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A STUDY ON PREDICTION OF WATER DISCHARGE PERFORMANCE FOR SHOWERHEAD PRODUCT DESIGN

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Abstract. *LIXIL Co. handles a wide range of water-related products such as showers, toilets, baths, and kitchens. The fluid behavior control is a key technology for developing of these products. Therefore, the numerical simulation with CFD plays an important role in product and technical development. The flow of water in showers has been simulated with the finite volume method (FVM). However, the simulation with fine droplets such as in a shower needs a lot of computational cost. To deal with this problem, MPS particle method [1] has been introduced to take an advantage of enabling for simulating such as splashing, droplets, and mixing. In this paper, the MPS particle method is studied to simulate the shower head design because it is the first use case for simulating the spout, coupling with mechanism analysis. Because computational efficiency is also an important factor for the product development, the computational performance on GPU against multi-CPU for the MPS particle method is also discussed.*

1 INTRODUCTION

1.1 FEATURES OF MPS

There are many types of particle methods proposed for continuum materials such as solids, fluids and gases. SPH (Smoothed Particle Hydrodynamics) is mainly used for compressible flow. In addition, the explicit scheme is adopted for time integration. In contrast, MPS is formulated for incompressible flow. Additionally, the semi-implicit scheme is used for time integration. Because most of engineering problems concerning fluid like materials in the production industries can be treated as incompressible, it is considered that MPS is suitable to treat these problems. Furthermore, the semi-implicit time integration scheme in MPS has an advantage in computational cost for longer process of manufacturing. Therefore, MPS has been used widely in many product developments processes.

1.2 MPS METHOD OUTLINE

The governing equations for incompressible flow consist of the continuity equation shown in Eq.1 and the Navier-Stokes equations.

$$\frac{D\rho}{Dt} = 0 \tag{1}$$

$$\frac{D\boldsymbol{u}}{Dt} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\boldsymbol{u} + \boldsymbol{g} \tag{2}$$

where, ρ ; density, $\boldsymbol{u}$; velocity, P ; pressure, ν ; diffusion coefficient, and $\boldsymbol{g}$; gravity. MPS defines the kernel function as follows,

$$w(r) = \begin{cases} \frac{r_e}{r} - 1 & (r < r_e) \\ 0 & (r \geq r_e) \end{cases} \tag{3}$$

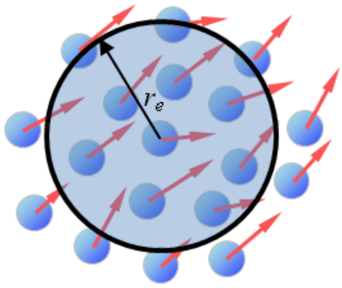


Figure 1: Governing region of MPS kernel function

r_e ; A particle interacts only with surrounding particles within the radius.
n_i ; Particle number density for particle i is defined using the kernel function,

$$n_i = \sum_{j \neq i} w(|\boldsymbol{r}_j - \boldsymbol{r}_i|) \tag{4}$$

Mathematical operations acting on arbitrary scalar ϕ and vector $\boldsymbol{u}$ at particle i are defined as the particle interaction approximation model as follows:

$$\langle \nabla\phi \rangle_i = \frac{d}{n_0}\sum_{j \neq i} \frac{\phi_j - \phi_i}{|\boldsymbol{r}_j - \boldsymbol{r}_i|} \frac{(\boldsymbol{r}_j - \boldsymbol{r}_i)}{|\boldsymbol{r}_j - \boldsymbol{r}_i|} w(|\boldsymbol{r}_j - \boldsymbol{r}_i|) \quad \text{gradient model} \tag{5}$$

$$\langle \nabla \cdot \boldsymbol{u} \rangle_i = \frac{2d}{n_0}\sum_{j \neq i} \frac{\vec{u}_{ij} \cdot (\boldsymbol{r}_j - \boldsymbol{r}_i)}{|\boldsymbol{r}_j - \boldsymbol{r}_i|^2} w(|\boldsymbol{r}_j - \boldsymbol{r}_i|) \quad \text{divergence} \tag{6}$$

$$\langle \nabla^2\phi \rangle_i = \frac{2d}{\lambda n_0}\sum_{j \neq i} (\phi_j - \phi_i) w(|\boldsymbol{r}_j - \boldsymbol{r}_i|) \quad \text{model} \tag{7}$$

where, d ; spatial dimension (2 or 3), n_0 ; initial particle number density, and λ ; correction coefficient. The governing equation Eq.2 is discretized with Eq.5-7 and solved under the condition Eq.1 with a semi-implicit algorithm similar to the conventional Simplified MAC method.

2 APPLICATION TO SHOWER HEAD

The prototype shower discussed in this study has high water-saving performance. The impeller in the shower head rotates at high speed. On the other hand, the holes in half areas in the shower head are blocked. By increasing the pressure in the blocked area, strong water flows can be released even with a small amount of water. This gives bathing experiences with a sense of water volume, having high water-saving performance. The possibility with MPS for product development is studied for this shower.

The major issues to be studied are as follows;

(1) Prediction of impeller rotation speed
(2) Prediction of droplet size and velocity
(3) Prediction of internal pressure of the shower head

Without coupling with mechanical analysis, it is difficult to simulate because an only constant rotational velocity can be applied to the impeller. To improve the accuracy, it is necessary to solve the problem by coupling the water flow and the motion of the impeller. Therefore, in this research, a coupling technique of MPS and rigid body dynamics are applied.

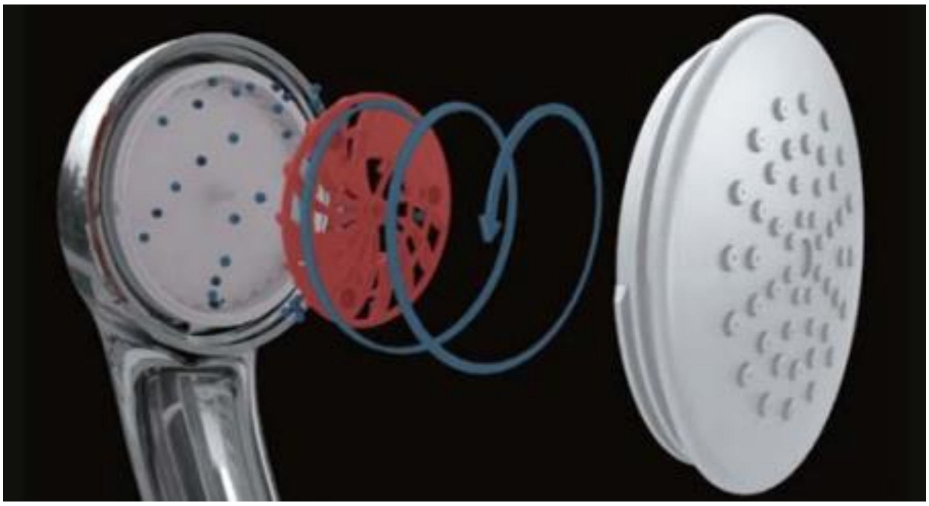


Figure 2: Shower head mechanism

2.1 PREDICTION OF IMPELLER ROTATION SPEED

First, the number of rotations of impellers in the shower head is compared with the experiments. The results are shown in Fig.3.

The simulated number of rotations of impeller is increased gradually. After the number of rotations is reached the maximum, it decreased slightly. After 0.5 seconds, it keeps the constant value. The rotating speed of impellers increases gradually by increasing the loads of water on impellers. As the water gradually increases in the shower head, the speed of impellers decreases because of the resistance of the water. The experimental rotating speed of impellers result is constant because of the difficulty of obtaining the number of rotations of impellers, depending on time. The stable simulated number of rotations of impeller is 1420rpm and experimented one is 1500rpm.

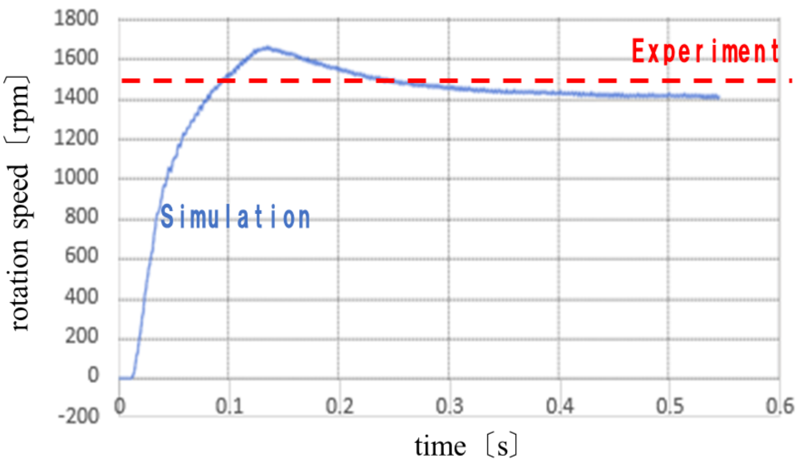


Figure 3: Impeller rotation speed and transition

2.2 PREDICTION OF DROPLET DIAMETER AND VELOCITY

The size and velocity of droplets at 150mm from the shower head is discussed. Because the size and velocity of droplets are the one of the important factors to determine the comfort of bathing, it is a big advantage to predict these in the simulation. The table1 is shown by comparing results in experiments and simulation with Fig.4 and 5. The diameter of the droplets in Fig.4 is compared with the photograph.

Although the diameter of the droplets is varied in experimental result and simulated one, the experimented diameter of the droplets average is 1.5mm and simulated one is 1.3mm by comparing the droplets having the diameter more than 0.5mm.

The velocity of the droplet is simulated as 6.4m/s. On the other hand, the roughly estimated velocity of an experiment is 5.6m/s.

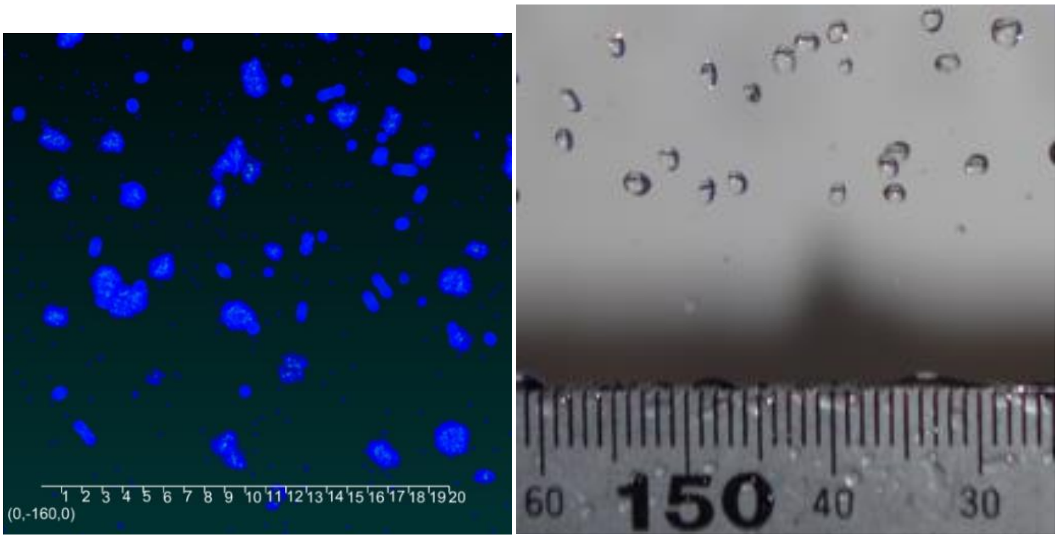


Figure 4: Result of droplet size

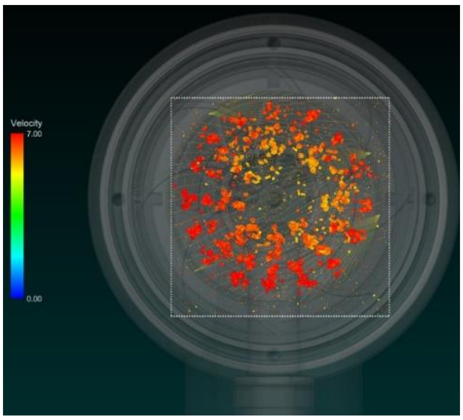


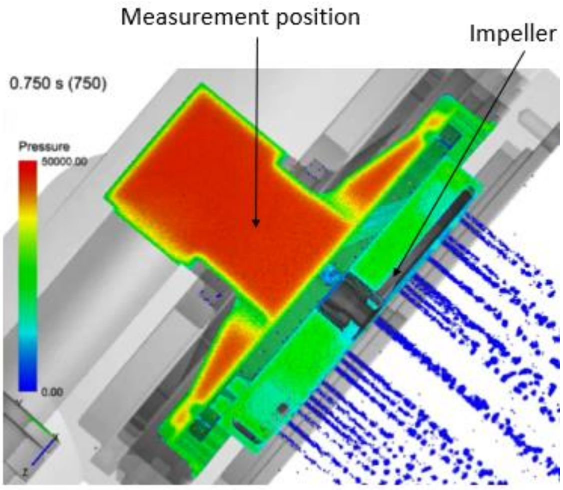
Figure 5: Result of droplet velocity

Table 1: Comparison of measurement and simulation

	Droplets of distance 150mm	
	Size[mm]	Velocity[m/s]
Simulation	1.3	6.4
Experiment	1.5	5.6

2.3 PREDICTION OF INTERNAL PRESSURE OF THE SHOWERHEAD

Finally, the pressure in the shower head is discussed. The simulated pressure is shown in Fig,6 and 7. As shown in Fig.7, the inner pressure at measured point keeps constant after 0.5 sec. In addition, it also shows the pressure is decreased from near at the impeller to a waterspout part.



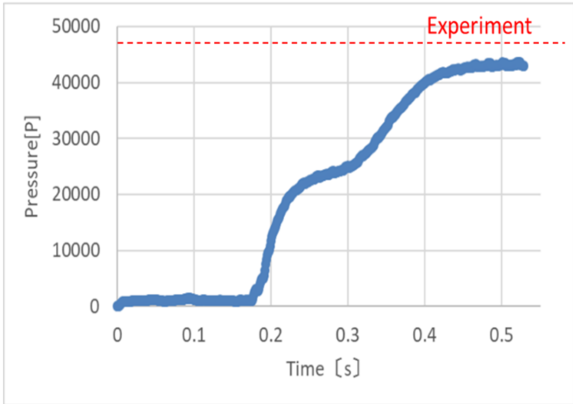


Figure 6: Result of Pressure

Figure 7: Result of Pressure and transition

2.4 SUMMARY OF RESULTS COMPARISON

The comparison of experimental result and simulated one are summarized in Table 2. As for the number of rotations, droplet diameter, velocity, and inner pressure, there are no big differences between the experimental result and simulated one. There is a big possibility of utilizing this simulation practically when it is used in the prediction in an early stage of its development.

Table 2: Summary of results comparison

	Rotation speed [rpm]	Internal pressure [KPa]	Droplets of distance 150mm	
			Size[mm]	Velocity[m/s]
Simulation	1420	47.8	1.3	6.4
Experiment	1500	43.0	1.5	5.6
Simulation/Experiment	0.95	1.11	0.87	1.14

3 IMPROVEMENT OF CALCULATION EFFICIENCY

When applying a simulation to the development of housing equipment, the balancing computational resource and its cost is very important. Therefore, the accurate simulation is required within the limited man-hour and budget. MPS algorithm is known to be suitable for GPU computation because it can process compacted algebra operation in parallel. Therefore, the computation times of the multi-CPU execution by the 56 CPUs built-in a common desktop PC and the GPU built-in 5120 CUDA core are compared with shower head model. As a result, it needs 17 hours for multi-CPU and 8 hours for GPU execution. It is shown that a larger and more expensive CPU cluster is needed to reduce the computation time of multi-CPU execution. Therefore, it is found that the parametric studies can be done several times in a day.

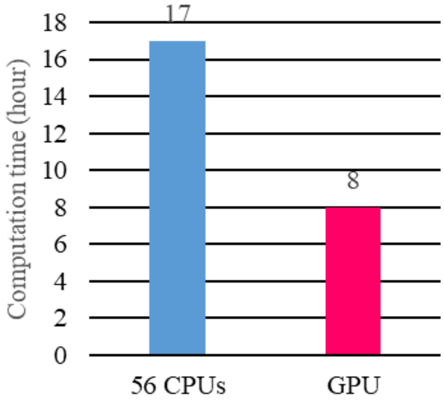


Figure 8: computation time

4 CONCLUSIONS

MPS particle method is applied to the development process of the shower head to study its practical possibility because it is the first use case for simulating the spout, coupling with mechanism analysis. The number of rotations of an impeller, water behavior and inner pressure of a shower head are simulated. The simulated results show a good agreement with experiments. There is a big possibility that MPS particle method can be applied to the development process of the products. On the other hand, some challenges have left in the computation time. In some case, it takes less time for development in experiments. If the computation time was decreased, MPS particle method would be used in more cases. Therefore, the decrease of the computational time and the improvement of the accuracy need further study.

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