About oscillation effect on the penetration depth of drop induced vortex ring

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Summary Over more than hundred years, oscillation of drop has been considered as an influential factor related to the penetration depth of drop impact onto liquid surface; however, there are still no commonly agreed explicit parameter and consistent conclusion for describing this phenomena up to now. A new shape factor S, has been proposed as the oscillation parameter to describe the related scenarios after impact of an oscillatory drop. It reveals good consistency of the maximum penetration depth with the S-peaks.

Visualization of water drop induced vortex rings

For the impact with small velocity, a drop may perform floating, bouncing and coalescing. After it coalesces, a vortex ring structure can be formed. Fig. 1(A) shows a typical visualization of vortex ring in the water target liquid. It has been noticed that the repeatability of experiments for drop with low impact energy is very sensitive to the experimental conditions, e.g., vibrations, liquid properties, and target tank size etc [1-2]. Any small perturbation could influence the trajectory of vortex ring, thus the penetration depth. After having a well-controlled environment, the repeatable experiments can then be achieved [3]. Moreover, as shown in Fig. 1(B), significant reduction of "meniscus interface layer" has been also improved and brought much better visualization of drop-surface interactions in comparison with that commonly obtained (e.g., as shown in Fig. 1(A)).

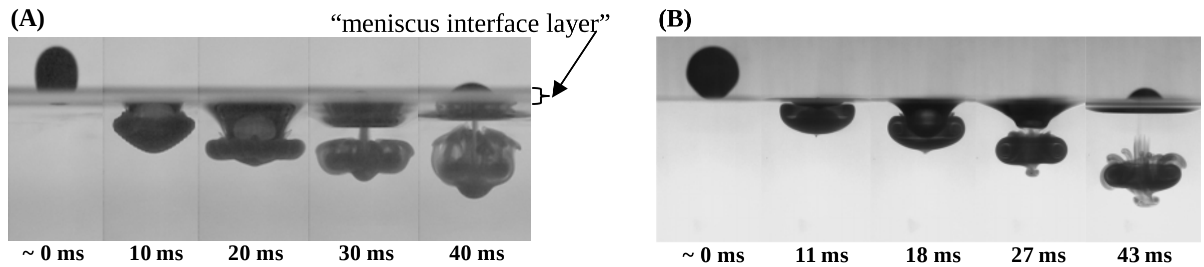

Fig 1. (A) Visualization of dyed drop-formed vortex ring (drop diameter D = 4.61mm and falling height H = 21mm). (B) Visualization with reduced "meniscus interference." (D = 5.50 mm and H = 22mm).

Characteristics of drop oscillation

Fig. 2 shows the visualization of an oscillating drop after pinch-off from a nozzle. To describe the oscillatory behavior of a drop, the axis ratio (e), is commonly used in the literature and defined as

$$e = \frac{b(t)}{a(t)}, \qquad (1)$$

where a and b, as shown in the inset of Fig. 2, represent the maximum horizontal and vertical length of a drop, respectively. When e-value is less than unity, it refers to the oblate shape in the gravitational direction and the prolate shape appears as e is higher than unity. In fact, the oscillation of a drop in the atmosphere combines different modes according to previous experimental and theoretical studies [4-5]. The frequency of the corresponding oscillation mode ($n = 0, 1, 2, 3\ldots$) has been derived by Rayleigh in 1879 and can be written as

$$f_n = \sqrt{\frac{n(n-1)(n+2)\sigma}{4\pi^2 \rho R^3}}, \qquad (2)$$

where n describes the mode of oscillation, R is the radius of the undisturbed drop, σ and ρ are surface tension and density of drop liquid, respectively. The mode n = 1 shows a translational motion of the center of mass. The mode n = 2 is the first and fundamental mode of oscillation for a freely falling drop. Based on the comparisons of experimental results and theoretical analyses of different oscillation modes, we found that the axis ratio e represents basically the oscillation mode of n = 2. Comparing it with the complex oscillations as shown in Fig, 2, it could be clearly noticed that the oscillation of only mode n = 2 is too simple to represent the real oscillations of a falling drop, especially for the time being just after the pinch-off. Therefore, a new shape factor S is proposed and defined as the ratio between the vertical distance (b_1, see the inset of Fig. 2) from bottom of the drop to the position where the maximum horizontal distance lies and the half distance of maximum horizontal distance (a), i.e.,

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$$S = \frac{b_1(t)}{a(t)}. \tag{3}$$

Fig. 3 shows the excellent overlap of S-t relationship of the experimental data (symbol) and the theoretical prediction (solid curve) based on the superimposed multiple modes of n = 2~5. The smaller peaks reveal the contributions of the higher oscillation modes ($n > 2$) of the drop. It does show that the shape factor S can be used to describe the oscillatory motion of a freely falling drop in more detail rather than the single oscillation mode of e.

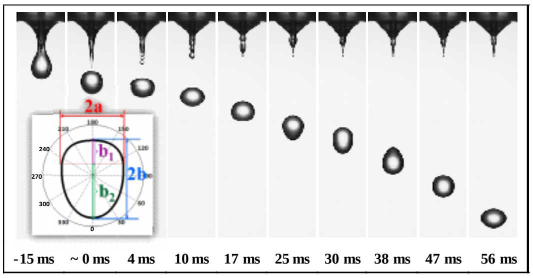

Fig 2. Drop oscillation after pinch-off from the nozzle. (Inset: nomenclature for drop shape analysis).

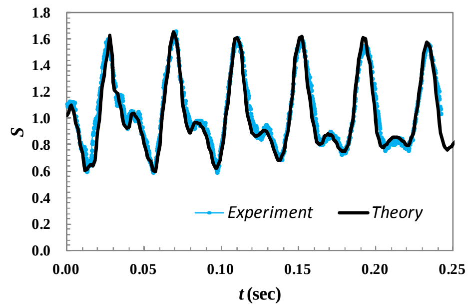

Fig 3. Comparison between theoretical and experimental results of shape factor S with time.

Relations of S, e and the maximum penetration depth (L_{max}) of vortex rings

The x-axis of Fig. 4 is the evolution of time after pinch-off normalized by the period of $n = 2$ mode (denoted as T_2). Fig. 4 clearly shows that the peaks of penetration depth L_{max} occur at the peaks of S, not that of e, although they both are almost in phase for high falling height (i.e., bigger t/T_2). It is worth noting that there are phase shifts between S and e and the phase shift delay is more significant as the drop size increases (not shown). This fact unveils the reason why Kutter [6] and Rodriguez [7] found the maximum L_{max} was produced when the drop shape before impact was prolate and the minimum penetration depth (L_{min}) was produced when the drop shape before impact was oblate. Chapman [8] and Durst [2] indicated that L_{max} occurred when the drop shape before impact was spherical with oscillation from oblate to prolate; in contrast, L_{min} appeared when the drop shape before impact went on oscillation from prolate to oblate. All the observations were consistent except the used shape factor e in the past is too simple to describe the complicated oscillation phenomena.

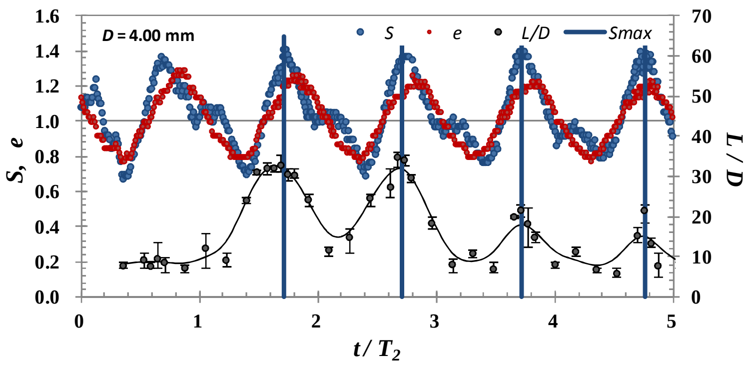

Fig 4. Relations between S, e and L/D with respect to time

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