Study on flow of solid particles in solid-liquid two phase flow through an abrupt contraction

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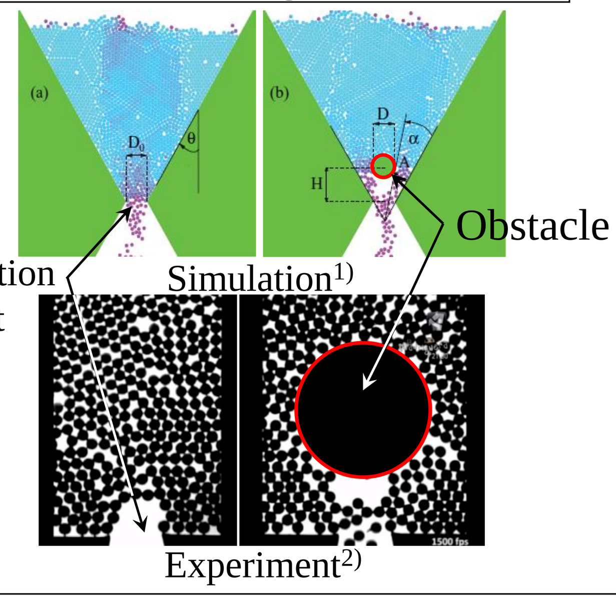
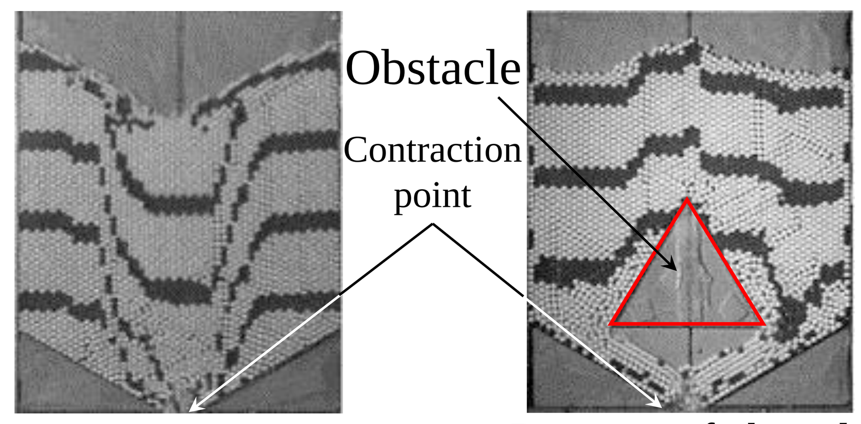
Introduction

It is important to transport objects smoothly in improving the efficiency of the production process. The transportation of objects stagnate in the abrupt contraction point. In order to avoid this problem, there is a method to set an obstacle in front of the abrupt contraction point. However, no such a method has been reported for solid-liquid two phase flow. We think that there is "specific obstacle effect" on solid-liquid two phase flow unlike an obstacle effect on granular flow with regard to flow situation. The purpose of this research is verifying the effect of mitigation of the stagnation of particles by an obstacle in front of the orifice on solid-liquid two phase flow by numerical simulation and experiment.

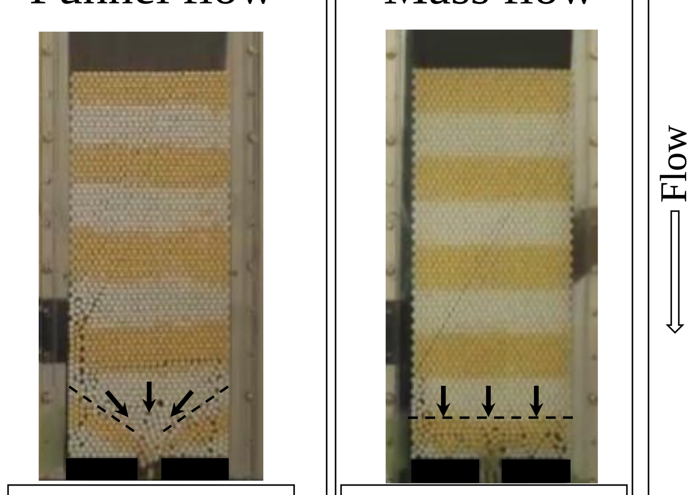
In the case of the granular flow



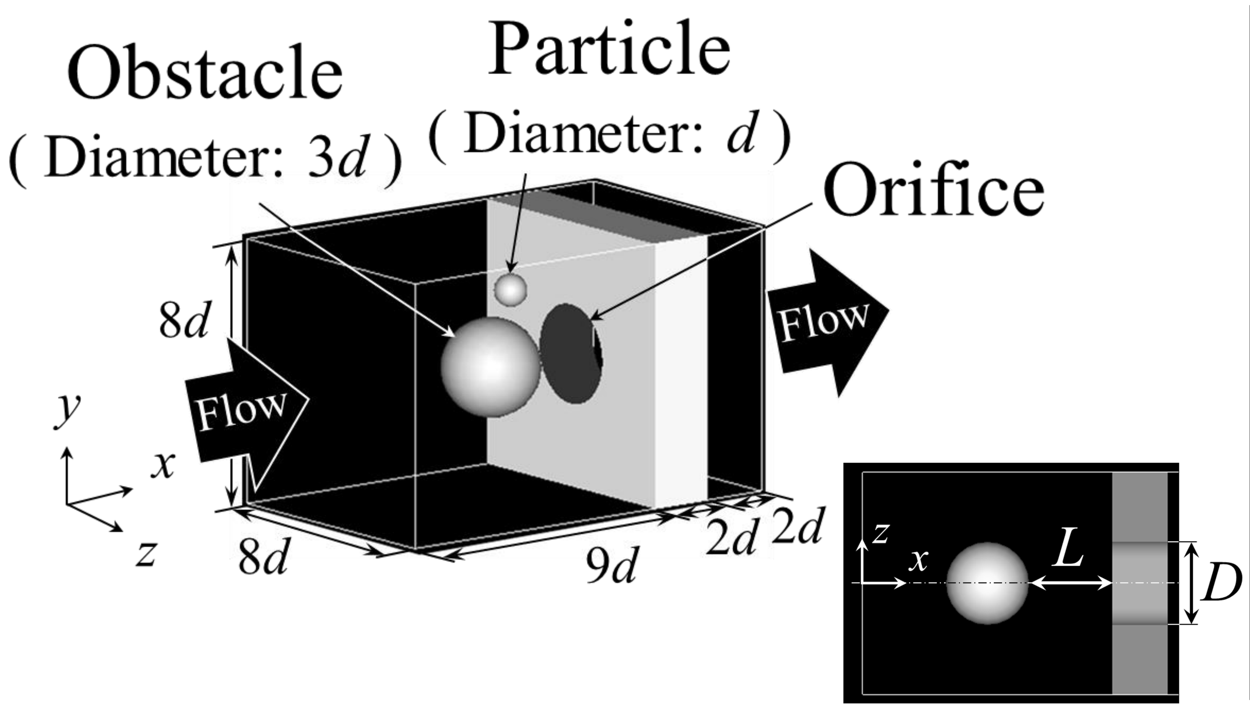
Difference in flow situation



Granular flow in silo[3]



Numerical Simulation (DEM-DNS: SNAP-F[4][5])



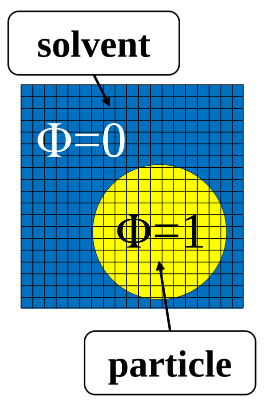
Governing equation

➢ Fluid field

$$\nabla \cdot \boldsymbol{v} = 0$$

$$\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v} \cdot \nabla \boldsymbol{v} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \boldsymbol{v} - \frac{1}{\rho}\boldsymbol{D} + \Phi \boldsymbol{\alpha}$$

$$\boldsymbol{\alpha} = \frac{\boldsymbol{v}^p - \boldsymbol{v}}{\Delta t} + \frac{1}{\rho}\nabla p + \boldsymbol{v} \cdot \nabla \boldsymbol{v} - \nu \nabla^2 \boldsymbol{v} + \frac{1}{\rho}\boldsymbol{D}$$



➢ Motion of particle ($\boldsymbol{v}^p = \boldsymbol{V} + \boldsymbol{\omega} \times \boldsymbol{r}$)

$$m\frac{d\boldsymbol{V}}{dt} = \boldsymbol{F}^c + \boldsymbol{F}^h \qquad \boldsymbol{F}^h = -\int \varphi^p(\rho\boldsymbol{\alpha} + \boldsymbol{D})d\boldsymbol{r}$$

$$I\frac{d\boldsymbol{\omega}}{dt} = \boldsymbol{T}^c + \boldsymbol{T}^h \qquad \boldsymbol{T}^h = -\int \varphi^p(\boldsymbol{r} \times \rho\boldsymbol{\alpha})d\boldsymbol{r}$$

[t: Time, $\boldsymbol{v}$: Velocity, ρ: Density, p: Pressure, μ: Viscosity, $\boldsymbol{D}$: Pressure gradient vector, Φ: Volume fraction of solid phase, $\boldsymbol{\alpha}$: Acceleration vector associated with the velocity of particles on the grid, $\boldsymbol{v}^p$: Particle velocity]

[m: Mass, $\boldsymbol{V}$: Translational velocity, $\boldsymbol{F}^c$: Contact force, $\boldsymbol{F}^h$: Hydrodynamic force, I: Moment of inertia, $\boldsymbol{\omega}$: Angular velocity, $\boldsymbol{T}^c$: Contact torque, $\boldsymbol{T}^h$: Hydrodynamic torque, φ^p: The volume fraction of the particle, whose sum is Φ]

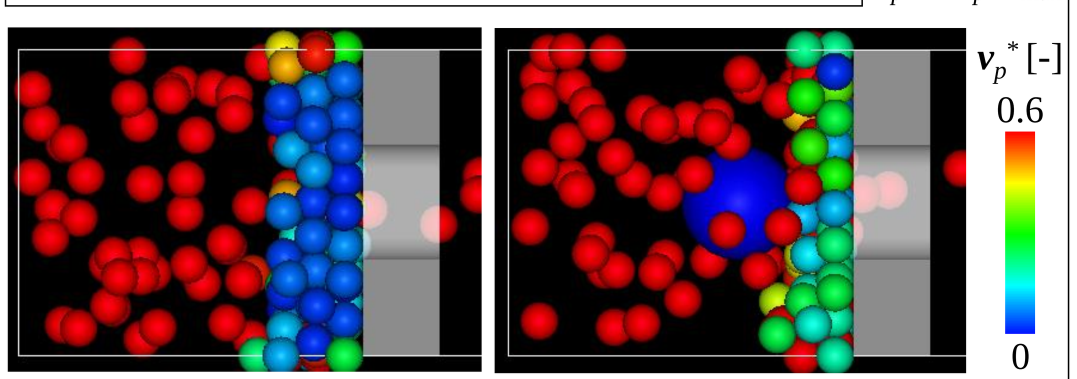
Condition

Nomenclature	Value
Maximum Reynolds number, Re_{max} [-]*	≈1
Concentration, Φ_s [vol%]	5, 10, 15
Distance of obstacle-orifice, L [m]	1d, 1.5d, 2d, 3d
Diameter of orifice, D [m]	3d, 4d

* Use maximum velocity when particle and obstacle are absent; v_{max}

An example of the result: Flow situation and $R(t)$ (Condition: Φ_s= 10 [vol%], D=3d)

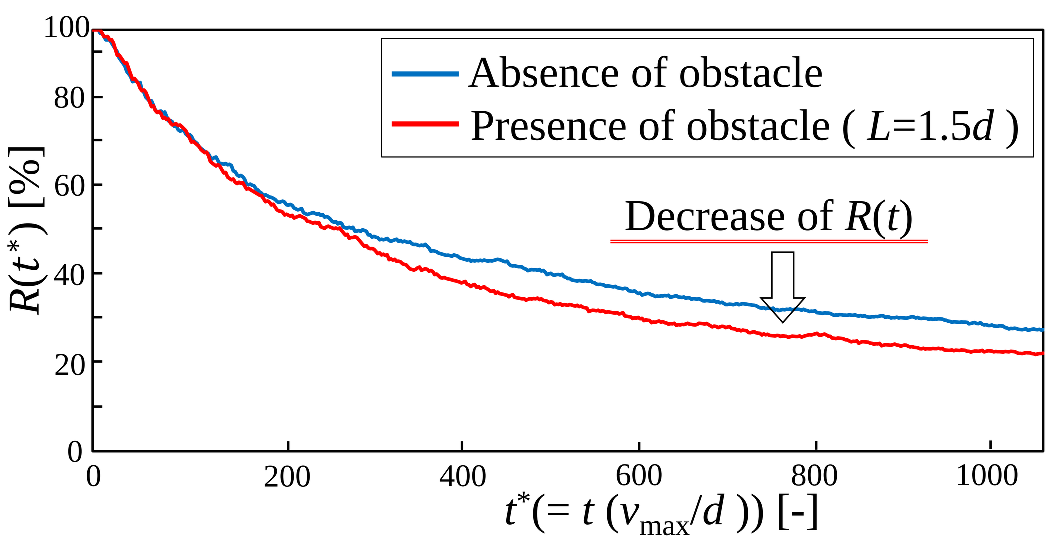
$v_p^* = v_p / v_{max}$



➢Evaluation method

$$R(t^*) = \left(1 - \frac{n_{out}(t^*)}{n_{in}(t^*)}\right) \times 100\ [\%]$$

[$R(t^*)$: Rejection rate of particles [%], $n_{in}(t^*)$: The number of inflow particles [-], $n_{out}(t^*)$: The number of outflow particles [-]]



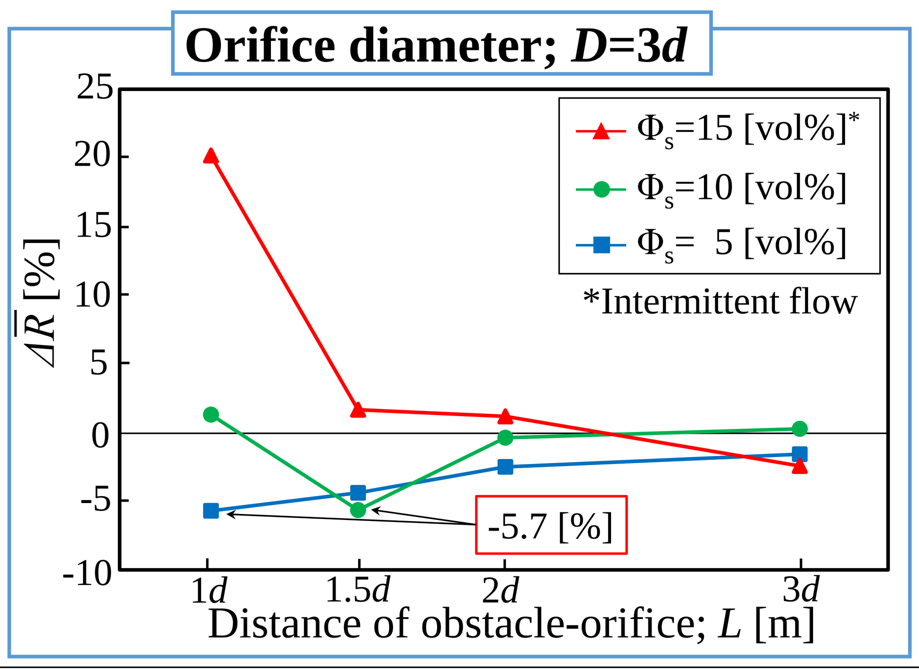
Result: The average rejection rate of particle $\Delta\bar{R}$ [%]

$$\Delta\bar{R} = \frac{1}{\Delta t^*}\int R(t^*)dt^* - \frac{1}{\Delta t^*}\int R_{abs.}(t^*)dt^*$$

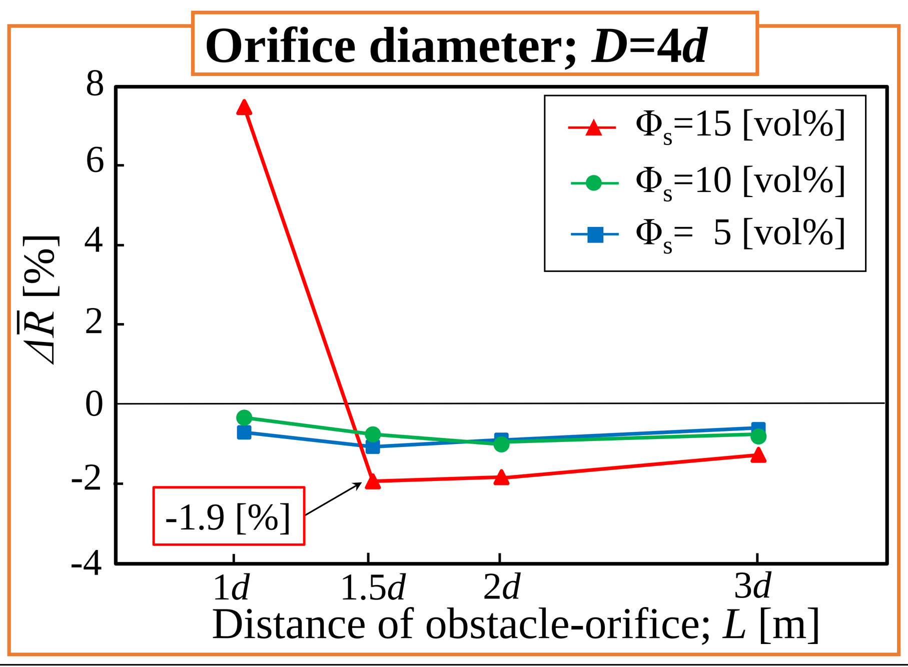
[$R_{abs.}(t^*)$: The rejection rate of particle at absence of obstacle [%]]

	Sampling number [-]	Δt^* [-]
D =3d	10	18.7
D =4d	10	26.5

Orifice diameter; D=3d

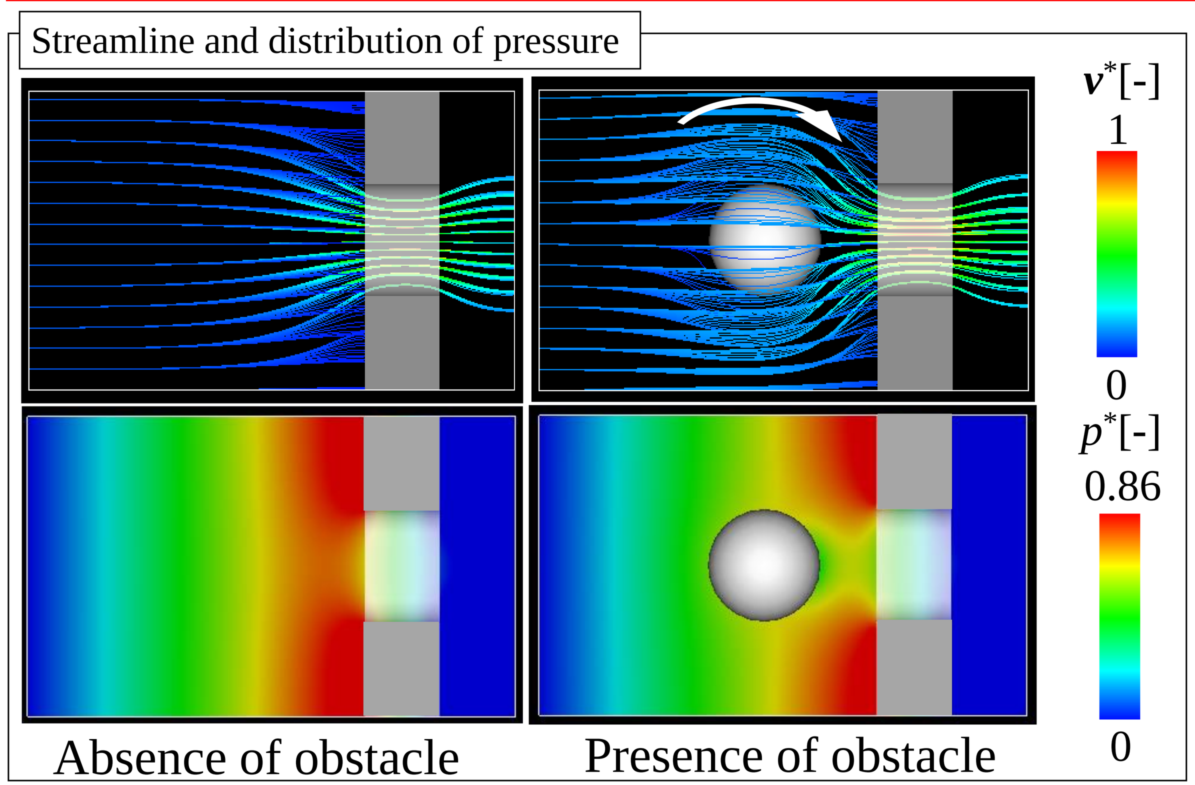


Orifice diameter; D=4d

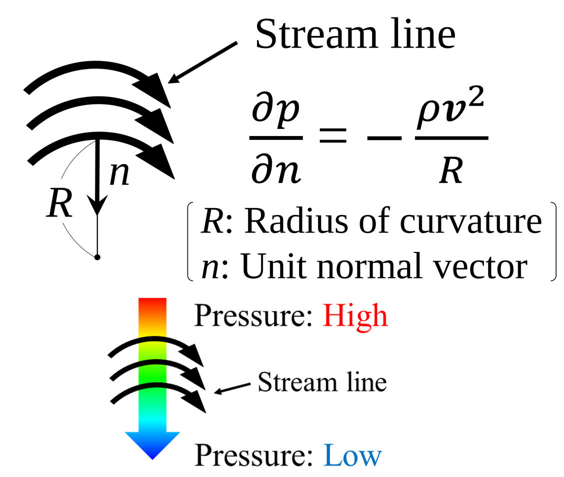


Consideration: Why does the rejection rate of particle decrease?

Streamline and distribution of pressure



Streamline curvature theorem[6]



$$\frac{\partial p}{\partial n} = -\frac{\rho v^2}{R}$$

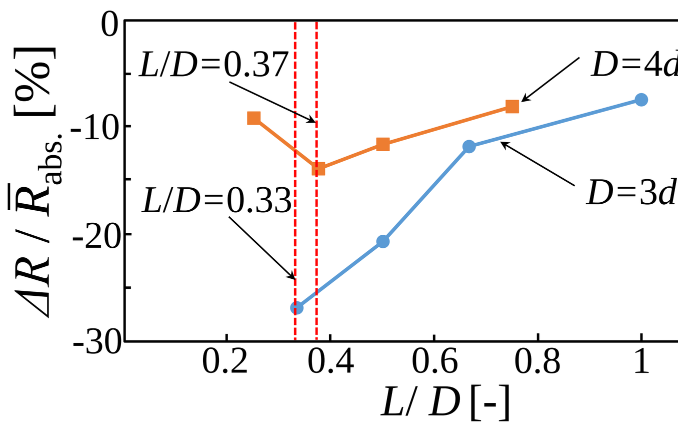
[R: Radius of curvature, n: Unit normal vector]

Present obstacle…

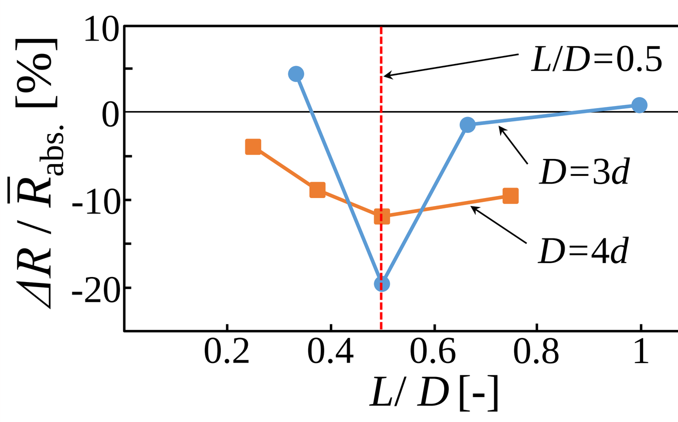
Induce pressure gradient by streamline curvature.

Consideration: Regularity?

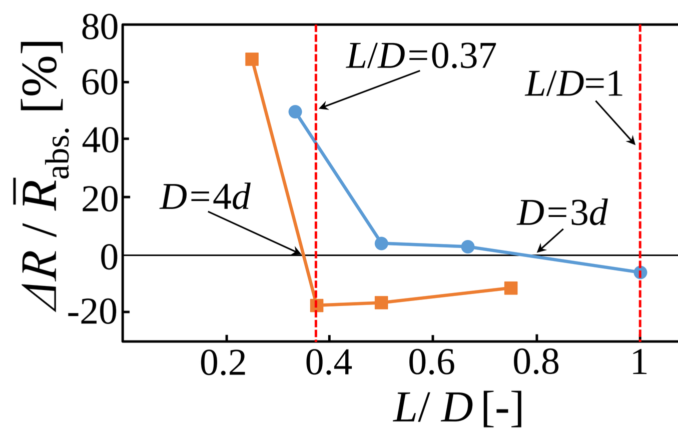
➢ Φ_s= 5 [vol%]



➢ Φ_s= 10 [vol%]



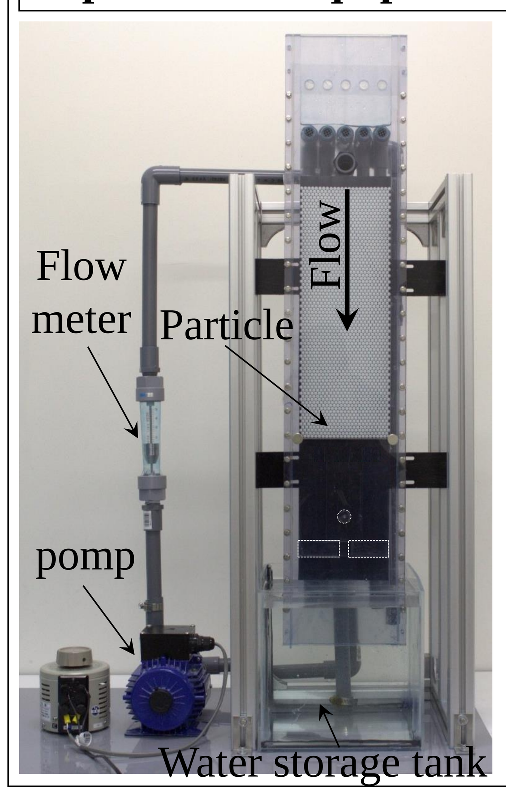
➢ Φ_s= 15 [vol%]

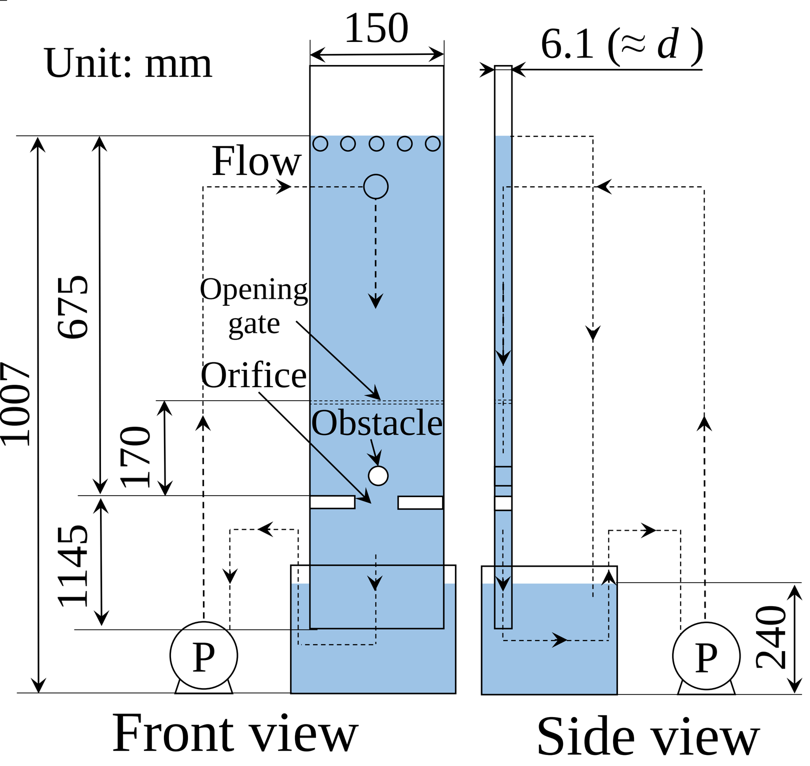


When Φ_s=10 [vol%]
$L : D = 1 : 2 \rightarrow \Delta R_{min}$

Experiment

Experimental equipment



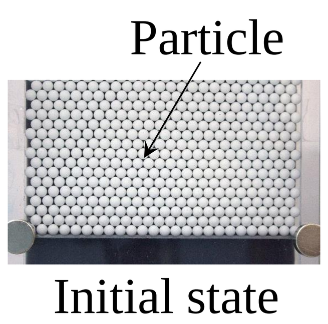


Condition

We use polystyrene particles and water, packing of particles is the closest packing.

Nomenclature	Value
Particle diameter, d [m]	6.0×10^{-3}
Density [kg/m³]	1.8×10^{3}

Nomenclature	Value
Number of packed particle [-]	1985
Hight of packed particle [m]	4.15×10^{-3}

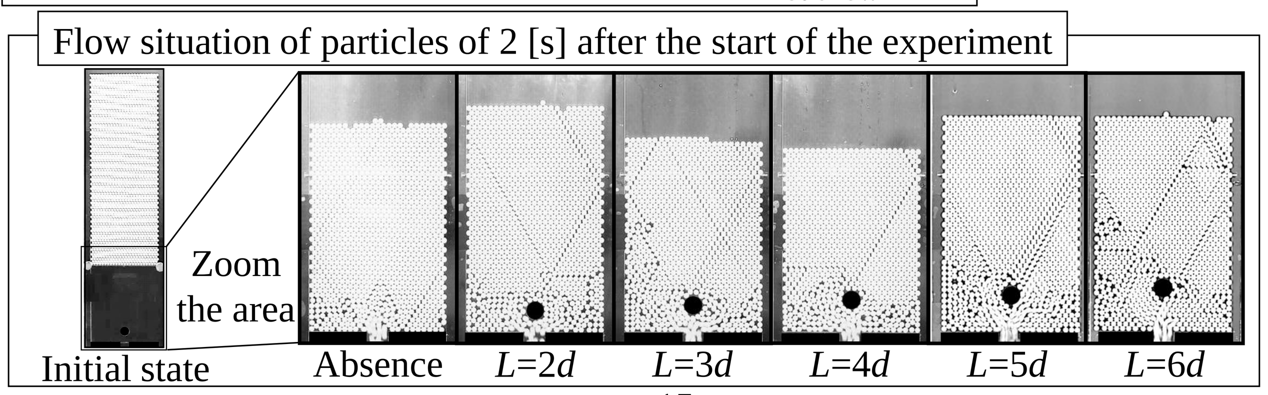


Nomenclature	Value
Maximum Reynolds number, Re_{max} [-]	≈23000
Diameter of obstacle, $D_{obs.}$ [m]	3d
Distance of obstacle-orifice, L [m]	2d, 3d, 4d, 5d, 6d
Diameter of orifice, D [m]	4d

* Use maximum velocity when particle and obstacle are absent; v_{max}

Result: Flow situation of particles and $\Delta t_{outflow}$ [%]

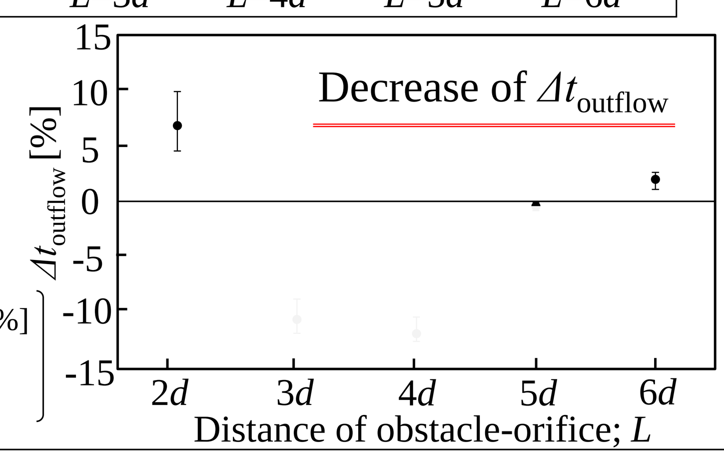
Flow situation of particles of 2 [s] after the start of the experiment



➢Evaluation method

$$\Delta t_{outflow} = \frac{t - t_{abs.}}{t_{abs.}} \times 100\ [\%]$$

[$\Delta t_{outflow}$: The reduction rate of outflow time [%]
t: Outflow time of presence of obstacle [s]
$t_{abs.}$: Outflow time of absence of obstacle [s]]



Conclusion

- In the numerical simulation and experiment, it was verified that an obstacle in front of the orifice had the effect of flow promotion of particles on solid-liquid two phase flow, unlike the obstacle effect on granular flow.
- Result of numerical simulation and experiment show that there is the optimum situation of the obstacle effect in solid-liquid two phase flow.
- The numerical simulation shows that the obstacle induces pressure gradient by streamline curvature.
- The numerical simulation result shows that the optimum distance of obstacle is L=0.5D to promote flow of particles in solid-liquid two phase flow of Φ_s=10 vol%.

Reference

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