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EFFECTS OF WALL CONDITION OF A PLUNGING BODY ON SPLASH

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ABSTRACT

Splashes generated by hydrogel sphere were simulated numerically and experimentally for investigating the effects of slip like mucus of living things. Numerical simulation using MPS (Moving Particle Semi-implicit) method was carried out. We defined the slip ratio as the swelling degree of hydrogel and installed the slip ratio into the MPS method. The swelling degree is the ratio of the weight of water against that of hydrogel. We simulated the splashes generated by the hydrogel spheres which had the different swelling degree plunging into water. As the evaluation of swelling degree on the surface of actual hydrogel spheres we also tested by using the hydrogel spheres plunging into water experimentally. The height of splash as a result of reaction of the air cavity became higher according to the increase of the swelling degree. The speed of hydrogel sphere sinking in water tank was also quicker in the numerical simulation. The reason of these results was that the velocity of water around the hydrogel sphere became quicker due to the slip on the surface.

INTRODUCTION

The form of splash like that living things or a drop makes is one of the attractive problems and sometimes our mind is healed by looking at its peculiar elegant form taken by a high speed camera. Worthington[1] studied the milk crown formed by a milk droplet and solid body falling into milk. And on the other hand, the form of splash is an appraisal in competitive swimming.

Most of objects make splash when plunging into the surface of liquid. But the form of splash differs respectively. The form of splash seems to be influenced by the surface condition of object. Of course, the shape of object and the speed of object influence the form of splash. Our interest is to understand the mechanism that an object makes splash, and the target in this study is to show the influence of the surface condition on the form of splash.

The difference of splash's form and the speed of object versus of the shape of object plunging into water were researched by Kubota et al [2]. The fingering and splashing of a droplet impacting a solid surface were researched by numerical simulation [3][4]. Duez et al.[5] reported relation between splash formation and sound generation, and studied the effect of the hydrophobic or hydrophilic surface of the body surface on splash. But the effect of surface condition with the mucus skin of living things like a frog or fish has not been considered in the previous studies. The principal ingredient of mucus such as a slimy skin of frog and fish is known mucin[6]. Sea tangle has mucilaginous on its surface, and the ingredient of mucilaginous is fucoidan. Their slimy surface is generated by these high polymer gels. In this paper we investigated the effect of these high polymer gels on splash. We used agar as a representation of high polymer gels. The agar is one of the hydrogels and is convenient for making gel material and easy to change its swelling degree. The swelling degree is the rate of water included in a hydrogel. The agar has the effect of increasing the slip on the surface of object, Kikuchi et al[7], and they pointed out that the coating of agar made the reduction of drag and it was expected to be applied to the bottom of ship as drag reduction.

In this paper, the numerical simulation and experimental simulation were carried out by the falling spherical object made of agar. We showed the effects of the swelling degree of agar on the velocity of water around plunging object, and it causes the difference of the form of splash and the sinking speed of object. We also indicate this research can be applied to the drag reduction of a swimsuit and a ship's body.

SIMULATION METHOD

GOVERNING EQUATIONS AND MPS METHOD

We developed the simulation system of MPS in two dimensions for investigating the splash. The flow in the calculation domain was obtained by solving the incompressible Navier-Stokes equations as follows,

$$\frac{Du}{Dt} = -\frac{1}{\rho}\nabla P + \nu\nabla^2 u + g \qquad (1)$$

where u is the velocity vector of fluid, ρ is the fluid density, P is the pressure, ν is the fluid kinematic viscosity, g is the gravity, respectively. The principal method of MPS is explained in Koshizuka[5]. In MPS method the interaction between each particles is evaluated by weight function as follows,

$$w(r) = \begin{cases} \frac{r_e}{r} - 1 & (0 \le r \le r_e) \\ 0 & (r_e \le r) \end{cases} \qquad (2)$$

where r is the distance of two particles and r_e is the cut-off radius. Assuming two particles i and j which possess scalar quantities of pressure p_i and p_j, the gradient model between these two particles is written as,

$$\nabla P_i = \frac{d}{n^0}\sum_{j \ne i}\left[\frac{p_j - p_i}{|\vec{r}_j - \vec{r}_i|^2}(\vec{r}_j - \vec{r}_i)w(|\vec{r}_j - \vec{r}_i|)\right] \qquad (3)$$

where d is the number of the space dimension. Parameter n^0 is called particle number density in MPS method. Since each particle processes the same mass, every particle number density should be constant and equal to n^0.

The Laplacian model in MPS method is written as,

$$\nabla^2 u_i = \frac{2d}{\lambda n^0}\sum\left[(u_j - u_i)w(|\vec{r}_j - \vec{r}_i|)\right] \qquad (4)$$

where λ is a parameter. We calculated assuming viscosity of liquid by Eq.4. The surface tension of liquid and the buoyancy of object are considered in calculation as interaction between particles.

SWELLING DEGREE AND BOUNDARY CONDITION

We installed the swelling degree as the index for the slip of the object made of agar. The swelling degree is the ratio of the

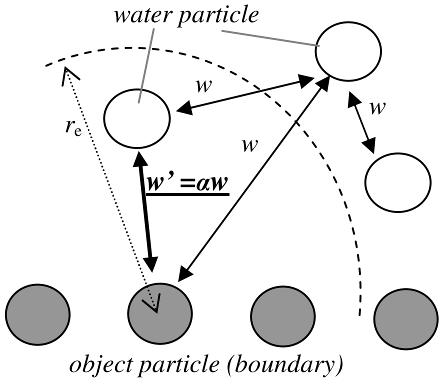

FIGURE 1 WEIGHT FUNCTION MULTIPLEXED WITH *A* ON BOUNDARY CONDITION.

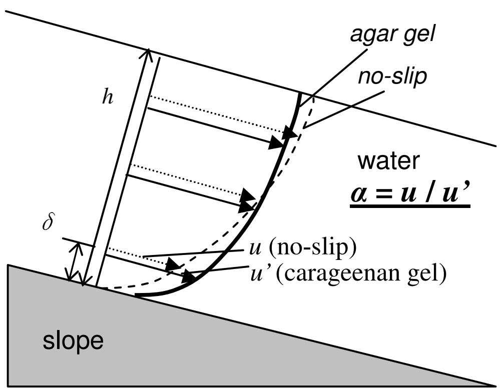

FIGURE 2 SLIP RATIO, α IS ESTIMATED FROM NO-SLIP CONDITION EXPERIMENTALLY.

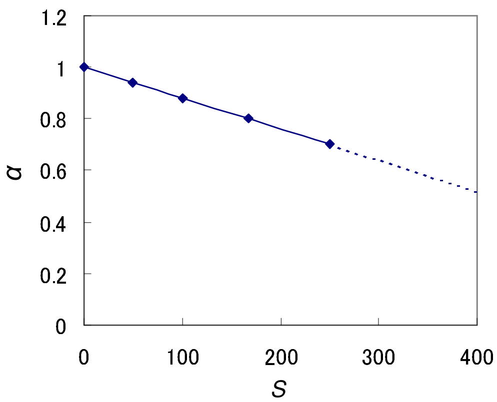

FIGURE 3 RELATIONSHIP OF SWELLING AND SLIP RATE, κ, OF BOUNDARY CONDITION BETWEEN LIQUID AND OBJECT WALL..

weight of water against that of agar as follows,

$$S = (m_{water} + m_{gel}) / m_{gel} \tag{5}$$

The increase of S means the water contained in the agar increases.

The interaction between particles is evaluated by w in Eq.(2) where the distance is under r_e. The slip condition on boundary of surface is multiplexed to the w (Koshizuka[8]). We defined the coefficient, α, as the slip ratio at the boundary condition of hydrogel sphere. The α changes the shear between a particle at the surface of hydrogel sphere and particles of water around hydrogel sphere as shown Fig.1. If the boundary condition is no-slip, the α becomes 1.0, and if the boundary condition is slip, the α is 0.0. Namely, the smaller α means it gives more slip on the surface. In this paper we applied the α to the Laplasian term in Eq.(4) at the particles on boundary and the particles of water where the distance is under r_e around the boundary as shown in Fig.1. The Eq.(4) was rewritten using $w'(r) = \alpha w(r)$ as follows,

$$\nabla^2 u_i = \frac{2d}{\lambda n^0} \sum \left[(u_j - u_i) w'(|\vec{r}_j - \vec{r}_i|) \right] \ ,$$

$$w'(r) = \alpha w(r), \tag{6}$$

$i \in \Gamma$, Γ is the particles at the surface of object and water around boundary

We obtained the α as the ratio of velocity u and u' according to the experimental result by Kikuchi et al[7] as shown in Fig.2. They obtained the u and u' near the surface of wall, at δ, versus of S. Figure 3 shows the transformation from the S to α obtained by the experimental result. The α decreases with the increase of S. Namely, the lager S means it gives more slip on the surface. In this paper, we transformed S to α using this relation, and calculated the flow field using Eq.(6) numerically only at the surface of object and water near the object.

SIMULATION CONDITION

We developed the MPS simulation system in two dimensions. The liquid was assumed water, namely the density of water, ρ_{water}, was 1000kg/m$_3$. The radius, R, of sphere was 1cm which was same as the experimental setup we will describe later. The density of object, ρ_{object}, was about 1200kg/m$_3$, which was assumed as acrylic resin. In this paper, we assumed that the weight of object was same under the different condition of S, thus, the kinetic energy impacting the surface of water was the same. The range of S was from 1 to 500 in this simulation. As the parameters for MPS, the cut-off radius r_e was 2.1 and the initial particle length l_0 was 1/8R according to the recommendation [8]. The influence of width of the water tank was confirmed that when the width of water case was 20R, the splash height and the speed was approximately attenuated. The width of water tank was sufficient distance in our simulation.

Fig.4 shows the snapshots of numerical simulation result in two dimensions, closing up to the splash and object. We define the maximum heights of splash; h_1 is the height of primary splash and h_2 is the height of partial splash. We confirmed the splash form was similar to the experiment result which we show later.

SIMULATION RESULT

FLOW NEAR THE SURFACE OF GEL SPHERE

Figure 5 shows the path lines of the particles of splash in the x-y plane. The graph of Fig. 6 shows the difference of averaged velocity of particles in Fig. 5. The path lines of each particles started from the surface of water at x = 0 to R. The blue line is the path lines of particles in S = 50, and the red line is the path lines in S = 350. Each red line is longer than blue line which starts from same position. These motions of particle indicate the velocity of water around hydrogel sphere was accelerated faster by effect of the slip on the surface. Further more, the simulation result shows the position of particle which makes first splash is the surface of water and near of radius of sphere. But the position of particle which the partial splash made was unclear, because the partial splash depended on the position where the air cavity closed.

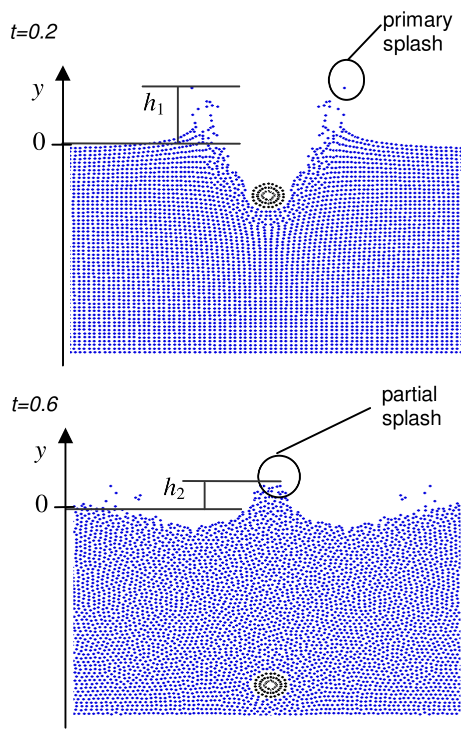

FIGURE 4 SNAPSHOTS OF NUMERICAL SIMULATION RESULTS. CROSS SECTION IS X-Z PLANE.. T = 0 IS THE TIME WHEN GEL SPHERE TOUCHES THE SURFACE OF WATER. S = 100.

HEIGHT OF SPLASH

We compared heights of splash by numerical simulation as shown in Fig. 7. The difference of the h_1 was small even if the S changed. The h_2 was different according to increasing from S = 50 to 450. The reason the h_1 changed little is that the surface of water was impacted in proportion to the kinetic energy by falling object but the kinetic energy of each cases were same because of same falling speed. On the other hand h_2 was influenced by velocity of water around object. The reflect force by kinetic energy of water around object made the partial splash. The velocity was different according to the swelling degree as we mentioned former subsection. The difference of velocity came from the slip condition parameter, α, namely the velocity of near surface of hydrogel sphere became more quickly.

SPEED OF SINKING OBJECT VERSUS OF SWELLING DEGREE

Figure 8 shows the sinking speed of hydrogel sphere after it was under the steady speed. The speed was increased with increasing of S. The slip of surface made the speed of sinking

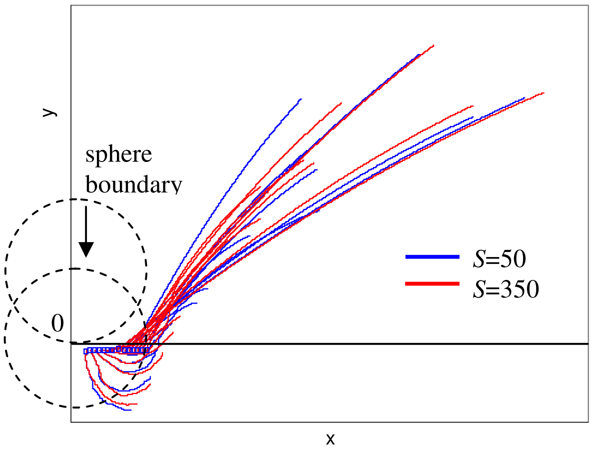

FIGURE 5 PATH LINES NEAR PLUNGING HYDOROGEL SPHERE, T = 0 TO 0.45SEC, THE LINES ARE THE PATH LINES OF PARTICLE WHICH STARTED FROM THE SURFACE OF WATER AT X = 0 TO R. BLUE LINE: S = 50, RED LINE :S = 350.

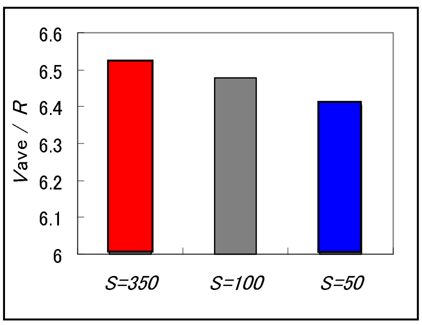

FIGURE 6 THE AVERAGED VELOCITY OF THE PARTICLES NEAR PLUNGING HYDOROGEL SPHERE VERSUS OF S.

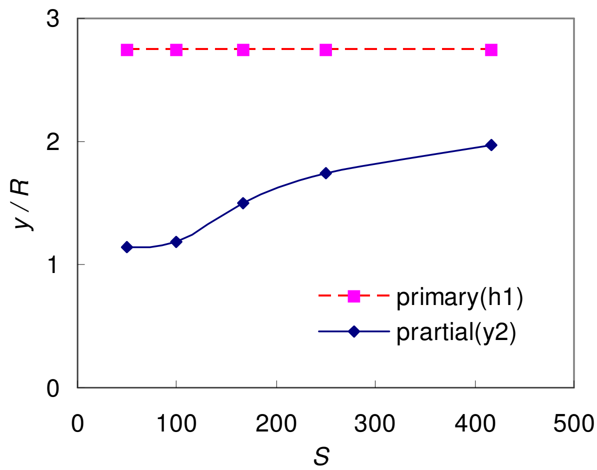

FIGURE 7 MAXIMUM HEIGHT OF PRIMARY SPLASH (H_1) AND PARTIAL SPLASH (H_2) VERSUS OF S.

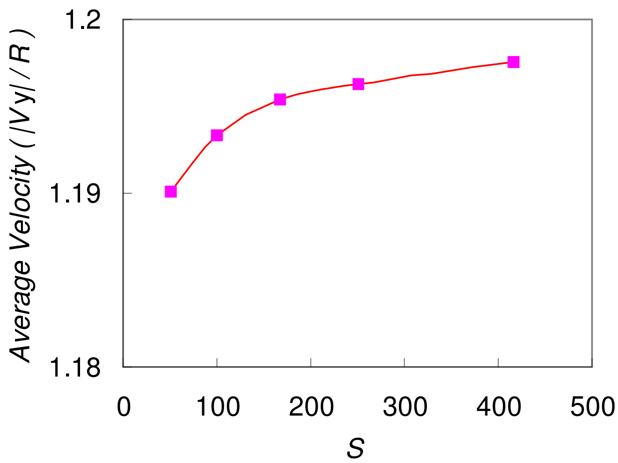

FIGURE 8 AVERAGE SPEED OF HYDROGEL SPHERE SINKING IN WATER, AVERAGED AFTER SPHERE WAS UNDER THE STEADY SPEED.

object more quickly. In the above section we showed the velocity around hydrogel sphere increased with the S increasing. As the velocity of liquid around the hydrogel sphere increases, the drag increases. But, in stead the drag increased, the sinking speed of hydrogel sphere increased. The drag was reduced by slip of surface with swelling degree. This result is same by the experimental research of Kikuchi[7] in which the shear between high polymer gel and liquid becomes less with increasing of swelling degree, thus our simulation result is appropriate. This result indicates the hydrogel sphere can sink more quickly with slip of surface condition.

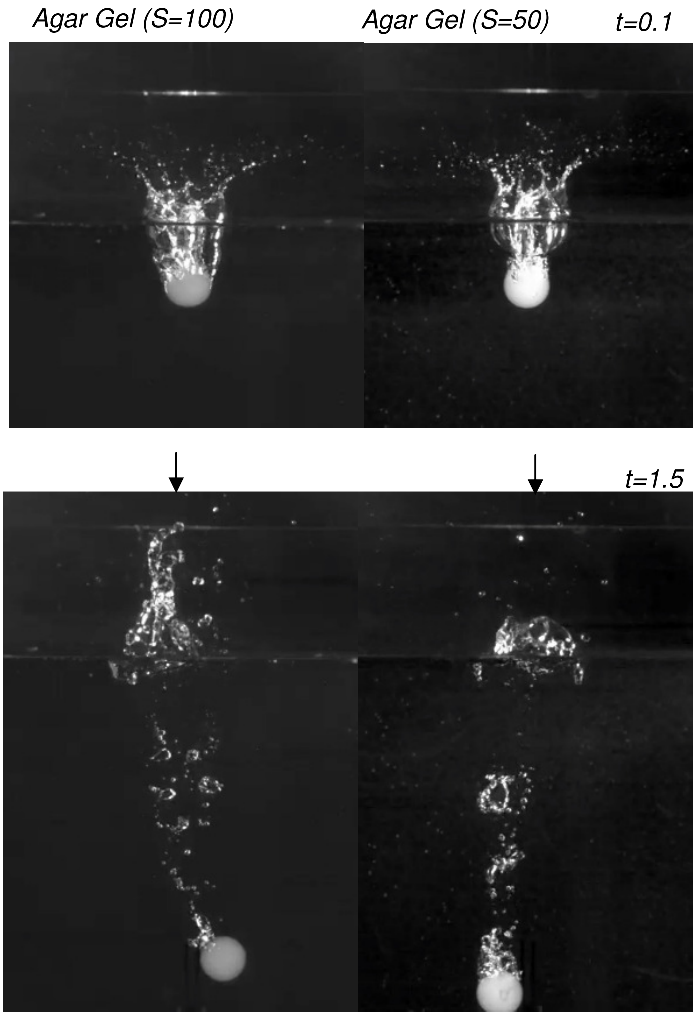

FIGURE 9 UPPER RAW SHOWS THE FIRST SPLASH OF HYDROGEL SPHERE (S=100, S=50). THE LOWER RAW SHOWS THE SECOND SPLASH. THE FORM OF SPLASH IS DIFFERENT EACH OTHER. THE SECOND SPLASH OF S=100 IS HIGHER THAN S=50.

EVALUATION BY EXPERIMENTAL SIMULATION

We carried out the experimental simulation in order to confirm the difference of swelling degree. We tested the splash by a sphere in order to simplify the shape of plunging object and focused on the effect of surface condition. To compare the characteristic of surface, we examined the falling test of hydrogel sphere made of agar. We observed the splash generated by hydrogel sphere using a high speed CMOS camera as shown in Fig.9. The radius of hydrogel sphere, R, was 1cm assuming a small size frog or fish. The initial height h was 50R, which the impact velocity of the hydrogel sphere at the water surface was 2.4 m/s. This speed was determined to the same as the representation speed of the live frog plunging into water that we experimented above. A launcher system held the models via suction at the initial height just before release. We released the hydrogel sphere by turning off the electric valve to the launcher system, and this enables the models to fall without rotation or horizontal displacement, producing reproducible results. The results of splash formation were taken with consecutive images from the side of the water tank using a high speed CMOS camera. The camera was set at 4000 frames per second so that precision in timing between consecutive frames was 0.25 ms.

As shown in Fig.9 the forms of splash were different each other. It is expected that the speed of water around hydrogel sphere was changed by the slip on the surface. The larger slip made the partial splash larger as shown in left picture S = 100. The height of partial splash of S = 100 is about three times higher than that of S = 50. But the speed sinking in water was almost same. The reason of the difference between the simulation result and experiment result comes from that a little deformation when S becomes larger. The hydrogel sphere with high swelling degree became soft. Furthermore, there was a problem that the weight of each hydrogel sphere could not be same completely because we made the volume of object same each other. These factor seems to made the different result. Thus, the investigation by using numerical simulation is an efficient way in order to eliminate those problems and focus on the effect of the swelling degree.

CONCLUSION

We confirmed that the swelling degree of surface influenced the form of splash and the drag reduction. The slip rate multiplexed to the weight function was installed to the MPS method in order to simulate the effect of slip on the surface by the swelling degree of agar. As the simulation result, we confirmed through the numerical simulation that the partial splash became higher according to increase of the swelling degree and the speed of the hydrogel sphere sinking in water also became more quickly. The reason was that the velocity of water near the hydrogel sphere became more quickly according to the increase of swelling degree. If the condition of surface is hydrophile, the contact angle becomes flatter than hydrophobicity condition. But the difference of the contact angle was not confirmed in this simulation. The relationship among the contact angle, the velocity of liquid and the exfoliation from surface of object is the key point understanding of the difference of splash. We need to investigate the surface contact angle through the simulation and this is the future work. We expect that this study can be applied to the surface of a ship's body, a tool of fishing or a swimsuit.

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