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Draining from Cylindrical Tanks with Vane-Type Suppressors – A PIV Study

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Abstract : The vortexing phenomenon that occurs in a cylindrical container is studied using PIV. The influence of the vane-type suppressors which prevent the vortex formation is investigated. An attempt has been made to understand the mechanism that is responsible for vortex suppressing. There is a strong updraft generated due to the suppressors which leads to annihilation of vorticity which appears to be responsible for vortex suppression.

Keywords : Vortexing, Vane-type Suppressors, PIV

1. Introduction

When liquid drains from a cylindrical tank through an axisymmetrically placed drain port, a vortex with an air core forms when the liquid level reaches a critical height. The air core extends up to and reduces the effective cross-sectional area of the drain outlet and consequently the flow rate (Abramson et al, 1962, Pasley et al, 1981, Zhou et al, 1990). Initial disturbances like rotational motion and vibration due to environmental disturbances can augment the vortex formation (Gowda et al, 1996). This phenomenon has practical relevance in fuel feed systems in space vehicles and rockets. During flight of space vehicles and rockets, such vortexing can affect the out flow from a liquid propellant tank to the engines. It is to be noted that the gravity force and the ambient pressure are very different in the outer space. However, the phenomenon is of pertinence in the initial stages of the flight. All the previous investigations mentioned are carried out under normal conditions as done in the present study. Also, this phenomenon is of importance in the operation of hydraulic intakes.

For preventing vortexing, Ramamurti and Tharakan have suggested the use of shaped ports (Ramamurti et al, 1992). Gowda et al. have used a dish-type and vane–type suppressor to prevent vortex formation (Gowda et al, 1996, 2005). However, the mechanism by which vortexing is prevented by these types of suppressors, especially the vane-type, is not very clear. Some studies are reported for the dish-type suppressor by Mizuki et al. (2003) regarding this aspect. In the present study an attempt is made to understand the changes in the flow field brought about by the vane-type suppressors with different numbers of vanes in a circular tank which ultimately prevent vortex formation. For this purpose, flow visualization studies using PIV (Particle Image

Velocimetry) to determine the flow patterns in a cylindrical tank with circular cross section without suppressor or with suppressor are carried out after imparting rotation to the liquid in the tank. To understand the mechanism of vortex suppression while draining, it is essential to know the changes in the flow field without draining when the suppressor is introduced. Hence, results are obtained when there is no draining and with draining. The flow field is visualized both in horizontal and vertical planes.

2. Experimental Arrangement

The schematic of the experimental apparatus is shown in Fig.1. Experiments are carried out using an acrylic tank with a circular cross section with an inner diameter of 90 mm and a height of 460 mm with a drain hole of 6 mm diameter centrally located at the bottom. Rotation is imparted to the liquid (water) in the container by controlled stirring, with the drain port closed by a stopper, using varying number of revolutions of the stirrer over a constant period of time (Gowda et al, 1996). The stirrer is a hollow tube of 18 mm diameter with a wall thickness of 0.5 mm and 500 mm long. It is introduced into the tank so that the lower tip is slightly above the bottom of the tank and held at an angle of 90 degree and the revolutions (120 RPM) are imparted manually. To check the reliability of the results obtained, the experiments are repeated several times. The vane-type suppressors used with different number of vanes are shown in Fig.2. The position of the suppressor at the bottom of the tank is shown in Fig.1.

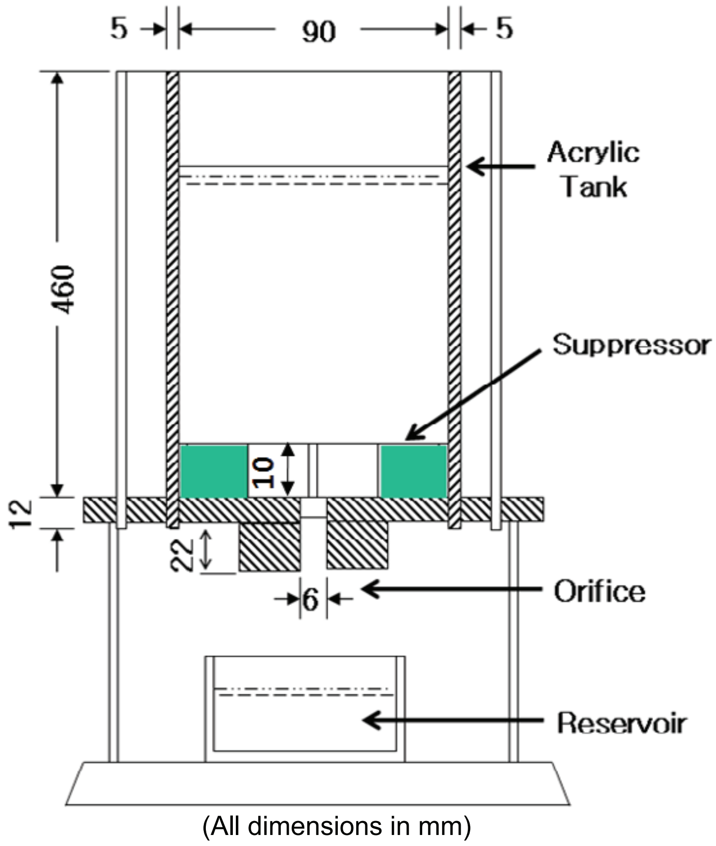


Fig. 1. Schematic diagram of cylindrical tank

A Diode Laser (820 mW) is utilized as a light source of the PIV system in the present study and Redlake MotionPro X3 High-speed CCD camera operated at 150 frames/sec (fps), yielding a time-step between frames of 0.0067 s is used (Fig. 3). The image resolution was 1280x1024 pixels and the particle images were processed using the proVISION software package. The seeding was done using high porous polymer 44 μm size particles. The cylindrical container is enclosed within an outer square tank (Fig.1). This is to facilitate the lighting of the entire circular cross sectional area of the former in the horizontal plane by the Laser sheet.

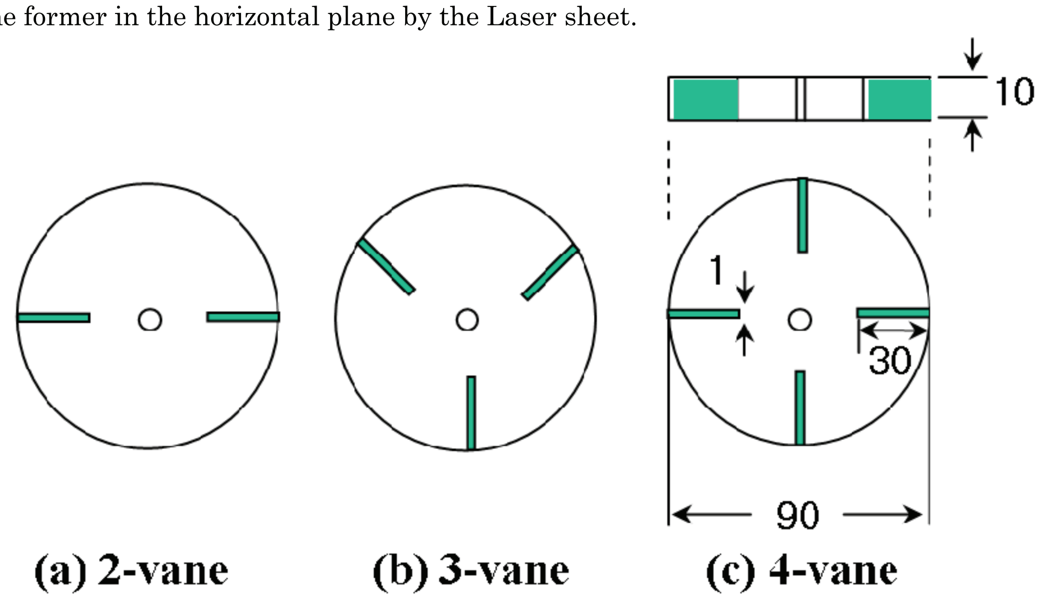


Fig. 2. Vane type suppressors

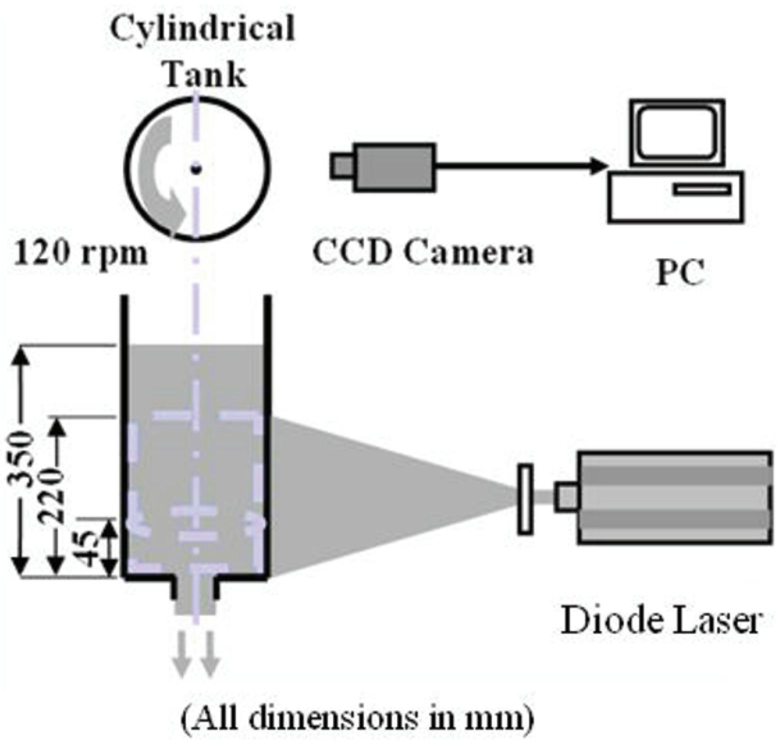


Fig. 3. Arrangement for PIV studies

3. Results

When rotation is imparted to the fluid in the container and draining is started, without any suppressor, a vortex with an air core is formed when the fluid level reaches a critical height as mentioned earlier. At lower values of RPM, the critical height at which the vortex forms depends on the magnitude of rotation (rotation speed) given. However, for 90 RPM and above, the critical height does not change (Gowda et al, 1996). Hence all the results presented are obtained at 120 RPM (corresponding peak vorticity of about 25 rad/s i.e., the vorticity maxima of the rotating fluid induced by the stirrer which is calculated as equal to $2\pi N/60$, N being the number of revolutions per minute). Experiments are done without and with draining. For each case the flow patterns are shown at 10, 20 and 30 s after imparting the rotation to indicate how the flow field and vorticity imparted is changing both pattern wise and magnitude wise. Results obtained without the suppressor are indicated as (WOS) and those with suppressor as (WS).

The patterns are shown in both horizontal and vertical planes. The horizontal plane is chosen at a height of 45 mm from the bottom of the tank (closest possible with the suppressor in position) as expected, the influence of the suppressor on the flow pattern could be observed at best at this height. In each case the colour codes indicate the magnitude of velocities. In all the figures T is the time elapsed in seconds after imparting rotation.

3.1 Results without draining

The instantaneous velocity vectors in the horizontal plane for the case without draining and without any suppressor (WOS) are obtained at T = 10, 20 and 30 s after imparting the rotation. They show that at T = 10 s, high velocities occur over an annular region extending approximately over 50 % of the tank diameter. There is a central core of reduced velocities of about 12 to 15 %.

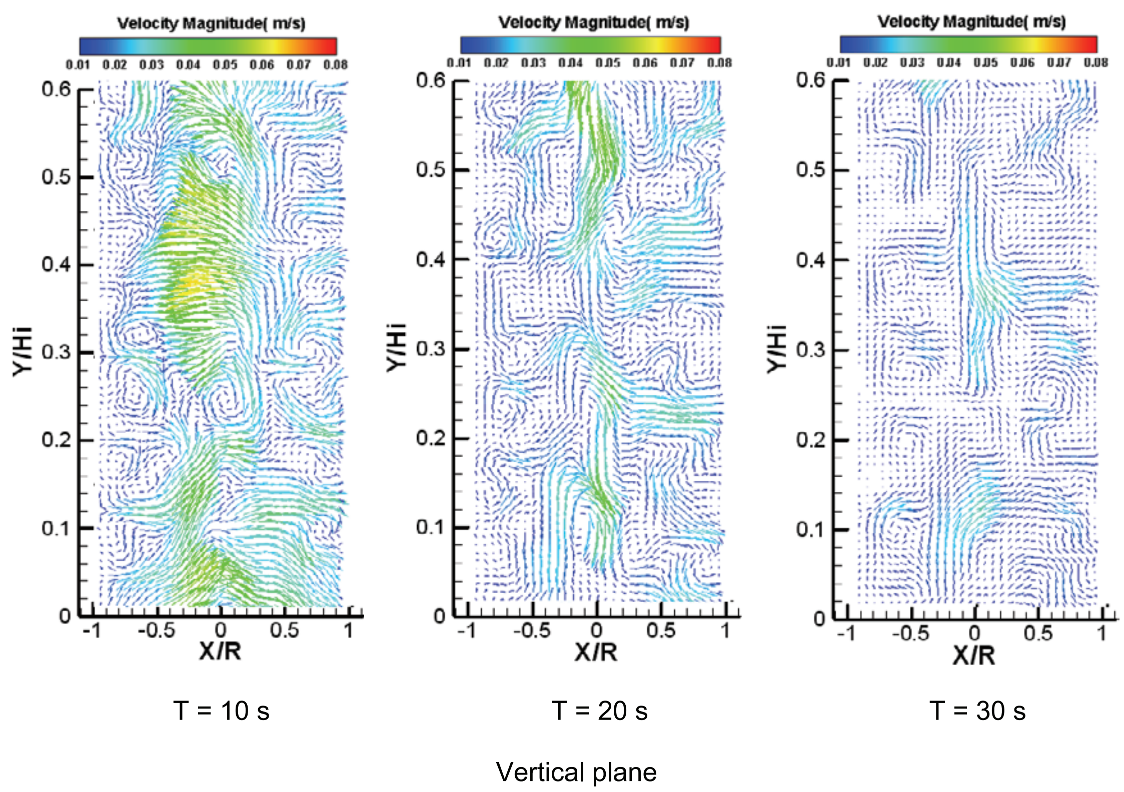
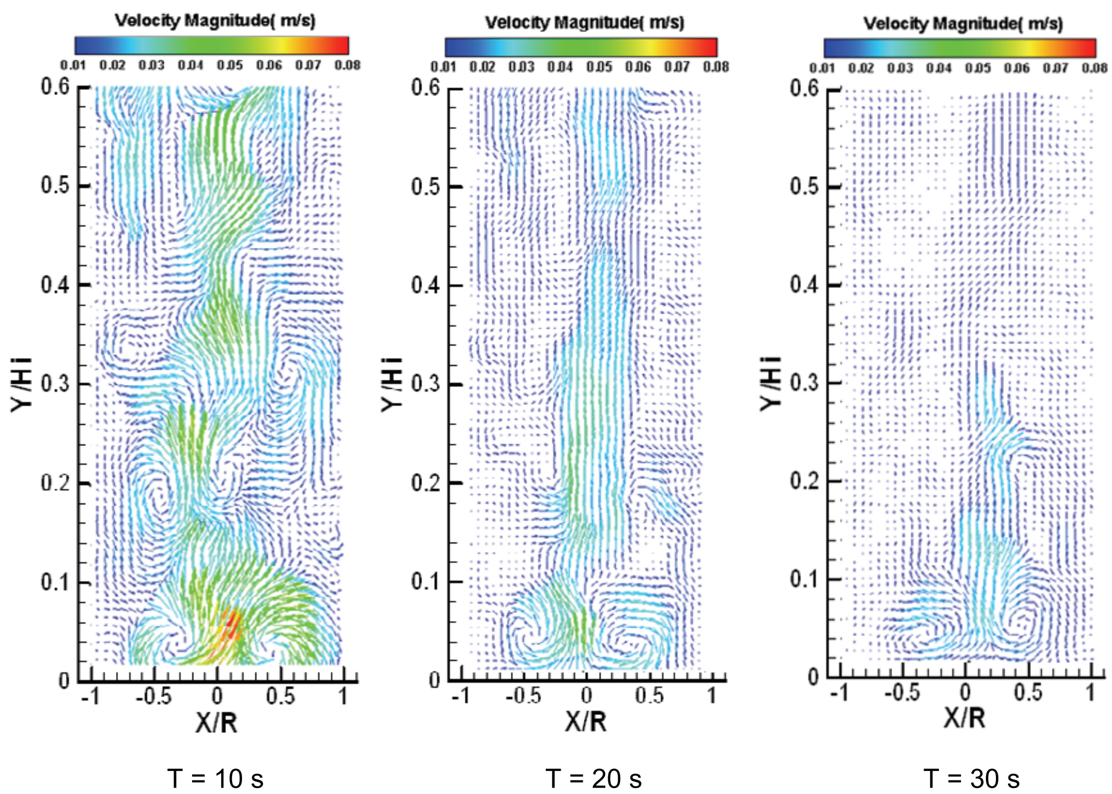


Fig. 4. Velocity vectors (WOS; no draining)

With increase in time the region of high velocities shrink and then the velocity becomes nearly uniform over the cross section except the low velocity core (T = 30 s). In the vertical plane (Fig. 4; T = 10, 20 and 30 s), complex pattern with many vortical cells along the height on either side of the wall are seen. The pattern at the bottom of the tank is seen to change considerably with time. The magnitude of the velocities reduce with time as can be made out by the colour codes.

The results for the two-vane suppressor in the horizontal plane (at T =10, 20 and 30s) indicate that the central core is shifted away from the axis and is also larger compared to that of the no-suppressor case. The rate of decay in the magnitude of velocities is faster in this case. In the vertical plane (Fig.5), at T = 10 s, two strong vortical patterns on either side of the axis are seen at the bottom which probably form a structure like that of a 'vortex ring'. As a result there is a strong upward flow at the center which is absent in Fig.4 (T = 10 s) for the no-suppressor case. With time, the velocities decay (T = 20 and 30 s); however, the two vortical patterns mentioned earlier persist and a strong upward flow along the axis at the bottom can be seen.



Vertical plane

Fig. 5. Velocity vectors (WS – 2 vanes; no draining)

In the case of three-vane and four-vane suppressors, the flow patterns are very similar to that observed for the two-vane case (hence not shown). In the horizontal plane the skewness of the vortical region at the center persists for these cases also. More interestingly, in the vertical plane, the 'vortex-ring' like structure at the bottom occurs in both these cases similar to the two-vane case. Also there is a strong updraft along the axis near the bottom. The vorticity decay with time is evident. The details are referred to and shown later while discussing the results.

3.2 Results with draining

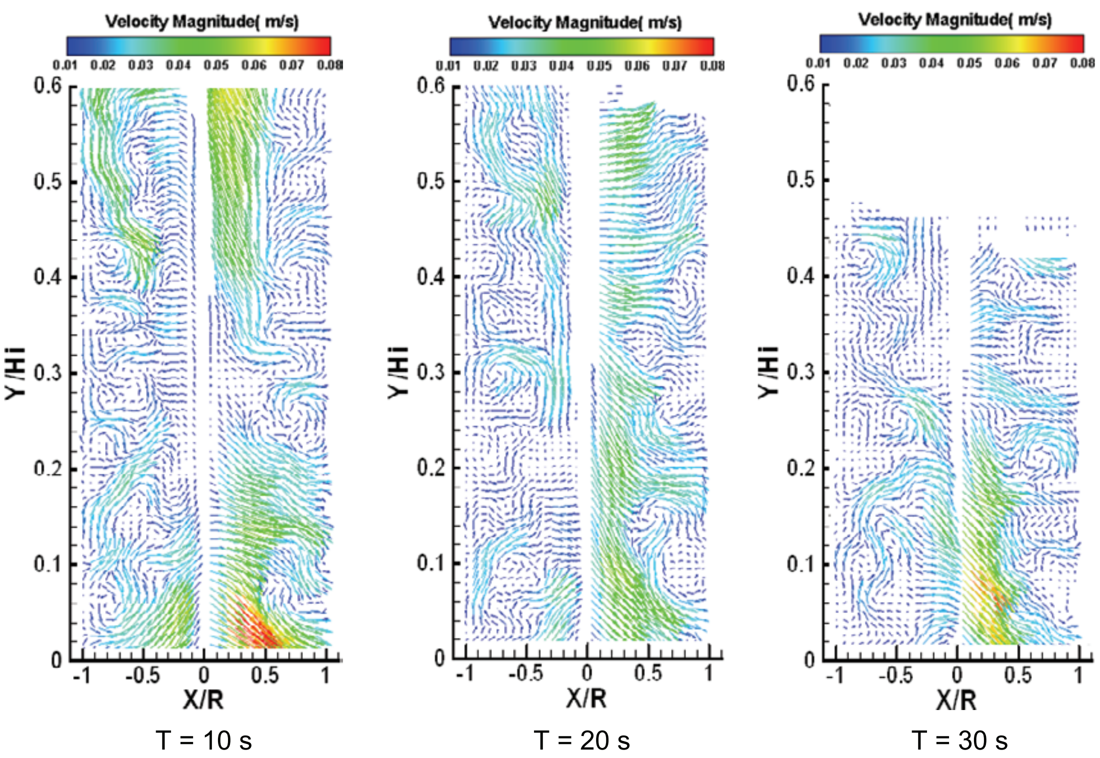


Fig. 6. Velocity vectors (WOS ; draining)

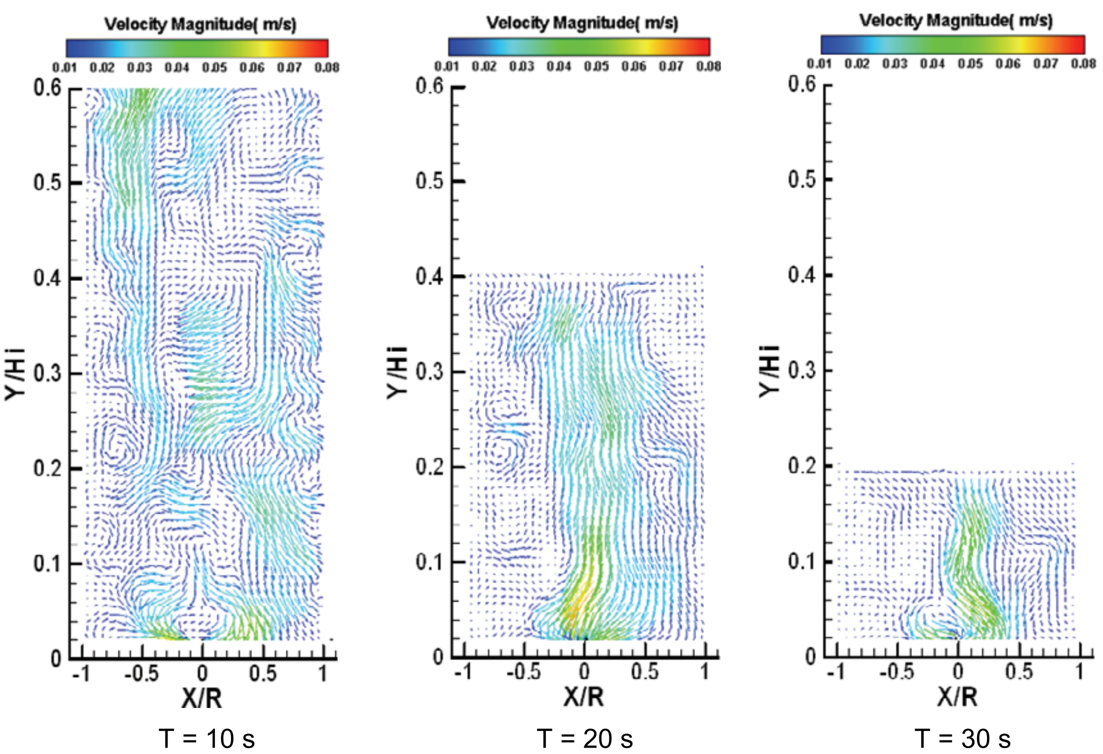


Fig. 7. Velocity vectors (WS – 2 vanes; draining)

The results with draining and without suppressor in the horizontal plane show a central hollow region at T = 10 s due to the air core of the vortex formed when the draining is started. With time (T = 20 and 30 s), the air core size decreases as the height of the water column is decreasing. The heights in the vertical plane (Fig.6 at T = 10, 20 and 30 s) indicate the rate of draining which is influenced by the vortex extending to the port. This aspect becomes clearer when these results are compared with the set of figures at T = 10, 20 and 30 s in Fig.7 (WS-2 vanes). In the latter case (i.e., with two-vane suppressor), the vortex is suppressed and the rate of draining is faster as can be made out clearly from Fig.7 at T = 30 s. Very similar trends were observed for the three-vane and four-vane suppressors. Thus the vortex formation is prevented by the suppressors.

4. Discussion

4.1 Results without draining

The vorticity introduced into the fluid by imparting rotation appears to have dissipated due to the presence of the suppressor. To have a better understanding of this process, the vorticity plots in the horizontal plane for the cases with and without suppressor (no draining) are shown in Figs. 8a and b. These are shown at an height of 45 mm from the bottom of the tank, at intervals T = 10, 20 and 30 s. In Fig.8a, the results for the case with no suppressor, it is seen that there is very little change in the magnitude of vorticity between T = 10 s and T = 30 s. The decay of vorticity is gradual and a very organized vortex at the center persists even at T = 30 s. When these pictures are compared with the corresponding vorticity plots for the case with the 2-vane suppressor (Fig.8b), the following striking differences are observed:

1) The decay rate is much faster, with a considerably low value at T = 30s.

2) Most importantly, the vorticity over the cross-section is diffused and distributed into small pockets with low intensity unlike the WOS case in Fig. 8a. This feature appears to be one of the primary mechanism responsible for the prevention of vortexing in the presence of a suppressor. The suppressor seems to cause a vortex breakdown in the flow field. Though we are dealing with an axi-symmetric flow there will be three-dimensional effect of the swirling flow which could also be contributing to the diffusion of vorticity. This aspect has not been considered in this study. Incidentally, there is very little difference in the patterns observed and the magnitude of vorticity between the cases with different number of vanes.

To throw more light on the features described above, the magnitude of the circumferential velocity along X at Y = 0 for the different cases are shown in Fig.9 a to d. In Fig.9a, the velocities reach a maximum around one third of the radius. There is symmetry in the distribution and very little decrease in the magnitudes between T = 10 s and 20 s. The core size reduces at T = 30 s and a flatter profile is seen beyond it. However, for the cases with the suppressor (Figs.9 b to d), the velocity profiles indicate no such regular or symmetrical variation, particularly with the elapse of time (T = 20 and 30 s). There is considerable reduction in the velocity magnitudes between T = 10 s and 20 s, indicating a faster decay as compared to the no-suppressor case (Fig.9a). Also, at T = 20 and 30 s, the variation with the suppressor is flatter in the central region unlike the no-suppressor case. There is very good correspondence between these figures (Fig.9 a to d) and the vorticity plots given in Fig.8. As mentioned earlier with reference to Fig. 8b the diffusion of vorticity over the cross section with time in the cases with suppressor is reflected in the flatter and irregular distribution of the magnitude of velocities at the corresponding instants.

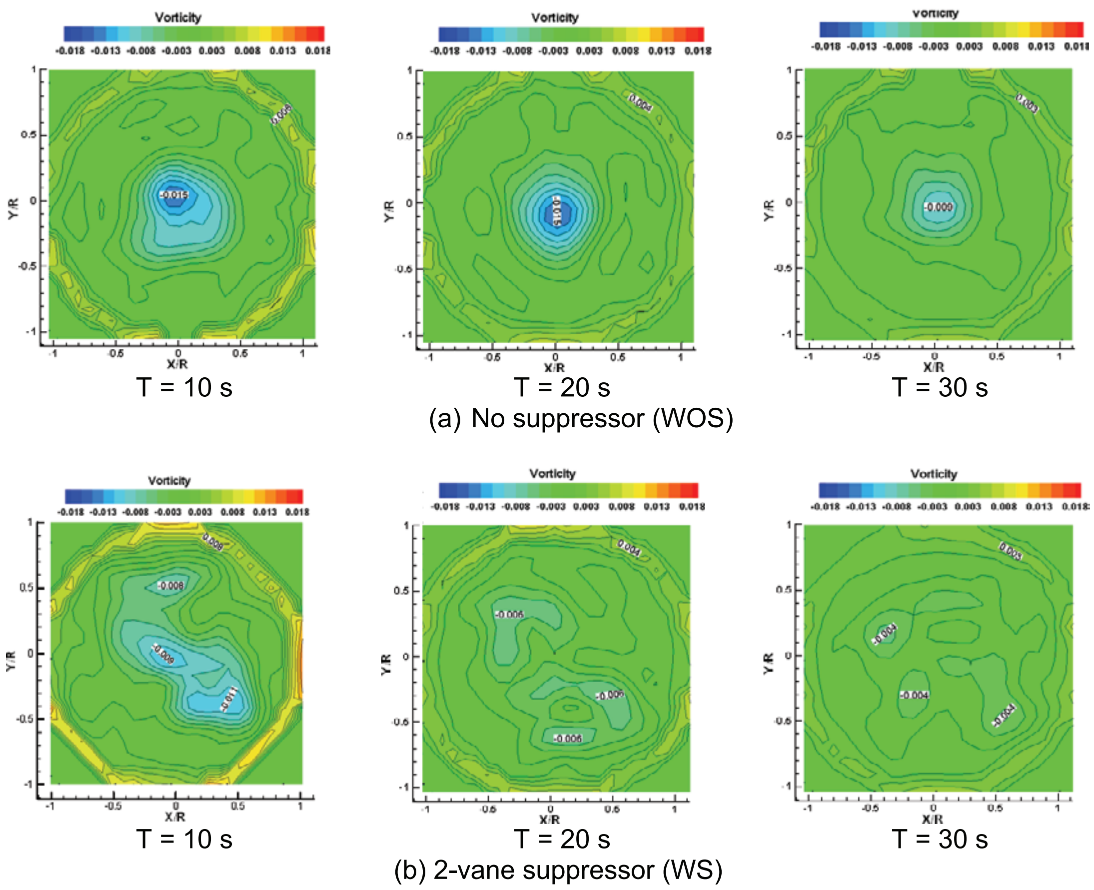
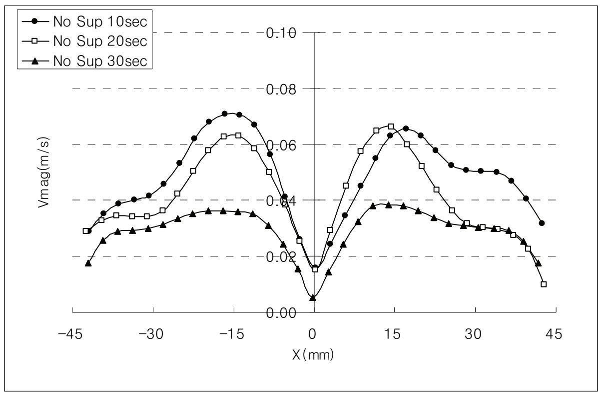
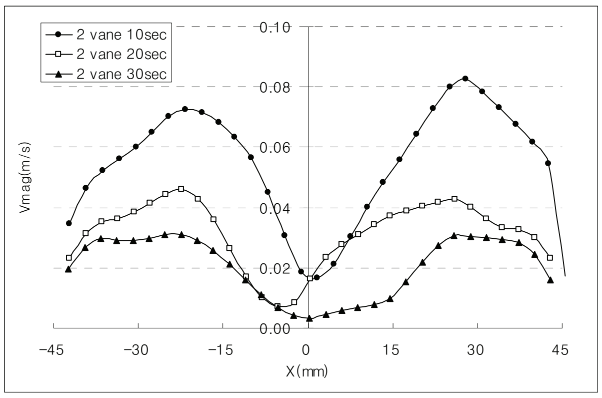


Fig. 8. Vorticity contours in horizontal plane

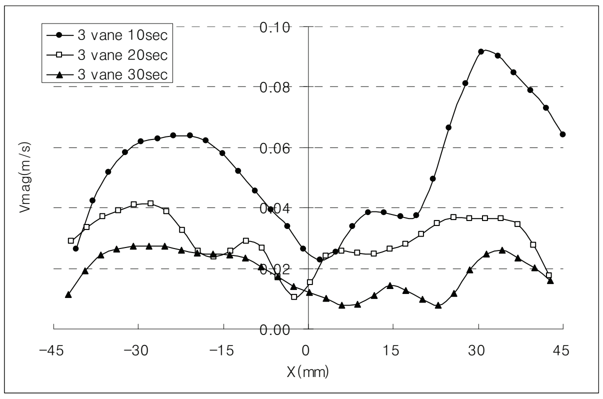
To determine other factors which contribute to the prevention of vortexing with the presence of the suppressors, the flow field in the vertical plane close to the bottom of the tank is considered. Both velocity vectors and vorticity distributions are shown for the different cases in Figs. 10 and 11 respectively. When the set of figures in Fig.10a (no suppressor case) are compared with those in Fig.10b (with the 2-vane suppressor), the striking difference in the flow pattern near the bottom becomes evident. In the latter case, the presence of the suppressor gives rise to a strong updraft (mentioned earlier) which persist with time. A vortex-ring like structure is seen which decays slowly with time. Whereas, in the former case (Fig.10a) at T= 10 s, there is a flow from one side to the other and the pattern changes with time and the velocity magnitudes reduce. In the other two cases with suppressor, 3-vane and 4-vane, flow patterns similar to that for the 2-vane suppressor are seen. Thus there is a marked difference in the flow field between the cases without suppressor and with suppressor. The strong updraft is present in all the cases with suppressor, which decays slowly with time. As long as this updraft is strong enough, it appears that the vortexing is prevented.



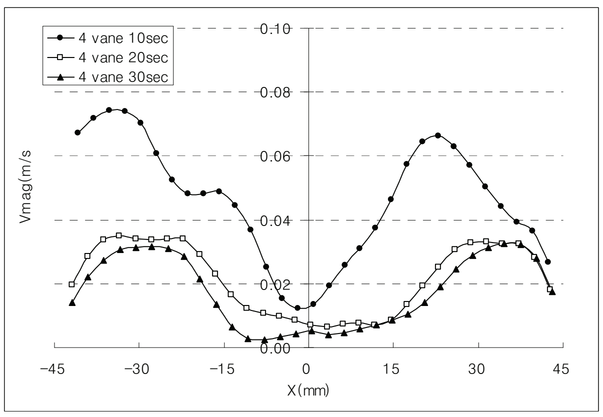
(a) No Suppressor,WOS



(b) 2-vane Suppressor,WS-2



(c) 3-vane Suppressor,WS-3



(d) 4-vane Suppressor,WS-4

Fig. 9. Velocity profiles along center line (Y=0.0) in horizontal plane (No draining)

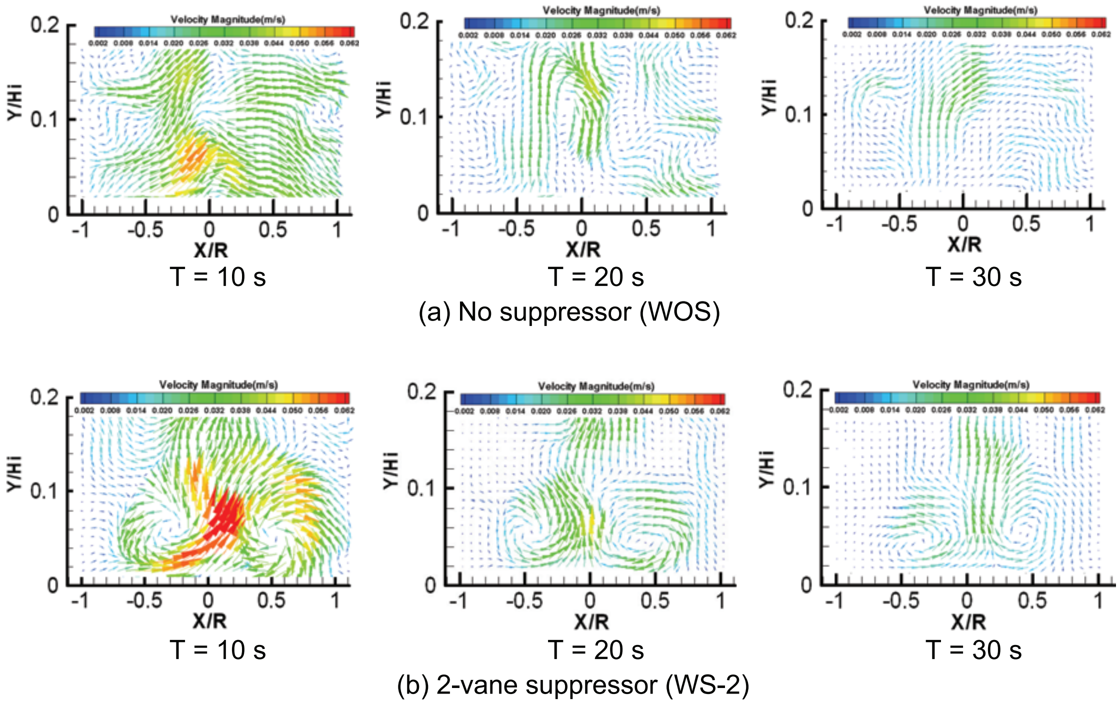


Fig. 10. Velocity vectors in vertical plane (No draining)

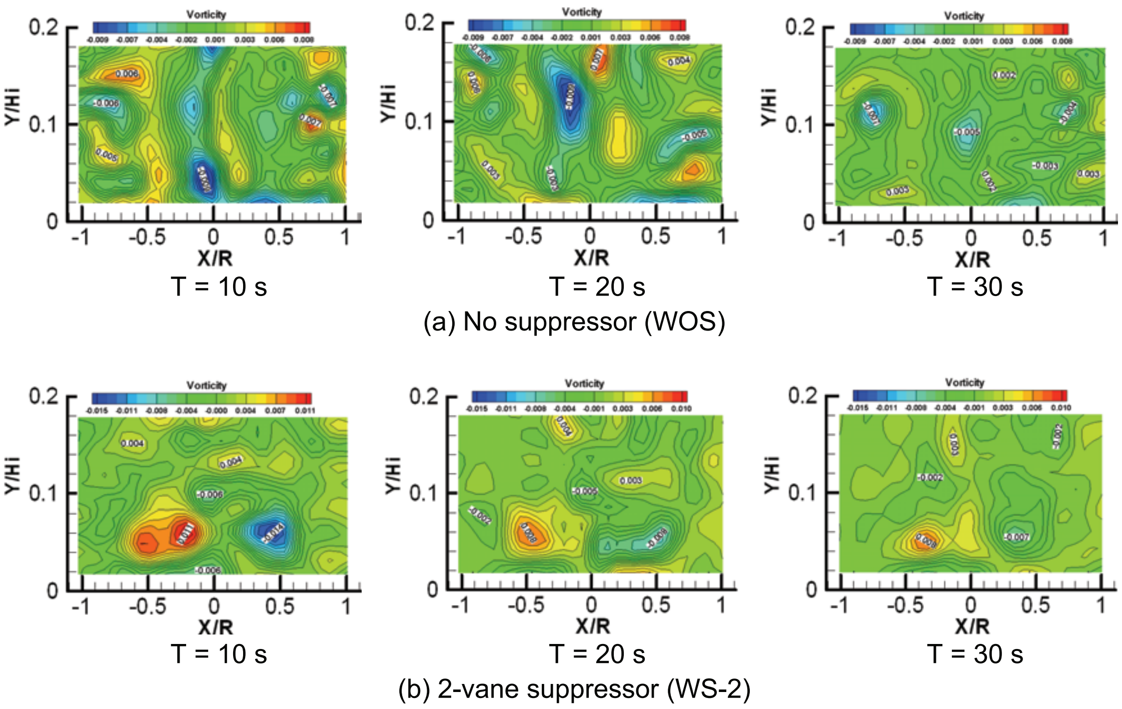


Fig. 11. Vorticity contours in vertical plane (No draining)

The vorticity contours in the vertical plane at the bottom portion are shown in Figs.11 a and b for the various cases. In Figs. 11b for the case with suppressor, particularly at T = 10 s, two concentrated vortex pockets can be seen which correspond to the vortex-ring like structure mentioned earlier. These pockets can be made out at T = 20 and 30 s also, but with reduced concentration of vorticity. However, apart from these pockets, the overall vorticity appears to be weak. The distribution of vorticity for the no-suppressor case is different with long vortex filaments (Fig.11a, T = 10 s). The decay rate of overall vorticity is seen to be comparatively slower than for the cases with suppressor.

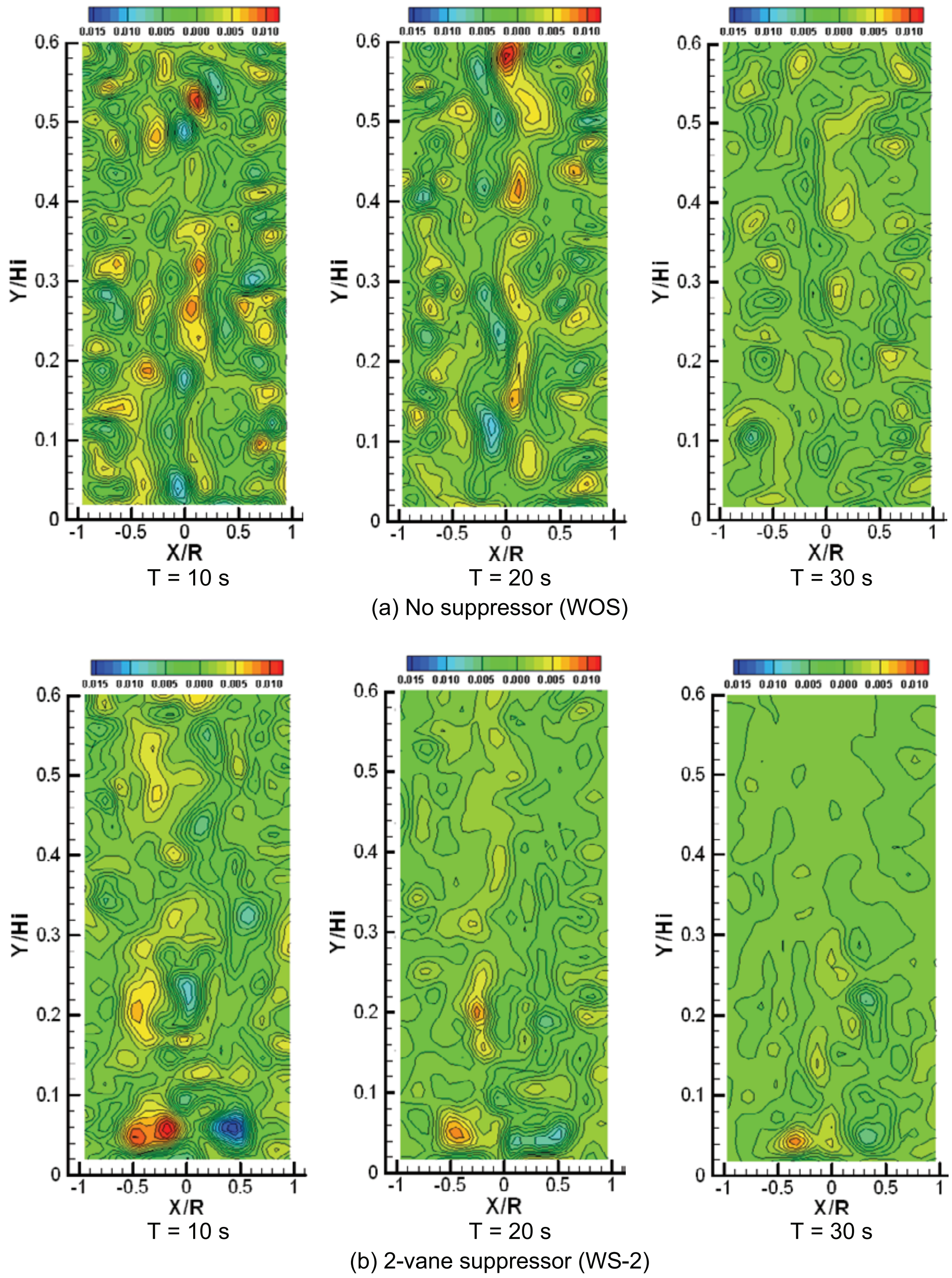


Fig. 12. Vorticity contours in vertical plane (no draining)

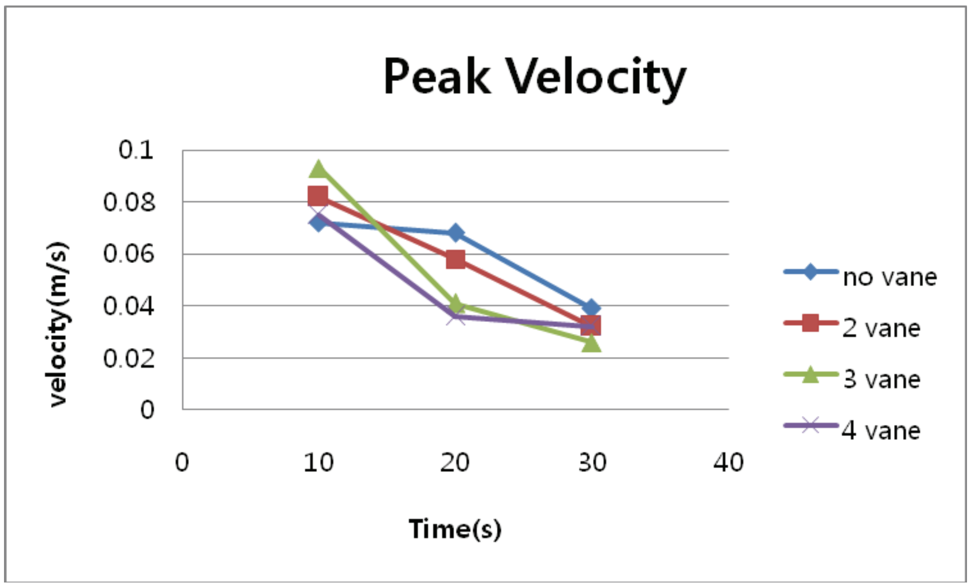
To have a clearer picture of the distribution of vorticity in the vertical plane, the distribution over the entire cross section across the height of the tank is shown in Fig.12. This is only shown for the no-suppressor case (Fig.12a, T = 10, 20 and 30 s) and the 2-vane case (Fig.12b, T = 10, 20, and 30 s) as these are typical cases. It is clear to see that the vorticity distribution across the height is different for the two cases in all instants. Without the suppressor (Fig.12a), there are long vortex filaments and the vorticity is more organized with concentrated lumps appearing on either side along the height. As time elapses (T = 20 and 30 s), the vortical structures near the walls appear to organize themselves into alternate arrangement (similar to Taylor vortices). The imprints of such ring vortices are seen across the height. Also, with time (at T = 20 s and 30 s) the vorticity decay rate is very slow as can be made out by the persistence of the vortex lumps. However, with the suppressor present (Fig.12b, T = 10, 20 and 30 s), the vorticity is quite disorganized and no such tendency towards an orderly nature of vorticity distribution is seen as time elapses. The decay with time is faster as compared to the corresponding cases in Fig.12a. It is very interesting to see that the intervention by the suppressor on the flow field at the bottom of the tank influences the flow structure right across the height of the tank.

It is pointed out here that there could be three-dimensional effects due to the swirling flow which the present study has not taken into consideration. This is a limitation of the study. Other types of investigations may be required to look into this aspect. However, the present study has brought out the essence of the phenomenon.

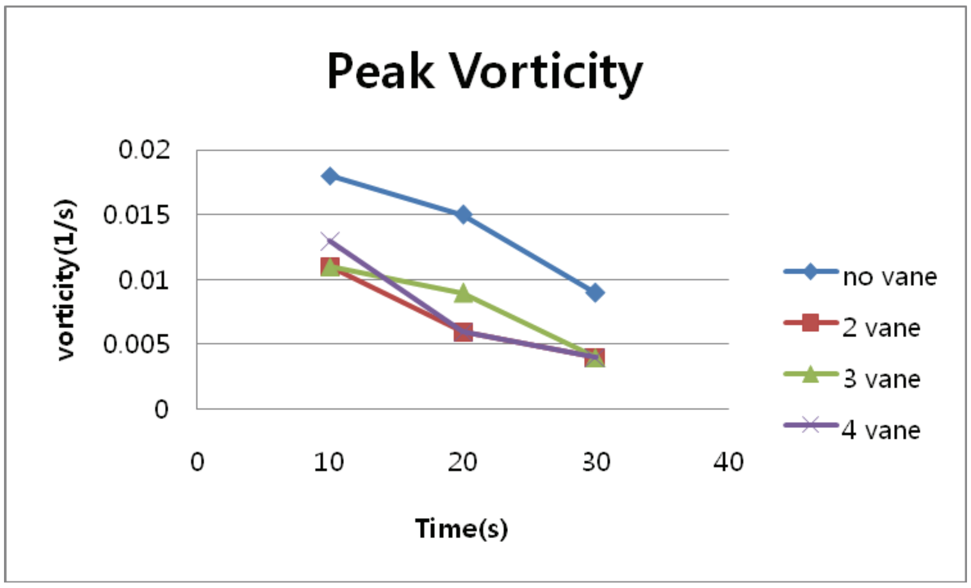
4.2 Results with draining

The velocity vectors in the vertical plane with draining were shown for the no-suppressor case and only for the 2-vane case in Figs.6 and 7. When there is no suppressor (Fig.6), the vortex formed extends into the drain port at all times which can be made out by the central core without any velocity vectors. However, in all the cases when the suppressor is present (Fig.7), the vectors indicate a continuous flow towards the drain port indicating the effectiveness of the suppressors in preventing the formation of a vortex with an air core. This is so for the 3-vane and the 4-vane cases also.

To have a quantitative idea of how the suppressors influence the flow field, the decay of peak velocity and the peak vorticity with time for the various cases are shown in Fig.13 a and b. It is seen that the vorticity decay with time is independent of the number of vanes whereas there is some influence of the number of vanes on the decay of the peak velocity. On the mean, the peak velocity for the WS case decreases by about 42 % between 10 and 30 s whereas for the case with WS, the decrease is about 65 %. Regarding the peak vorticity, for the WS case, the decrease is about 50 % between 10 and 30 s and for the WS case the decrease is about 70 % in the same interval. These values clearly indicate the role played by the suppressors on the phenomenon.



(a) Peak velocity



(b) Peak vorticity

Fig. 13. Decay of peak velocity and peak vorticity with time

The results without draining indicate that the suppressors give rise to an updraft. As long as these updrafts are strong enough, vortexing is seen to be suppressed. The updraft is generated irrespective of the number of vanes. Another feature is the weakening of the vorticity with time when the suppressor is present. There appears to be a sort of breakdown in the vortex concentration into smaller packets which tend to suppress a central vortex being formed. This probably leads to a pressure recovery which stops the vortex from being extended to the port area.

5. Concluding Remarks

Detailed experiments have been conducted using PIV to investigate the suppression of vortexing during draining using vane type suppressors. The results have revealed that the suppressors in general give rise to an upward flow which prevents vortexing. The vane suppressors appear to act like a pump, pushing fluid upwards. A 'vortex ring' like structure is seen at the bottom which may have a role in the creation of the updraft. Furthermore, the presence of the suppressor leads to a breakdown of vorticity and causes diffusion of vorticity which tends to suppress the formation of a central vortex and its extension to the drainport.

Acknowledgement

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