Effect of air core on the shape and discharge of the outflow through a bottom outlet

Yiyi Ma,[1] Yu Qian,[1,2] and David Z. Zhu[1,2,a)]
[1)] *Department of Civil Engineering, Zhejiang University, Hangzhou 310058, China*
[2)] *Department of Civil and Environmental Engineering, University of Alberta, Edmonton AB T6G 2W2, Canada*

(Received 3 December 2012; accepted 28 January 2013; published online 10 March 2013)

Abstract Experiments were conducted to study the generation of air core and its effect on the outflow shape and discharge in a cylindrical water tank with a bottom well-designed outlet. Depending on the stages of the air core in the tank, the outflow shape can vary from a smooth water jet to a smooth spindle shape with air-core, and to water sprays. The diameter of the nozzle size also has influence on the outflow pattern. The existence of the penetrated air core can dramatically reduce the outflow discharge, with the discharge coefficient decreasing with the nozzle diameter. [doi:10.1063/2.1302203]

Keywords air core, discharge, outflow shape, spray, vortex

Air core induced by intake vortex is a common phenomenon in many industrial processes. In water intake engineering, the occurrence of air core can cause a decrease in pump efficiency and damages in machinery. For water intakes, the critical submergence is defined as the depth when the air core begins to penetrate into the water intake. A number of studies have been conducted on the critical submergence in water intakes.[1–3] The size and generation of the air core is strongly controlled by the strength of vortices in the water body and the nozzle diameter as well.[2,4] The air core has an important effect on decreasing the discharge coefficient at intakes.[3–5] However, there are no reported studies examining the effect of air core on the behaviours of the outflow shape, the breakup of the water jet, and outflow discharge. The use of air core to break up water jet has been a common practice in the spray formation in various engineering applications, such as process industries,[6] spray combustion,[7] agricultural insecticides or fertilizer spraying[8] and so on. Due to its importance to the quality of atomization, the breakup behavior of liquid sheet, caused by the interaction between the air core (or air jet) and liquid, has been studied widely such as the mechanism of interaction between the two phases,[7] different breakup regimes,[9] droplets classes analysis[10] and so on.

In this paper, an experimental study was conducted in a cylindrical water tank with a well designed bottom outlet (Fig. 1). The objectives of the experiments are (1) to observe the vortices and the resulting air core in the tank, and their relationship to the outflow shape, and (2) to study how the air core affects the outflow discharge. Four outlets were used with the size of $d_0 = 5$ mm, 10 mm, 15 mm, 20 mm. These outlets were precisely milled from aluminium blocks. A still camera and a video camera were used to record the experimental process. For different outlet sizes, experiments were repeated by creating large vortices, small vortices and

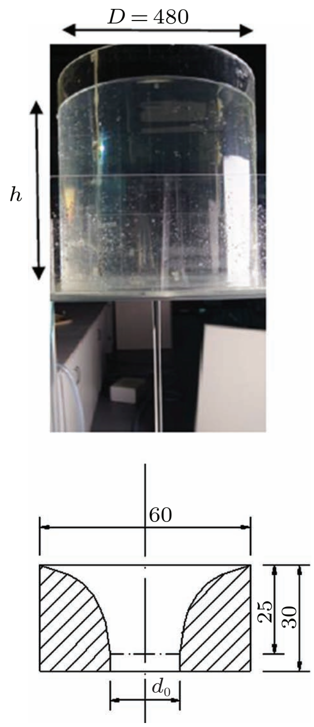
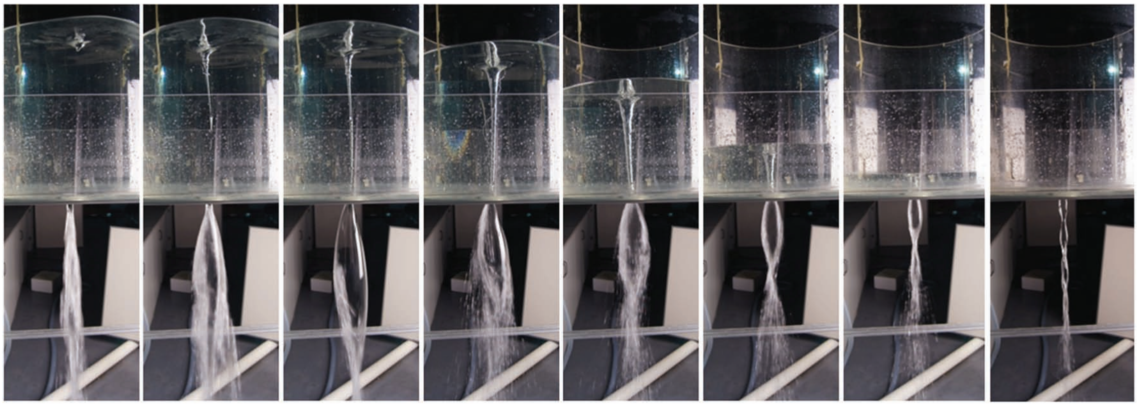


Fig. 1. Photo showing the experimental apparatus and outflow jet with details of the outlet dimension (D is the inner diameter of the tank; h is the water depth; d_0 is the nozzle diameter). All dimensions are in millimetres.

no vortices in the tank. For the experiments without vortices, the system is maintained for 15 minutes after the filling of water. Experiments were started by unplugging the bottom outlet, and the change of water level was video-taped. The flow rate was then obtained from the change in the water volume with time.

The initial vortices were generated using sticks. Large vortices were generated using a long aluminium stick with a square cross-section of 3 cm × 3 cm. The stick was inserted into the water close to the bottom

[a)] Corresponding author. Email: david.zhu@ualberta.ca.



(a) $t = 8$ s (b) $t = 10$ s (c) $t = 12$ s (d) $t = 26$ s (e) $t = 66$ s (f) $t = 168$ s (g) $t = 248$ s (h) $t = 296$ s

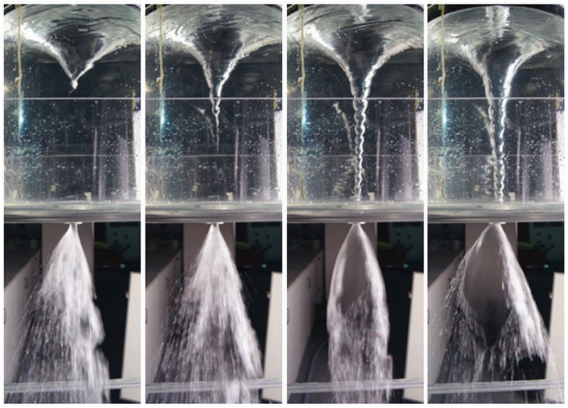
Fig. 2. The evolution of the experiment with initial small vortices for $d_0 = 20$ mm.

and moved along the wall of the tank. A total of 20 rounds of stirring were completed in 15 s. After the stirring, the centre of the water surface dipped by about 10 cm compared to that near the wall. The surface rotational of water speed was also estimated by tracing the movements of the surface particles, which was found to be about 2π rad/s at half the radius from the tank centre. Small vortices were generated using a shorter round stick with a diameter of 2 cm. The stick was inserted into the water to a depth of 20 cm, and a total of 10 rounds of stirring were completed in 10 s by moving along the wall of the tank. Different as the large vortices, no noticeable free surface dip was observed, and the rotational speed at the same location was only about 0.4π rad/s. As will be discussed later in the paper, the results of this study are not sensitive to the strength of these initial vortices, thus no further measurements were conducted.

Figure 2 shows the progress of an experiment with initial small vortices in the tank for $d_0 = 20$ mm. The water level in the tank dropped during the experiment due to the bottom outlet. The initial stirring created swirling in the tank, and a small surface dimple was observed a few seconds after the experiment was started (Fig. 2(a)). An air core formed from the dimple and grew very quickly downwards. In about 4 s, the air core penetrated all the way to the bottom of the tank (Fig. 2(c)). The effect of the air core was observed to have a dramatic effect on the behaviour of the outflow pattern: the outflow suddenly became spindle-shaped and had a very smooth surface once the air core fully penetrated to the bottom (Fig. 2(c)). However, this pattern did not last long due to the movement of the unstable air core in the tank, and it could easily break up to water droplets (Fig. 2(d)). The air core grew thicker when the water level dropped (Fig. 2(e)). Subsequently, the air core became relatively stable and meanwhile, the outflow gradually formed the spindle shape again, although it was not as smooth and stable as before (Figs. 2(e)–2(h)). The change of the air core diameter could be explained by the principle of least resistance path, as discussed by Datta and Som.[4] Once the air core fully penetrated, the air outside began to fill in and its diameter grew due to the continuous ingress of air, until the critical value of air core diameter was reached with a larger resistance. Thus, this critical air core diameter could be regarded as the stable air core diameter. It could also be seen that the size of the spindle decreased when the water level and the discharge decreased during the experiment. As the water level and the discharge decreased further, multiple spindles appeared (Fig. 2(g)), and finally the outflow became jetting-type of the flow (Fig. 2(h)) —— note this jetting flow is different as it has a larger flow rate with an air core inside each drops. Binnie and Davidson's theory[11] gives some useful explanation to the final jetting-type flow: If the jet is spinning, it is possible that the surface-tension forces are balanced by the centrifugal, vibration about the equilibrium position. Therefore, undulations of outflow jet will be developed as the swirl gets feeble. The experiment was finished in about 300 s when the tank was fully drained.

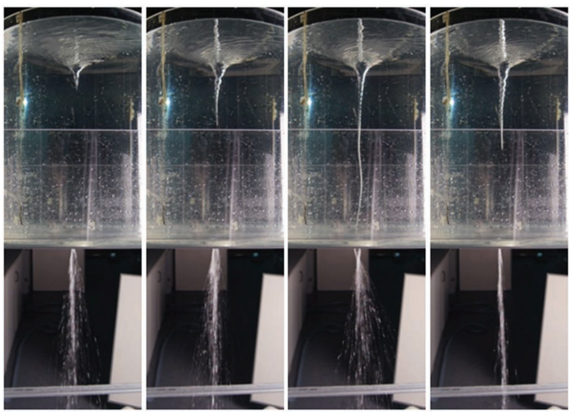
Figure 3 shows the same experiment as in Fig. 2 but with large initial vortices for $d_0 = 20$ mm. Water in the tank swirled much strongly and the funnel-shape water surface existed (Fig. 3(a)). The air core started to form and stretch to the bottom as soon as the tank was unplugged. Note that the air core was much larger and its surface showed a helical shape. Accordingly, the outflow outside the nozzle was much more divergent before the air core fully penetrated (Figs. 3(a) and 3(b)). Once the air core reached the bottom, the outflow immediately presented a constrictive appearance (Fig. 3(c)) and its surface also became much smooth. However, the outflow stretched so wide that it could not form a complete spindle shape as it broke very quickly. Figure 3(d) shows that the outflow spread at a wide angle due to a larger air core and stronger vortices in the tank, and the outflow disintegrated into small droplets like sprays. Similar phenomena were observed for $d_0 = 10$ mm and 15 mm.

For $d_0 = 5$ mm, however, the flow process was quite



(a) $t=1$ s (b) $t=3$ s (c) $t=4$ s (d) $t=13$ s

Fig. 3. The experiment with large initial vortices for $d_0 =$ 20 mm.



(a) $t=13$ s (b) $t=26$ s (c) $t=27$ s (d) $t=28$ s

Fig. 4. The experiment with large initial vortices for $d_0 =$ 5 mm.

different. Even with large initial vortices, the air core in the tank appeared to be much smaller than the one for $d_0 = 20$ mm (Figs. 3 and 4). In addition, the air core initially stretched to the bottom but it quickly retreated back (Figs. 4(a)–4(d)). It repeated this stretching and retreating process a few times in the earlier stage of the experiment. Subsequently, the strength of the vortices decreased due to the viscous dissipation in the tank, and the air core would not extend to the bottom of the tank. For 5 mm nozzle, although the air core was able to penetrate to the bottom, it could not maintain long enough. As a result, although a small "spindle" could be observed in Fig. 4(c), it was quite different from those in large size nozzles. This difference is believed to be caused by the relatively small nozzle size. It can be similarly explained by Datta and Som's "minimum resistance" theory,[4] which was used in the prediction of air core characteristics in a swirl spray pressure nozzle. According to this theory, an increase in the area of the orifice diameter can reduce the resistance offered by the nozzle to the swirling motion of liquid inside it. In turn, it means that the reduction in the orifice size will result

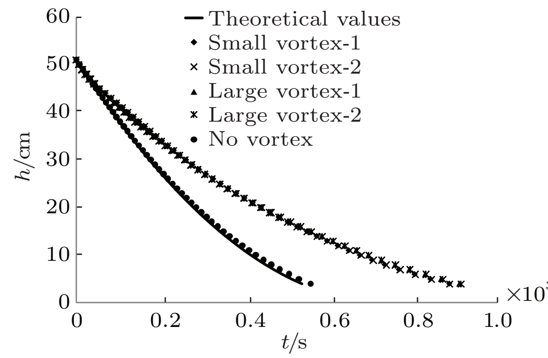


Fig. 5. Variation of water depth h with time for $d_0 =$ 10 mm.

in larger resistance and thus make the air core harder to stretch to the orifice. Therefore, the above-mentioned unsteadiness of air core appears.

The outflow shape without vortices is shown in Fig. 1, which appeared to be a circular water jet with a smooth surface and without any disturbances. It kept the same shape from the beginning all the way to the end of the experiment.

The outflow discharge was obtained for each experiment in order to examine the effect of the air core on the flow rate. Figure 5 shows the change of water level with time for $d_0 = 10$ mm. The experiment was conducted without vortices, with small and large vortices (each of which was repeated once). Figure 5 shows that the discharge was much smaller (i.e., h drops slower) when there was an air core extending all the way to the tank bottom. Also there was no difference in discharge between the initial small vortices and large vortices. The theoretical curve was obtained based on the orifice flow prediction —— $Q = Ca\sqrt{2gh}$,[12] where a is the area of the outlet and the discharge coefficient C is taken as one here as the outlet is well designed without further flow contraction. To calculate the discharge, the measured water depth data were smoothed by taking a moving average of five adjacent points, except for the first and last two data points.

From Fig. 6 the flow rates with no vortex compare very well with the theoretical curve for $d_0 = 10$ mm, 15 mm, 20 mm, i.e., the discharge coefficient C is close to one, unlike a typical orifice where C is about 0.6 due to flow contraction. However, with initial stirring, vortices appeared after the tank was unplugged. After an early stage of the experiment, the air core became penetrated through the tank, the discharge difference between that with and without vortices increased. It was observed in the experiment that, when the air core began to reach the bottom (around $h = 45$ cm), the flow rate suffered a sharp reduction. It also should be mentioned that the strength of the initial vortices had little effect on the discharges (Figs. 6(a) and 6(b)). However, the strength of disturbance was related to when the air core fully penetrated. As can be seen from Fig. 6(b) for $d_0 = 15$ mm, with small vortices, discharge decreased

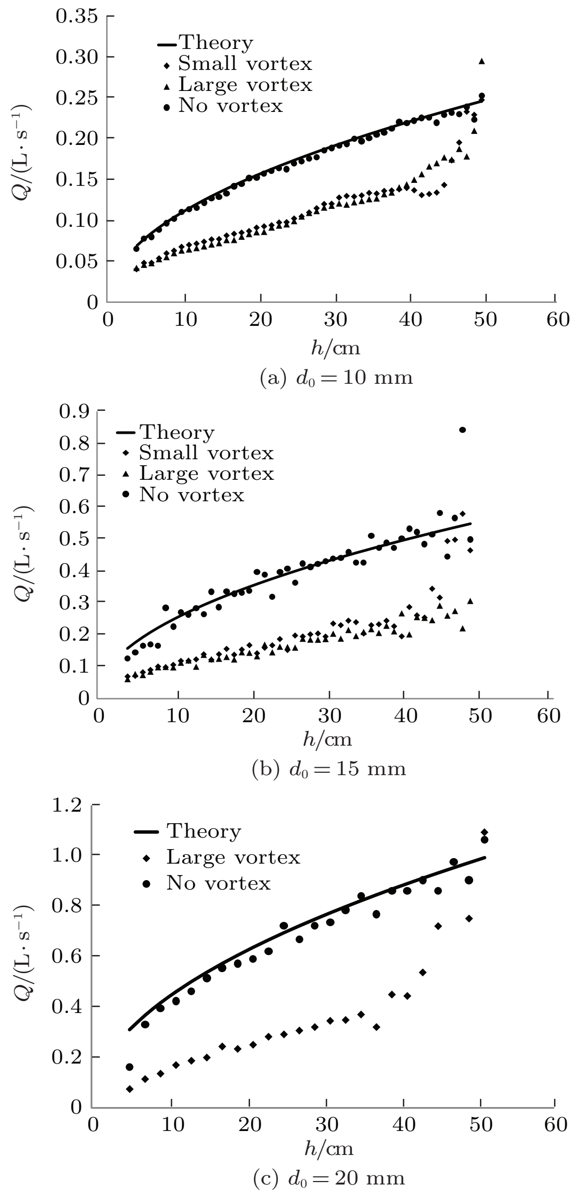


Fig. 6. Variation of flow rate Q with water depth h under different conditions.

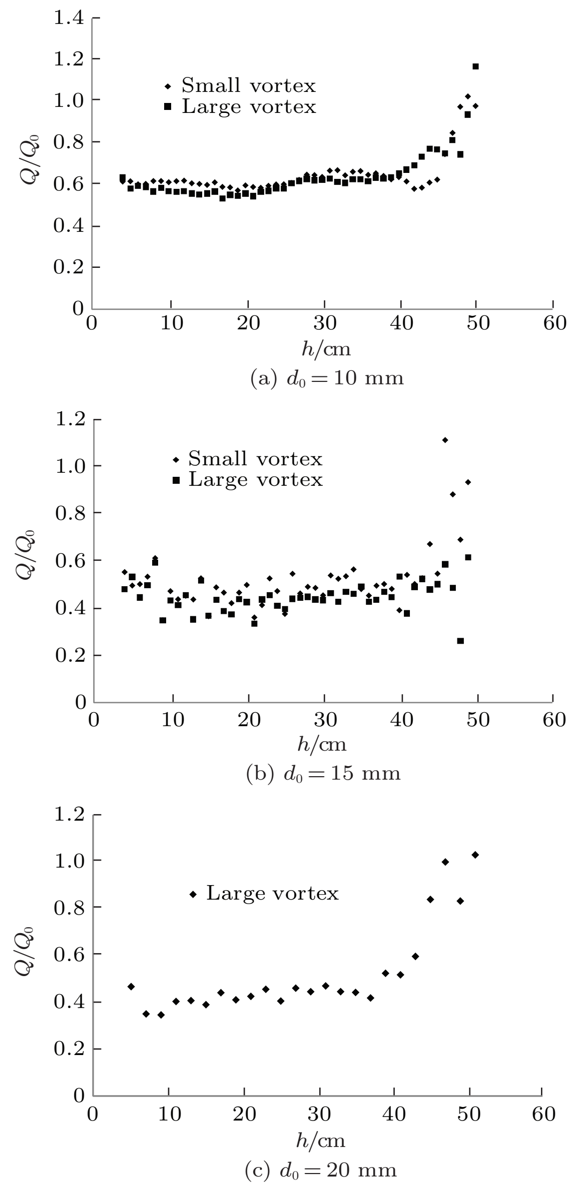


Fig. 7. Ratio of the flow rates with and without vortex. Q_0 is the flow rate without vortex and Q is that with vortex.

around the height $h = 45$ cm while with large vortices, the data deviated from the theoretical curve from the beginning. From Fig. 6(b) the air core had fully developed before the water level reached $h = 48$ cm with initial large vortices while it finished around $h = 45$ cm with small vortices.

The size of the air core influences the effective flow area at the outlet and thus controls the coefficient of discharge. The ratios of the flow rates with and without vortex, i.e., the discharge coefficient C when vortex occurs, are studied in Fig. 7. The trends of the values of C shown in the diagrams are similar and all can be divided into two parts: a gradually decreasing section in the beginning of the experiment and a relatively stable one after the air core is fully penetrated. The gradually decreasing of C reflects the transition from no air core to a fully penetrated air core and the stable part represents the discharge efficiency of the outlet with an air core. The following C refers to the discharge coefficient in the stable part. For $d_0 = 10$ mm (Fig. 7(a)), C was close to 0.6 when the depth dropped below 45 cm (when the air core fully penetrated) under different disturbance. Similarly for $d_0 = 15$ mm (Fig. 7(b)), C fluctuated around 0.5 though the data were a little scattered. For $d_0 = 20$ mm, the average of C in the stable section was around 0.4. It can be concluded that C decreased as the nozzle diameter increased and it was little affected by the strength of vortex. Besides, in a single experiment, C did not change much as the water depth dropped. However, Liu et al.'s experimental results showed that the discharge coefficient depended on the initial water height and it decreased when the initial water height decreased.[5]

Except the above-mentioned effects of penetrated air core had on the discharge at the outlet, the experiments also revealed that, the outflow shape was related to the status of the air core in the upper water layer. In a single experiment, as the air core developed with the falling water depth, outflow shape could be observed varying from a smooth water jet, to a smooth spindle shape with air-core, and to water sprays. It could be obtained by comparing the experiments under different conditions that the intensity of the vortex and the diameter of the nozzles were also important factors of affecting the pattern of outflow. When the nozzle diameter decreased to a certain level like $d_0 = 5$ mm, the unsteadiness of air core would appear.

1. F. Kocabas, and S. Unal, Advances in Engineering Software **41**, 802 (2010).
2. N. Yildirim, and F. Kocabas, Journal of Hydraulic Engineering-ASCE **124**, 103 (1998).
3. A. J. Odgaard, Journal of Hydraulic Engineering, ASCE **112**, 610 (1986).
4. A. Datta, and S. K. Som, International Journal of Heat and Fluid Flow **21**, 412 (2000).
5. T. S. Liu, P. Merati, and S. A. Woodiga, et al., Proceedings of the Institution of Mechanical Engineers Part D——Journal of Automobile Engineering **222**, 565 (2008).
6. S. S. Yao, J. Zhang, and T. G. Fang, Experimental Thermal and Fluid Science **39**, 158 (2012).
7. V. Kulkarni, D. Sivakumar, and C. Oommen, Journal of Fluids Engineering-Transactions of the ASME **132**, 011303-1 (2010).
8. A. Dechelette, O. Campanella, and C. Corvalan, et al., Chemical Engineering Science **66**, 6367 (2011).
9. D. Sivakumar, and V. Kulkarni, Experiments in Fluids **51**, 587 (2011).
10. J. L. Santolaya, L. A. Aisa, and E. Calvo, et al., Chemical Engineering and Processing **49**, 125 (2010).
11. A. M. Binnie, and J. F. Davidson, Proceedings of the Royal Society of London Series A——Mathematical and Physical Sciences **199**, 443 (1949).
12. E. F. Brater, H. W. King, and J. E. Lindell, et al., *Handbook of Hydraulics* (McGraw-Hill, USA, 1996).