The performance of the water-entry cavity on a high-pressure gas-driven projectile

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Abstract. We present the experimental results of water-entry cavity on a slender projectile, which moves in the opposite direction of gravity. The regime of the cavity including sheet cavity, supercavity and trailing cavity is exhibited and its relevance to Euler and Weber numbers are illuminated. Meanwhile, various pinch-off performances of the supercavity are analysed and the resulting re-entrance jet or cavity ripples are presented.

1. Introduction
Most existing works on water-entry cavity problems focus on a moving solid object impacting a free fluid surface and the cavity is formed by the air entrainment behind the moving solid. The first research can dates back to 1897, when Worthington & Cole investigated spheres impacting onto liquid surfaces using single-spark illumination photography. With the developments in experimental techniques and numerical simulation schemes, there are notable progresses on understanding the mechanism and characteristics of the water-entry cavity in the past decades.
Here, we pay attention to a different water-entry cavity. In our study, a slender projectile is driven by a high-pressure gas and moves in the opposite direction of gravity. The projectile launches from a gas-filled canister and enters the water with cavities around and/or behind it. A brief sketch for the comparison between two water-entry cavities are shown in Figure 1.

Figure 1. Sketch map of water-entry cavity.

Figure 2. Schematic of the experimental set-up.
2. Experimental set-up

The experiment is conducted to observe the performance of the cavity on a high-pressure gas-driven projectile, which is a slender cylinder with hemispherical head. The experimental set-up is shown in Figure 2. The octagonal water tank is with 800mm diameter and 1500mm height and filled with 800mm height of water. The pressure on the top of the water level can be adjusted by a vacuum pump. The water tank contains three glass windows (40mm width and 100mm height) for the input of the light sources and the high-speed camera recording. The images are taken at 2000 frames/sec. The high-pressure gas from the pressure regulator tank runs into the inner of the canister to accelerate the projectile and the duration of ventilation is controlled by the pressure regulating valve. The preset-gas inside the canister is connected with the vacuumized air above the free surface inside the water tank and the connection is governed by a ball valve to avoid the gas at the front of the canister being over compressed. The canister and water tank are separated by a membrane which can sustain a pressure difference within 0.2atm. The projectile (28.6mm diameter and 170mm long) is initially placed at the bottom of the canister. The pressures at the bottom of the canister and at the top of the water tank are measured by the pressure gauges.

3. Results

Define the Froude number, Euler number and Weber number as

\[ Fr = \frac{V}{\sqrt{gD}}, \quad Er = \frac{P_{wb}}{\left(0.5\rho V^2\right)}, \quad We = \frac{\rho V^3 D}{\sigma}, \]

where \( g \) is the acceleration of gravity, \( D \) is the diameter of the projectile, \( \rho = 998.2 \text{ kg/m}^3 \) and \( \sigma = 72.59 \text{ mN/m} \) is the density and surface tension of water, respectively. \( P_{wb} \) is the static pressure at the bottom of the water tank, \( V \) is the velocity when the bottom of the projectile gets out of the canister. In our experiments, \( P_{wb} \) ranges from \( 4.1 \times 10^3 \) to \( 4.8 \times 10^4 \) Pa, and \( V \) ranges from 3.17 to 10.31 m/s. Since the experimental projectile model does not change, the Bond numbers \( Bo = \frac{\rho g D^2}{\sigma} \) maintain a constant value.

3.1. The regime of the cavity

In our experiments, the shapes of the cavities vary with the flow conditions. Sheet cavity, supercavity and trailing cavity can be observed, as shown in Figure 3. The cavity performance corresponding to the Weber-Euler number is plotted in Figure 4, where the separated points are experiments results and the solid line is a fitted curve. It can be seen that with large Euler number and small Weber number, there is no cavity along the side of the projectile but a trailing cavity attached to its bottom; as the Euler number decreasing and Weber number increasing, sheet cavity is generated and the trailing cavity still exists; under small Euler number and large Weber number, a supercavity is formed and the trailing cavity disappears since the bottom of the projectile is inside the supercavity.

![Figure 3. The shape of the cavities](image)

![Figure 4. The cavity performance corresponding to the Euler-Weber number Variation.](image)
We denote the pressure at the bottom of the canister as $P_{cd}$. Figure 5 exhibits the bottom pressure variation under case A, F and G, which is respectively corresponding to non-cavity, sheet cavity and supercavity situation. For each case, we denote $t_1$ as the time when the projectile start moving and $t_2$ as the time when the membrane gets broken. The time difference between $t_1$ and $t_2$ are almost identical, which stands that the mean velocity of projectile inside the canister is almost identical. Since the background pressure is approximately equal, the larger pressure inside the canister causes a higher launching velocity of the projectile. After $t_2$, $P_{cd}$ is greater than $P_{wb}$ in case A, approximately equal $P_{wb}$ in case B, and less than $P_{wb}$ in case C. The comparison among Figure 5 shows that the differences between $P_{cd}$ and $P_{wb}$ effect the amount of gas attached to the projectile. It can be concluded that the launching velocity and the pressure difference mainly determine the cavity performance.

![Figure 5](image)

**Figure 5.** The monitored pressure variation of case A: $P_{wb} = 5.1 \times 10^4 Pa$ , $V = 12.4m / s$ ; case F: $P_{wb} = 5.0 \times 10^4 Pa$ , $V = 5.9m / s$ ; and case C: $P_{wb} = 5.0 \times 10^4 Pa$ , $V = 3.2m / s$ .

3.2. The pinch-off of the supercavity

In our experiments, three kinds of supercavity pinch-offs are observed and presented in Figure 6. For case A, the cavity surface is smooth and after the pinch-off a re-entrance jet is immediately produced and injects into the cavity. The trajectory of the re-entrance jet is very clear and its velocity is nearly twice of the supercavity' tail velocity. For case B, the end of the supercavity is not 'perfectly' closed when first pinch-off happens. A fraction of gas still moves downward along its surface to form a smooth closure area. Then the second pinch-off takes place and a re-entrance jet appears and impacts the inside of the supercavity. The extra gas are shed off downward. For case C, the closure style of the supercavity is particular. We regard the shrinking part of the cavity as the 'cavity neck', and its length here is considerable long. Therefore, the closure area is a line instead a point (in 2D view) and multi pinch-offs happen successively in a very short time. The corresponding pressure variation is given in Figure 7. The large pressure difference between $P_{cd}$ and $P_{wb}$ in case C makes more gas ejecting from the canister and such gas can continuously supply into the supercavity, which leads to the multi pinch-offs.

![Figure 6](image)

**Figure 6.** The supercavity pinch-off of case A: $P_{wb} = 5.1 \times 10^4 Pa$ , $V = 12.4m / s$ ; case B: $P_{wb} = 5.1 \times 10^4 Pa$ , $V = 10.8m / s$ ; and case C: $P_{wb} = 1.9 \times 10^4 Pa$ , $V = 9.7m / s$ .
Figure 7. The monitored pressure variation of case A: $P_{a} = 5.1 \times 10^4 \text{Pa}$, $V = 12.4 \text{m/s}$; case B: $P_{a} = 5.1 \times 10^4 \text{Pa}$, $V = 10.8 \text{m/s}$; and case C: $P_{a} = 1.9 \times 10^4 \text{Pa}$, $V = 9.7 \text{m/s}$.

3.3. The trailing cavity ripples
The surface of the trailing cavity becomes fluctuation after pinch-off for all cases except the supercavity ones in our experiments. Such surface undulations are called as 'cavity ripples', which has been previously studied by Gekle et al. (2008), Grumstrup et al. (2007), Bodily et al. (2014) and Mansoor et al. (2014). However, the mechanism still remains many unsolved questions. The evolution of the cavity ripples is shown in Figure 6. The fluctuation is very obvious right after the pinch-off. The amplitude of the fluctuation declines rapidly, however, the fluctuating frequency nearly keeps constant, which can be concluded from the quasi-periodic shedding.

Figure 8. The evolution of the cavity ripples.
(case F: $p_{in} = 4.0 \times 10^4 \text{Pa}$, $P_{a} = 5.0 \times 10^4 \text{Pa}$, $V = 5.9 \text{m/s}$;)

4. Conclusion
The water-entry cavity on a high-pressure gas-driven projectile is studied by experimental means. Its performance is a consequence of various flow conditions such as the launching velocity, the background pressure and the pressure inside the canister. Three kinds of supercavity regarding to the pinch-off behaviors are analyzed and the trailing cavity ripples are also observed.

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