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PIV study of vortexing during draining from square tanks[†]

C. H. Sohn[*], M. G. Ju and B. H. L. Gowda

School of Mechanical Engineering, Kyungpook National University, 702-701, 1370 Sankyuk-dong, Puk-gu, Daegu, Korea

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Abstract

The flow field in square tanks with various corner roundings is studied to investigate drain flow characteristics. An attempt is made to understand the mechanism of flow field responsible for vortex suppression by the different radius of rounding at the corner. For this purpose, flow visualization studies using particle image velocimetry are employed to determine the flow patterns in a square tank. Results are obtained for no draining and with draining experiments. The flow field is visualized both in horizontal and vertical planes. The results reveal that the secondary vortices formed at the corners are responsible for vortex suppression.

Keywords: Vortex flow; PIV; Square tank; Corner rounding; Drain flow

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1. Introduction

When liquid drains from a cylindrical tank with a free surface through an axisymmetrically placed drain port, a dip is formed on the free surface [1], which instantaneously extends to the drain port. A vortex with an air core then forms when the liquid level reaches a critical height. The formation of the dip and the onset of the vortex occur almost simultaneously. Critical height (H_c) is then taken as the liquid level at this instant. Measuring this height with the scale attached to the container is convenient as there is hardly any distortion in the free surface. The air core extends up to and reduces the effective cross-sectional area of the drain outlet. Consequently, the flow rate is reduced [2-4]. An analytical study of this problem was investigated by Forbes and Hocking [5]. Initial disturbances such as rotational motion and vibration due to environmental disturbances can augment the vortex formation [6]. This phenomenon has practical relevance in fuel feed systems in space vehicles and rockets. During flights of space vehicles and rockets, such vortexing can affect the outflow from the liquid propellant tank to the engines. This phenomenon is of importance in the operation of hydraulic intakes.

Some related investigations that deal with swirling flows in a container with a free surface but without draining are described below. An experimental analysis of vortex motion generated by a swirling flow of viscoelastic fluid with a free surface using particle image velocimetry (PIV) was conducted by Wei et al. [7]. An inertia-driven vortex was pushed to the corner between the free surface and the cylindrical wall by a counter-rotating vortex. The influence of surfactants on the dip formed at the free surface was studied and the value of the dip was found to be related to determining the solution viscoelasticity for the onset of drag reduction. A numerical analysis of the above problem was conducted by Yu et al. [8], and the experimental results have been qualitatively reproduced. The flow field generated in a cylindrical casing with a free surface due to the rotation of a disk at the bottom was studied both experimentally and using numerical simulation by Itoh et al. [9]. Viscoelastic fluid with different concentrations of surfactants was used and the extent of the inverse flow region, where the fluid rotates in the direction opposite to the rotating disk, has been clarified in detail. Tamano et al. [10], using the same experimental facility as above, carried out the flow visualization of the ring vortex formed near the center of the rotating disk that is periodically shed away from the disk.

As mentioned earlier, a vortex forms with rotation imparting and draining in a cylindrical container with a free surface. To prevent vortexing, Ramamurti and Tharakan [11] suggested the use of shaped ports. Gowda et al. [12] and Gowda and Udhayakumar [13] used a dish-type and vane-type suppressor to prevent vortex formation. Gowda [6] showed that vortexing is suppressed in a square container with sharp corners, even with rotation and draining. However, vortexing occurs in a container with circular cross-section with rotation imparting and draining. Hence, it is relevant to study the influence of corner radius in a square container on vortexing. It is interesting and important to determine the radius of corner rounding that prevents vortexing.

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[*] Corresponding author. Tel.: +82 53-950-5570, Fax.: +82 53 950 5570
E-mail address: chsohn@knu.ac.kr

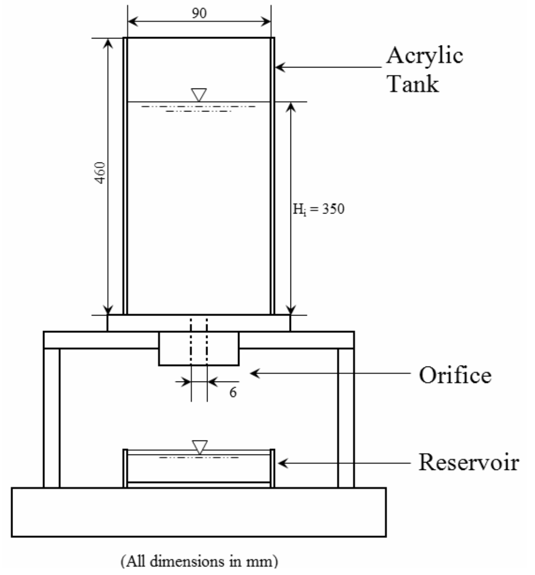
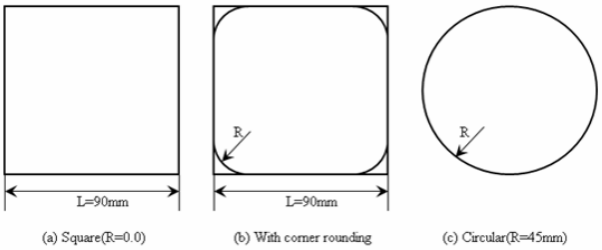


Fig. 1. Diagram of square tank.



(a) Square(R=0.0) (b) With corner rounding (c) Circular(R=45mm)

Case	R/L
1	0.00
2	0.22
3	0.33
4	0.4
5	0.5

L : Length of square tank
R : Radius of corner

Fig. 2. Cases considered.

In the present study, the flow field in square tanks with different radius of rounding at the corner is studied to investigate drain flow characteristics and to determine how the vortex pattern changes with corner radius. Furthermore, an attempt is made to understand the changes in the flow field brought about by the corner radius in the square tank that ultimately prevents vortex formation. For this purpose, flow visualization studies using PIV to determine the flow patterns in a square tank are carried out after imparting rotation to the liquid in the tank. Results are obtained for no draining and with draining experiments. The flow field is visualized both in the horizontal and the vertical planes.

2. Experiments

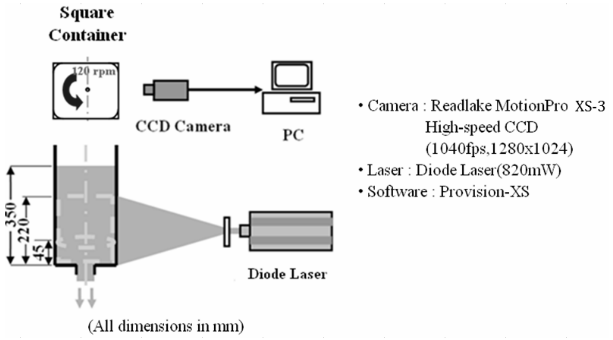


Fig. 3. Experimental arrangement for PIV studies.

The schematic of the experimental apparatus and the cases considered are shown in Figs. 1 and 2. Experiments were conducted using an acrylic tank with square cross-section measuring 90 mm x 90 mm, and tanks with different corner radii, R. The different corner radii were achieved by using transparent plastic sheets of 0.5 mm thickness carefully bent to obtain the necessary shape and introduced into the square tanks. Considerable time and effort were expended to achieve the required radius at all the corners. The drain port with a diameter of 6 mm was axially located. With the drain port closed by a stopper, rotation was imparted to the liquid (water) in the container by controlled stirring using varying numbers of revolution of the stirrer over a constant period [6]. The stirrer, with a diameter of 18 mm, was a hollow tube with a wall thickness of 0.5 mm and length of 500 mm. It was introduced into the tank so that the lower tip was slightly above the bottom of the tank and the revolutions were imparted manually. To check the reliability of the results obtained, the experiments concerning the measurement of the critical height were repeated several times. The experiments were conducted with initial height of liquid (H_i) equal to 350 mm (Fig. 3) as this initial height has been found to be very convenient for observation.

A Diode Laser (820 mW) was utilized as a light source of the PIV system. Redlake MotionPro XS3 High-speed CCD camera operated at 150 fps and yielding a time-step between frames of 0.0067 s was employed. The image resolution was 1280x1024 pixels and the particle images were processed using the Provision software package. The seeding was accomplished using high porous polymer particles of 44 μm size. The schematic of the experimental arrangement with PIV is shown in Fig. 3.

3. Results and discussion

As mentioned earlier, when rotation is imparted to the fluid in the container and draining is started without any suppressor, a vortex is formed. At lower values of RPM, the critical height, H_c (at which the vortex forms) depends on the magnitude of the rotation given. However, for 90 RPM and above, the critical height does not vary considerably [13]. Hence, all the results presented are obtained at 120 RPM (corresponding peak vorticity of approximately 25 rad/s).

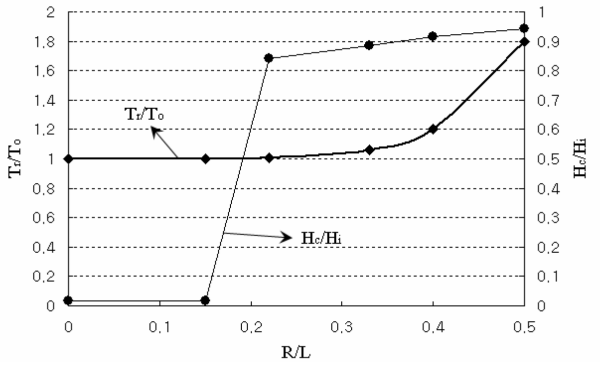
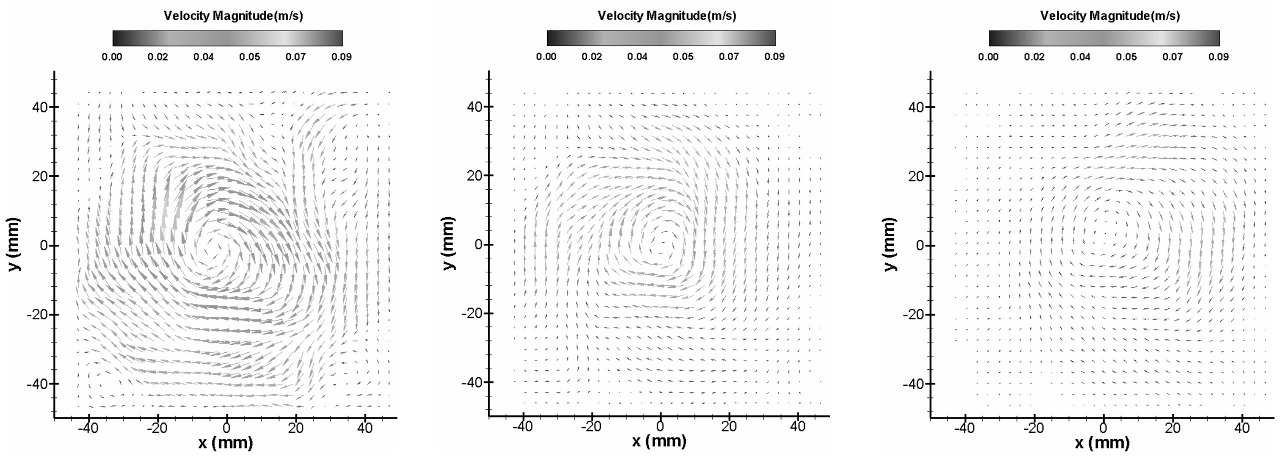


Fig. 4. Influence of corner radius on draining time and critical height.



(a) t=10 s

(b) t=20 s

(c) t=30 s

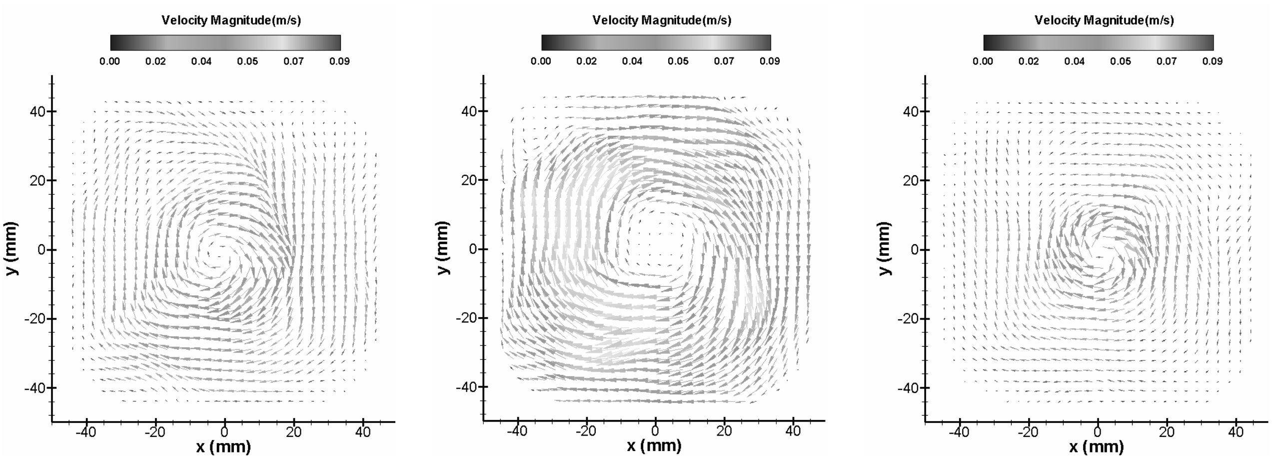
Fig. 5. Velocity vectors in the horizontal plane (No draining; R/L=0.0, square).

The influence of the corner rounding on the draining time and the critical height are shown in Fig. 4. T_r is the draining time with rotation and T_o is the time without rotation imparted. As seen from Fig. 4, the draining time is not affected until R/L is equal to 0.25. Beyond 0.25, the draining time gradually increases. After R/L = 0.4, a steep increase is seen. However, as seen from the figure, the vortex formation is suppressed only up to R/L = 0.15. Though vortex formation also occurs between R/L = 0.15 and 0.25, the vortex does not extend to the port and does not influence the time of draining. For R/L greater than 0.25, the critical height H_c continuously increases, although at a gradual rate. In spite of the gradual increase observed, the vortex becomes sufficiently strong and extends into the drain port, thus considerably influencing the draining time (Fig. 4). To understand the reasons for these observed features, PIV measurements are conducted.

The PIV results for the experiment with rotation imparting and no draining in the horizontal plane are presented in Figs. 5 to 8 for the cases R/L = 0 (square), 0.22, 0.33, and 0.5 (circular). In each figure, t is the time elapsed after imparting the rotation to the liquid in the container. The results are obtained at a height of 45 mm from the bottom (Fig. 3). This height is chosen for experimental convenience. For the square tank, at t = 10 s (Fig. 5(a)), two vortices are seen at the corners, which extend to nearly 25% of the tank on each side. Though a strong vortical pattern in the cross-section is seen, the flow field is not symmetrical. With time, the corner vortices decay (Figs. 5(a) and 5(b)), as well as the overall vorticity, which can be made out by the reduction in the lengths of the velocity vectors. The flow tends to become nearly axisymmetric in the central portion.

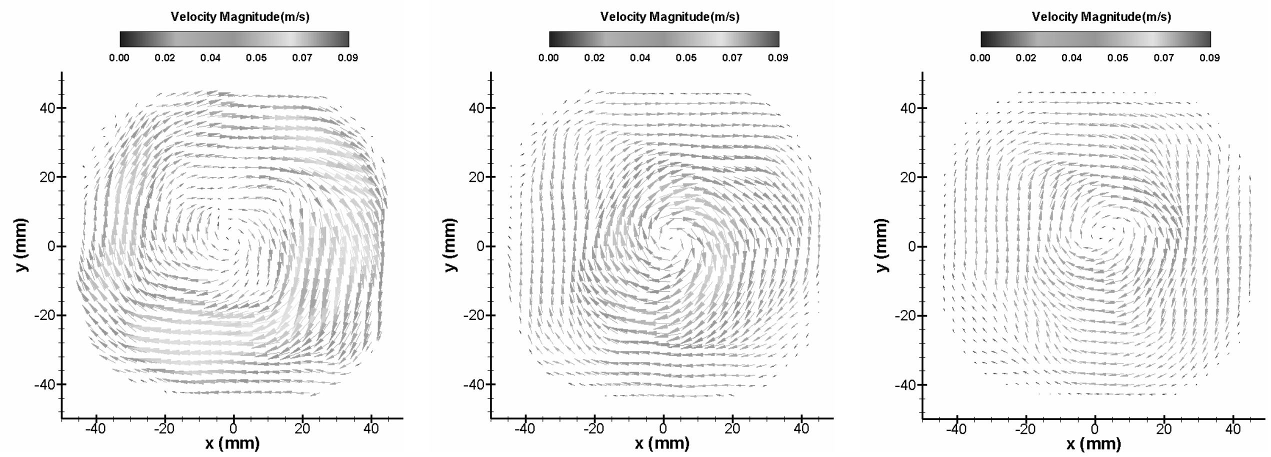
With R/L = 0.22 and t = 10 s (Fig. 6(a)), a more uniform distribution of vorticity (also stronger) across the cross-section of the tank is seen compared to the square cross-section (Fig. 5(a)). Furthermore, there is a slower decay of vorticity with time in this case (Figs. 6(b) and 6(c)) as compared to that in Figs. 5b and 5c. This trend of reduction in the decay rate with time intensifies with the increase in R/L (Figs. 7(a) to 7(c)). For the circular cross-section (Figs. 8(a) to 8(c)), it is clearly seen that the decay rate is minimum. The flow fields in this case exhibit axisymmetry.

Results in the vertical plane with no draining are presented in Figs. 9 to 12 for the various cases mentioned earlier. Although the velocity vectors have been obtained for the entire height of the tank, only the results showing a height of up to 45 mm are presented because it has been observed that this



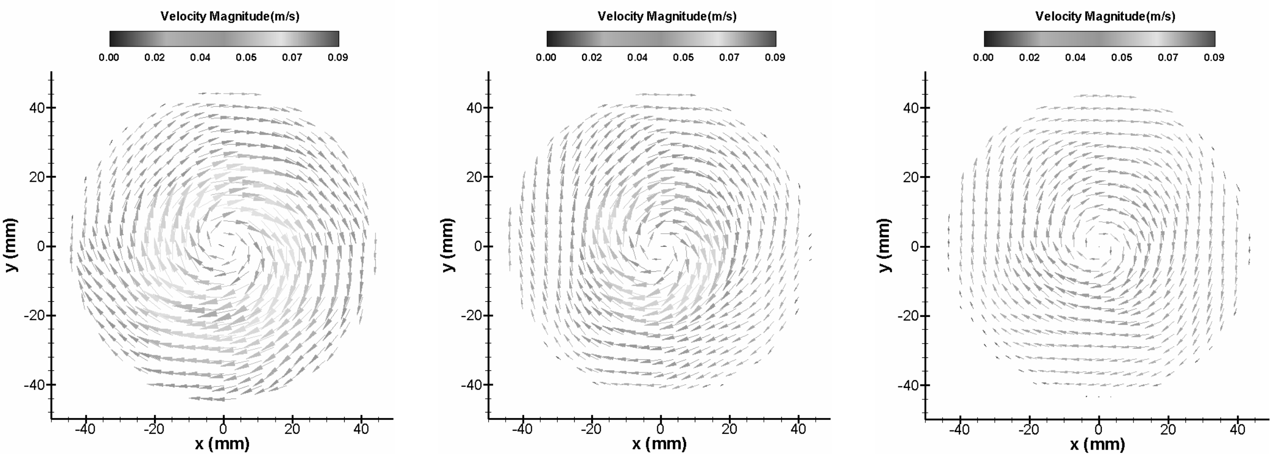
(a) t=10 s (b) t=20 s (c) t=30 s

Fig. 6. Velocity vectors in the horizontal plane (No draining; R/L=0.22).



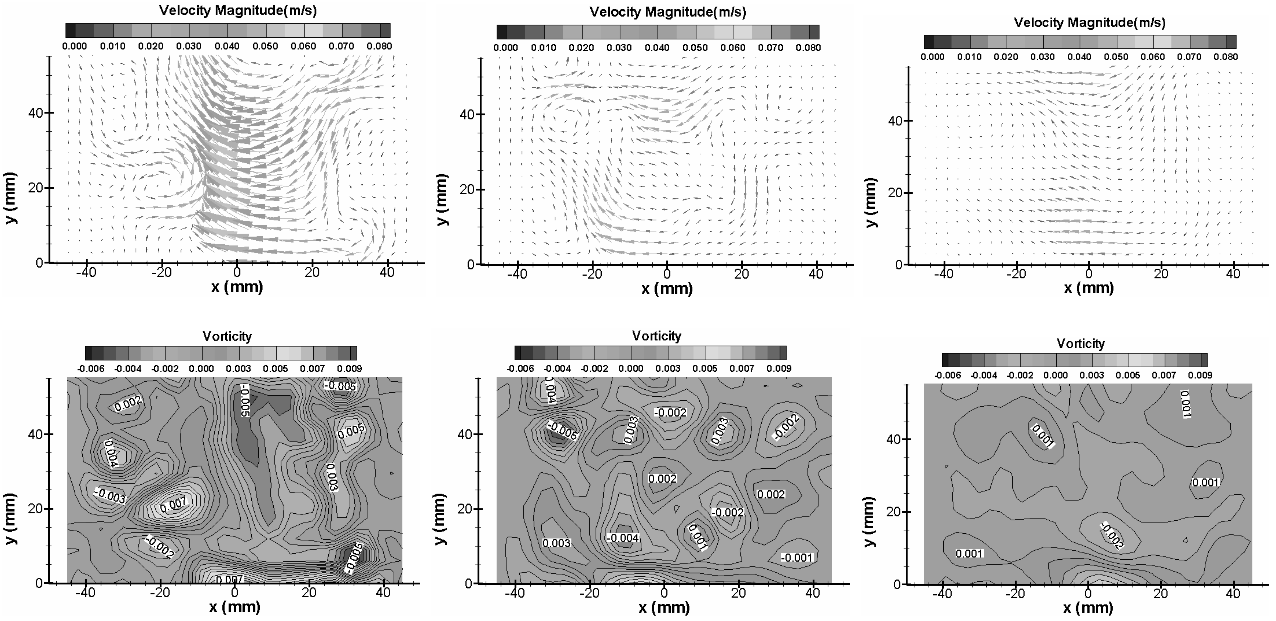
(a) t=10 s (b) t=20 s (c) t=30 s

Fig. 7. Velocity vectors in the horizontal plane (No draining; R/L=0.33).



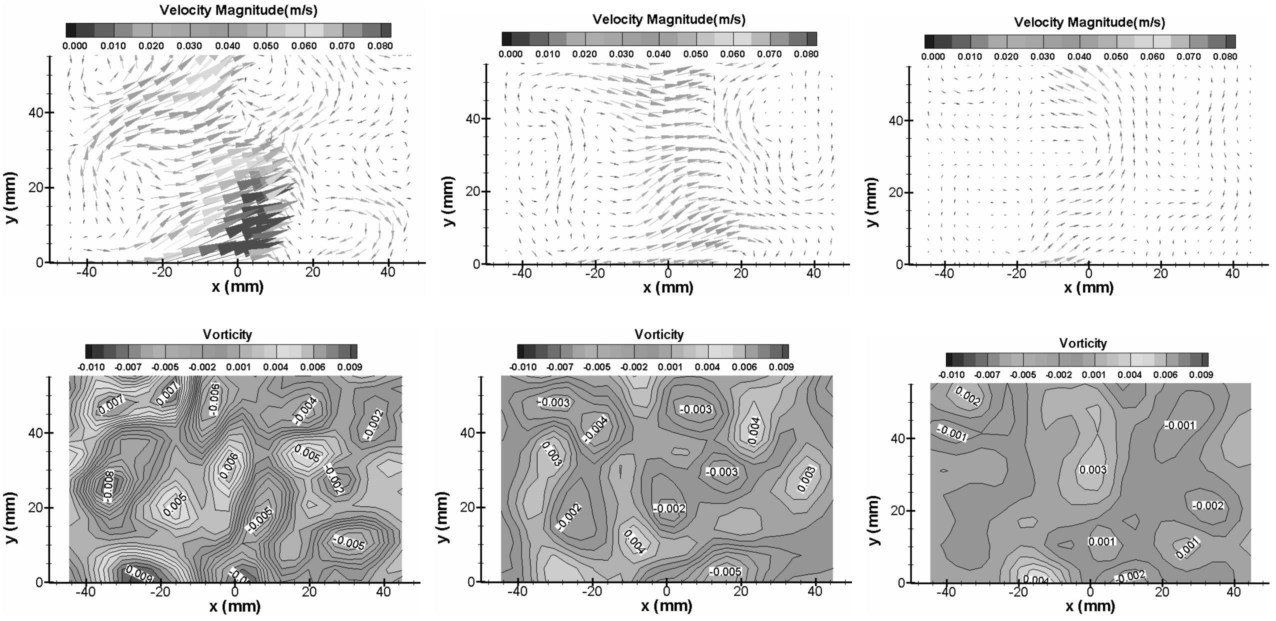
(a) t=10 s (b) t=20 s (c) t=30 s

Fig. 8. Velocity vectors in the horizontal plane (No draining; R/L=0.5, circular).



(a) t=10 s (b) t=20 s (c) t=30 s

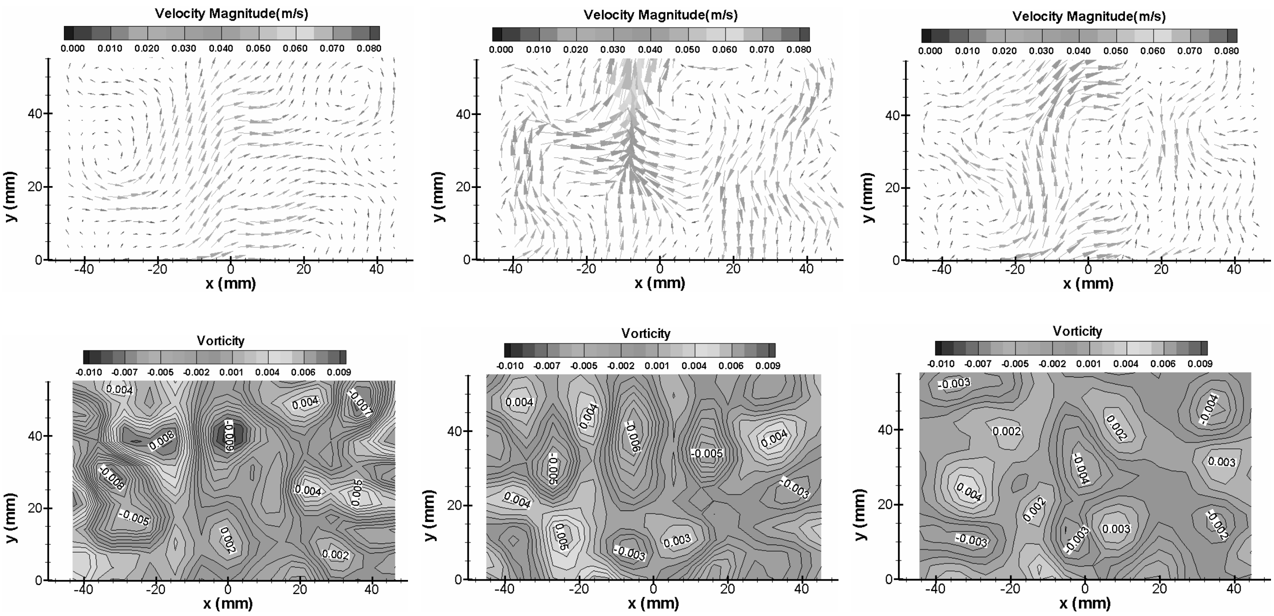
Fig. 9. Velocity vectors and vorticity contours in the vertical plane (No draining; R/L=0.0, square).



(a) t=10 s (b) t=20 s (c) t=30 s

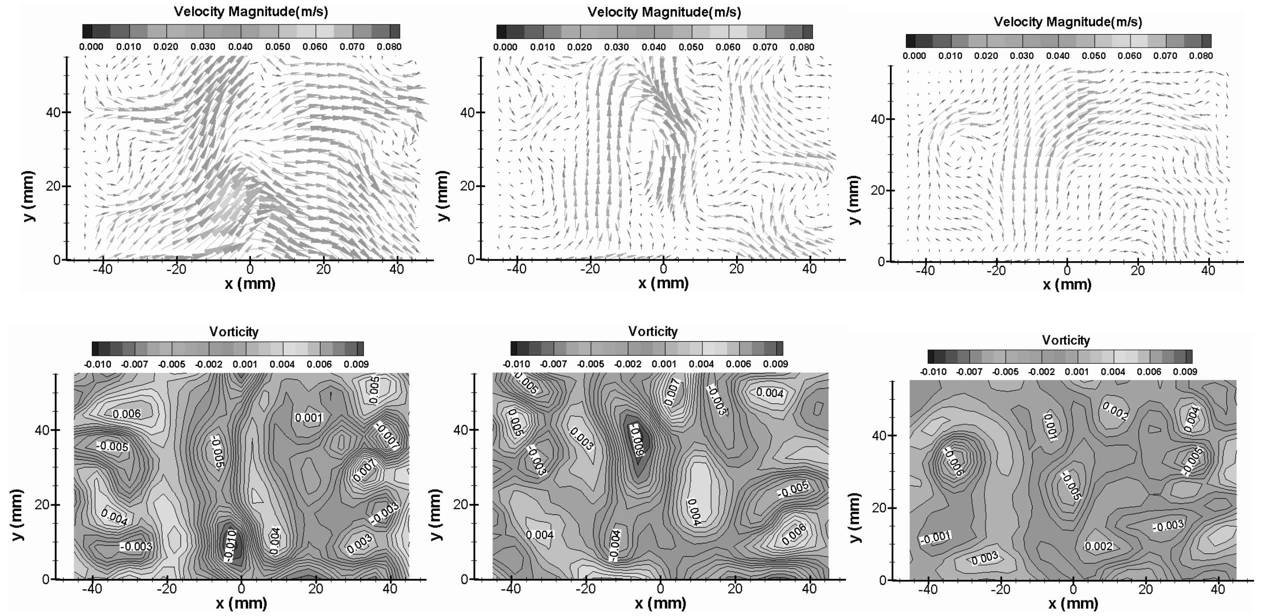
Fig. 10. Velocity vectors and vorticity contours in the vertical plane (No draining; R/L=0.22).

region plays a crucial role in vortex formation or suppression. In each figure, both the velocity vectors and the vorticity contours are presented. For R/L = 0 (Figs. 9(a) to 9(c), square section), a complex flow pattern with a flow in the horizontal direction very close to the bottom surface is seen. However, what is striking is the rapid decay of vorticity with time (from (a) to (c)). In Fig. 9(c), both the magnitude of the velocity vectors and the intensity of vorticity are much lower compared to those in Fig. 9(a). The results presented by Figs. 10(a) to 10(c) show that decay of the same between case (a) (t=10 s) and case (c) (t=30 s) is comparatively lower. This trend continues and intensifies with the increase in R/L ratio (Fig. 11). For the circular section (Fig. 12), the decay between (a) and (c) is minimum. These results correspond with the results earlier described for the horizontal plane. Another observable feature is the difference in the flow very near the bottom wall



(a) t=10 s (b) t=20 s (c) t=30 s

Fig. 11. Velocity vectors and vorticity contours in the vertical plane (No draining; R/L=0.33).



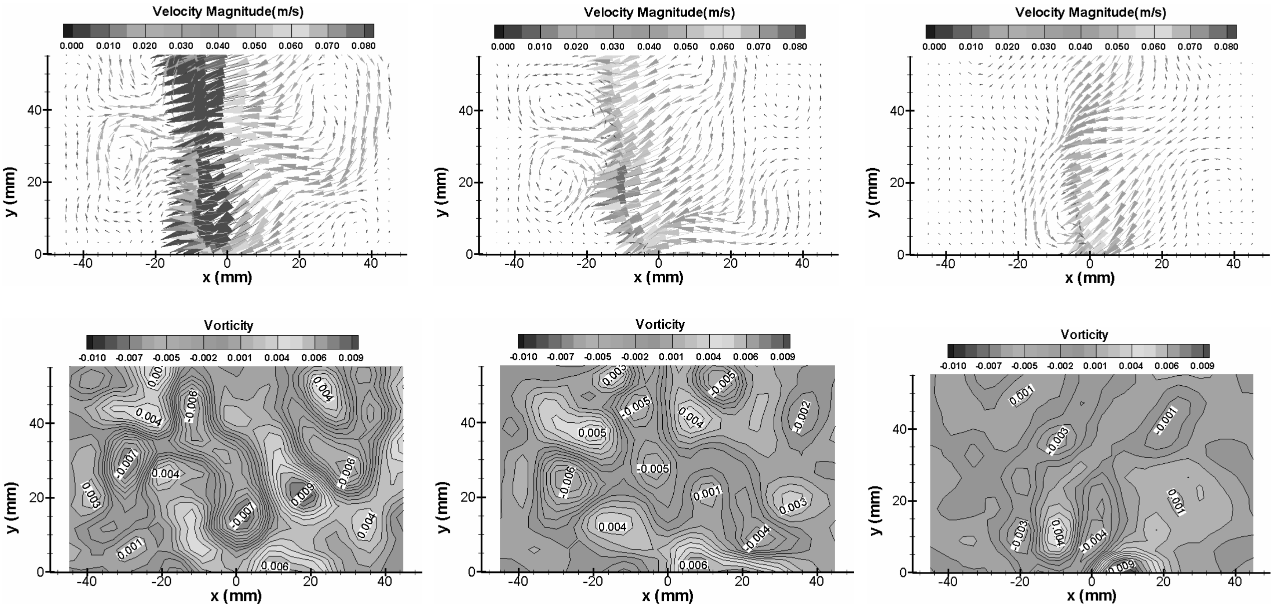
(a) t=10 s (b) t=20 s (c) t=30 s

Fig. 12. Velocity vectors and vorticity contours in the vertical plane (No draining; R/L=0.5, circular).

between the various cases. The horizontal flow observed in Fig. 9 for the square section gradually changes with the change in the cross-sectional shape (Figs. 10 to 12).

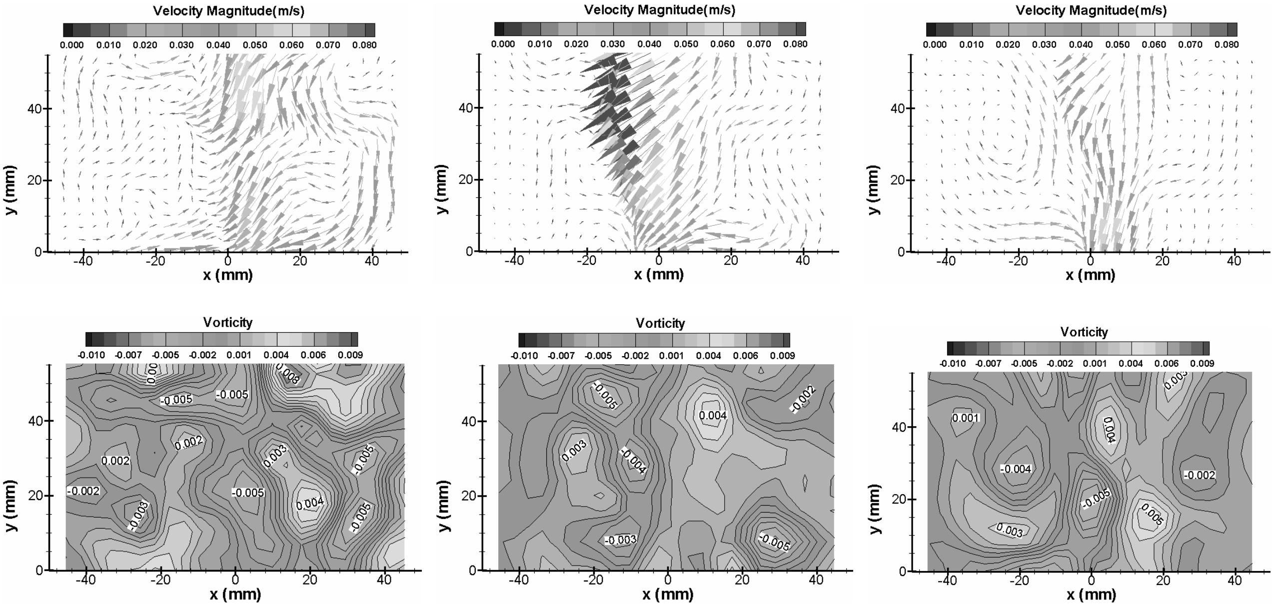
Results in the vertical plane with draining are presented in Figs. 13 to 16. No vortex is seen in Fig. 13, and a general flow towards the port area located at x = 0 is observed. With time, the vortical patterns on the outer sides tend to decay. This is reflected in the vorticity contours. The vortex does not appear or extend to the port, even in the case of R/L = 0.33 (Fig. 15). The presence of the vortex is clearly seen in Fig. 16, where the occurrence of the vortex and the accompanying air entrainment appears to intensify the vorticity on either side, as can be inferred from the vorticity contours.

To have a better understanding of the phenomenon, the velocity variation across the cross-section in the horizontal plane (x-y plane) along y=0 is plotted in Fig. 17. The figure presents



(a) t=10 s (b) t=20 s (c) t=30 s

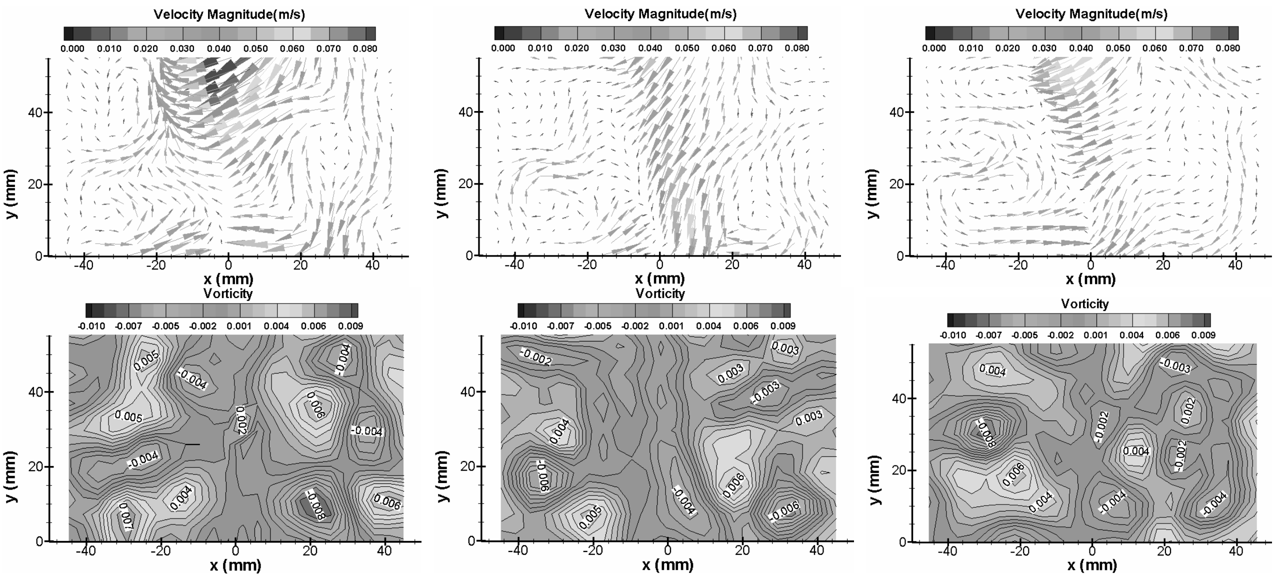
Fig. 13. Velocity vectors and vorticity contours in the vertical plane (With draining; R/L=0.0, square).



(a) t=10 s (b) t=20 s (c) t=30 s

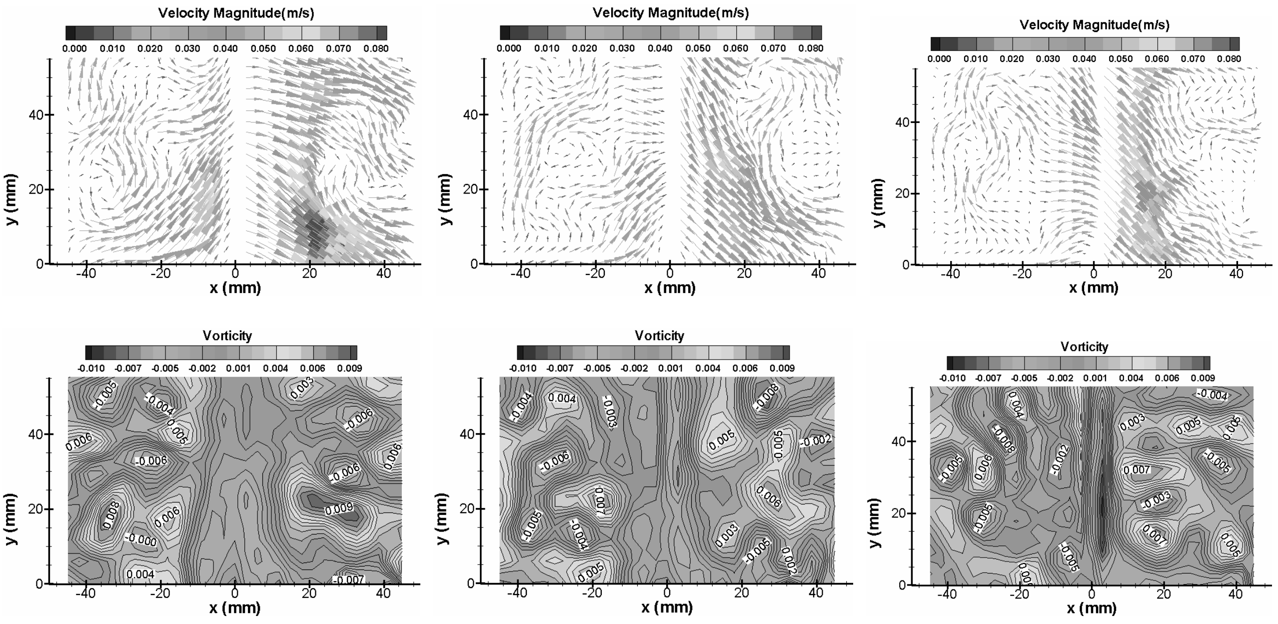
Fig. 14. Velocity vectors and vorticity contours in the vertical plane (With draining; R/L=0.22).

the tangential components at various x - positions where only the magnitudes are indicated. The profiles are obtained for the case with draining at a height of 45 mm, the same height of the vector plots shown earlier. The profiles are similar to that of the combination of free and forced vortex. The dotted lines indicate the extent of the vortex. The interesting features observed are as follows: 1) The velocity profiles become steeper near the axis of the tank and away from the axis as R/L increases; 2) the width of the dip increase with R/L; and 3) the decay of velocity with time is slower with the increase in R/L, with maximum decay rate observed for the square cross-section and minimum for the circular. In addition, although vortex is present at this height for R/L = 0.22 and 0.33 (as indicated by the dotted line), it does not extend to the port, unlike in the case of the circular cross-section. This is in agreement with the descriptions in Figs. 4(a) and 4(b).



(a) t=10 s (b) t=20 s (c) t=30 s

Fig. 15. Velocity vectors and vorticity contours in the vertical plane (With draining; R/L=0.33).



(a) t=10 sec (b) t=20 sec (c) t=30 sec

Fig. 16. Velocity vectors and vorticity contours in the vertical plane (With draining; R/L=0.5, circular).

In the case of the square section, an apparent mechanism that absorbs or annuls the vorticity with time is observed. This should mostly originate from the corner secondary vortices that occur in this case. It is evident that even a slight alteration on the circular cross-section prevents the vortex from extending to the port, reducing its influence on the drain time. Conversely, corner rounding can be introduced in the case of the square, and possibly in other geometries with sharp corners, where vortex suppression can still be achieved. This may have a significant role because while the square section suppresses the vortex, it has sharp corners that may lead to stress concentration and structural disadvantages.

4. Conclusions

This study reported on vortexing phenomenon in square-shaped cylindrical tanks without and with various degrees of corner rounding. It determined that the vortex formation is

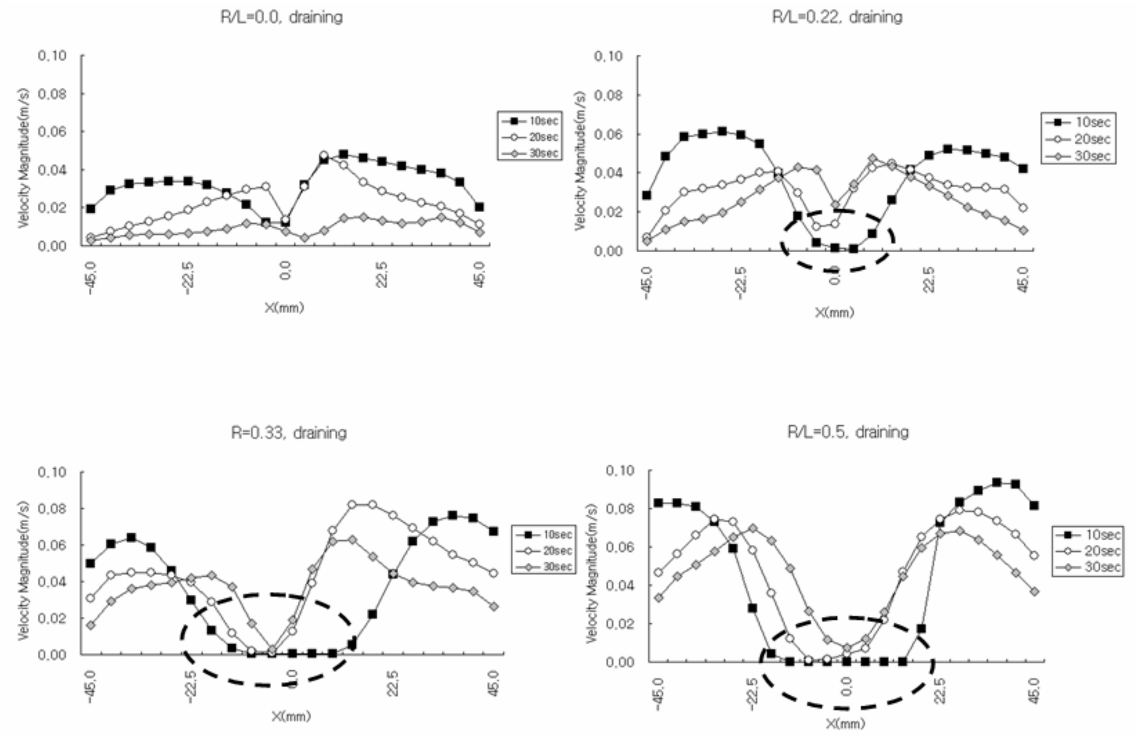


Fig. 17. Average velocity along y = 0.0 (With draining; average velocity at t±5 s).

suppressed in these cases, contrary to the observations on the circular cross-section. This is basically due to the fast decay or annulling of the vorticity introduced, as PIV results have effectively revealed. The corner secondary vortices seen in the case of the square shape seem to be responsible for this phenomenon. The vortex is formed; however, despite the considerable corner rounding, it is not strong enough to extend to the port and affect the outflow rate. The mechanism in these cases could be the flat surfaces that promote the decay of vorticity. These findings have considerable practical significance as the use of square cross-section with very small corner rounding also results in vortex suppression and negative structural stress concentration.

Acknowledgement

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Nomenclature

H_c : Critical height of liquid, mm
H_i : Initial height of liquid, mm
L : Side dimension of the square tank, mm
R : Radius of corner rounding, mm
t : Time elapsed after imparting rotation, s
T_o : Time of emptying without rotation, s
T_r : Time of emptying with rotation, s

Chang Hyun Sohn received his M.Sc .(Eng) in Mechanical Engineering in 1985 from KAIST. He also received his Ph.D. in Mechanical Engineering in 1991 from KAIST. He worked in ADD for 3 years. He worked in Cambridge University as a visiting assistant professor in 1996. He works in Mechanical Engineering, Kyungpook National University as a professor since 1994. His research interests are CFD, PIV, Flow Induced Vibration and Thermal-hydraulics in Mechanical Engineering Field.

Myoung Gun Ju received his M Sc (Eng) in Mechanical Engineering in 2009 in Kyoungpook National University.

B. H. Lakshmana Gowda received his M.Sc .(Eng) in 1965 from Indian Institute of Science, Bangalore. He also received his Ph.D. in 1974 from Indian Institute of Technology, Madras. He worked in Indian Institute of Technology, Madras as a professor since 1967. He worked in Kyungpook National University as a visiting professor from 2004. He works in Mechanical Engineering, BTL Institute of Tecnology, Bommasandra, Bangalore since 2008. His research interests are Turbulent Shear Flows, Flow Induced Vibration and Flow Around Three-Dimensional Bluff Bodies.