Experimental and Numerical Study of Dam Break Flow Impact on a Vertical Cylinder

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Motivation and Objective

- Computational Fluid Dynamics (CFD) has been an efficient method to study the wave-body interactions associated with violent water impact on the structures.
- In order to provide accurate and reliable measurement data for validation of the CFD codes, we have carried out an experiment of the dam break impact on a vertical cylinder placed over a dry horizontal bed.

Dam-Break Experiment※

- Free surface variation is recorded by a high-speed video camera and the pressures on the cylinder and the downstream vertical wall are measured by pressure sensors.

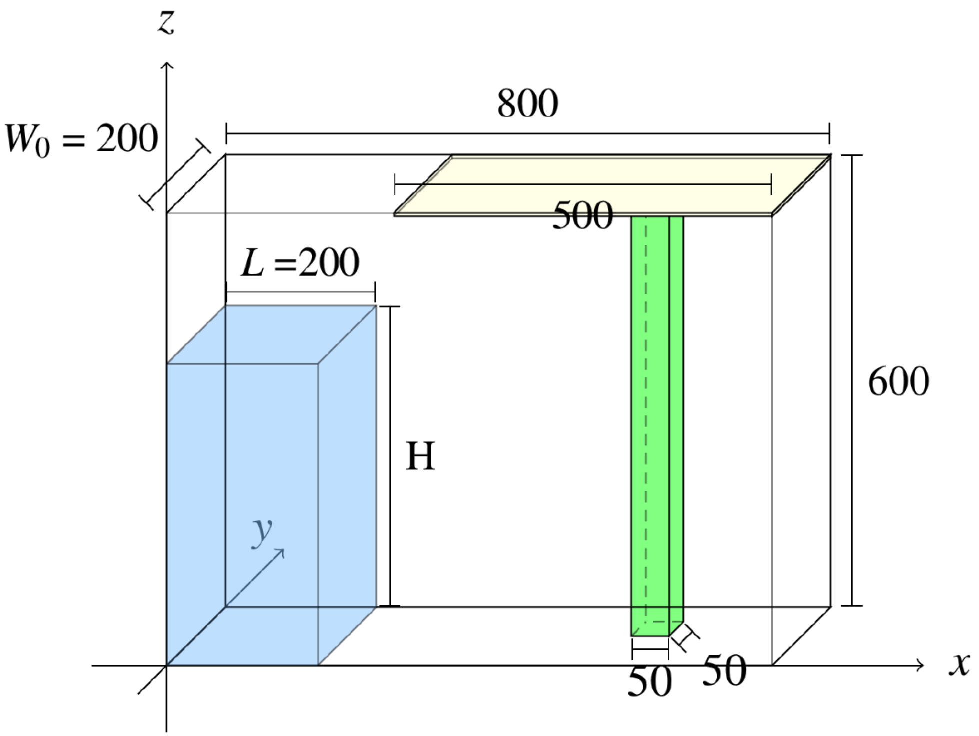
- The gate motion is thoroughly studied and a novel gate motion formula is proposed based on the experimental data. The effect of gate obstruction on the experimental measurements (i.e. time of impact with the cylindrical obstacle) is investigated.

- The effect of the cross-section of the cylinder is studied by examining the pressure signals on the cylinder and the downstream vertical wall.

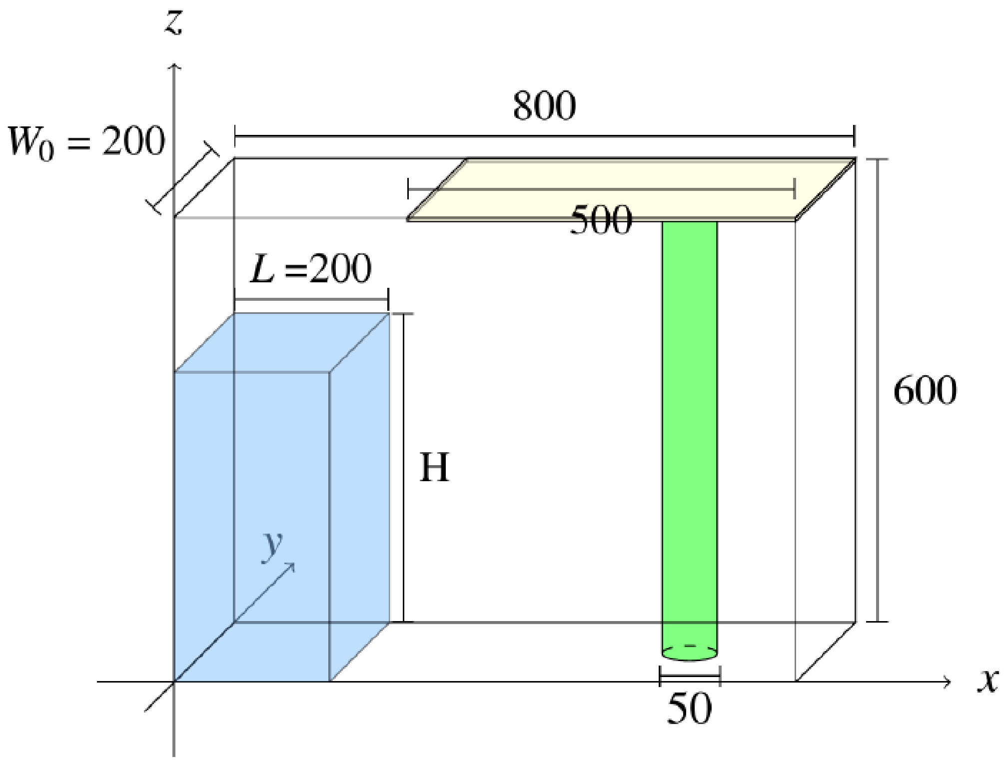
※ Mohamed M. Kamra, Jabir Al Salami, Makoto Sueyoshi, Changhong Hu, Experimental study of the interaction of dambreak with a vertical cylinder, Journal of Fluids and Structures, V. 86, pp. 185-199 (2019)

Dam-Break Experiment: Setup

- The experiment tank have been used in a series of experiments conducted in the Research Institute for Applied Mechanics, Kyushu University.



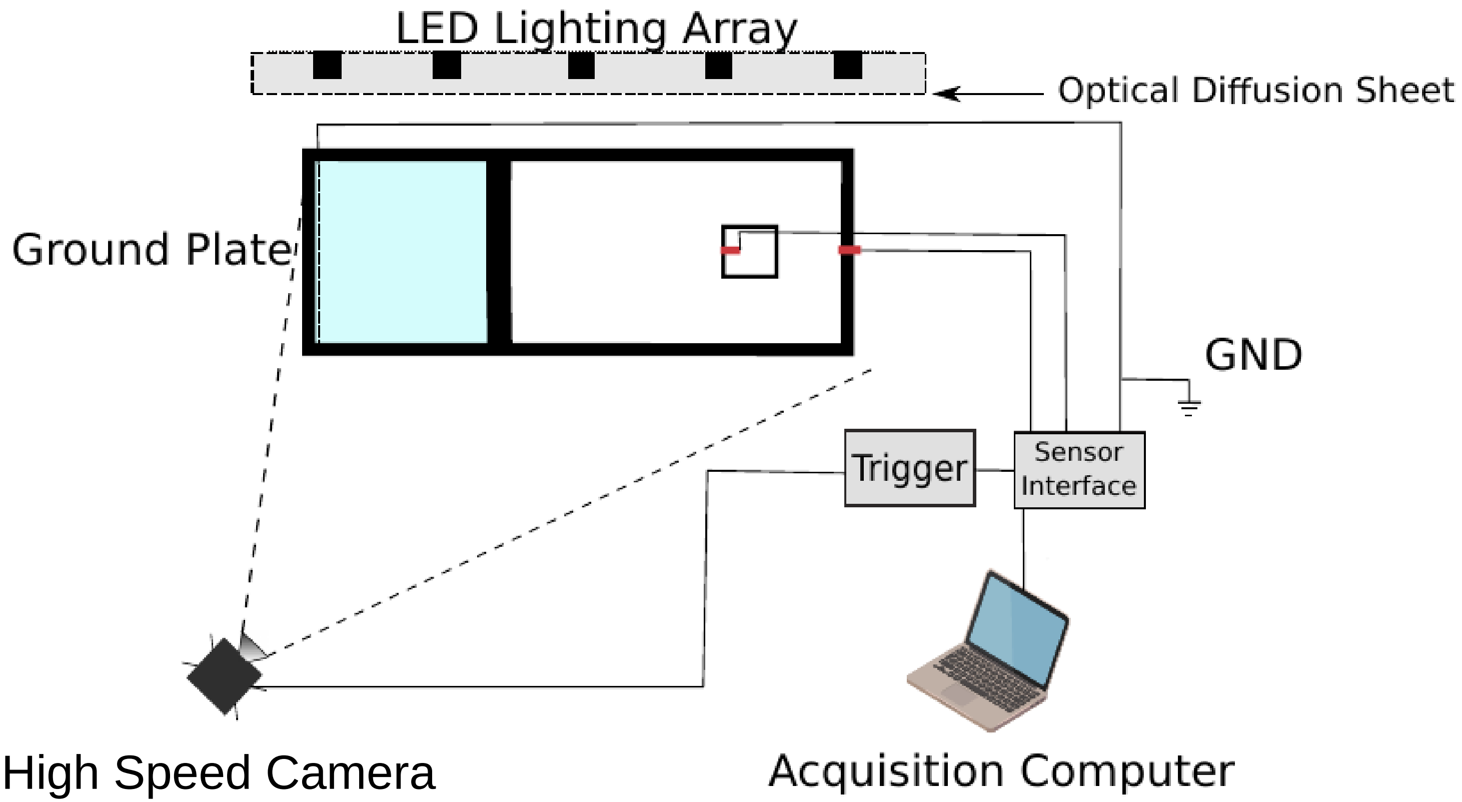
Square cylinder

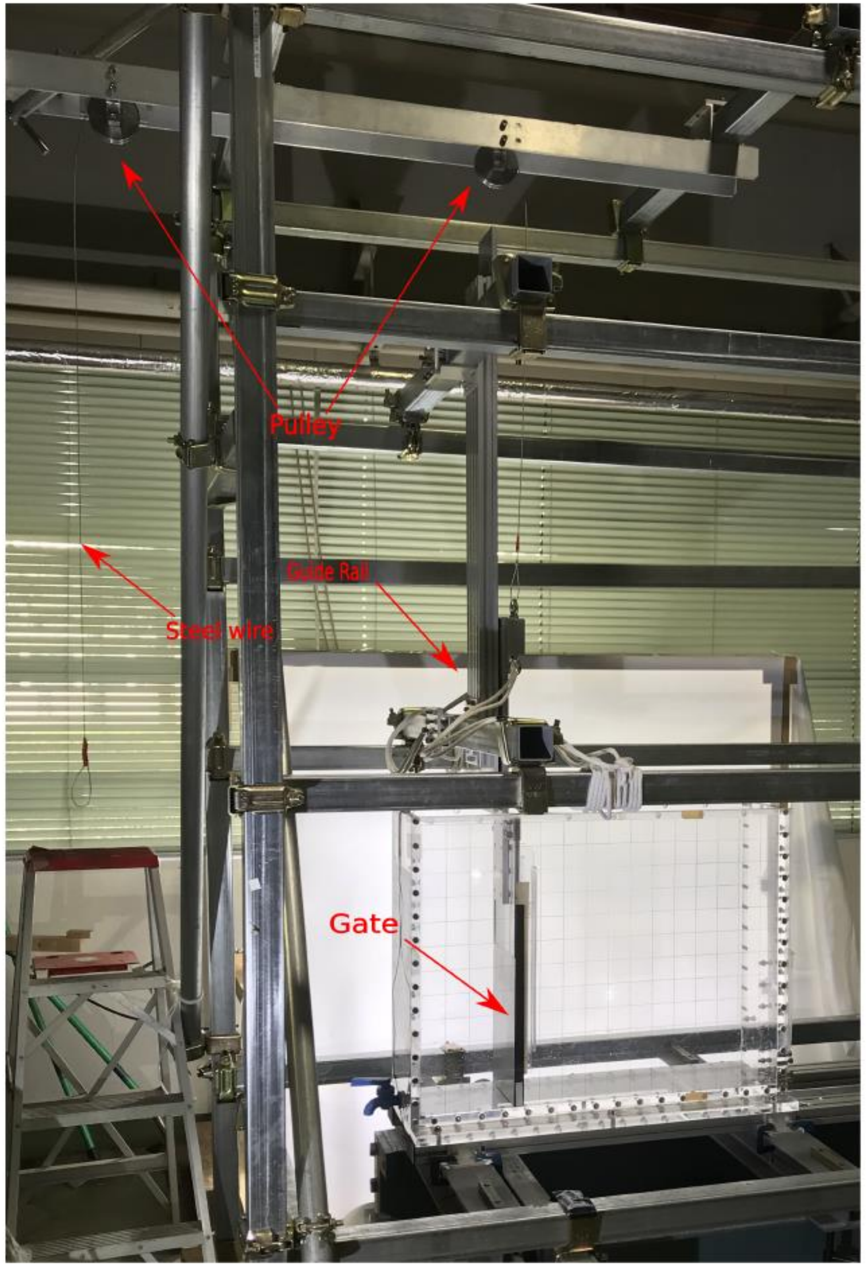


Circular cylinder

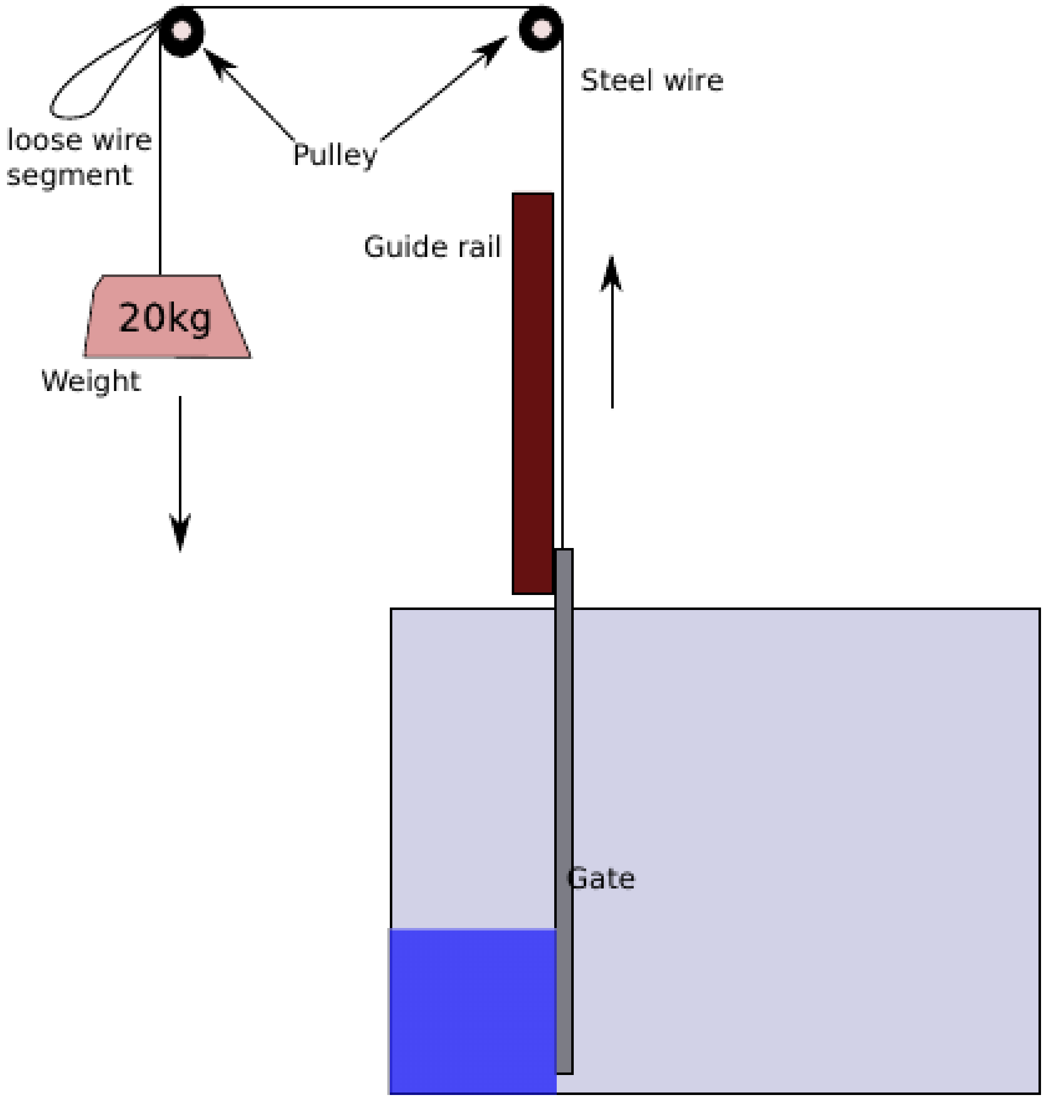
Dam-Break Experiment: Setup

Overall setup of the dam break experiment





Dam-Break Experiment: Gate Release System



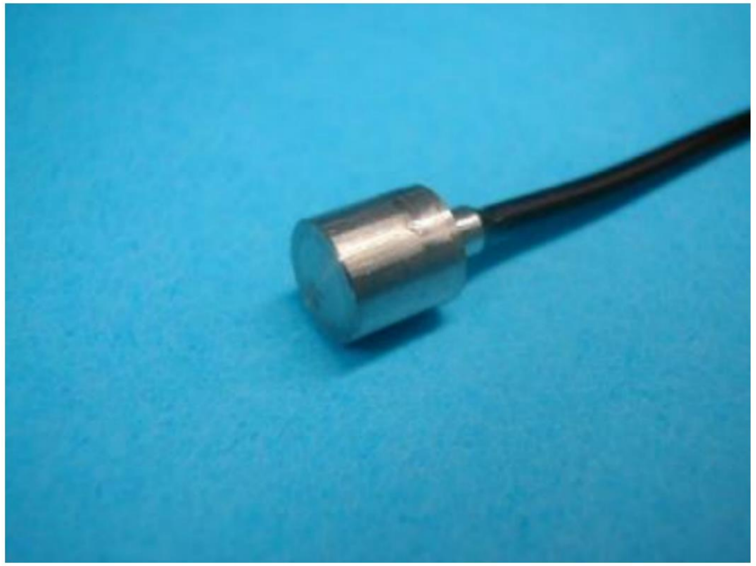
Dam-Break Experiment: Camera and Sensor

High Speed Camera:

- Model: FASTCAM Mini WX100
- The resolution was set to 2048x1472 and frame rate to 1500 frames per second.

Pressure Sensor:

- Piezo-resistive SSK P306V-05S
- Sensor diameter of 0.8cm and a capacity of 49 kPa.



Dam Break Experiment: Uncertainty

Two major uncertainties in the experiment:

- ***Pressure-Sensor Related***: Non-linearity, Hysteresis, Thermal effect, ... Etc. For this sensor, it rates at 0.5% of its rated capacity at the time of purchase. One major concern is the thermal shock when the difference of temperature between water and air is significant.

- ***Gate Related***: Mostly related to the rubber lining of the gate which is used for sealing. Its wetness, temperature, initial deformed shape affect its resistance during the motion and induce some randomness of the gate motion during the experiment. Also some water droplet were occasionally observed under the gate which induce some splash near the wave front at the initial stages.

Dam Break Experiment: Contents

- A total of 28 experimental runs were conducted. The experiments were conducted over a three day period which caused some disparity in air and water temperatures.

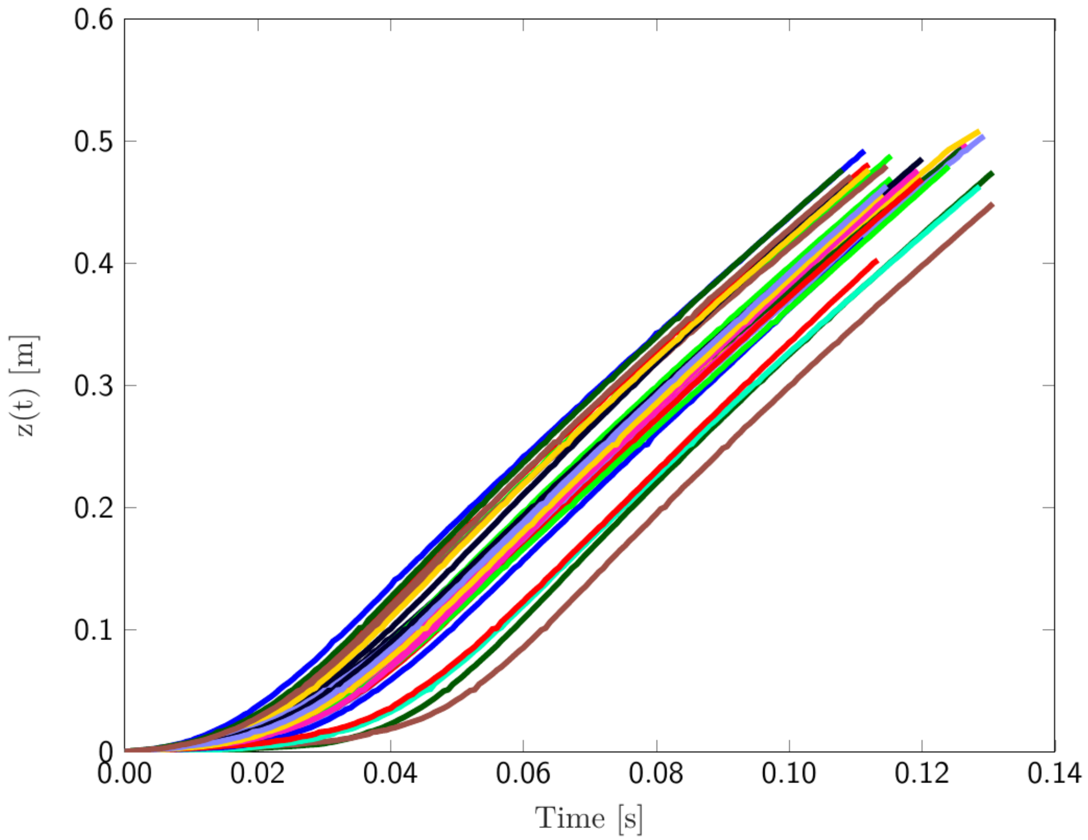
Experiment Type	Number of trial runs
No obstacle case	9
Square obstacle case	10
Circular obstacle case	9

- A statistical analysis of the results was carried out to outline the uncertainty in the measurements.
- Measurements were fitted to a normal distribution function to show the mean and standard deviation of the measured quantities.

Dam-Break Experiment: Gate Motion

- The motion of the gate is obtained from a recorded video from the high speed camera using a motion capturing software.

- Due to the previously outlined uncertainties in the experiment, the gate motion was found to exhibit a random behavior.



Dam Break Experiment: Formula of Gate Motion

- The gate motion can be roughly divided into two stages: an acceleration stage and a uniform speed stage.
- The acceleration in the first stage is found to be variable, and can be expressed by the following formula.

$$z(t) = \begin{cases} a\,t\,e^{b\,t} & t \le t_0 \\ a\,t_0\,e^{b\,t_0} + v_0\,(t - t_0) & t > t_0 \end{cases}$$

$$a = \frac{v_0}{(1 + b\,t)e^{b\,t}}$$

t_0: duration of the acceleration stage

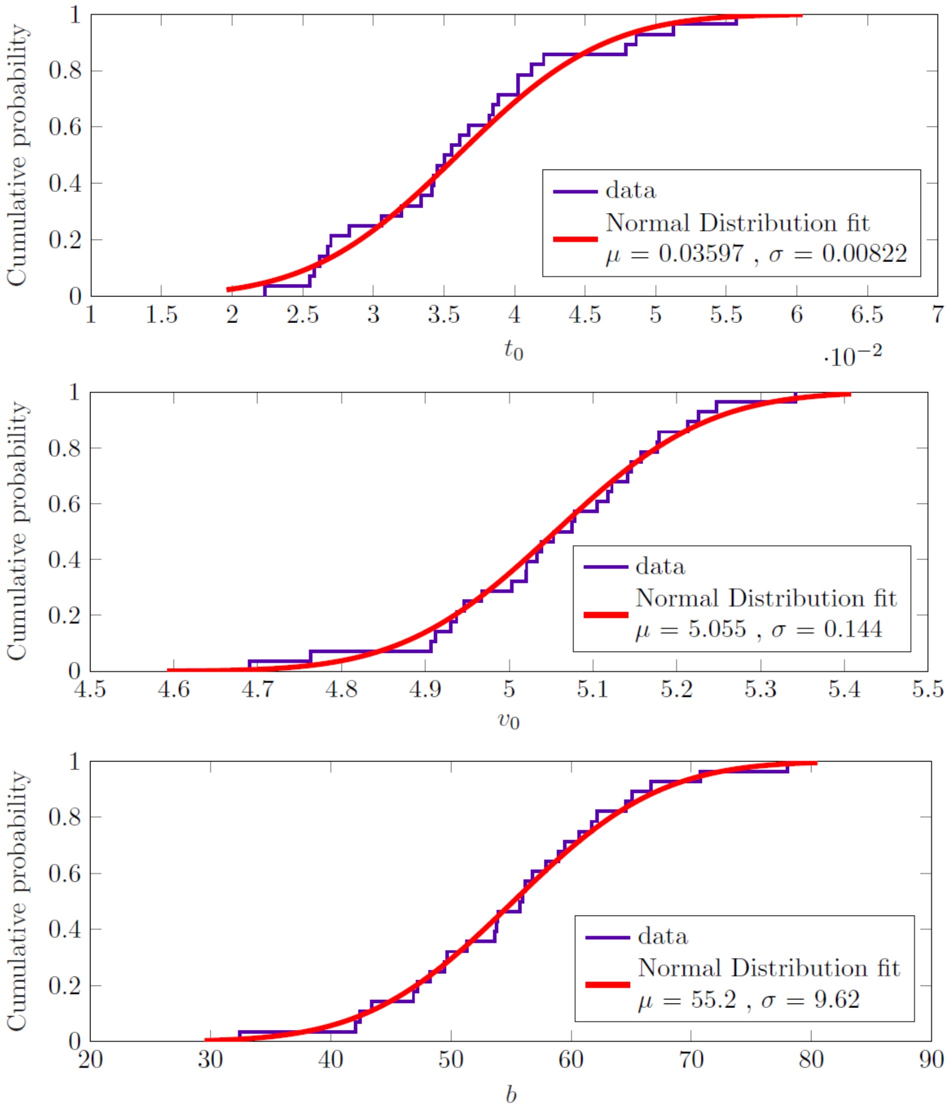
v_0: speed in the constant speed stage

a, b: acceleration variability in the first stage

Dam Break Experiment: Gate Motion

- All gate motions are fitted to the formula, and the parameters of the motion profile formula are statistically analyzed.

- The data follows a normal distribution. It can be observed that the variance in v_0 is very small when compared to the other two parameters t_0, b.

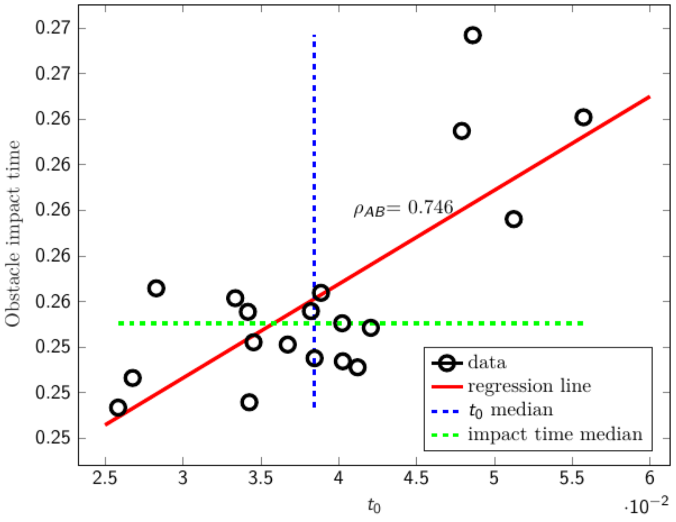


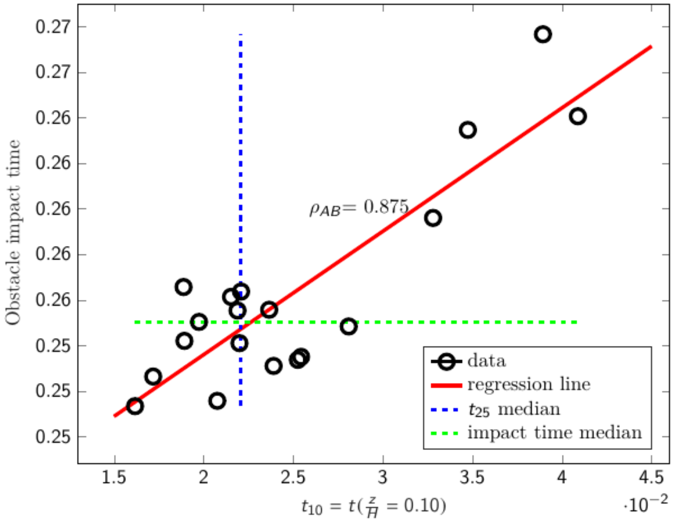
Dam Break Experiment: Effect on Obstacle Impact Time

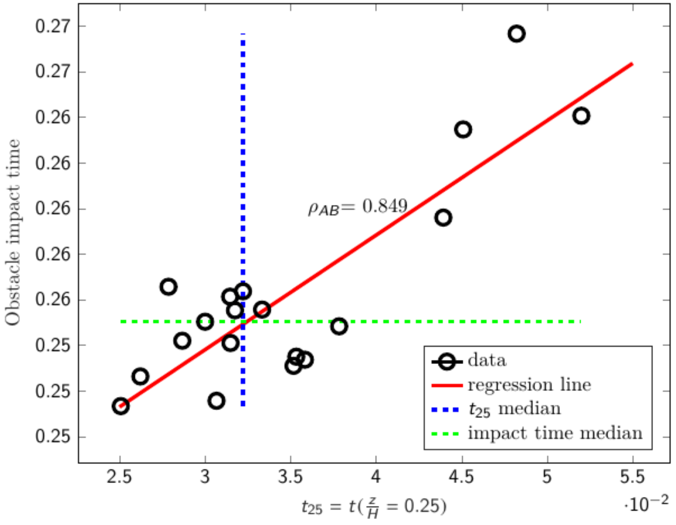
- We found that the gate motion clearly influences the characteristics of the dam break impact.

- This can be demonstrated by the correlation between obstacle impact time and motion characteristics of the gate.

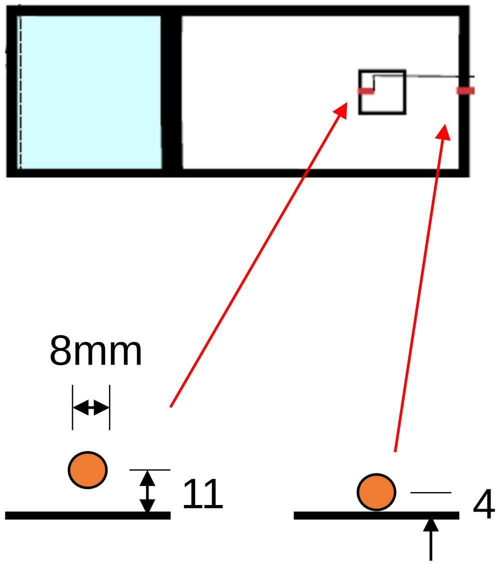
- A strong correlation between the impact time and the duration of the acceleration stage of gate motion especially in its beginning (until $\frac{z}{H} = 10 - 25\%$) .

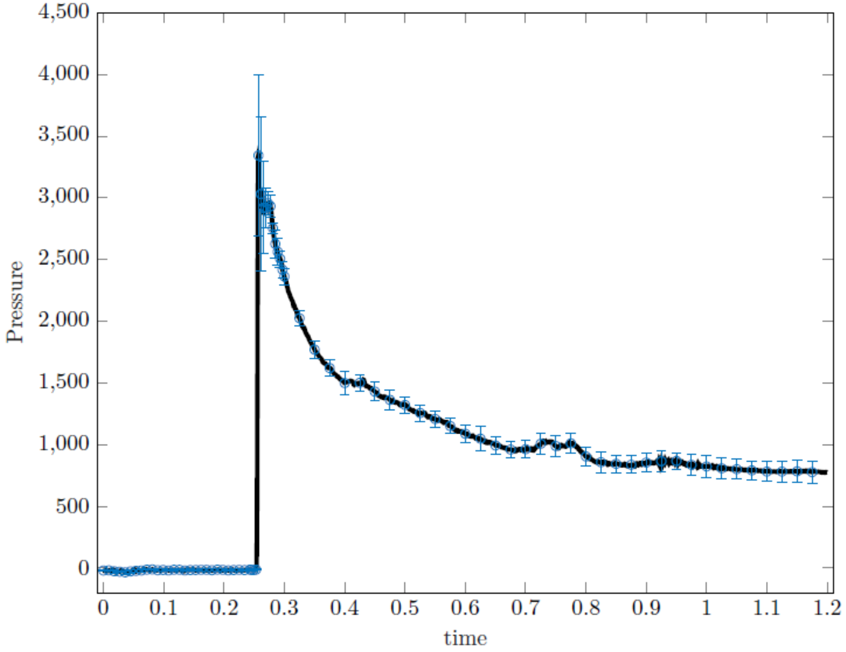




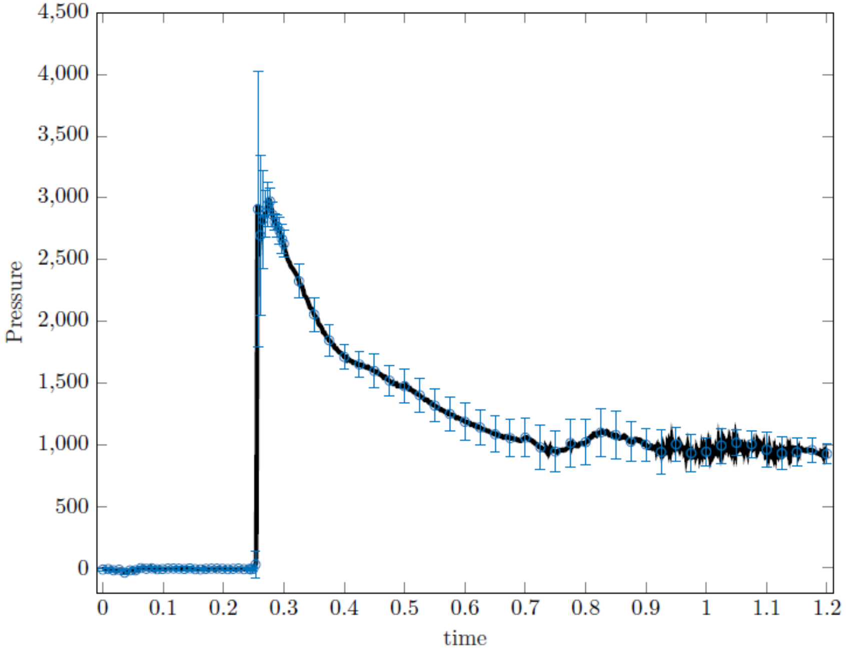


Dam Break Experiment: Impact Pressure on Cylinder





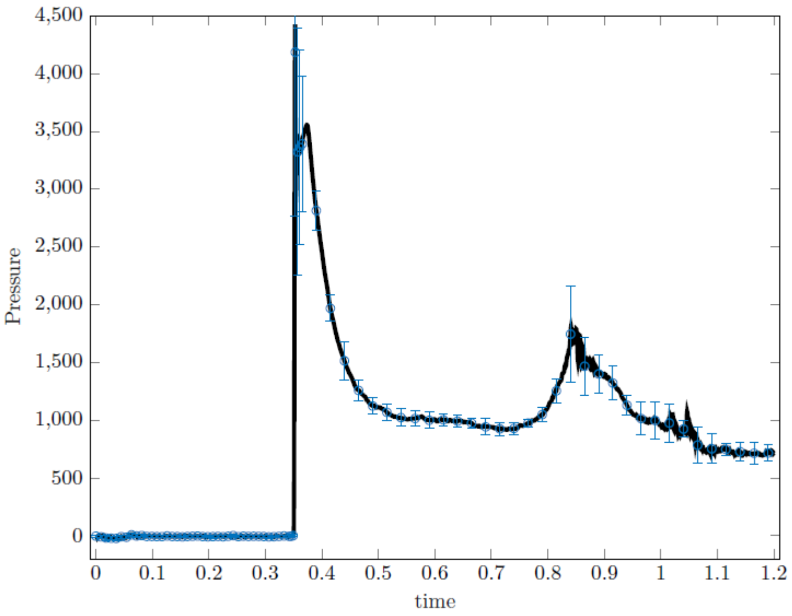
(a) Square cylinder



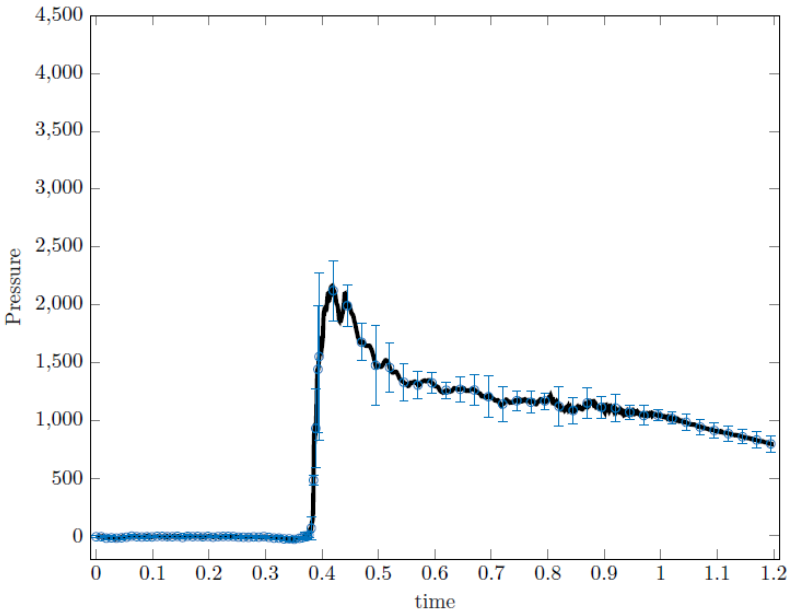
(b) Circular cylinder

- The pressure of circular cylinder is slightly higher than the square cylinder.
- The variance in the measurements of the circular cylinder is significantly higher than the square cylinder.

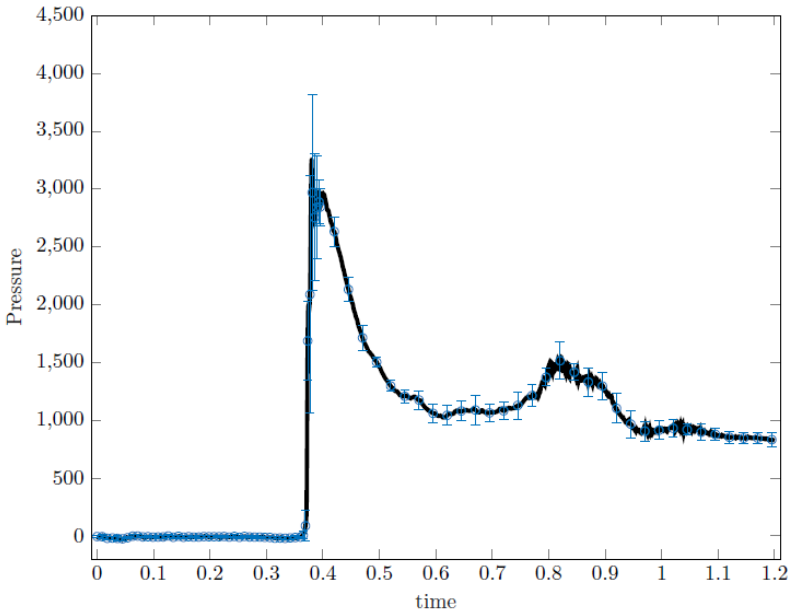
Dam Break Experiment: Impact Pressure on Vertical Wall



(a) No obstacle



(b) Square cylinder



(c) Circular cylinder

- A significantly lower pressure impulse (nearly 50% lower) is observed for the square cylinder.
- The circular cylinder case shows a very similar characteristics to the no-obstacle case but with a lower pressure peak.

Dam Break Simulation

- The main purpose of the experiment is to provide accurate and reliable data for the validation of CFD codes.
- Two in-house CFD codes, an unstructured mesh FVM code and a Cumulant LBM code, are used to simulate the experimental cases.

Unstructured Mesh FVM Code by Dr. Mohamed Kamra

※ Mohamed M. Kamra, "Development of an Unstructured Grid Solver for Complex Wave Impact Problems", PhD Thesis, Kyushu University 2018

Cumulant LBM Code by Dr. Seiya Watanabe

※ Seiya Watanabe, "Implementation of AMR method to lattice Boltzmann method for large-scale GPU simulation of multiphase flow", PhD Thesis, Tokyo Institute of Technology, 2019

Unstructured Mesh FVM Code

- Original Code developed as part of Dr. Kamra's PhD degree research※
- Interface capturing scheme: UMTHINC VOF
- Various turbulence models: RANS and LES
- Parallel programming model: OpenMP
- New parallel version: MPI or MPI+OpenMP
- A CUDA GPU version is under development

※ Mohamed M. Kamra, "Development of an Unstructured Grid Solver for Complex Wave Impact Problems", PhD Thesis, Kyushu University 2018

FVM Simulation: Parameters

Parameter	Value
Pressure-Velocity coupling	PISO method
Number of PISO steps	4
Number of non-orthognality pressure correction steps	1
Velocity gradient method	Face-Averaged Green-Gauss method
Pressure gradient method	Cell-based least square method
Convection scheme	TVD-Van Leer scheme
Turbulence Model	Standard k-ϵ model
Timestepping scheme	Implicit Euler method
Maximum Courant Number (CFL)	0.40

FVM

FVM Simulation: Parameters

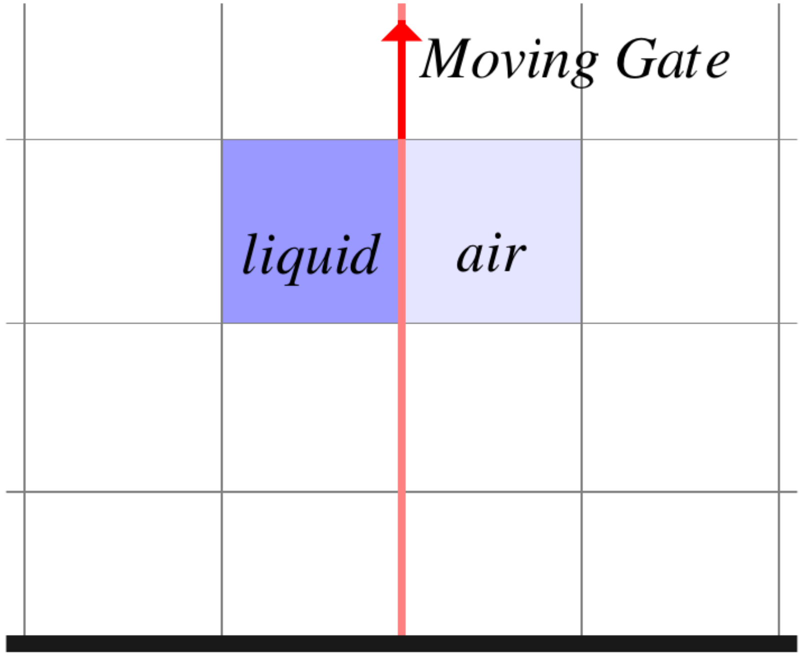
Parameter	Value
Water density (kg/m^3)	999.7
Air density (kg/m^3)	1.246
Water dynamic viscosity ($kg/(m\,s)$)	0.00001778
Air dynamic viscosity ($kg/(m\,s)$)	0.001307
Gravity acceleration (m/s^2)	9.8
Surface Tension Coefficient σ (N/m)	0.0742
Wall adhesion contact angle($^\circ$)	47

Parameter	Value
UMTHINC: β	4.0
UMTHINC: Volume fraction gradient	Node-Averaged Green-Gauss method
UMTHINC: $\widetilde{d}$ calculation method	Developed revised method with 32 quadrature points
UMTHINC: α_f calculation method	Integrated with 25 points distributed on face surface

Approximate Gate Model

FVM

- The gate is treated as a zero thickness flat plate snapped to the cell faces coinciding on the gate surface plane.
- Such cell faces are treated as double sided wall boundary (shell boundary with a finite wall velocity).



- At t = 0: Create a list of the mesh internal faces (not boundary faces) coinciding on the gate surface plane designated as gate face list.
- While ($t < t_{gate}$)
  - Compute $Z_{gate}(t)$ from the gate motion profile
  - Examine the gate face list and omit faces where z-component of the face center is less than $Z_{gate}(t)$
  - Update the wall velocity of the faces remaining in the list based on the gate motion profile

where t_{gate} is the duration of gate motion

Parameter	Value
Gate motion profile	Developed two equation profile
Gate motion profile: v_0 (m/s)	5.055
Gate motion profile: t_0(s)	0.036
Gate motion profile: b	55.2

FVM

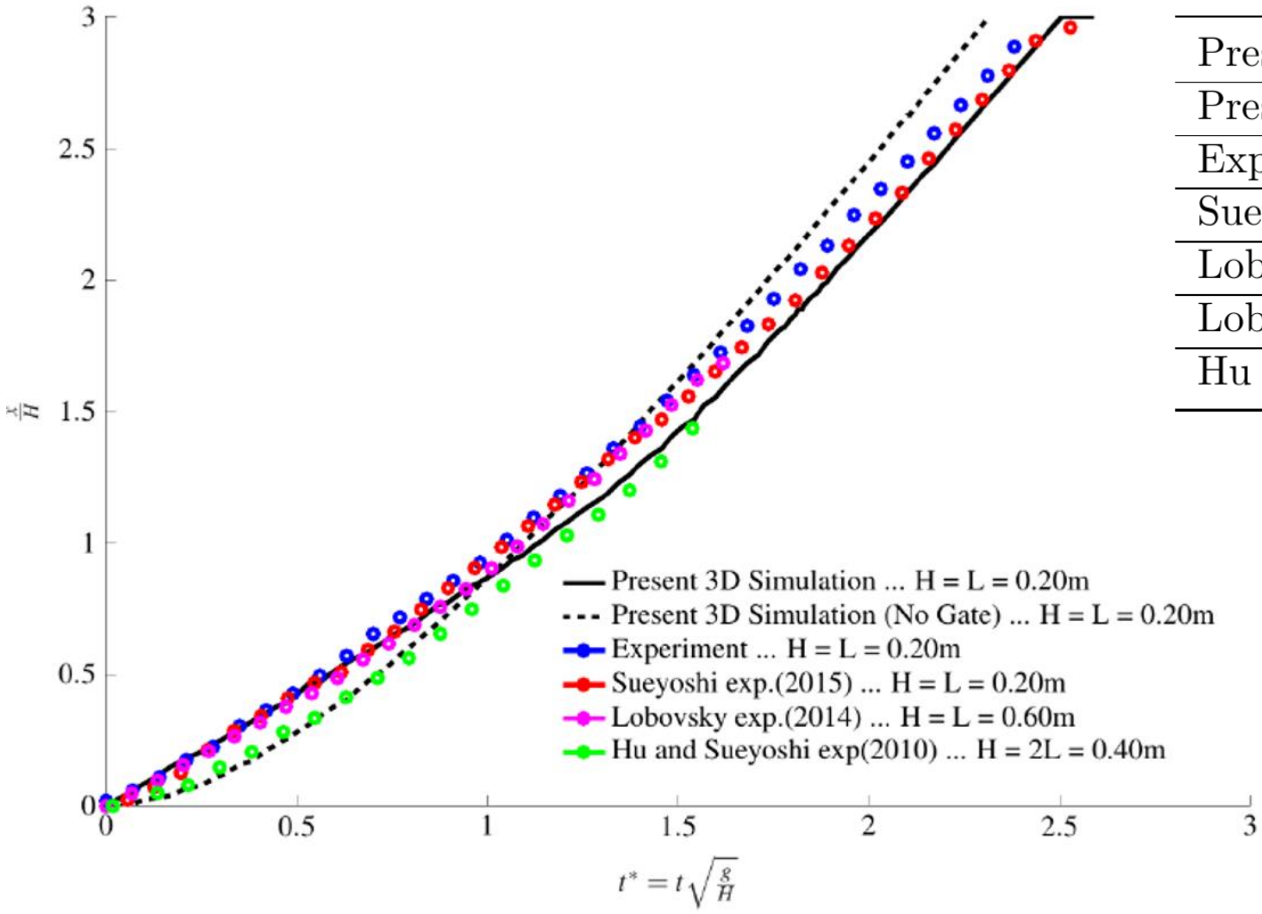
Case of no Obstacle: Mesh

- The unstructured mesh was generated used GMSH open-source software and it consists of 1,958,114 cells.

- Minimum spacing of 0.5mm, maximum spacing of 5mm

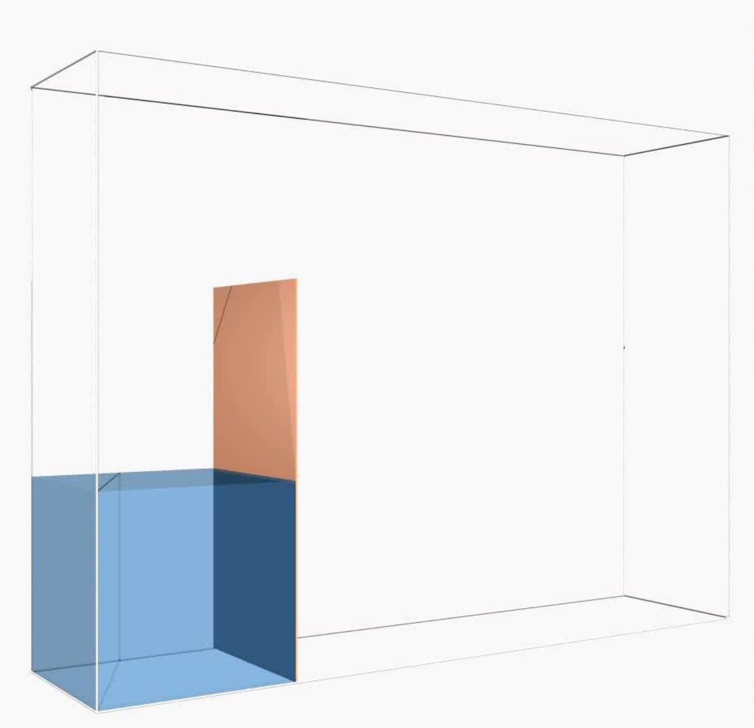
FVM

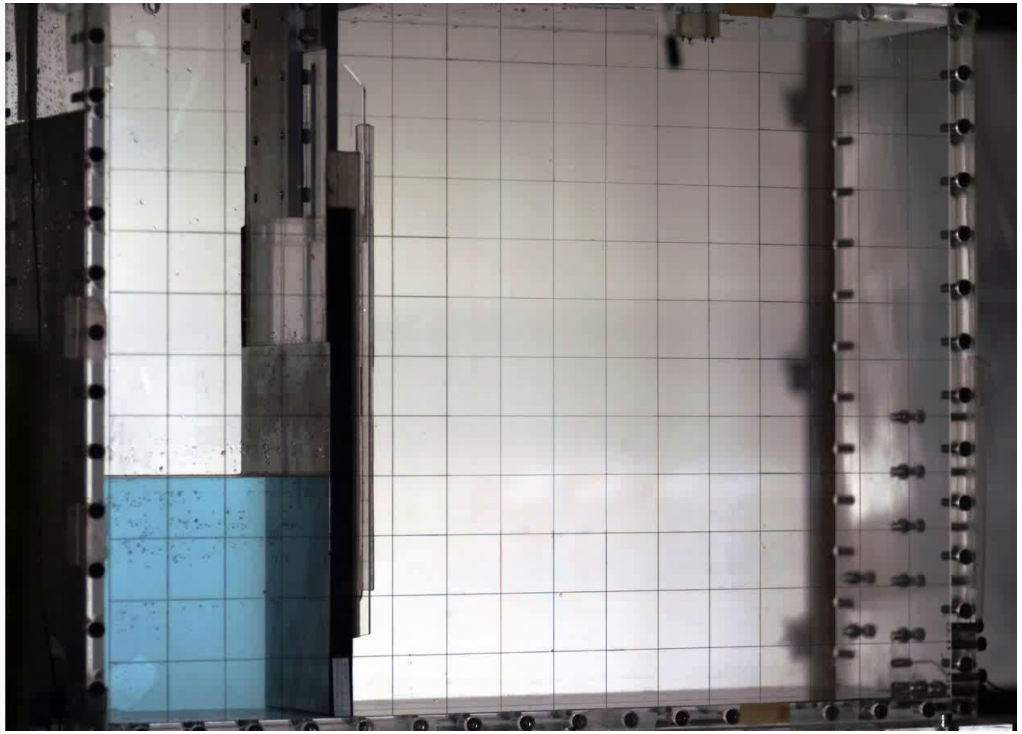
Case of no Obstacle: Front Propagation



Numerical/Experimental run	Avg. velocity
Present Method (3D), with Gate , H = L = 0.20m	1.42
Present Method (3D), without Gate , H = L = 0.2m	1.65
Experiment, H = L = 0.20m	1.38
Sueyoshi exp. (2015) , H = L = 0.20m	1.33
Lobovsky exp. (2014) , H = L = 0.60m	1.34
Lobovsky exp. (2014) , H = 0.5L = 0.30m	1.56
Hu and Sueyoshi exp. (2010), H = 2L = 0.40m	1.17

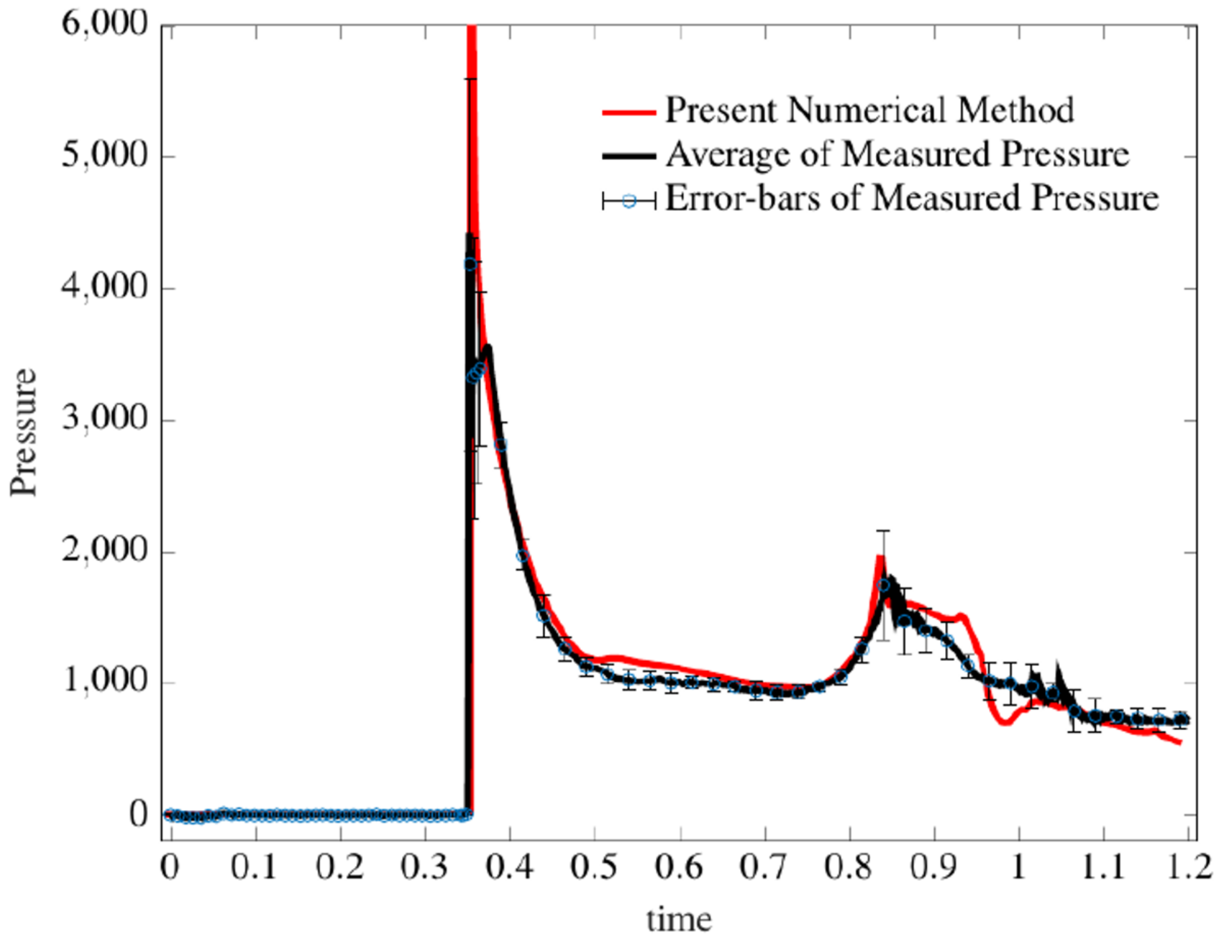
Case of no Obstacle: Free Surface Evolution



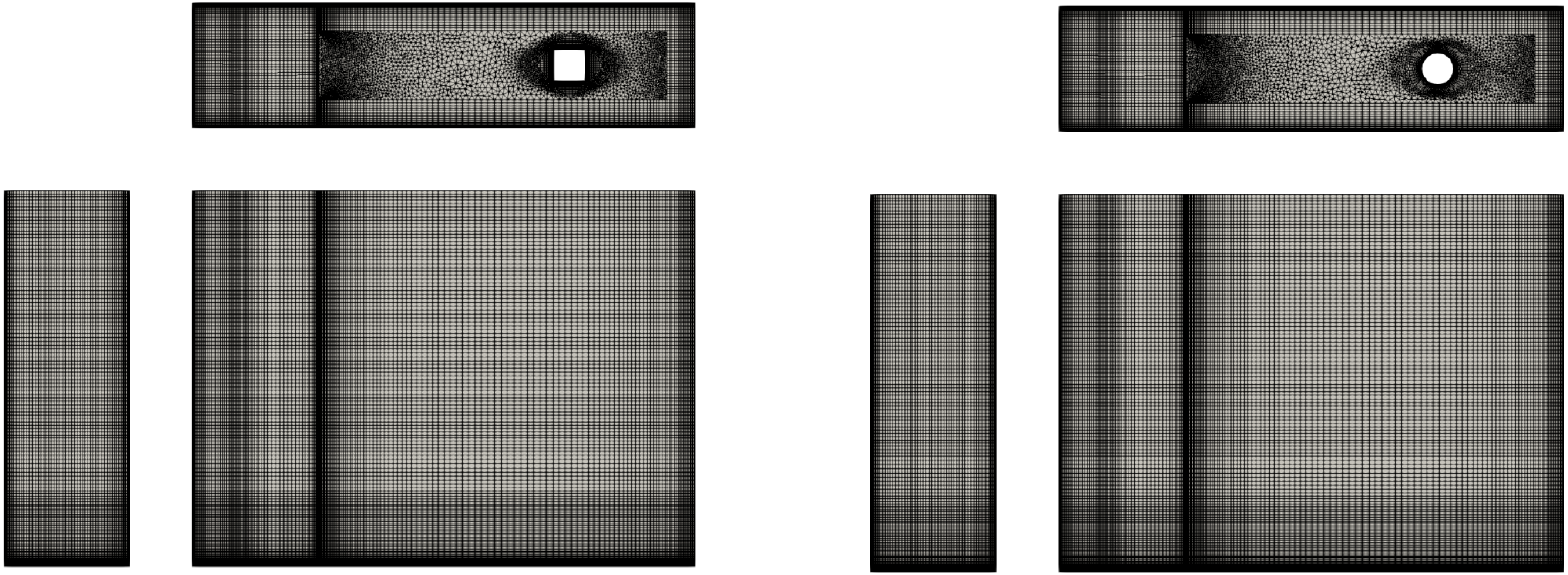


FVM

Case of no Obstacle: Pressure Dynamics



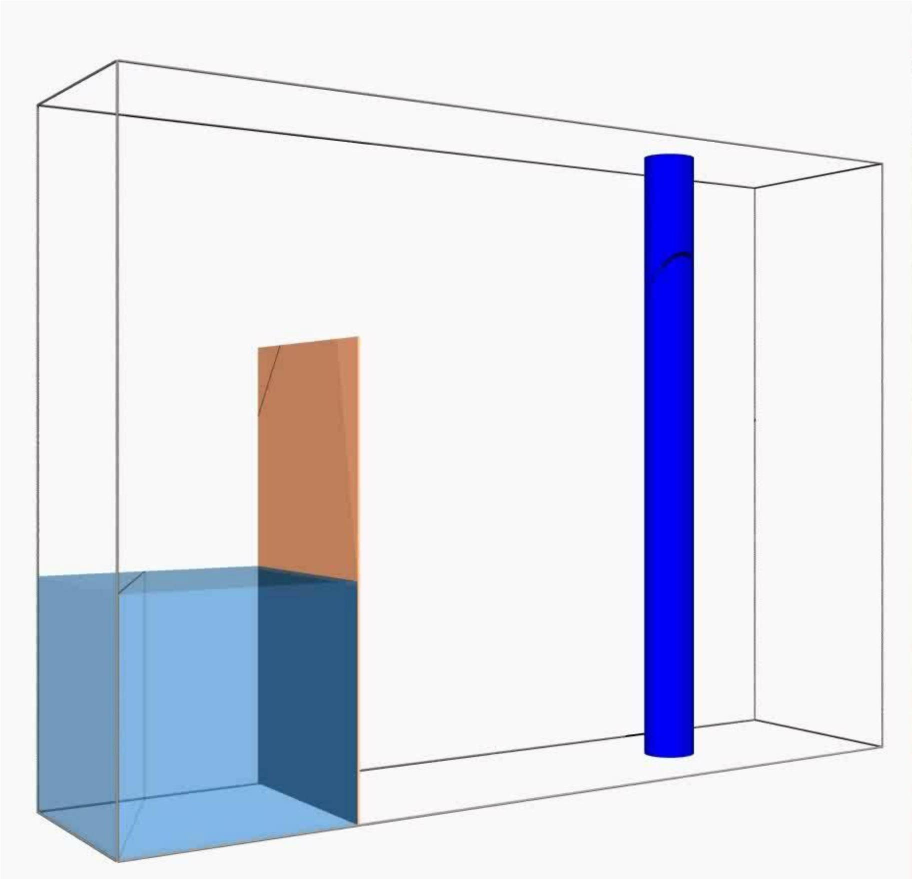
Case of Vertical Cylinder

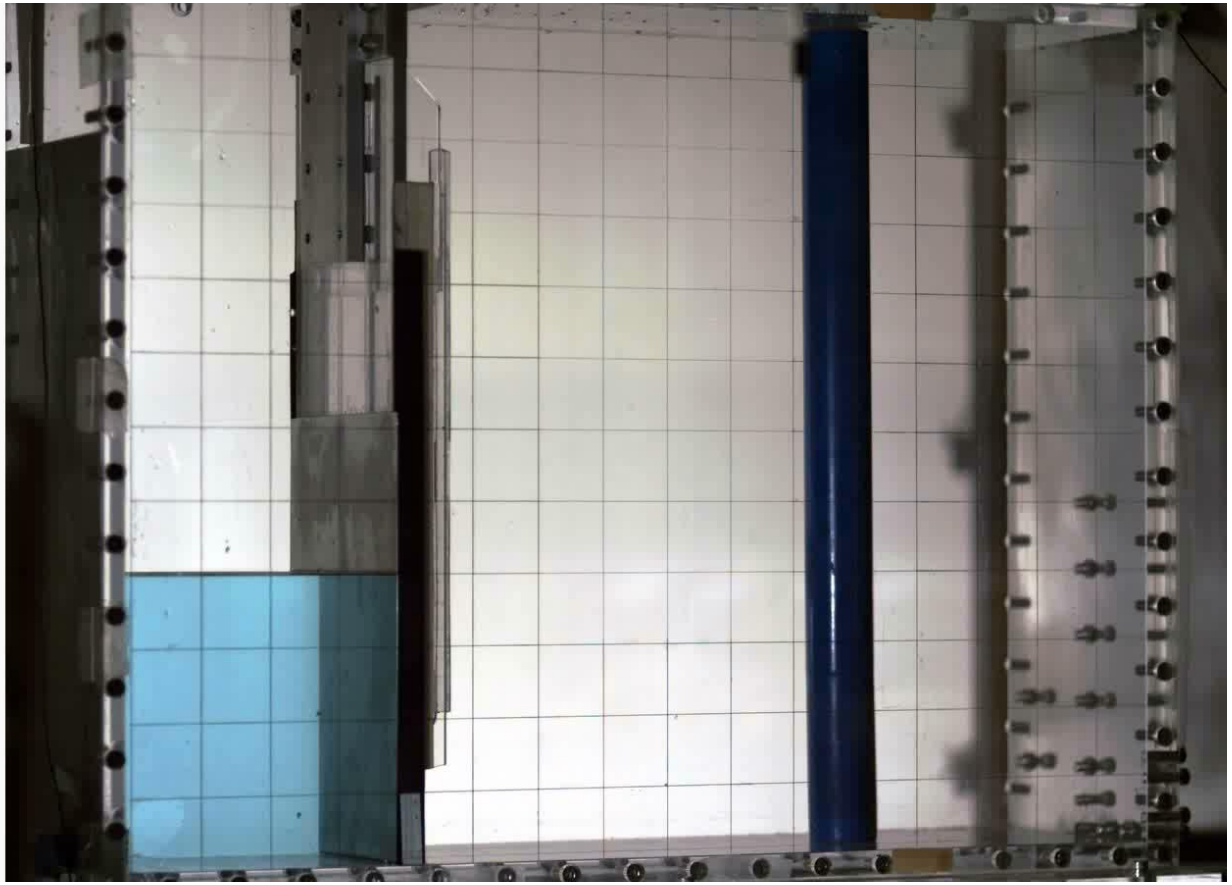


- Mesh was generated using GMSH
- Minimum spacing of 0.5mm and maximum spacing of 5mm .
- Cell number: 2,311,574 for circular cylinder case and 2,393,826 for square cylinder case.

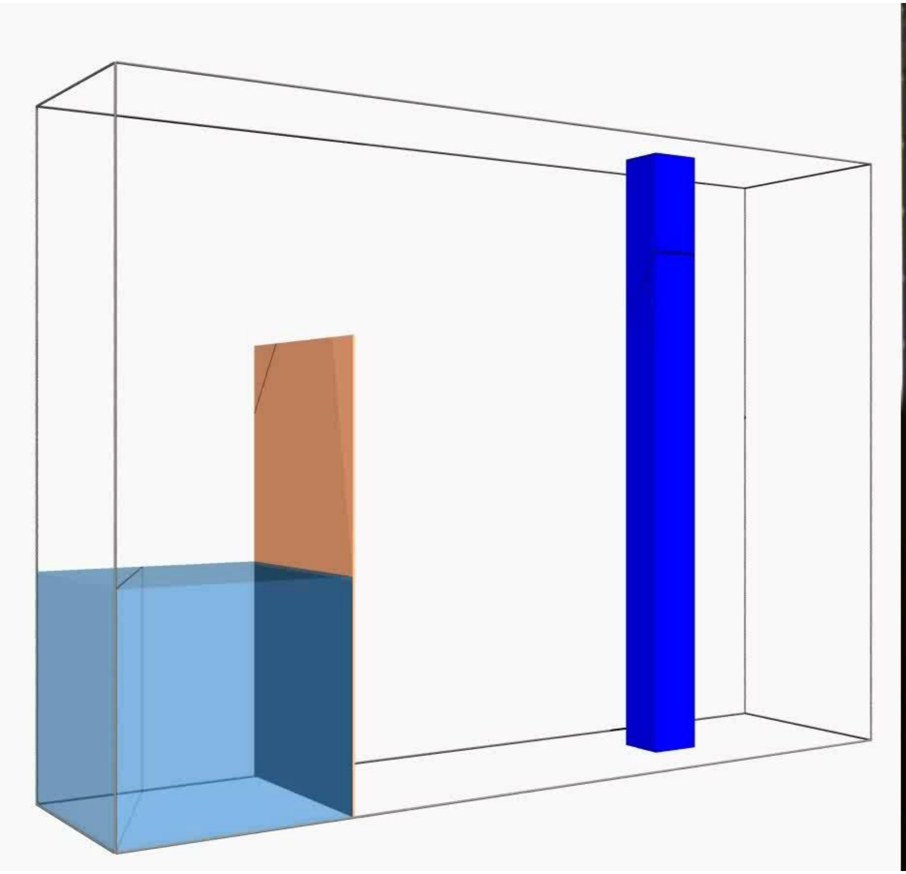
Case of Circular Cylinder

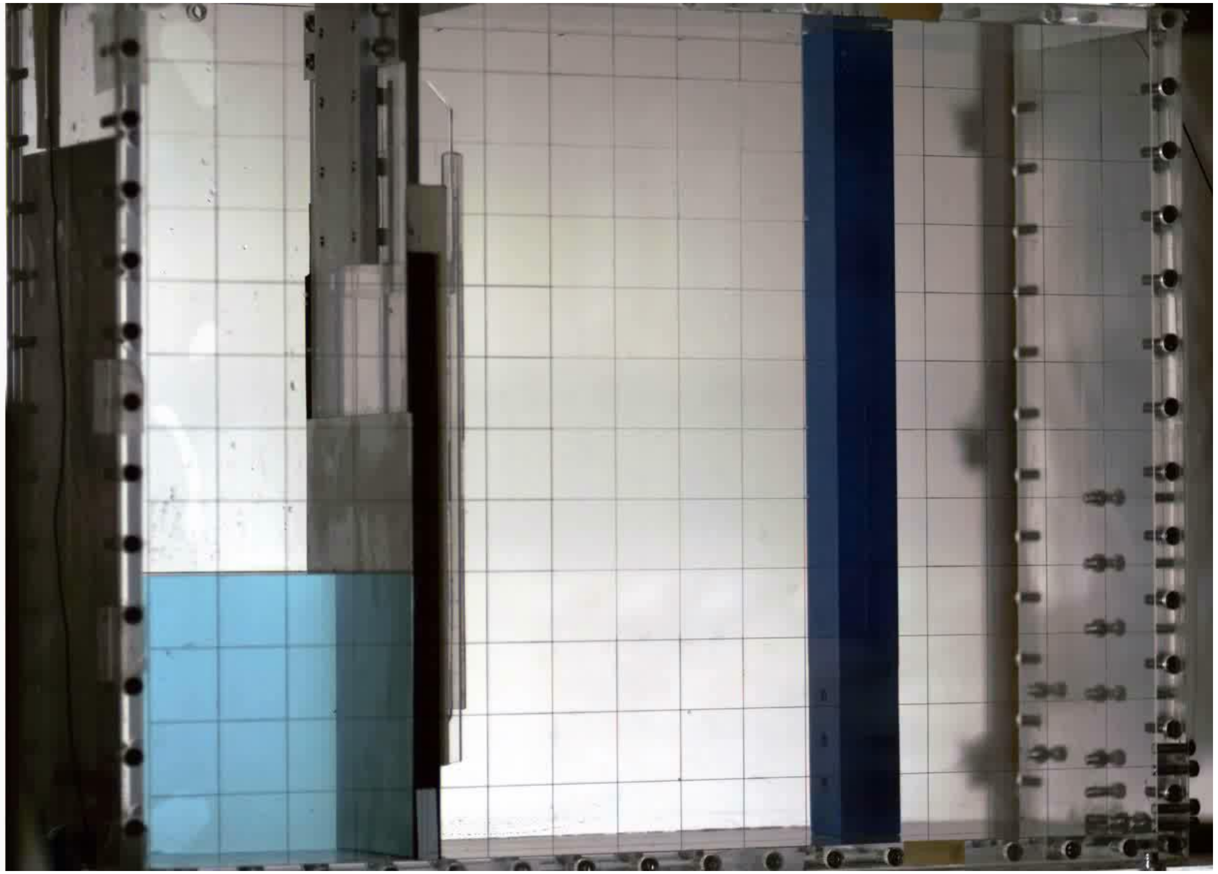
FVM



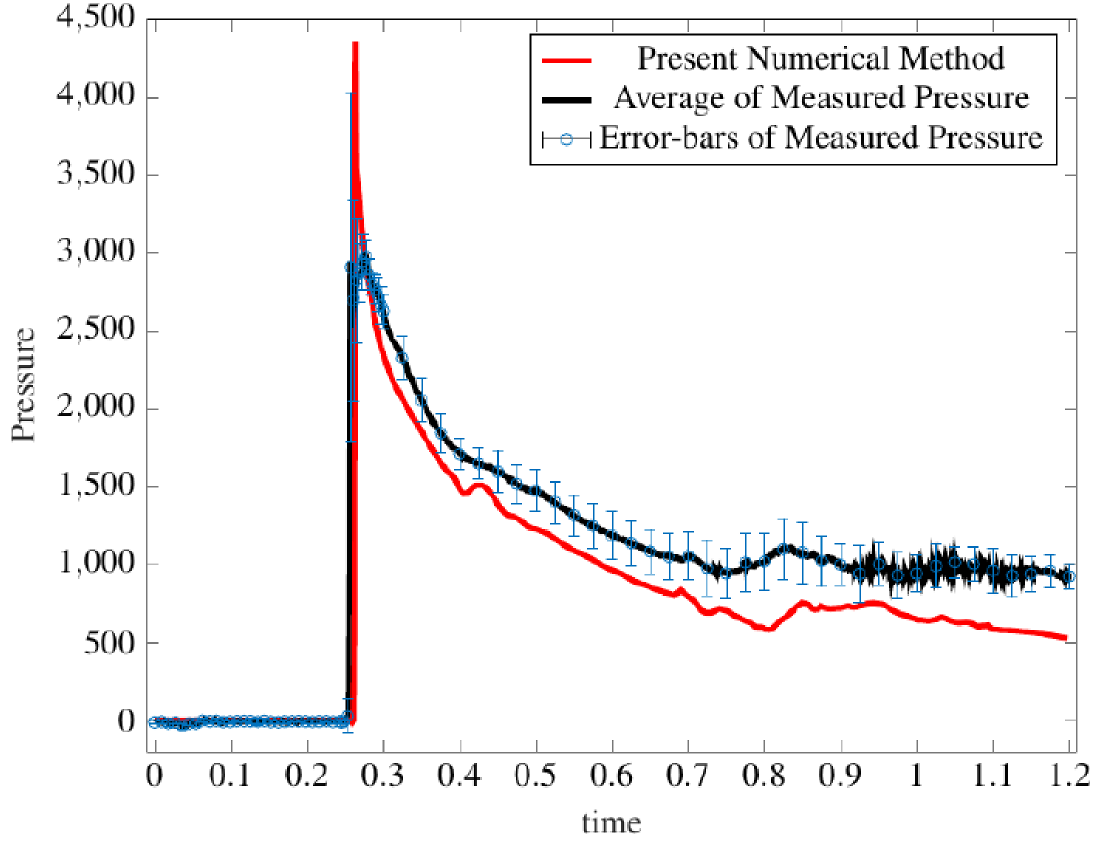


Case of Square Cylinder

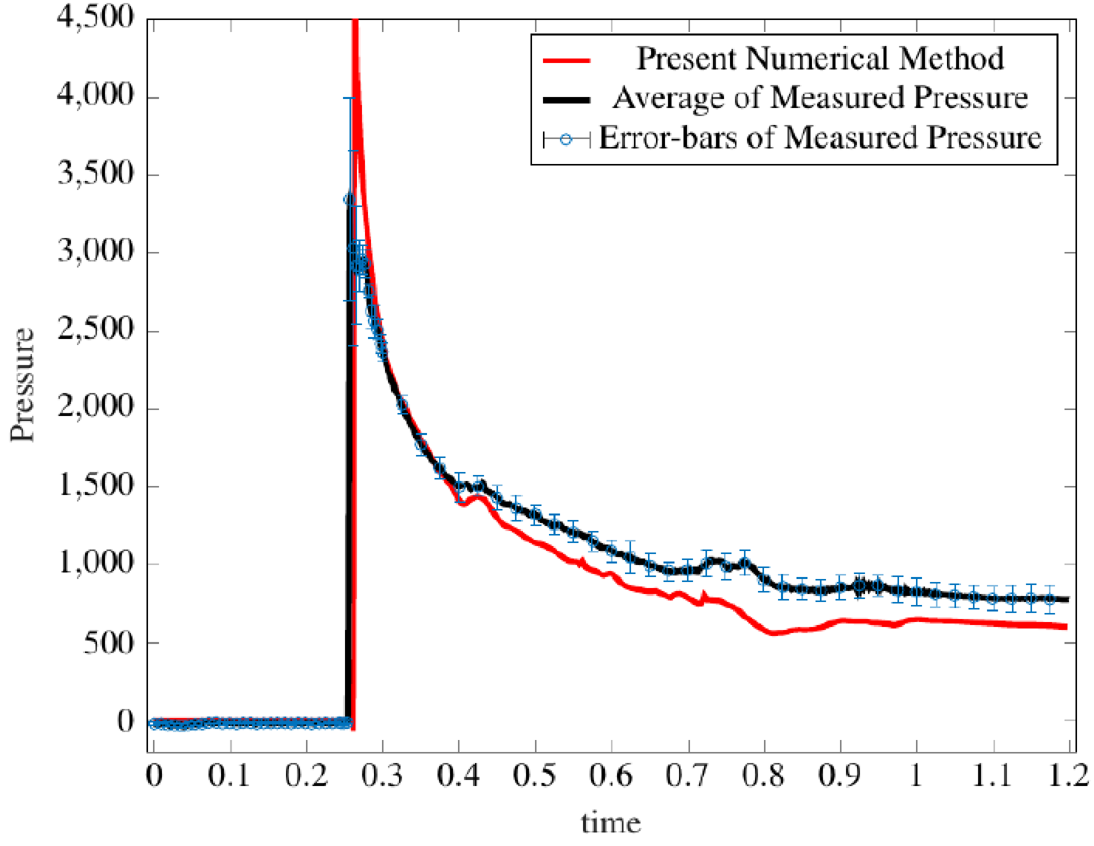




Pressure on the Cylinder



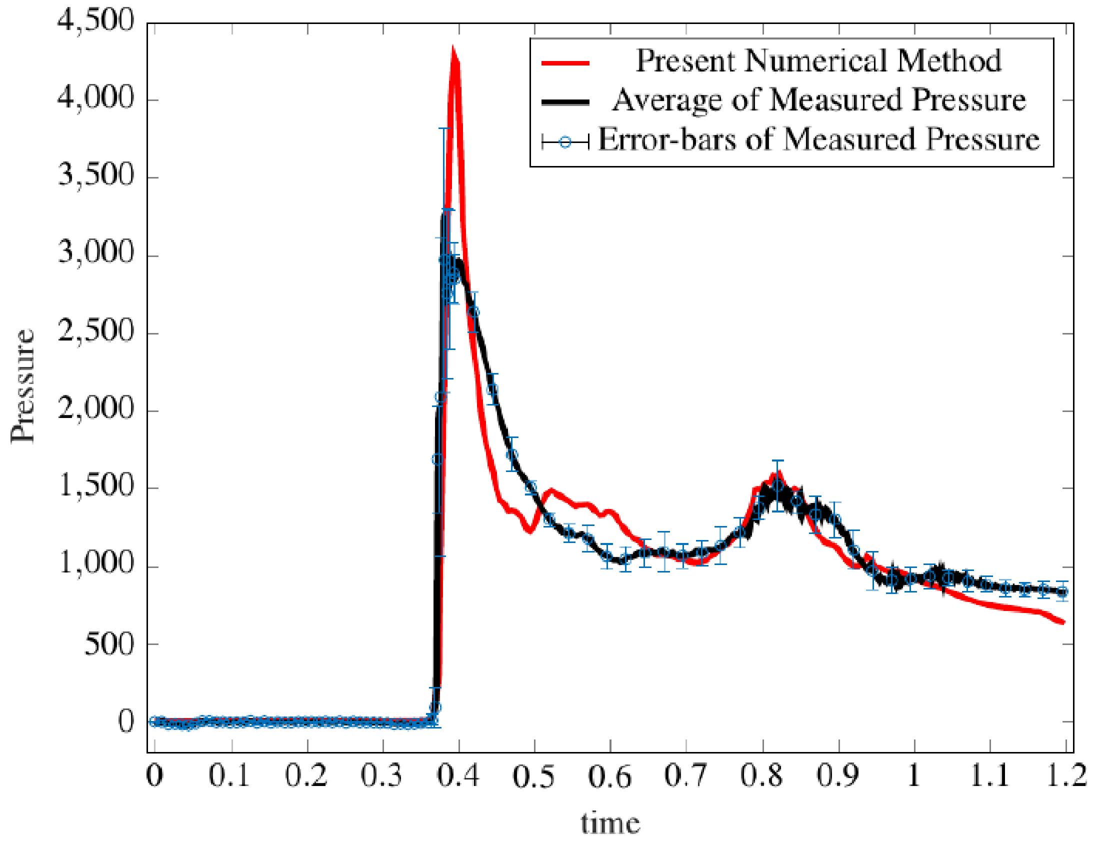
Circular Cylinder



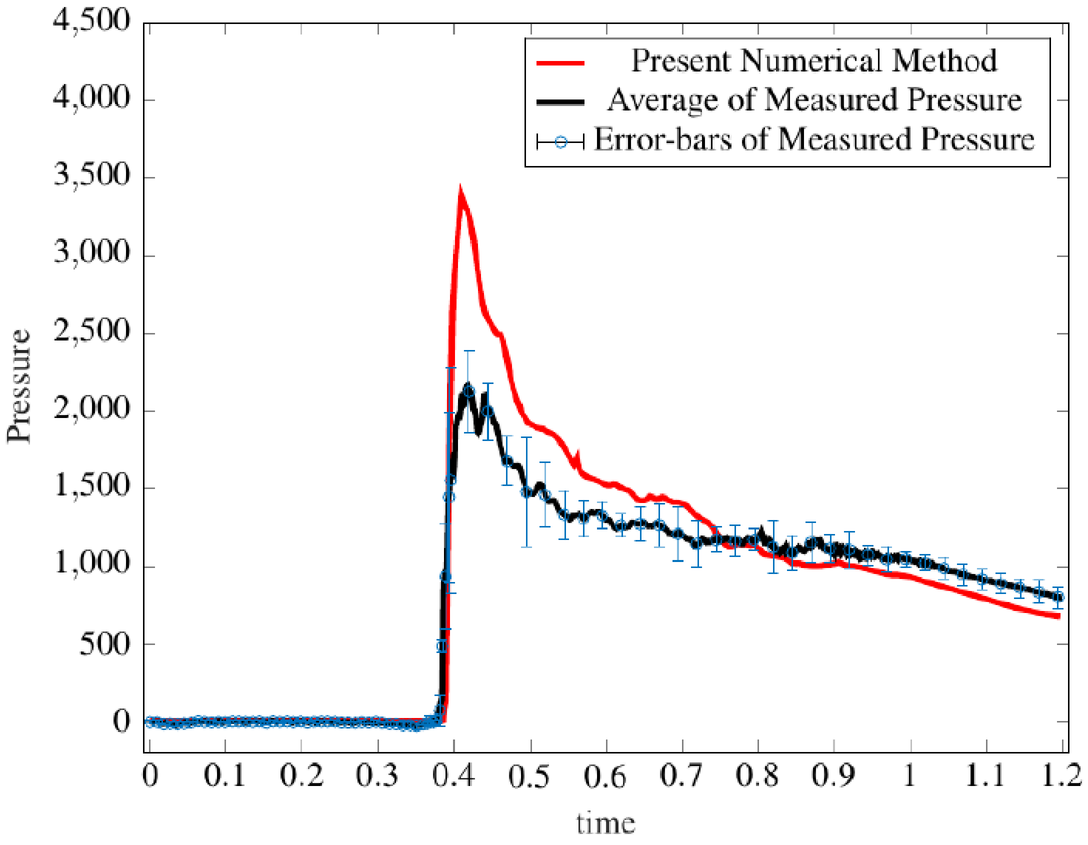
Square Cylinder

FVM

Pressure on the Downstream Wall



Circular Cylinder



Square Cylinder

Cumulant LBM Code

- Original Code developed as part of Dr. Watanabe's PhD degree research in Tokyo Institute of Technology ※
- Cumulant model
- AMR method
- Phase field method as interface capturing scheme
- DEM (Distinct Element Method) for solid bodies
- GPU implementation

※ Seiya Watanabe, "Implementation of AMR method to lattice Boltzmann method for large-scale GPU simulation of multiphase flow", PhD Thesis, Tokyo Institute of Technology, 2019

Lattice Boltzmann Method

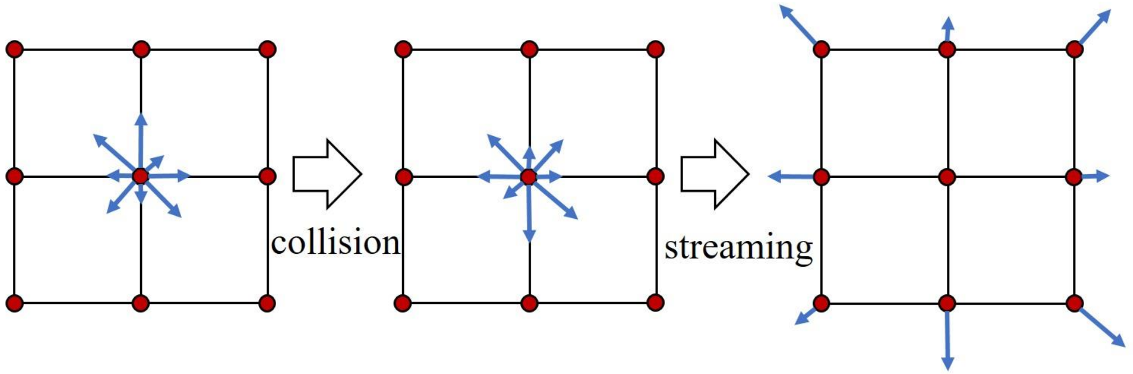
Assuming fluid as a set of virtual particles that stream and collide on a lattice point

→Solving the velocity distribution function f_{ijk} of virtual particles

$$f_{ijk}\left(\boldsymbol{x} + \boldsymbol{\xi}_{ijk}\Delta t, t + \Delta t\right) = f_{ijk}(\boldsymbol{x}, t) + \Omega_{ijk}$$

ξ_{ijk}: velocity of velocity distribution function

Ω_{ijk}: collision operator



Macroscopic variables

$$\rho(\boldsymbol{x}, t) = \sum_{i,j,k=-1}^{1} f_{ijk}(\boldsymbol{x}, t) \qquad \rho\boldsymbol{u}(\boldsymbol{x}, t) = \sum_{i,j,k=-1}^{1} \boldsymbol{\xi}_{ijk} f_{ijk}(\boldsymbol{x}, t)$$

Collision model : Single Relaxation Time (SRT)

- A basic model used in LBM computation
- Using single relaxation parameter τ
- Instability at high Reynolds numbers because of no numerical viscosity

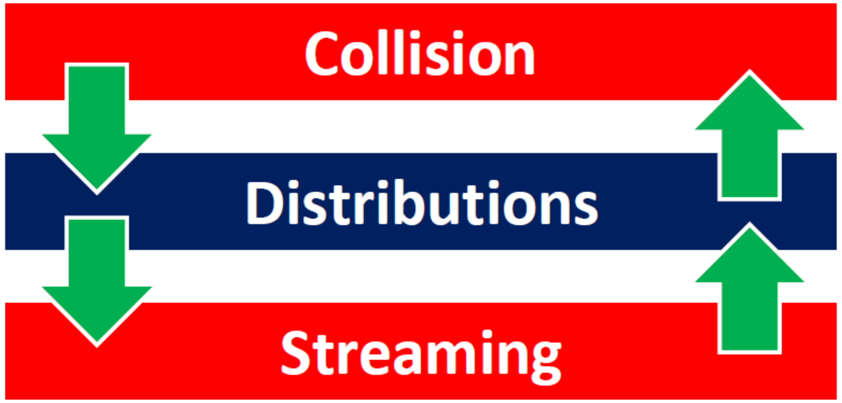
Collision operator

$$\Omega_{ijk} = -\frac{1}{\tau}\left(f_{ijk} - f_{ijk}^{\mathrm{eq}}\right)$$

$$\tau = \frac{\Delta t}{2} + \frac{\nu}{c_s^2}$$

ν : kinematic viscosity

c_s : Sound speed



f^{eq}: Equilibrium distribution (Maxwell-Boltzmann distribution for ideal gas)

$$f^{\mathrm{eq}} = \frac{\rho}{(\sqrt{\pi} c_s)^D} e^{-\frac{(\boldsymbol{\xi}-\boldsymbol{u})^2}{2c_s^2}}$$

Collision model : Cumulant model (CUM)

LBM

- Originally developed for turbulence flow simulations
- Distribution function f_{ijk} translaformed to cumulant C_{ijk} for collision calculation
- Numerical viscosity was introduced which works as LES model

$$C^*_{\alpha\beta\gamma} = (1-\omega_{\alpha\beta\gamma})C_{\alpha\beta\gamma} + \omega_{\alpha\beta\gamma}C^{eq}_{\alpha\beta\gamma}$$

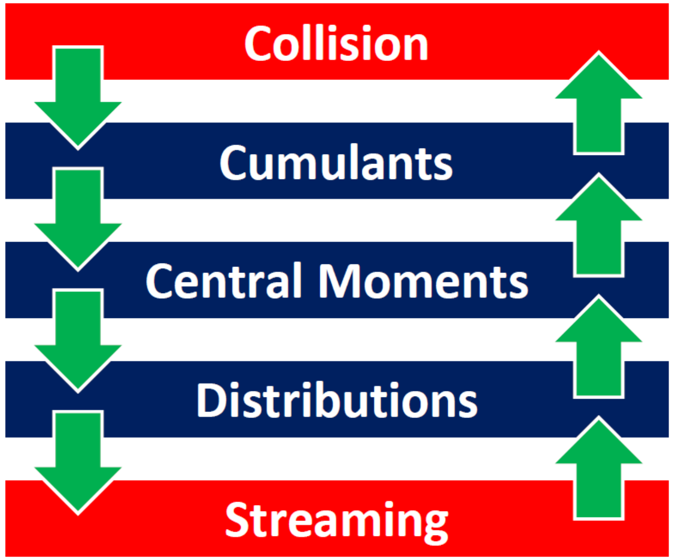
$$C_{\alpha\beta\gamma} = C^{-\alpha-\beta-\gamma}\frac{\partial^\alpha\partial^\beta\partial^\gamma}{\partial\Xi^\alpha\partial\Upsilon^\beta\partial Z^\gamma}\ln(F[\Xi,\Upsilon,Z])\bigg|_{\Xi=\Upsilon=Z=0}$$

$$M_{\alpha\beta\gamma} = \sum_{i,j,k} i^\alpha j^\beta k^\gamma f_{ijk}$$

$$\boldsymbol{f} = f_{ijk}(\boldsymbol{x},t)$$

$$f_{ijk}(\boldsymbol{x},t) = f^*_{ijk}(\boldsymbol{x}+\Delta x\boldsymbol{e}_{ijk}, t+\Delta t)$$

Cumulant

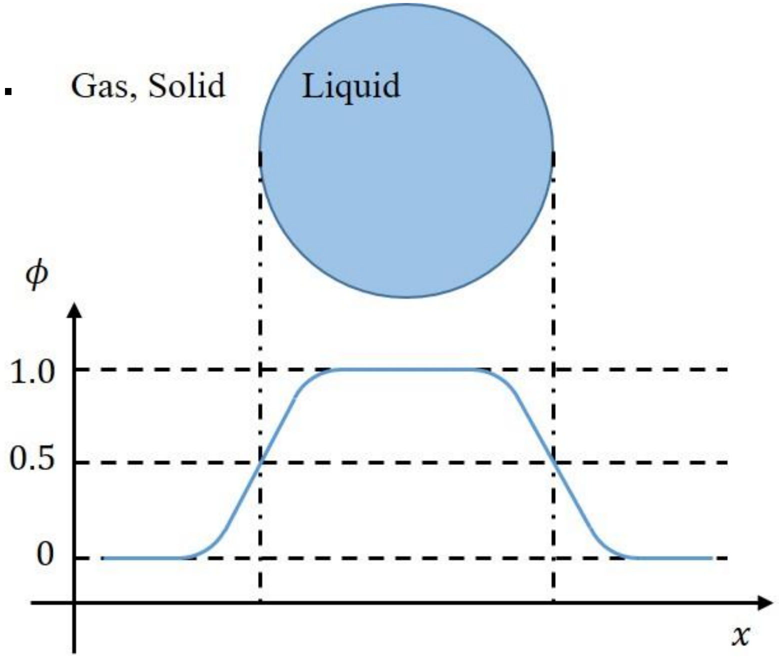


Geier, M., Schönherr, M., Pasquali, A., & Krafczyk, M. The cumulant lattice Boltzmann equation in three dimensions: Theory and validation. Computers & Mathematics with Applications, 70(4), 507-547 (2015).

Interface Capturing Scheme: Phase Field Method

ϕ : order variable; $\phi = 1$: liquid phase; $\phi = 0$: gas phase

Interfaces are represented by a smooth profile ($0 < \phi < 1$).



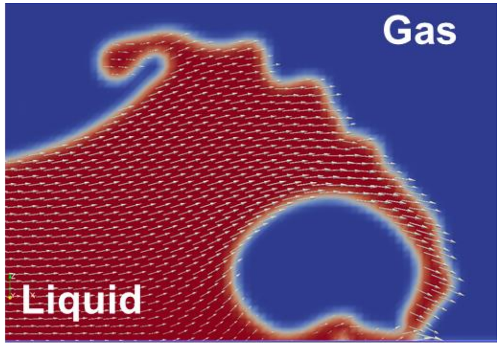
Allen-Cahn equation

$$\frac{\partial \phi}{\partial t} + \nabla \cdot (\boldsymbol{u}\phi) = \nabla \cdot \left[M \left(\nabla \phi - \frac{1-4(\phi-0.5)^2}{W} \boldsymbol{n} \right) \right]$$

$\boldsymbol{u}$: speed vector
M: mobility parameter
W: interface thickness
$\boldsymbol{n}$: unit normal vector of interface

Free-surface LBM

- Computing only liquid phase
- Boundary condition at gas-liquid interface



Contents of LBM Simulation

- **Comparison of collision models:** Single relaxation model (SRT) vs. Cumulant model
- **Effect of grid resolution:** 5 types of grid resolution
- **Effect of time step :** dt = 8.0×10^{-6} s , 4.0×10^{-6} s, 2.0×10^{-6} s
- **Effect of mobility parameter :** 3 types of mobility parameter

Comparison of Two Collision Models

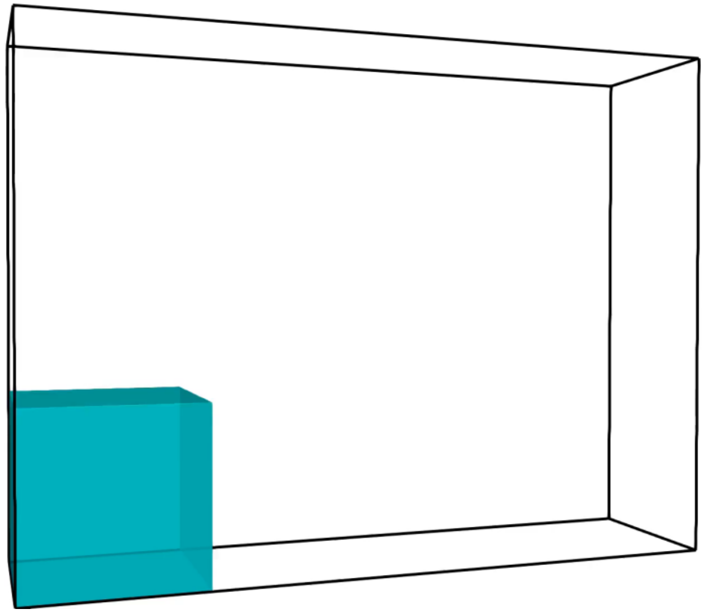
LBM

Free surface

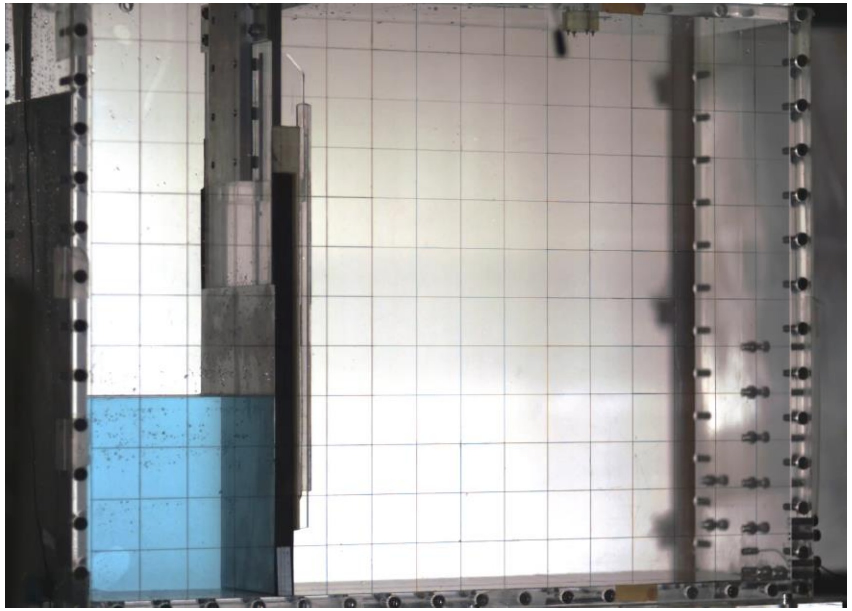
Computation condition

- uniform grid $600 \times 450 \times 150$
- grid interval 1.33 mm
- Time step 8.0×10^{-6} s

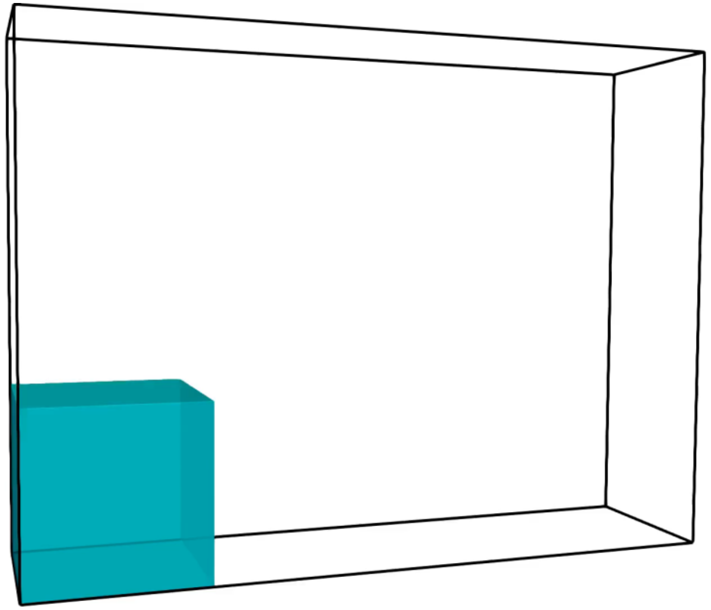
LBM-SRT



Experiment

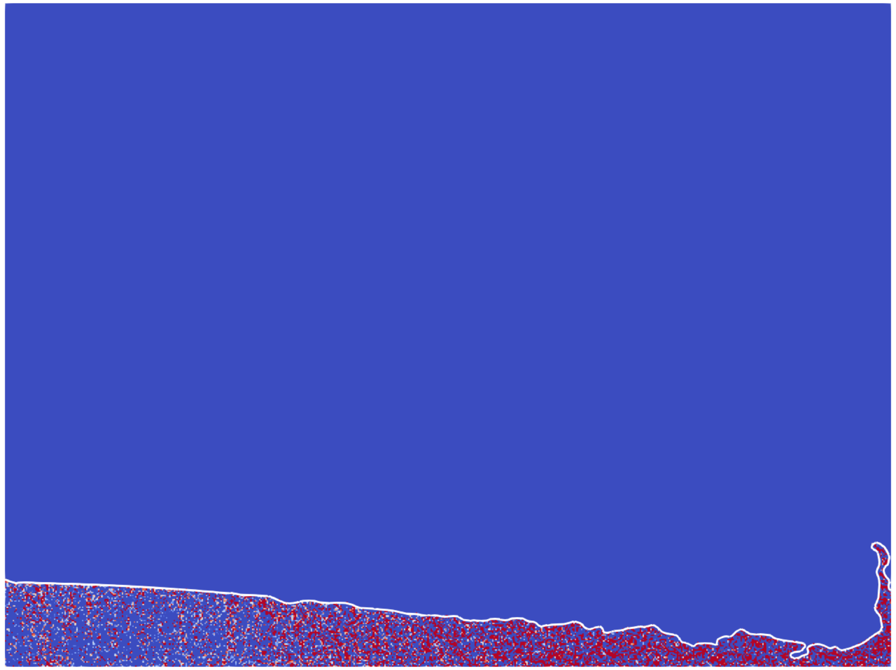


LBM-Cumulant

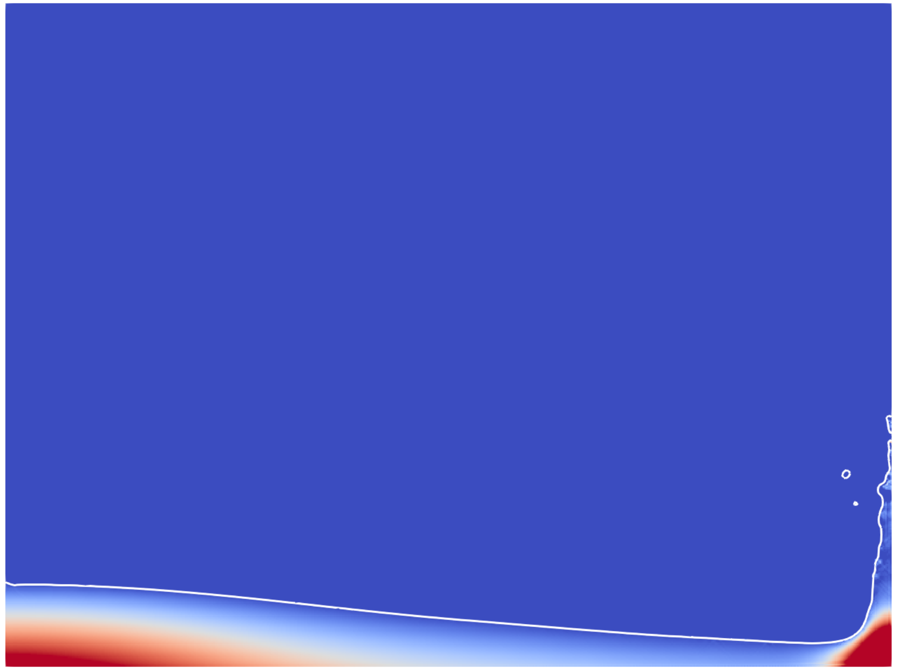


Comparison of Two Collision Models

Pressure field



LBM-SRT（With LES model）

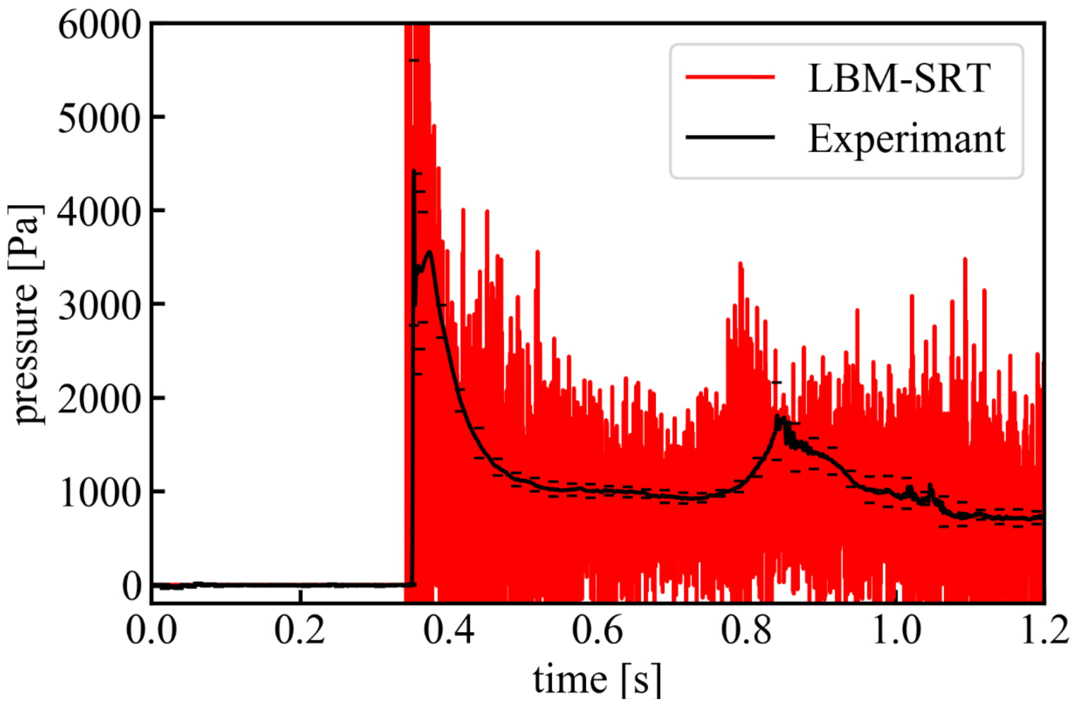


LBM-Cumulant

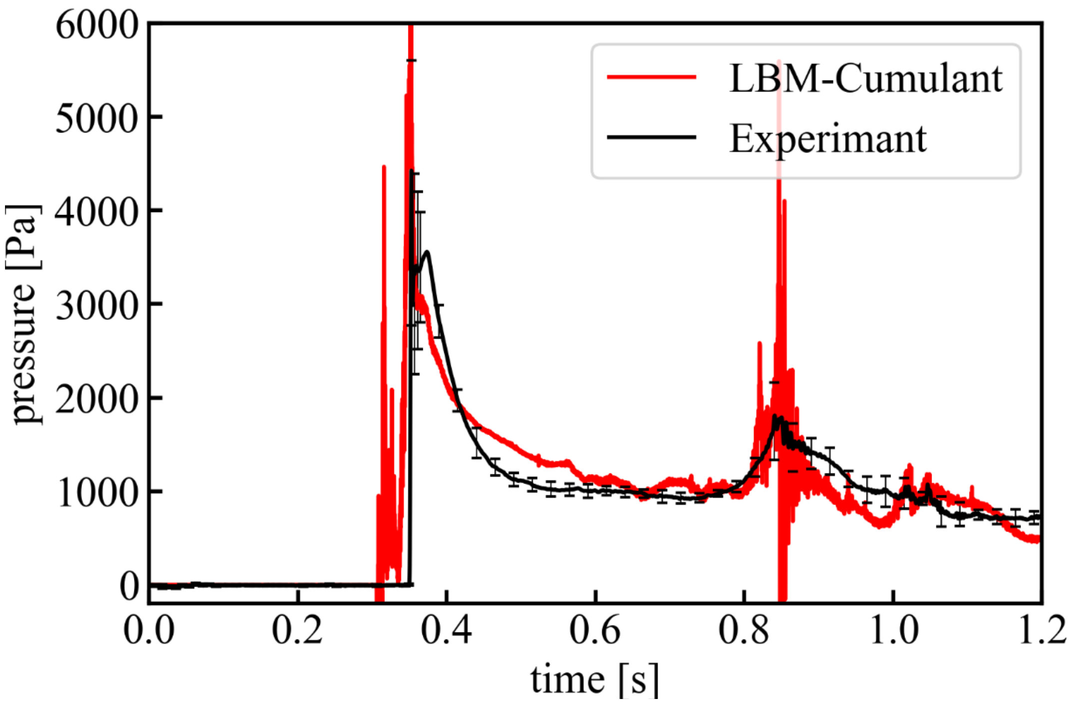
Comparison of Two Collision Models

LBM

Pressure on the wall

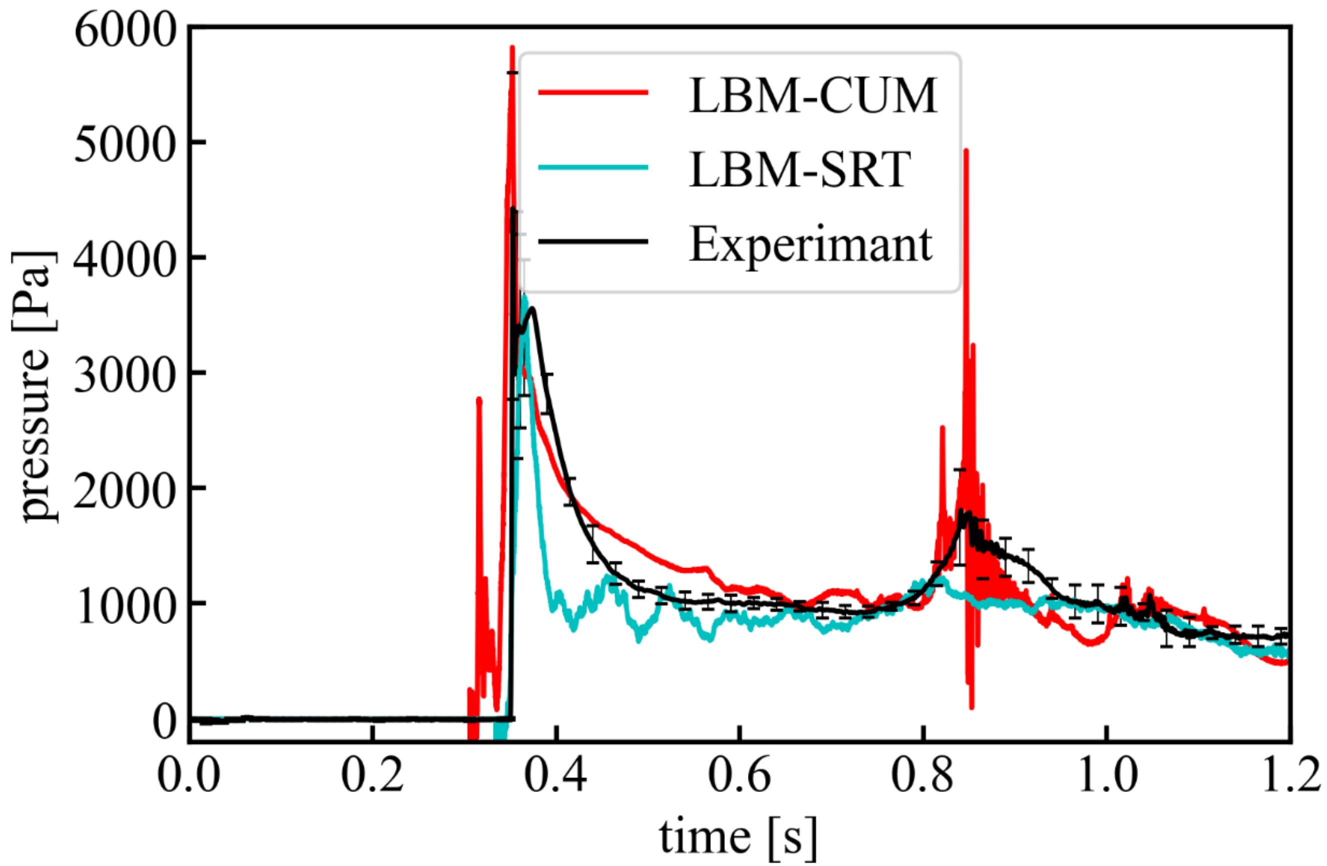


LBM-SRT（With LES model）



LBM-Cumulant

Comparison of Moving Averaged Pressure



- The average time is as 8×10^{-4}s

Grid Convergence Test

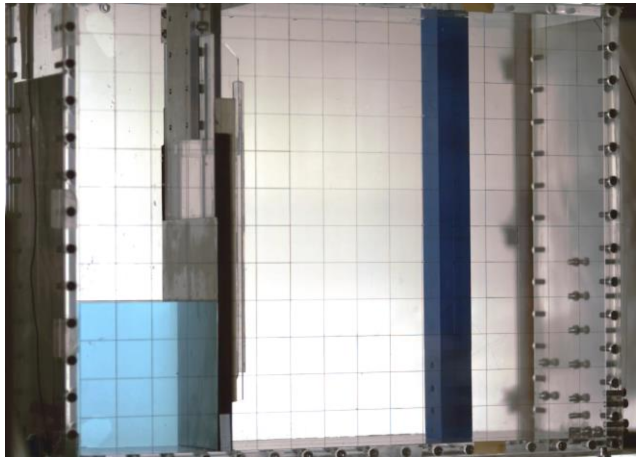
LBM

Lattice grid	Number of lattice points	Grid interval	Time step	GPU time
$100 \times 75 \times 25$	187,500	8.0 mm	4.8×10^{-5} s	4 minutes
$200 \times 150 \times 50$	1,500,000	4.0 mm	2.4×10^{-5} s	24 minutes
$400 \times 300 \times 100$	12,000,000	2.0 mm	1.2×10^{-5} s	2.8 hours
$600 \times 450 \times 150$	40,500,000	1.33 mm	8.0×10^{-6} s	20 hours
$800 \times 600 \times 200$	96,000,000	1.0 mm	6.0×10^{-6} s	50 hours

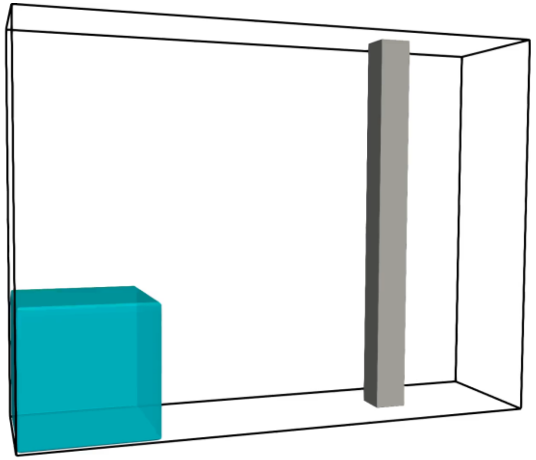
LBM

Grid Convergence Test (Square Cylinder)

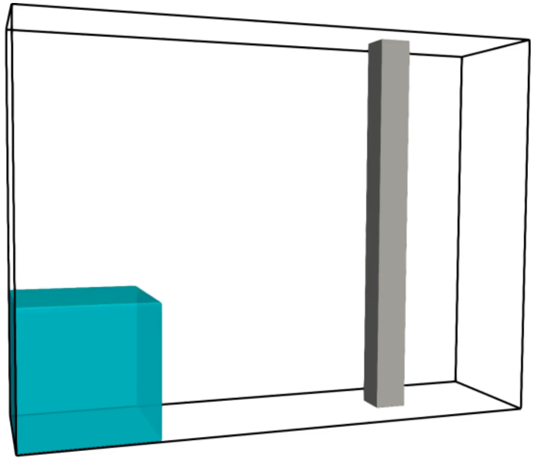
Experiment



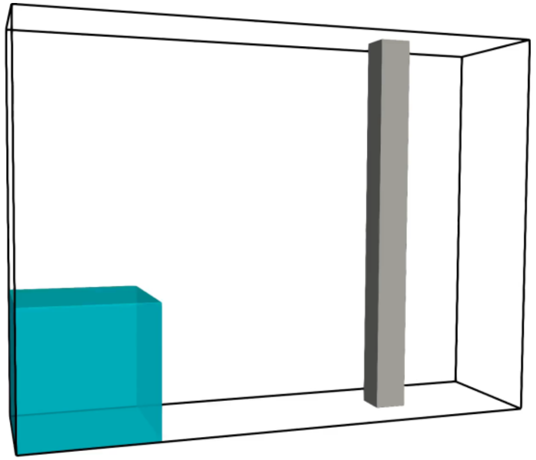
LBM-Cumulant



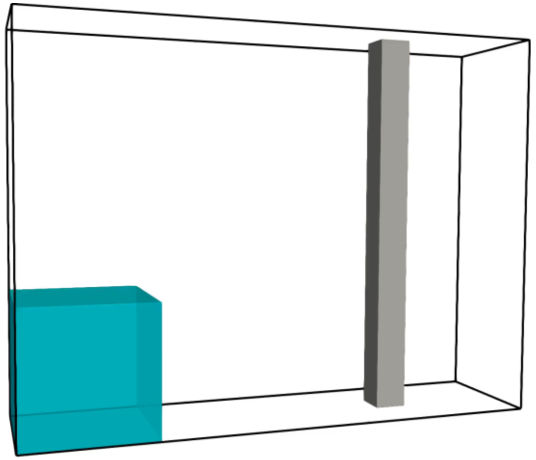
$100 \times 75 \times 25$



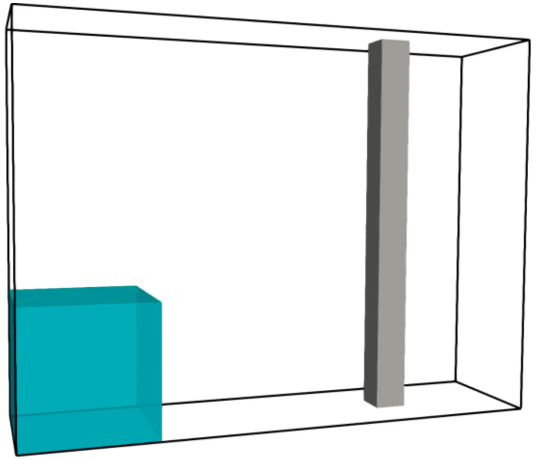
$200 \times 150 \times 50$



$400 \times 300 \times 100$



$600 \times 450 \times 150$



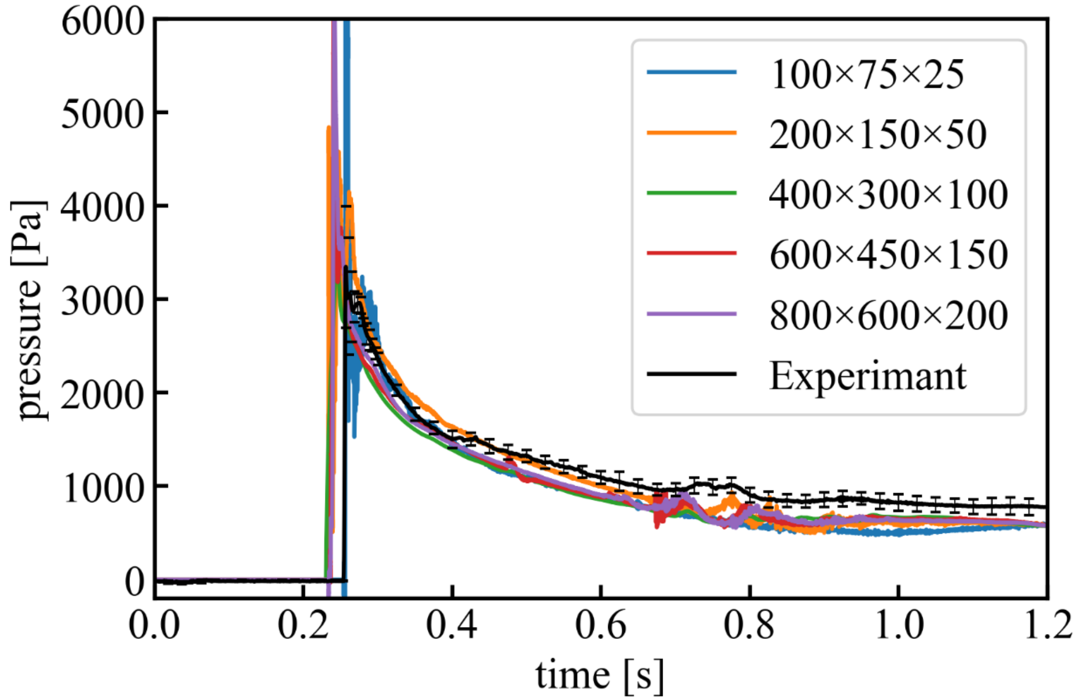
$800 \times 600 \times 200$

Grid Convergence Test (Square Cylinder)

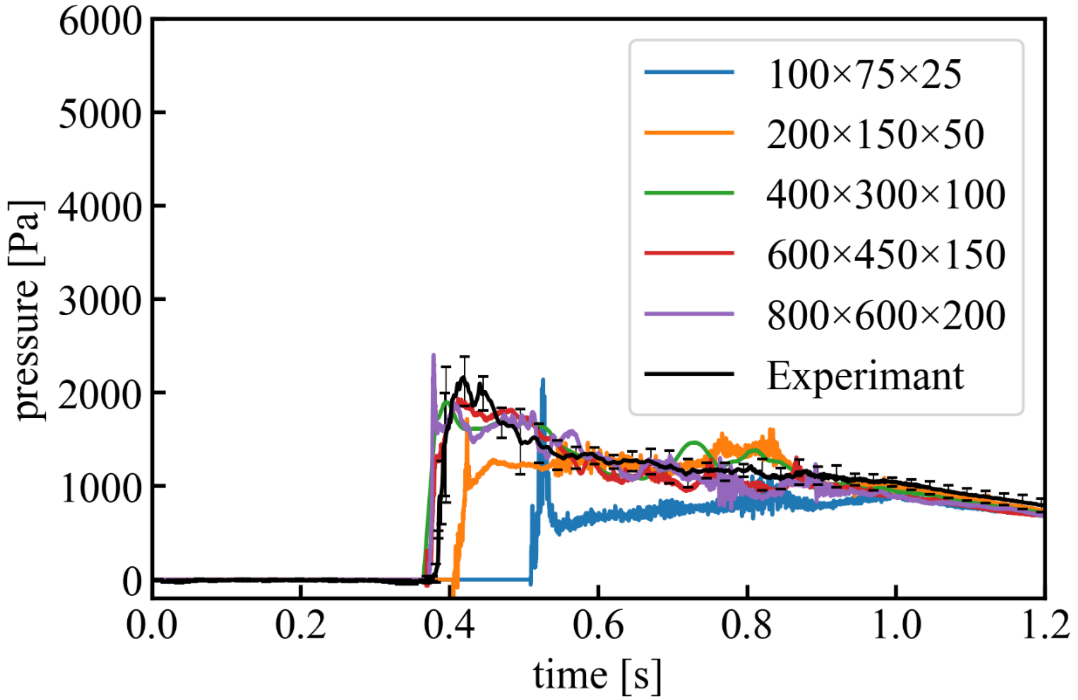
LBM

LBM-Cumulant

Pressure



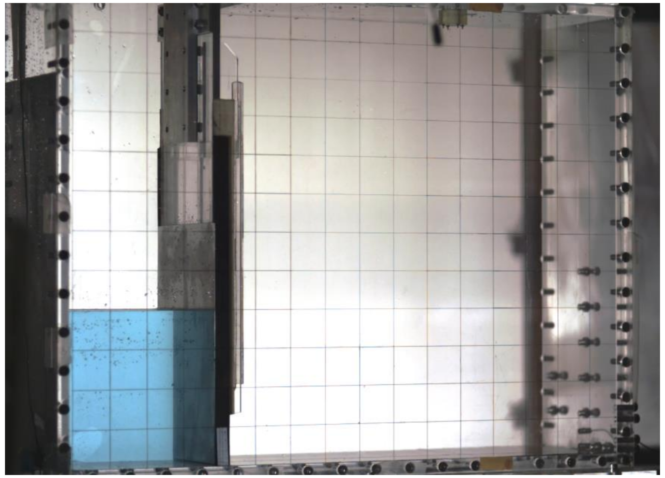
Square Cylinder Surface



Downstream Wall

Effect of Time-Step (No Obstacle)

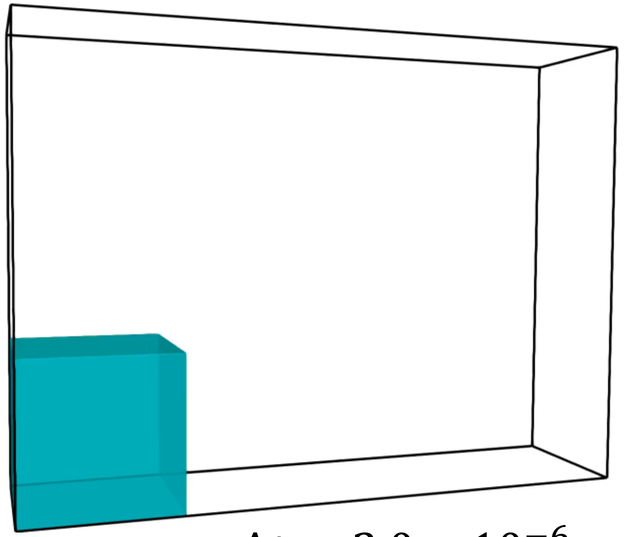
LBM



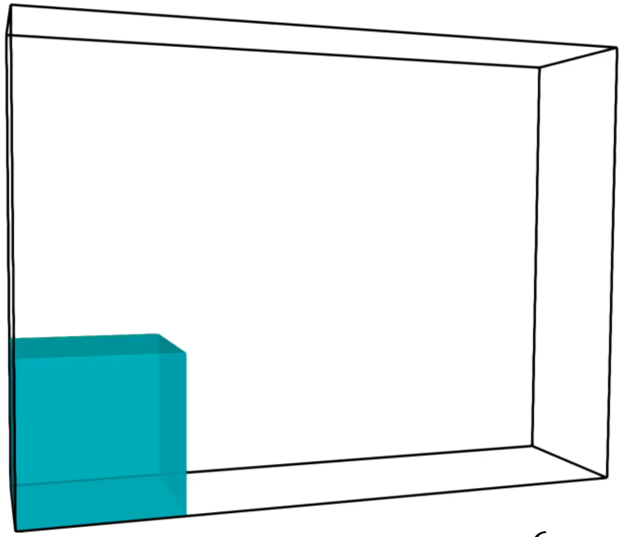
Experiment

Cumulant Model

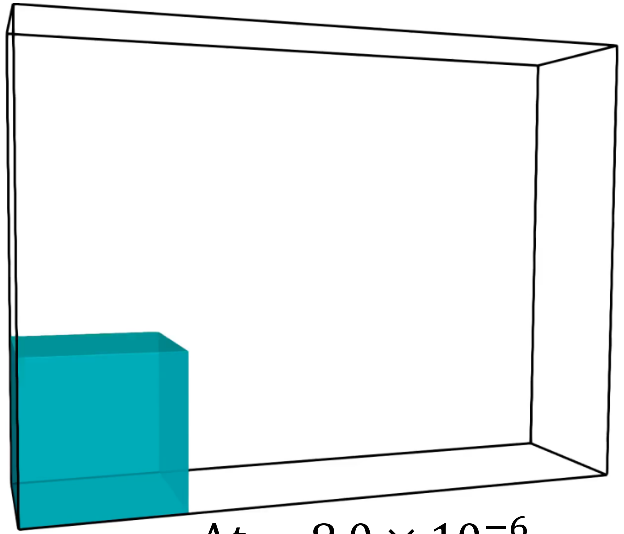
- Uniform grid　　$600 \times 450 \times 150$
- Grid interval　　1.33mm
- Time step　　8.0×10^{-6} s
  4.0×10^{-6} s
  2.0×10^{-6} s



$\Delta t = 2.0 \times 10^{-6}$



$\Delta t = 4.0 \times 10^{-6}$

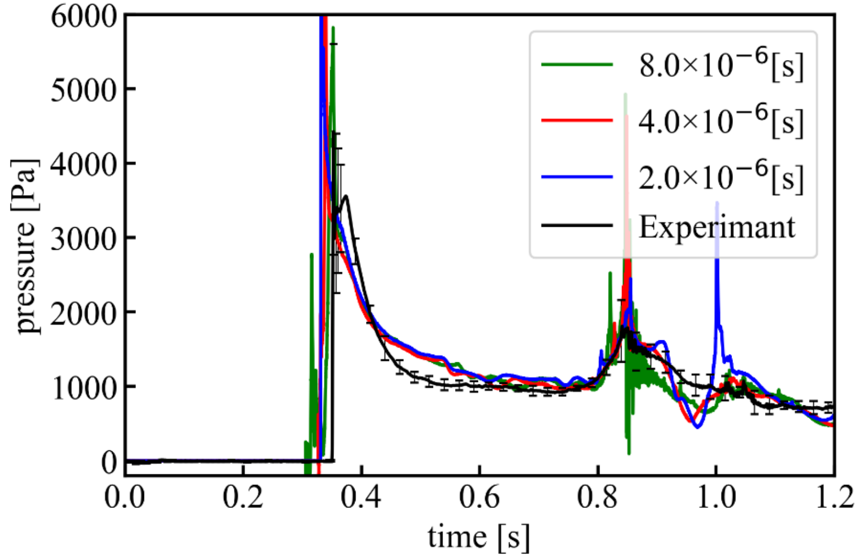


$\Delta t = 8.0 \times 10^{-6}$

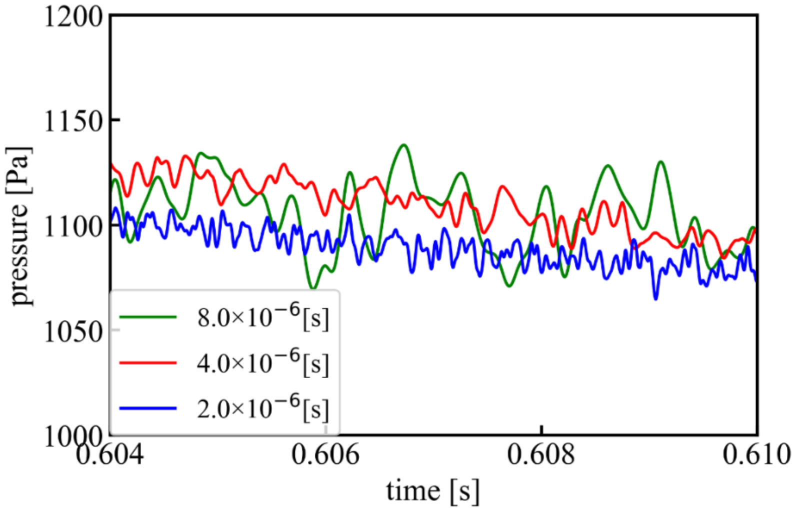
LBM

Effect of Time-Step (No Obstacle)

Pressure on the wall



Comparison with experiment



Enlarged view

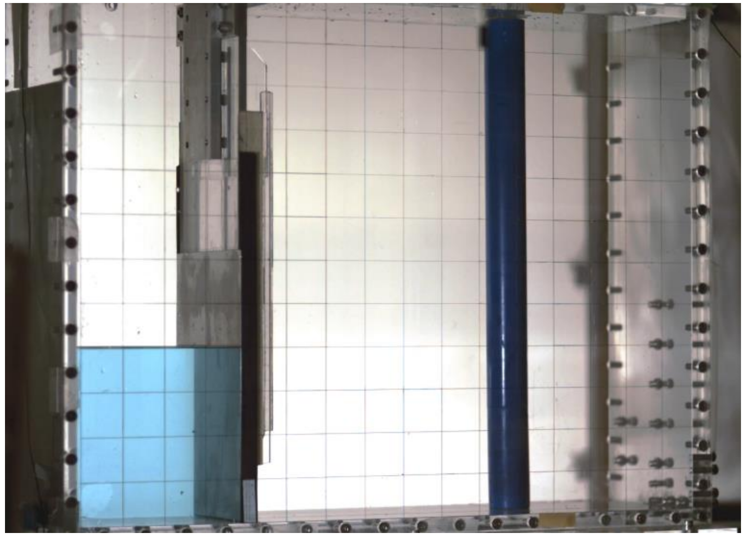
Time step [s]	Sound speed [m/s]
8.0×10^{-6}	96.2250
4.0×10^{-6}	192.4500
2.0×10^{-6}	384.9002

- Using small time step, the frequency of pressure oscillation increased and the amplitude decreased.

Effect of Interface Parameter (Circular Cylinder)

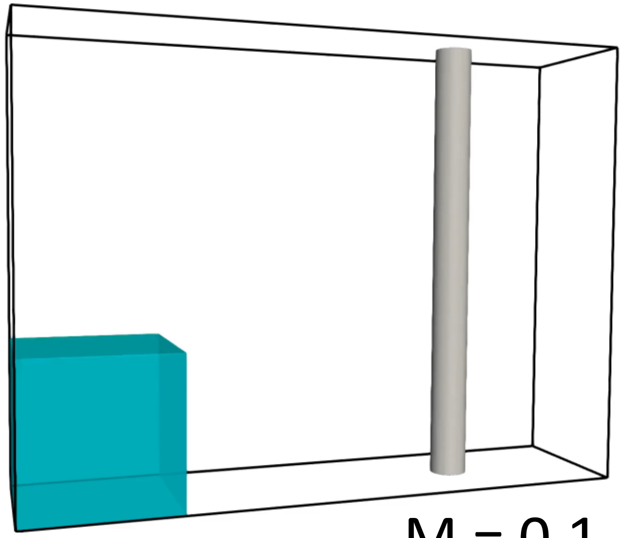
LBM

Experiment

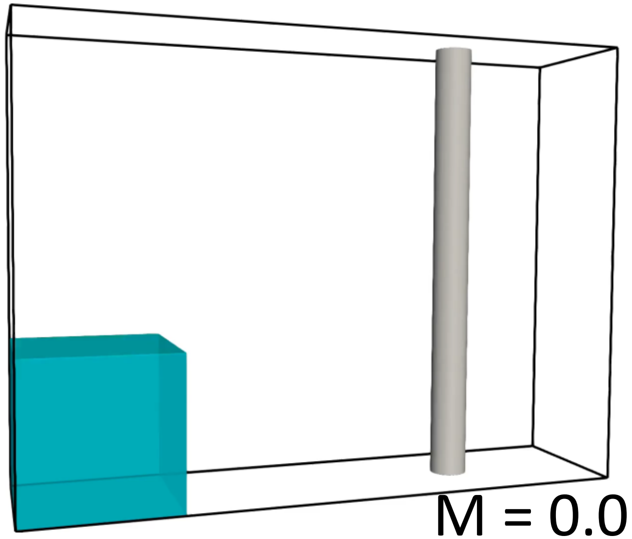


Cumulant Model

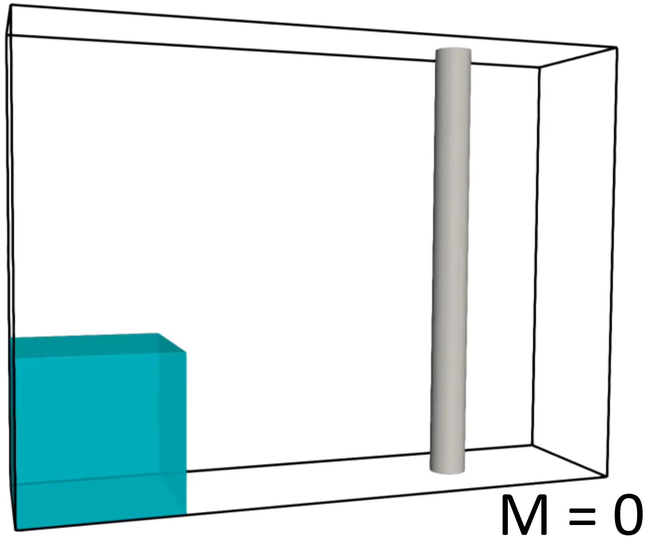
- Uniform grid　　$600 \times 450 \times 150$
- Grid interval　　1.33mm
- Time step　　4.0×10^{-6} s
- Mobility　　0.1, 0.05, 0.01



M = 0.1



M = 0.05

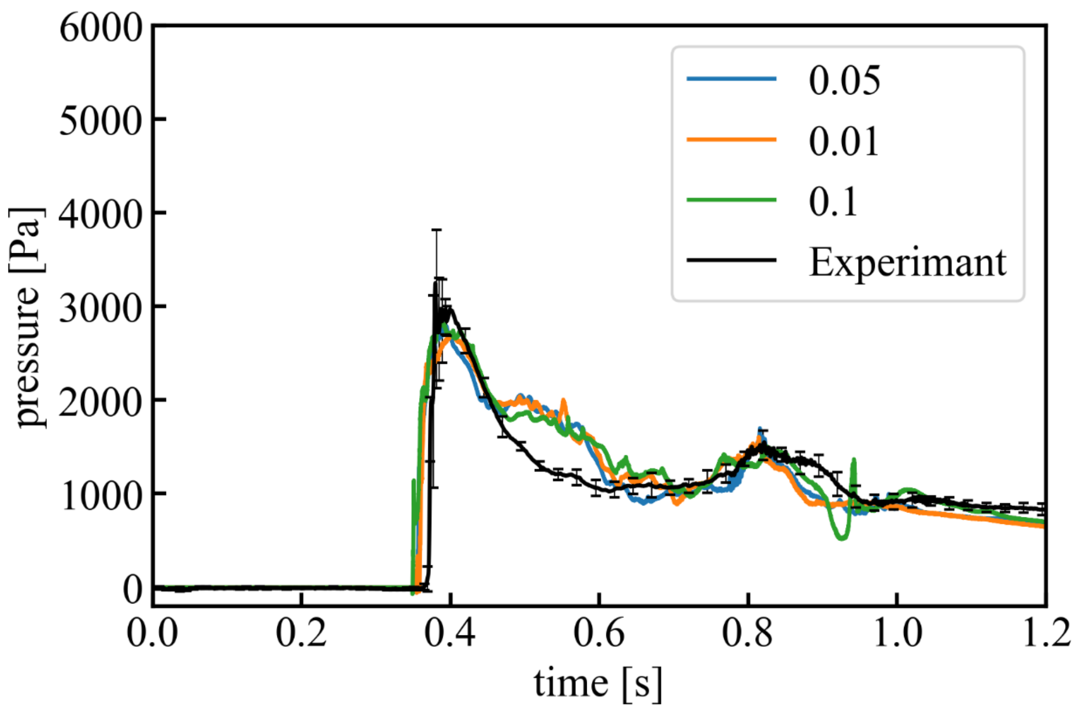


M = 0.01

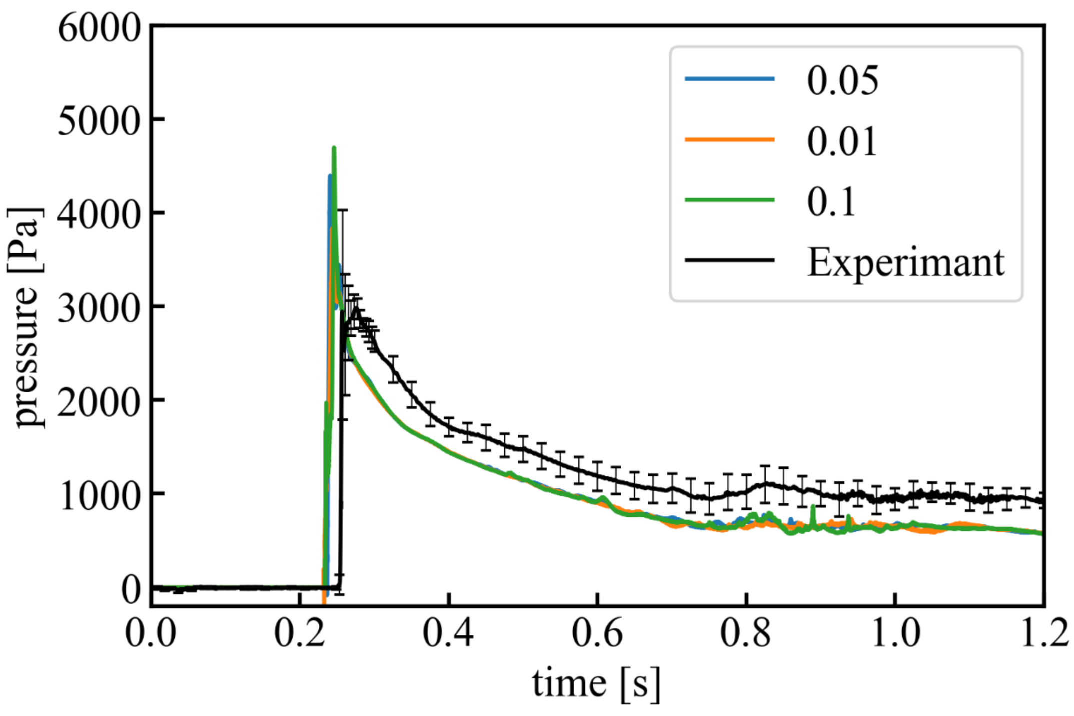
Effect of Interface Parameter (Circular Cylinder)

LBM

Pressure



Downstream Wall



Square Cylinder Surface

Summary of Experiment

- An experiment of the dam-break impact on a vertical cylinder, placed over a dry horizontal bed, has been carried out. The measured data can be used to validate the CFD codes on free surface impact prediction.
- The gate motion of the experiment has been studied and a gate motion formula was proposed which better fits the experimental data.
- The correlation between the gate motion and the time of impact on the cylindrical obstacle was found and its importance in the study of dam-break flows is demonstrated.
- Vertical cylinders with circular and square section were investigated in the experiment and the difference of free surface variation and pressure dynamics were discussed.

Summary of CFD Simulation

- Two in-house CFD codes, an unstructured mesh FVM code and a Cumulant LBM code, have been used to simulate the experimental cases.
- The FVM code with UMTHINC as the interface capturing scheme, gives good agreement with the newly conducted experiments on both free surface variation and pressures using a mesh with about 2M cells.
- Numerical simulation by LBM shows that the severe pressure oscillation by the SRT model can be greatly suppressed by the Cumulant model. Therefore by further improvement it is possible to apply the Cumulant LBM code to prediction of free surface impact problems.
- A lattice point number of 40M is required to achieve same quality as FVM with 2M cells. The computation time for LBM with 40M points is about 20 hours by using a multi-GPU system, while about 6 hours is required for FVM simulation (2M cells, in a PC cluster system).

Thank You!