration.
- MPS has been widely applied to industries: nuclear, ship, civil, automobile, material, movie, computer game and medicine.