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Particle Simulation for Fluid Dynamics with Free Surfaces

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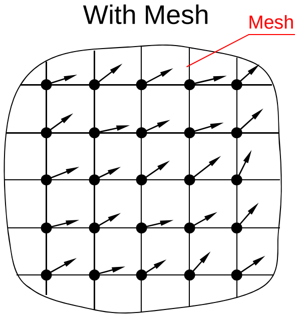
Contents

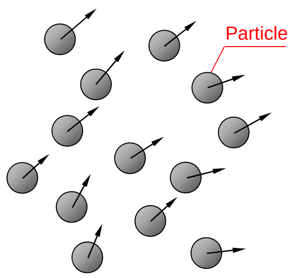
- Particle Simulation
- Application to Nuclear Engineering
- Application to Other Fields
  - Ship Engineering
  - Civil Engineering
  - Automobile Engineering
  - Visualization
  - Biomechanics
- Concluding Remarks

Particle Simulation

Particle Method

Mesh Methods FVM／FEM	Particle Methods
With Mesh	Without Mesh





MPS (Moving Particle Semi-implicit) Method: Koshizuka and Oka, Nucl. Sci. Eng. (1996)

Particle Methods for Fluid Dynamics

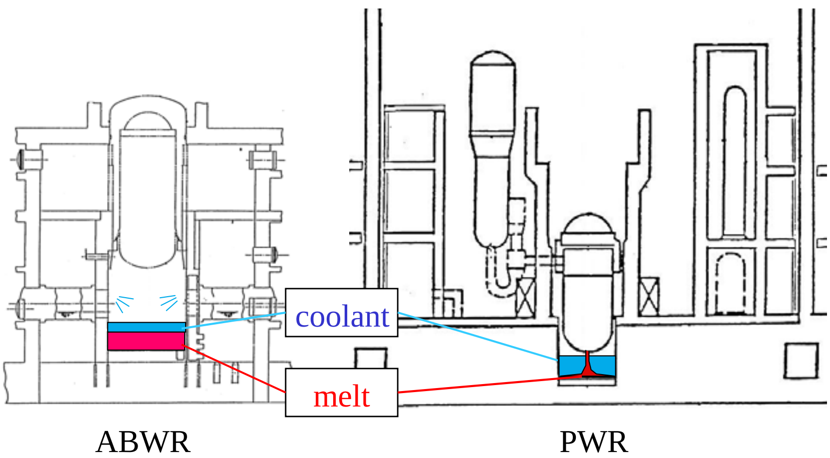
PAF (Particle-and-Force): Daly et al., LA-3144 (1965)
Concept of particle simulation was established

SPH (Smoothed Particle Hydrodynamics):
Lucy, Astron. J. (1977)
Compressible, Explicit, Non-viscous, Astrophysics

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

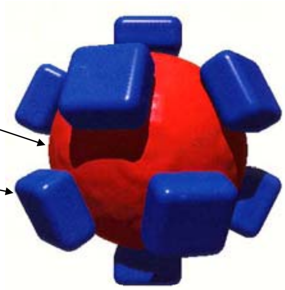
Particle FEM:
Idelsohn et al., Computers and Structures (2003)
Delaunay, FEM, Lagrangian, Multi-physics

Vapor Explosions in LWR Severe Accidents



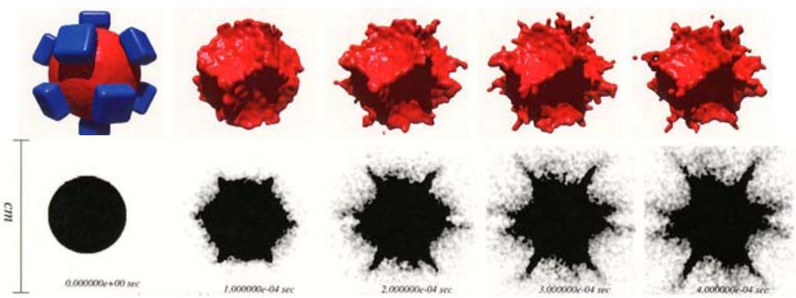
3-D analysis

Molten tin droplet
  diameter：5 mm
Water jets
  number：12
  size：1.4 x 1.4 x 0.6 mm
  velocity：70 m/s
Used particles：70,067



Surface tension and steam are neglected.

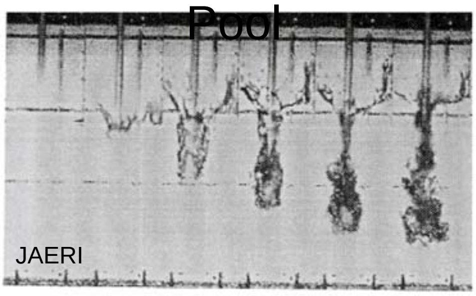
Melt Drop Fragmentation in Vapor Explosions

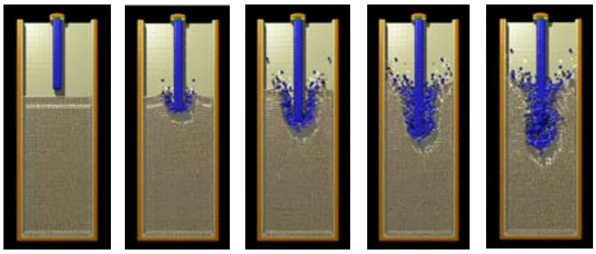


Upper : Fragmentation of a tin drop   lower : X-ray projection (calculation)

S. Koshizuka, H. Ikeda and Y. Oka, *Nucl. Eng. Des.* **189**, 423-433 (1999)

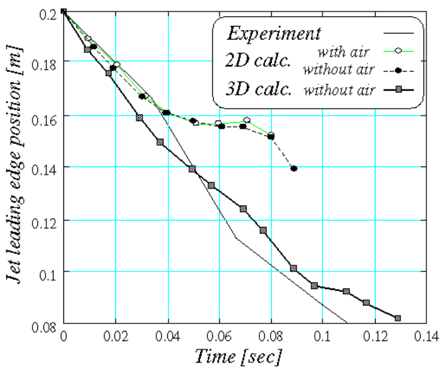
Water Jet Injection into Fluorinert Pool



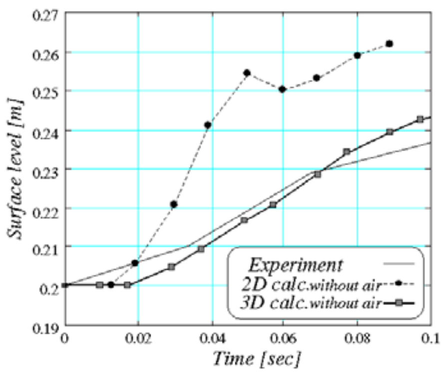


Comparison: exp. and cal.

Jet Penetration Length

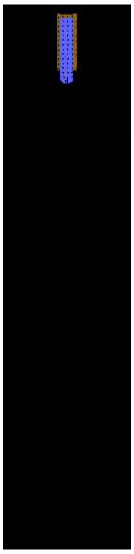


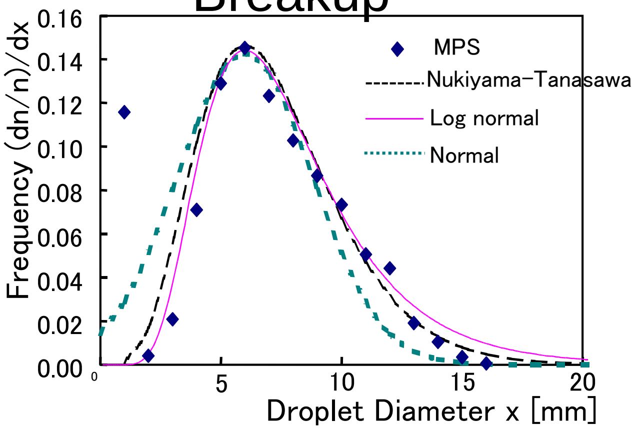
Pool Surface Height



H. Ikeda, S. Koshizuka, Y. Oka, H. S. Park and J. Sugimoto,
J. Nucl. Sci. Technol. **38**, 174-182 (2001)

Droplet Diameter Distribution after Jet Breakup



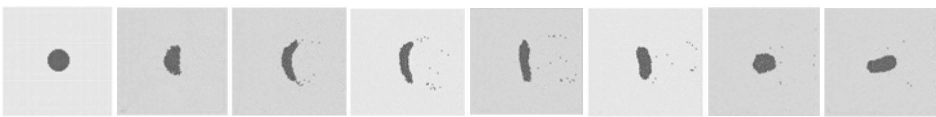


K. Shibata, S. Koshizuka and Y. Oka, *J. Nucl. Sci. Technol.* **41**, 715-722 (2004)

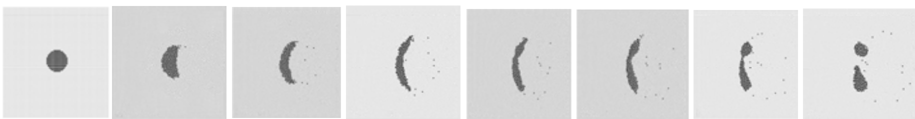
Droplet Breakup (critical We)

$$We = \frac{\rho D U^2}{\sigma} \sim \frac{\text{dynamic pressure}}{\text{surface tension}}$$

We=12



We=13



K. Nomura, S. Koshizuka and Y. Oka, *J. Nucl. Sci. Technol.* **38**, 1057-1064 (2001)
R.-Q. Duan, S. Koshizuka and Y. Oka, *J. Nucl. Sci. Technol.* **40**, 501-508 (2003)
R.-Q. Duan, S. Koshizuka and Y. Oka, *Nucl. Eng. Des.* **225**, 37-48 (2003)

Droplet Deposition onto BWR Fuel

Droplet Diameter 0.72mm; Liquid FilmThickness 0.45mm

U_0 0.5m/s

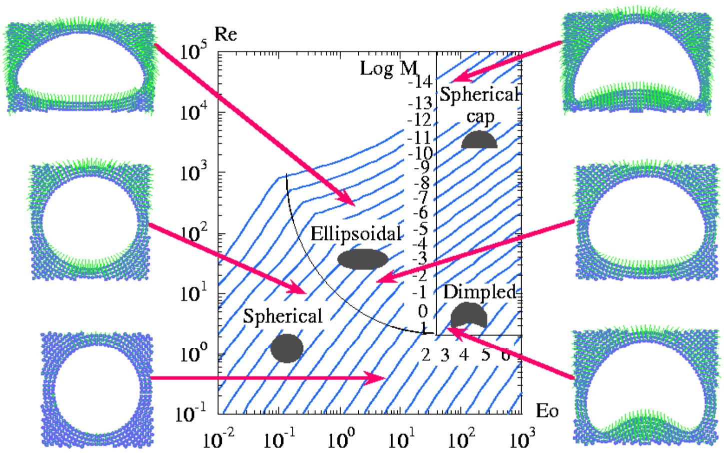
Coalescence

U_0 6m/s

Splash

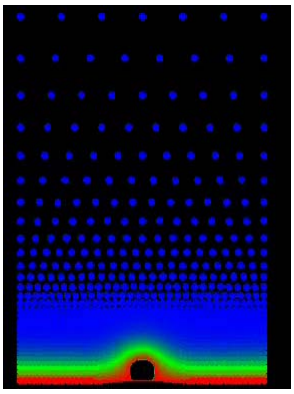
H. Xie, S. Koshizuka and Y. Oka, *J. Nucl. Sci. Technol.* **41**, 569-578 (2004)
H. Xie, S. Koshizuka and Y. Oka, *Int. J. Num. Methods Fluids* **45**, 1009-1023 (2004)
H. Xie, S. Koshizuka and Y. Oka, *Nucl. Eng. Des.* **235**, 1687-1697 (2004)

Rising bubble shape calculated by MPS-MAFL



H. Y. Yoon, S. Koshizuka and Y. Oka, *Nucl. Sci. Eng.* **133**, 192-200 (1999)

Simulation of nucleate boiling



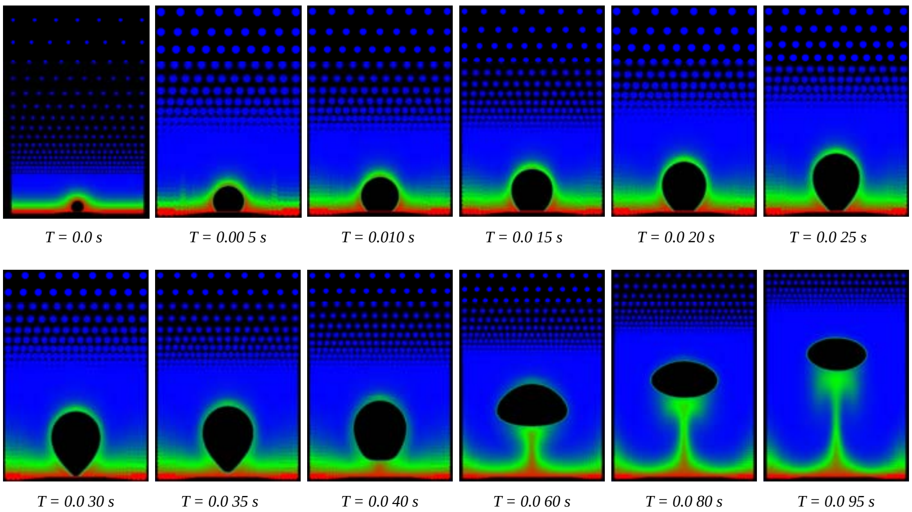
Fluid : water
Pressure : atomospheric
Bottom wall temp. ：110℃
Bulk water temp. ：96℃

Initial bubble radius：0.3 mm
Contact angle：45˚

red：hot, blue：cold

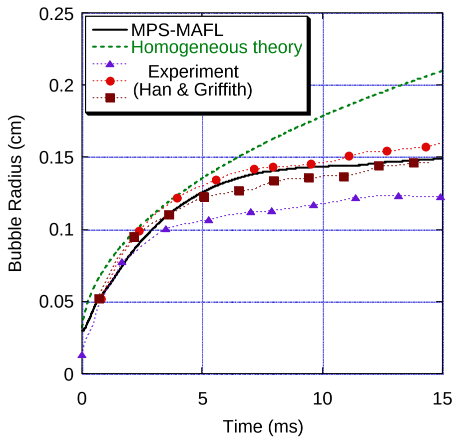
Quantitative direct simulation was successful.

Calculation Result (Tw = 110˚ C)

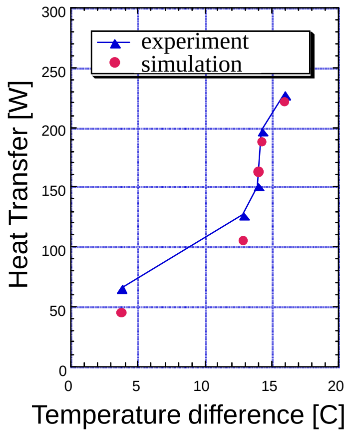


Exp: Han-Griffith (1965)

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)

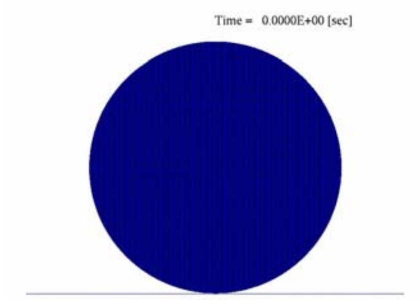
Liquid Droplet Impingement (2D)

- evaluation of pipe inner wall thinning -

Dry wall

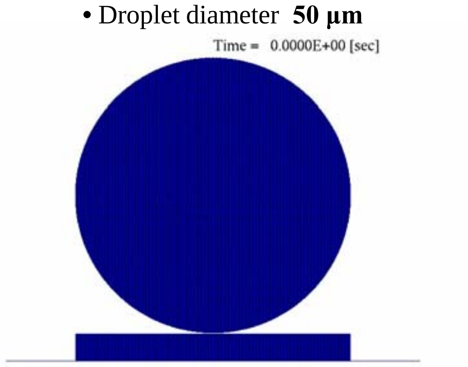
- Impact velocity **200m/s**
- Droplet diameter **50 μm**

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)

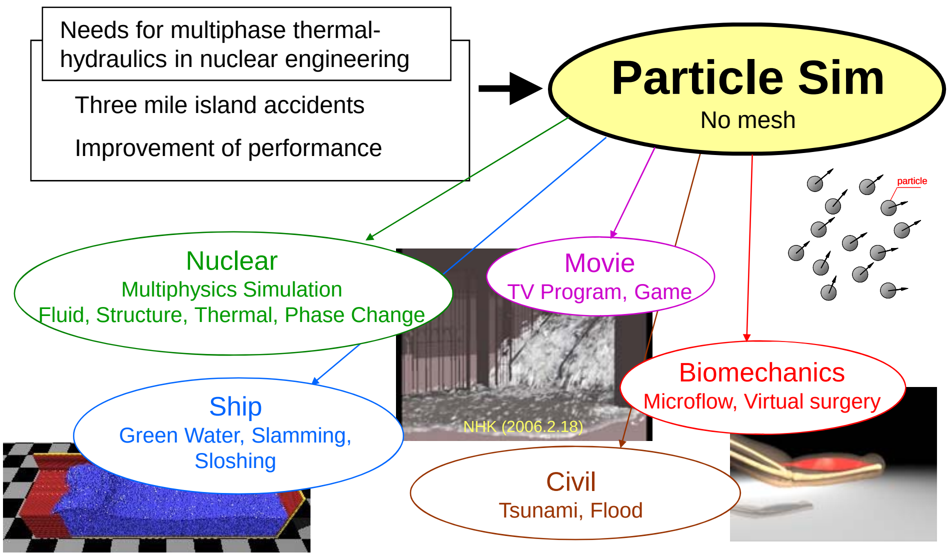
Summary of Nuclear Application

- MPS method have been used for various multiphase thermal-hydraulic problems in nuclear engineering: vapor explosions, droplet breakup, jet breakup, droplet diameter distribution, droplet deposition to BWR fuel, rising bubble, nucleate boiling and liquid droplet impingement.

Ongoing researches in nuclear engineering

- COMPASS code development: multiphysics and multiphase MPS code for core disruptive accidents in sodium-cooled fast reactors
- Numerical analysis of liquid droplet impingement causing pipe wall thinning.
- MPS-DEM simulation for debris coolabolity (Prof Morita et al.)

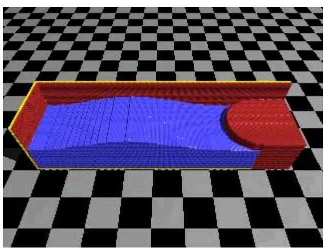
Deployment of Particle Simulation



Shipping Water on Ship Deck

experiment in NMRI

particle simulation



Particles

Marching cubes

海猿3 (Umizaru 3) 2010.9

oil eruption onto a platform: particle simulation, rendering

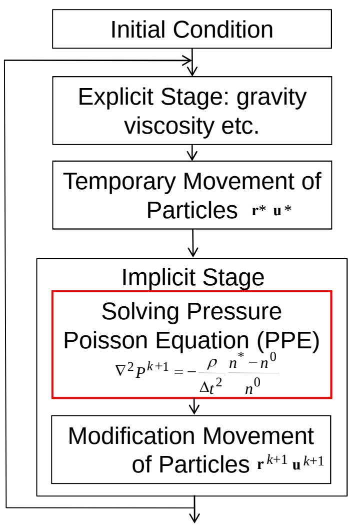
oil eruption close-up: particle simulation, rendering

storm: particle simulation, scene

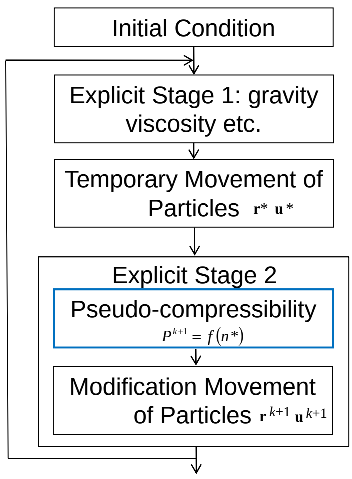
platform sinking: 1 2

Semi-implicit and Explicit Algorithms

Semi-implicit



Explicit (pseudo-compressible)



MPS-explicit Algorithm

Pressure Function

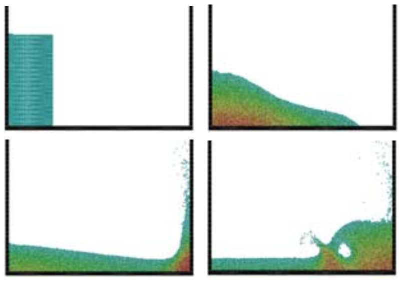
$$P^{k+1} = \frac{c^2}{n^0}\left(n^{k+1} - n^0\right)$$

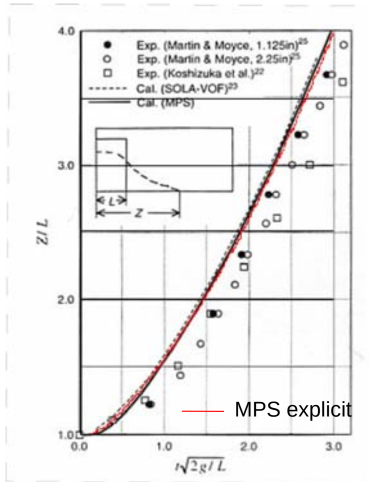
c : sound speed

Δt limitation

velocity Courant number C_u =0.2

Mach number: M=0.2

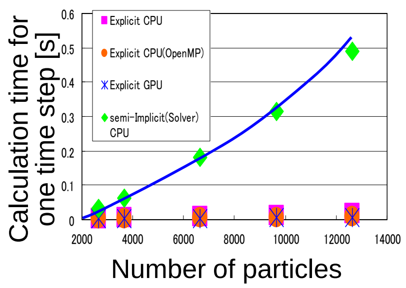


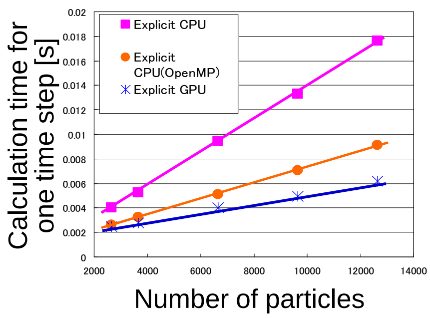


Leading edge position

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.

Concluding Remarks

- Particle simulation has been used for complex thermal-hydraulic problems in nuclear engineering.
- Particle simulation is now widely used in various fields: ship engineering, civil engineering, automobile engineering, visualization and biomechanics.