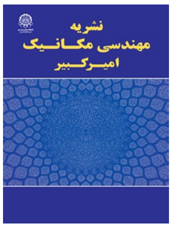

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Experimental Study of Impacting a Spherical Hydrophobic Particle on an Air-Water Interface

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ABSTRACT: In this study, the impact of spherical hydrophobic particles on an air-water interface was analyzed experimentally. The aim of this study is to obtain a critical impact velocity in which the hydrophobic particle remains on the liquid surface so that it penetrates completely at higher velocities than the critical velocity. A mathematical model was developed based on energy balance to predict the critical velocity. The Teflon particles of diameter 3-5 mm were used. Distilled water with a density of 1000.71 kg/m3 was used as the fluid. Particle falls into the fluid were captured by using a high-speed video camera with the rate of 4500 fps. For Teflon spherical hydrophobic particles, two floatation and penetration regimes were observed from experiments. After processing of sequential images, the motion of a particle inside the fluid was obtained and for the first time, the maximum penetration depth, rebound depth, rebound height and the pinch off depth were determined for each particle and it was found that, at critical velocities, particle penetration is associated with oscillations, and at higher velocities than the critical number, the number of oscillations is decreased. The dependence of maximum penetration depth on drop height was studied and it was found that with increasing drop height, the maximum penetration depth is also increased. Also, the effect of particle size on critical velocity was investigated and it was observed that with increasing the particle size, the critical velocity is decreased. In addition, the particle velocity and the velocity of the three-phase contact line were plotted at critical conditions. The developed mathematical model was also compared with the experimental observations, and it was found that there is a good agreement with the measured values.

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1- Introduction

Most studies on the particle impact with the gas-fluid surface focused on the flow above or below the main surface. The most important applications that can be mentioned are refined gas-containing particles, evaporated droplets in contact with catalyst particles (FCC) [1], the spray dryer system [2], particle coloring, the movement of fine objects on liquid surfaces [3], the recovery of valuable minerals using film flotation [4] and etc.

In this study, for simulation of the Film flotation process, the impact of spherical hydrophobic particles on a gas-liquid interface was studied experimentally. We focused on comparing the impact of spherical hydrophobic Teflon particles at low velocities, on a planar surface of a Newtonian fluid, which has been underestimated. After processing of sequential images, the motion of a particle inside the fluid was obtained and for the first time, the maximum penetration depth, rebound depth, rebound height and the pinch-off depth was determined for each particle.

2. Mathematical Modeling

A mathematical model based on the energy balance was presented to predict the behavior of particle penetration in the fluid. Fig. 1 illustrates a spherical particle of diameter d impacting on the gas-liquid interface with a critical velocity vc. The particle penetrates into the liquid and reaches zero velocity. Critical velocity of the particle can be predicted using the energy balance between the initial and the final states as defined in Eq. (1).

$$\begin{aligned}\Delta E &= Q - W\\ \Delta E &= -W\\ \Delta E &= \Delta E_p + \Delta E_l + \Delta E_g\end{aligned} \tag{1}$$

Where ΔE is the total energy change, W is total work associated with all the resistance forces (drag, buoyancy, and capillary) and Q is heat change that for an adiabatic system is zero.

$$\begin{aligned}\Delta E_p &= -\frac{1}{2} m v_c^2 - mgbd\\ \Delta E_l &= \frac{1}{30}\pi \rho_l g r_c^2 \left[(b-1)d\right]^2\\ \Delta E_g &= 0\end{aligned} \tag{2}$$

Assuming that the temperature of the system stays

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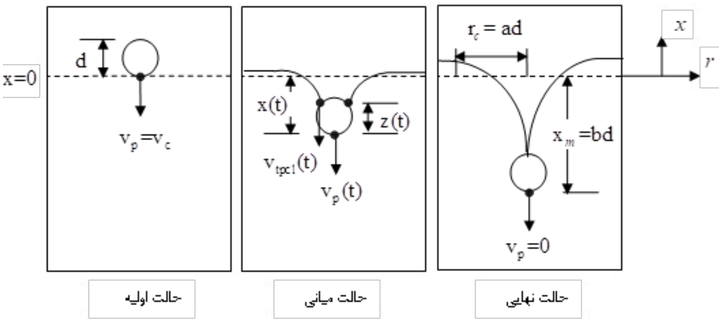


Fig. 1.The particle impact on the gas-liquid interface with a critical velocity vc

constant during the process, we consider the internal energy changes of the system to be zero. It is also assumed that there is no change in the gas phase energy. Due to the small size of particle in compare with the volume of fluid and the low impact velocity, kinetic energy change of fluid can be ignored. Therefore, the energy change of liquid is equal to the potential energy change [4].

Where b is a dimensionless constant that is used to define the maximum depth of penetration of particle. The work term is obtained by integrating each of resistance forces over the distance traveled by the particle. The work due to buoyancy is obtained by integrating the buoyancy force for partially submerged particle over the distance traveled by the particle. Vs is the volume of the part of the particle that is submerged in the fluid (Fig. 2) as defined in Eq. (3).

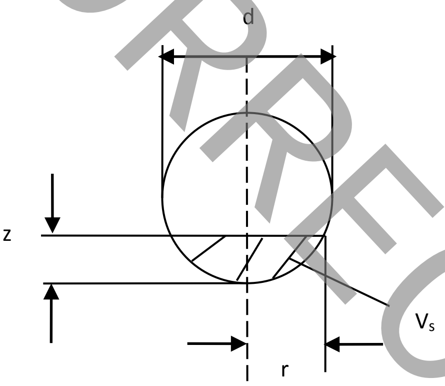


Fig. 2. Part of particle submerged in the fluid

$$V_s=-\frac{1}{6}\pi z\left(3r^2+z^2\right)$$
$$r=\sqrt{\left(\frac{d}{2}\right)^2-\left(\frac{d}{2}+z\right)^2} \tag{3}$$
$$V_s=\pi z^2\left(\frac{d}{2}+\frac{z}{3}\right), z=x-x_{TPCL}$$

Where r is the radius of wettability and z is the depth of wettability of the particle in the fluid, x is the distance of the particle stagnation point to the initial surface of the fluid and xTpcl is the distance of three-phase contact line on the particle to the initial surface of the fluid. A quadratic fit to the measurements of x and xTpcl is obtained for all particle sizes according to the Eq. (4).

$$x_{tpcl}=-\frac{b-1}{b}\frac{1}{bd}x^2 \tag{4}$$

By combining Eq. (3) and Eq. (4), the relation for the particle's wettability depth is obtained according to Eq. (5). By substituting each of the work and energy terms into Eq. (1), the final equation to define the critical impact velocity was obtained according to the Eq. (6).

$$z=\left(1+\frac{b-1}{b}\frac{x}{bd}\right)x \tag{5}$$

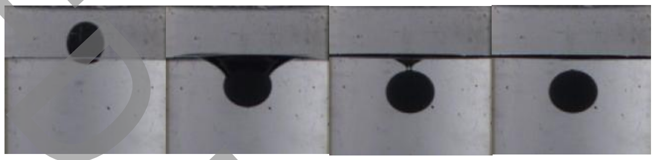
$$\frac{1}{2}mv_c^2+mgbd$$

$$=-\int_0^{-bd}\pi\left(\frac{d}{2}\right)^2\frac{1}{2}\rho_l\left|v-v_{TPCL}\right|^2\frac{18.5}{\mathrm{Re}_p^{0.6}}dx-\int_0^{-bd}\pi d\sigma_{gl}\left(\frac{-2z}{d}-1-\cos\theta_a\right)dx$$

$$-\int_0^{-bd}\rho_l g\pi z^2\left(\frac{d}{2}+\frac{z}{3}\right)+\frac{1}{30}\pi\rho_l g\left(ad\right)^2\left[(b-1)d\right]^2 \tag{6}$$

3. Results and Discussion

Fig. 3 shows the particle motion in the fluids both at the critical condition and near it. As can be seen, the velocity of particles that penetrated the fluids has a very small difference in critical velocity.



Penetration: $d=3\mathrm{mm}, v_I=0.4390\mathrm{m/s}$

Floating: $d=3\mathrm{mm}, v_c=0.4389\mathrm{m/s}$

Figure 3. Spherical Teflon particle colliding with the air-water interface

The data sets for the relative velocity of the particle and the contact line (vrel) is approximated by a quadratic curve according to Eq. (7)

$$v_{rel}=v_p-v_{TPCL}=v_c\left[\frac{1}{b^2}\left(\frac{x}{d}\right)^2+\frac{2}{b}\left(\frac{x}{d}\right)+1\right] \tag{7}$$

Finally, for estimating the accuracy of the predicted model, Eq. (6) and the measured critical velocity as a function of particle diameter are plotted in Fig. 4. As can be seen, the critical velocity decreases with increasing particle diameter. That is, larger particles require less kinetic energy to float. It is also observed that the data are consistent with the predicted mathematical model.

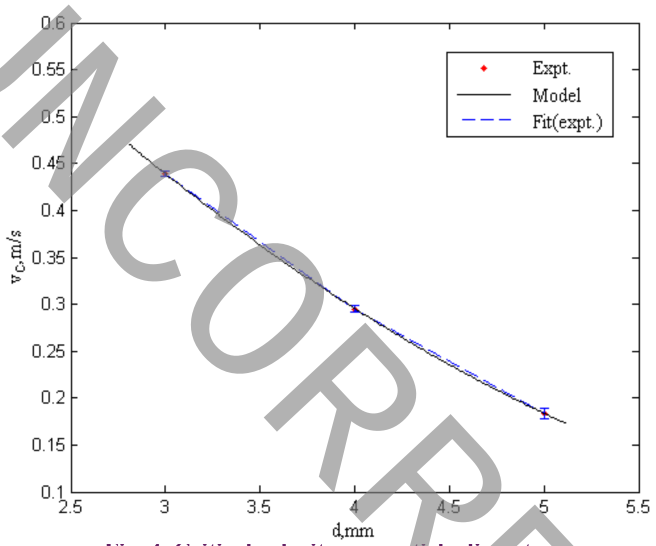


Fig. 4. Critical velocity vs. particle diameter

4. Conclusion

In this study, the penetration behavior of spherical hydrophobic particles on collision with the surface of pure was investigated. It was found that the collision of these particles has two regimes: flotation and penetration. The particle continues to move inside the fluids, and eventually, it separates from the surface and at a lower velocity, reaches a stable state (the penetration regime) or oscillates at a critical condition and then floats on the surface of the fluid (floatation regime). It was also observed that if the particle's impact velocity is less than the critical value, even if it is denser than the liquid, does not penetrate. This is due to the surface tension and buoyancy forces on the particle. By image processing, the motion of a particle inside the fluid was obtained and for the first time, the maximum penetration depth, rebound depth, rebound height and the pinch-off depth were determined for each particle and It was found that, at higher velocities than the critical, the number of oscillations decreases, so that the particle gets separated from the liquid surface without any oscillations.

References

[1] S. Mitra, E. Doroodchi, V. Pareek, J. B. Joshi, and G. M. Evans, "Collision behaviour of a smaller particle into a larger stationary droplet," Advanced Powder Technology, vol. 26, pp. 280-295, 2015.

[2] M. van der Hoeven, "Particle-droplet collisions in spray drying," 2008.

[3] D. Vella, D.-G. Lee, and H.-Y. Kim, "The load supported by small floating objects," Langmuir, vol. 22, pp. 5979-5981, 2006.

[4] D. Liu, Q. He, and G. Evans, "Penetration behaviour of individual hydrophilic particle at a gas–liquid interface," Advanced Powder Technology, vol. 21, pp. 401-411, 2010.