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ON A QUANTITATIVE FEATURE OF MAXIMUM PENETRATION DEPTH OF DROP-FORMED VORTEX RINGS

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Visualization method(s): meniscus interface reduction in a well-controlled experimental facility
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ABSTRACT: The formation of vortex rings produced by the drop impact with small velocity is beautiful and also important in nature and industrial applications. It has been long since noticed that drop experiment with low impact energy is very sensitive to the experimental conditions, e.g., vibrations, liquid contamination, nozzles, flow feeding conditions, and target tank size etc. Any small perturbation could influence the trajectory of vortex ring so that significantly changes of the penetration depth. Over the past hundred years, oscillation of drop has been considered as an influential factor that is related to the penetration depth of drop impact onto liquid surface; however, there is still no consistent conclusion for describing the common feature of the phenomena up to now [1-5]. Main aim of this paper is to find out whether there is any quantitative result of the maximum penetration depth for various drop fluids. We revealed firstly how to design a facility to produce repeatable experiments with minimum disturbances. The “black interference zone” caused by the meniscus interface has been also minimized. Based on a well-defined criterion for determination of vortex penetration depth, it shows repeatable development of vortex rings from various liquids. Furthermore, the linear relationship of maximum penetration depth and drop size has been found with good consistence for different literature data and test liquids for the first time.

INTRODUCTION. At low energy drop impact onto liquid surface, a drop may perform floating, bouncing and coalescing. After it coalesces, a vortex ring structure is formed. The earliest report describing the formation and performance of vortex ring under liquid surface could be up to 1858[6]. The ring travels downward in the target liquid to some distance with the growth of its diameter. After it reached some depth, the shape of the vortex ring started to become irregular.

In the last several decades, oscillation of drop has been considered as an influential factor related to the penetration depth of drop impacted onto liquid surface [1-5]; however, there is no general consensus on what kind of drop shape can produce the maximum penetration depth. Some have been said that the maximum penetration depth of vortex ring occurs with spherical drop shape changing from oblate to prolate [3, 5], some have indicated it was produced when the drop shape before impact was prolate [2, 4]. The inconsistent arguments may be attributable to either the repeatability of experiment for drop impact at low energy or an ill-defined penetration depth of vortex rings.

Except for the drop shape, there has been far less research on the effects of the size, the viscosity, and the surface tension of the drop or target liquid. It should be noted that these liquid properties will lead to variations of oscillatory behavior of drops, thus the penetration depth. This article outlines and illustrates a new approach to achieve highly repeatable and reliable experiments for drop impact onto liquid surface. To compare with the maximum penetration depth produced from different liquids, it is necessary to define how to measure the penetration depth of vortex rings for further comparison purpose. Based on the experiments from carefully designed facility and well-defined measurement of the penetration depth, better understanding of relations between the maximum penetration depth and various effects of liquid properties can then be obtained.

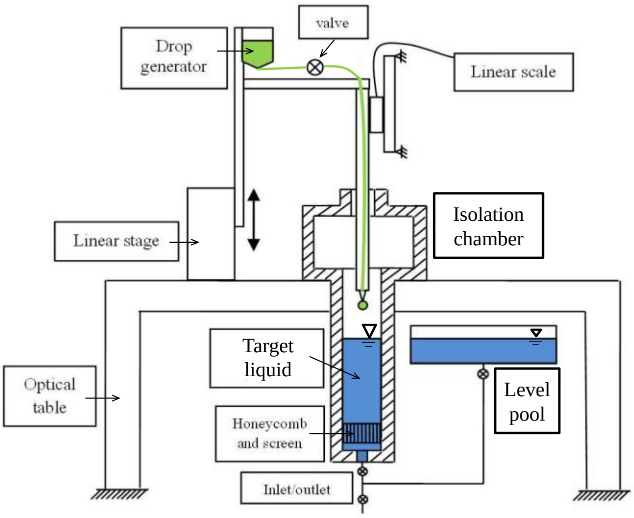

Fig. 1 Experimental set up

IMPROVED METHOD OF EXPERIMENT. Figure 1 Schematic diagram of experimental setup. The phenomenon of vortex ring was recorded by the following two methods. A high speed camera (NAC Memrecam GX-1) was use to record the detailed phenomenon occurring in the target liquid where the vortex ring was formed after drop impact. A CCD camera was used to record the penetration of vortex ring in the target liquid. Surface tension was measured by du Noüy ring method. Temperature and density of liquid were measured by temperature recorder (Chino AH3760) and mass-volume method, respectively. The target liquid surface maintained as unchanged by a level pool referred to [6].

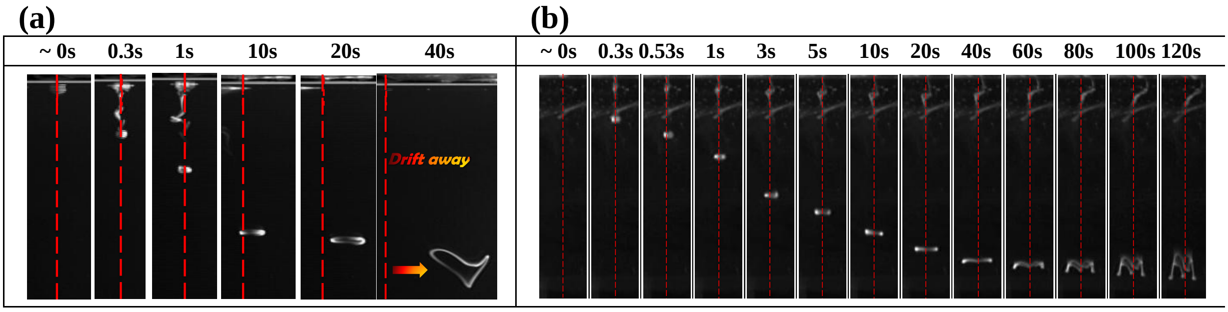

Fig. 2 Sequences of vortex ring penetration recorded by CCD camera (a) in good air flow isolation chamber, D = 4.61 mm, H = 16.33mm. (b) with minimum current disturbances. D = 4.66mm, H = 25mm.

As shown in Figure 2(a), the vortex ring drifted away from the impact line, shown as the dashed line for reference, and the shape was also changed significantly for large elapsed time. The deviation from vertical trajectory of vortex rings indicates that internal flow current may exist inside the target liquid. The current could be resulted from various causes. First, it could be produced when filling the tank with fresh liquid. Second, it could be grown by natural convection due to the evaporation of water in the free surface of target liquid. The current could be also stronger if heat source, e.g. high power lamp, for visualization was used near the tank. To avoid the heating effect, LED light was used and placed 1.5 meter away from the tank. Also, the LED light was turn off when there was no recording. Third, current could be produced by the vortex ring itself as the previous vortex ring penetrated and diffused. Finally, it was decided to use a smaller cross section tank with the idea that the wall would a bit restrict the freedom of induced side slip but not influence the penetration nature of vortex ring inside the target liquid. Tank length, width and height are then designed as 50mm, 50mm and 450mm, respectively. As can be seen in Figure 1, the experimental set up has been also made to prevent disturbance of external air current and surface contamination by integrating the drop system with a closed chamber. To minimize the possible turbulence during filling fresh liquid, a settling chamber consisting of honeycomb and screens was installed at the bottom of the tank. Honeycomb reduces mainly the lateral turbulence, while screen reduces the axial turbulences. The honeycomb was made from ceramic with the cell size of 2.5 mm and the length of 40 mm. The screens were made from two stainless steel sheets of 30 meshes per inch. As a result, the turbulence has been significantly reduced after the settling chamber. The filling of tank was then well-controlled by a slowly filling from the bottom of the tank. All above-mentioned efforts ensured the repeatable conditions for experiments. Figure 2(b) shows the typical example of vortex ring motion in the present experiment. At the beginning after impact, vortex ring moves very fast, and it descends slowly later on. As the time goes further, the vortex ring almost comes to a stop and splits into many smaller vortex rings. In such a well-controlled environment, the repeatable experiments can be finally achieved. Moreover, as shown in Figure 3(b), significant reduction of “black interference zone” caused by meniscus can be also improved and brought much better visualization of drop-surface interactions in comparison with that commonly obtained (e.g., as shown in Figure 3(a)) by carefully adjusting dynamics contact angle of filling liquid.

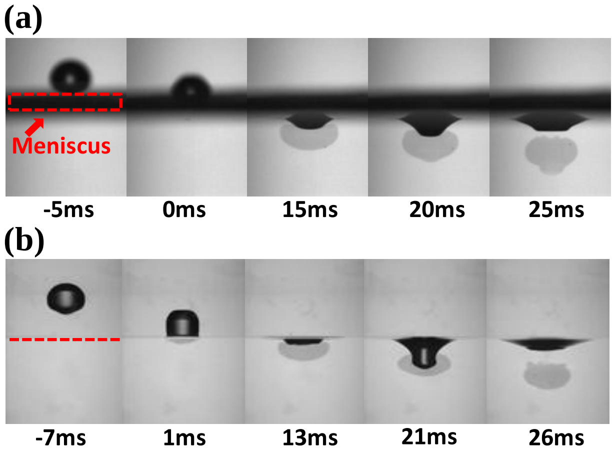

Fig. 3 (a) Visualization without reduction of meniscus effect. D=5.52mm, H=24mm. (b) Reduced meniscus of the free surface allowing clear visualization of drop impact onto the liquid surface. D= 5.52mm, H=22mm.

RESULTS AND DISCUSSIONS.

CRITERION FOR PENETRATION DEPTH L. On the basis of good repeatability of vortex ring generation, the pathline equation could be then determined as a function of time by:

$$Z(t_L) = a\left(\ln(t_L+1)\right)^b + ct_L \, , \qquad (1)$$

where a, b, and c are the fitting constants. Subsequently, the penetration velocity V_p could be calculated and given by:

$$V_P(t_L) = ab\left(t_L+1\right)^{1-b} + c \qquad (2)$$

To determine the penetration depth L, since it is not practical to choose zero as V_p in such a disturbance-sensitive experiment, the “final stop” position of the vortex ring is therefore dependent on the “stop threshold” of V_p values being chosen. Figure 4(a) shows the relations of displacement Z, and V_p of three different impact heights with respect to the elapsed time t. By taking V_p = 1mm/s as the stop threshold, only one case (H = 20.42mm) satisfied this criterion. The other two cases could not be applicable because vortex rings have already diffused and difficult to be identified before reaching the penetration velocity of 1 mm/s. In contrast, L could be found for all three cases for higher velocity by choosing 3 mm/s and 5 mm/s as the stop thresholds. However, it should keep in mind that choosing higher stop threshold causes shorter L and higher measuring uncertainties may also be caused for the determination of penetration depth when vortex ring still quickly moves. For the case of V_p = 3mm/s, all vortex rings penetrate slowly and none has diffused. As a compromise, V_p = 3mm/s was chosen as the criterion to measure penetration depth in this paper. Figure 4(b) shows the measured L by different stop thresholds. Although the measured magnitudes of penetration depth change for different choices; however, the variation trends and peak positions do remain almost the same for all three tested cases. This means we have found a suitable criterion to determine the peak positions of the penetration depth of vortex ring and which is not sensitive to the choosing value of V_p.

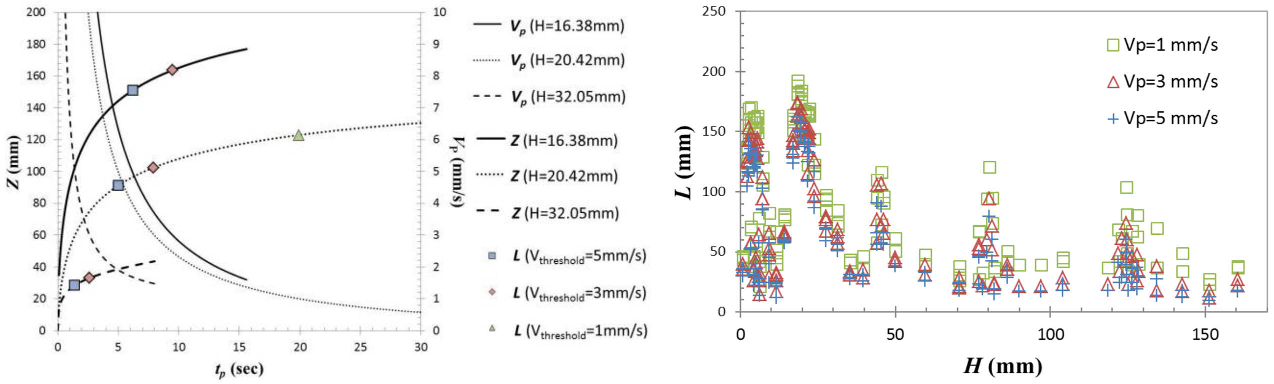

Fig. 4 (a) Penetration displacement Z and velocity V_p of vortex ring versus elapsed time t_p for drops from three falling height. (b) Penetration depth L determined by different stop criteria: V_p = 1mm/s, 3mm/s, and 5mm/s.

RELATION BETWEEN THE MAXIMUM PENETRATION DEPTH AND VARIOUS LIQUID PROPERTIES.

Table 1 Combination of test drop liquid and target liquid.

Case	1	2	3
Drop liquid	Water	60% Glycerol	60% Glycerol
Target liquid	Water	Water	60% Glycerol

Table 2 Measurement of liquid properties.

Liquid	ρ (kg/m^3)	μ (cP)	σ (N/m)
Water	998	1.0	0.072
60% Glycerol	1100	11.2	0.066

Table 1 shows three different kinds of liquid mixture used in this study. To visualize water drop impacting onto water target liquid (case 1), the water drop was mixed with fluorescent dye with a concentration of 400 mg/L. The surface tension of fluorescent dye mixture was measured and the property change was small (< 5%). Figures 5(a-c) show the sequential images of the developing vortex rings induced by drop impact of different drop-liquid combinations. It can be observed in all cases that the cavity expands and then retracts while the immersed drop evolves into a vortex ring. Very interesting scenario can be observed in Figure 5(b): a drop with higher viscosity does not diffuse so quickly in the target liquid as that of water drop in Figure 5(a). It created thus a much clearer visualization of vortex ring formation with transparent and beautiful inner structures. In contrast, Figure 5(c) shows visualization result of no vortex ring for 60% glycerol drop impacting onto the pool of the same liquid. The blob shaped outcome is believed due to the strong viscous effect of the target liquid which hinders the vorticity formation (or rotational motion) of the target liquid. It was noteworthy that the developing time of the vortex ring for Figure 5(c) was almost three times longer than the rest two cases. It reveals the significant dissipation and transfer retardation of impacting kinetic energy due to the viscous effect of target liquid. This offers a clear evidence that the increase of viscosity of target liquid significantly hinders the mass and momentum transfer by drop impact.

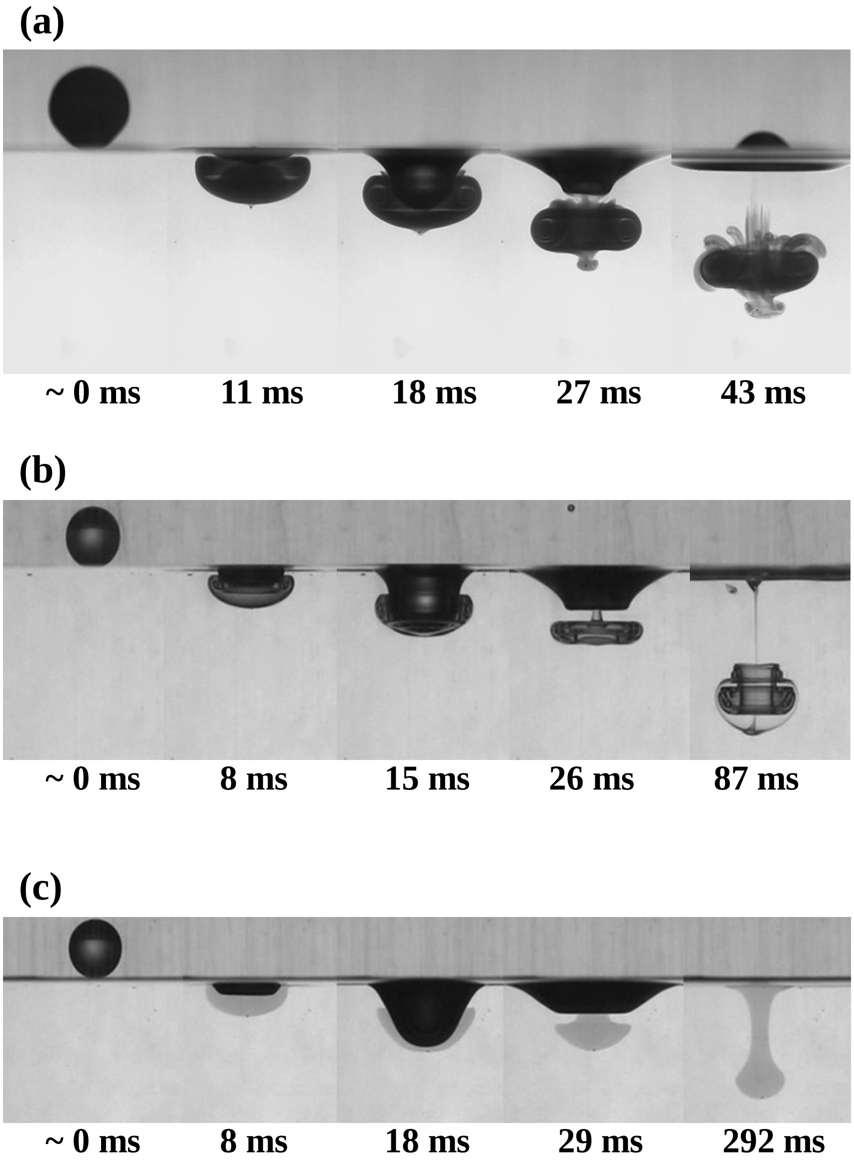

Fig. 5 The phenomena of vortex rings vary from different liquid drop impacts. (a) Water(+fluorescent dye)→Water. (b) 60% Glycerol(+fluorescent dye)→Water. (c) 60% Glycerol(+fluorescent dye)→60% Glycerol.

It has been long since known that the penetration depth of vortex ring varies with the same period of drop oscillations in the literature [7]. However, up to now, there is still no quantitative result to describe the corresponding transportation of vortex ring. A quantitative measure was thus made about the maximum penetration depth (Lmax) with respect to the impacting drop size and the result is shown in Figure 6. It indicates that the maximum penetration depth is linearly and positively correlated for different drop sizes of water drop to water target liquid experiments (case 1). The data of Chapman and Critchlow, Rodriguez and Mesler, as well as Durst are also shown in Figure 6 for comparisons. It is worth noting that the L-criteria were not the same or missed in different studies. Moreover, due to the lack of drop sizes in the study of Durst, the corresponding drop sizes are obtained from the nozzle radius based on Tate's law (R/Rnozzle~[σ/ρgR2]1/3, where R denotes drop radius corresponding to the nozzle radius Rnozzle) [8]. However, all data surprisingly overlap quite well around the line fitted by the present results. Another surprising observation is that the drop data of 60% glycerol mixture impacting onto the water surface (case 2) is also falling on the linear line in Figure 6. It suggests that the maximum penetration depth by single drop impact is not sensitive to the drop viscosity for drop with ten times higher viscosity than water drop (see Table 2).

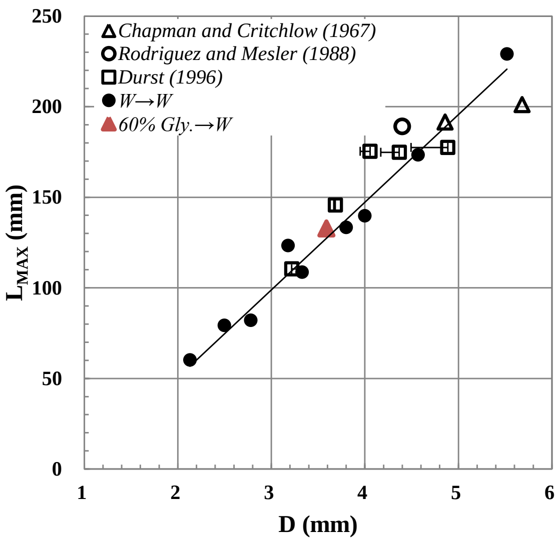

Fig. 6 Relations of the maximum penetration depth L_{max} , drop size, and various liquid properties (inset). The error bars in the data of Durst indicate the extent of difference between predicted drop sizes from Tate' law and measured drop sizes dependent of the nozzle radius in the present experiment.

CONCLUDING REMARKS. This study demonstrates the importance to control the experimental environments for disturbance-sensitive investigations, i.e., the vortex rings formation and penetration by a single drop impacting onto liquid tank. It reveals although there have been various difficulties to be overcome; however repeatable and reliable experiments can be still achievable in a well-controlled experimental environment. Moreover, a suitable criterion for determination of the penetration length is helpful to measure the outcome of vortex ring for quantitative evaluation. A linear relationship of maximum penetration depth and drop size has been found for two different drop liquids of glycerol mixture (upto 60%) and the obtainable data from literature. Increasing viscosity of target liquid suppresses the formation of vortex ring caused by drop impact.

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References

1. Thomson, J. J. & Newall, H. F.: *On the Formation of Vortex Rings by Drops falling into Liquids, and some allied Phenomena.* Proceedings of the Royal Society A, Vol.39, pp. 417-436, 1885.
2. Kutter, V. V.: *Die anwendung von Wirbelringen zur Bestimmung von Oberflachenspannungen.* Physikalische Zeithchrift XVII 23 573-579, 1916
3. Chapman, D. S., Critchlow, P. R.: *Formation of vortex rings from falling drops*. Journal of Fluid Mechanics 29 177-185, 1967
4. Rodriguez, F., Mesler, R.: *The Penetration of Drop-Formed Vortex Rings into Pools of Liquid*. J COLLOID INTERF SCI.121 121-129, 1988.
5. Durst, F.: *Penetration length and diameter development of vortex rings generated by impacting water drops.* Experiments in Fluids 21 110-117, 1996.
6. Rogers, W.B.: *On the formation of rotating rings by air and liquids under certain conditions of discharge*. American Journal of Science, and Arts, Ser. 26, 246, 1858.
7. Bisighini, A., Cossali, G. E., Tropea, C. & Roisman, I. V.: *Crater evolution after the impact of a drop onto a semi-infinite liquid target.* Physical Review E 82, 2010.
8. Tate, T.: *On the magnitude of a drop of liquid formed under different circumstances*. Philos. Mag. 27, 176, 1864.