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Visualization Studies using PIV in a Cylindrical Tank with and without Vortex Suppressor

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Abstract : Vortexing occurs during draining from tanks which reduces the rate of outflow. The phenomenon is augmented by initial rotation. The use of a vortex suppressor in a circular tank prevents vortexing. The reasons for the suppression of the vortexing are not clear. In this paper quantitative flow visualization results using PIV are presented which bring out the flow structure under various conditions. The suppressor leads to a faster decay in the rotational component.

Keywords : Visualization, PIV, Rotation, Vortex, Suppressor

1. Introduction

When liquid drains from a cylindrical tank through an axisymmetrically placed circular orifice (drain), a dip develops on the free surface of the liquid as the surface level reaches a certain critical height H_c. The dip quickly develops into a vortex with an air core, which extends to the bottom port, reducing the effective cross-sectional area of the drain outlet (e.g., Abramson et al. 1962, Lubin and Springer 1967, Zhou and Graebel 1990) and consequently the flow rate. The presence of initial rotation and vibration can augment the vortex formation (Gowda et al. 1996a & 1997) and affect the discharge rates further; these disturbances may be caused due to environmental disturbances. The formation of a vortex has practical relevance in the design of liquid-propellant tanks and fuel feed systems in space vehicles and rockets. Also, this phenomenon is of importance in the operation of hydraulic intakes.

Ramamurti and Tharakan 1992, have suggested shaped ports for preventing vortex formation. Gowda et al. 1996b, have suggested a suppressor to prevent vortex formation during draining after imparting initial rotation. However, the mechanism by which the vortexing is prevented by the suppressor in a circular tank is not clear. In the present study an attempt is made to understand the changes in the flow field brought about by the suppressor in a circular tank which ultimately prevents the vortex formation. With this objective, quantitative flow visualization studies are carried out using PIV (Particle Image Velocimetry) to determine the flow pattern in a cylindrical tank with circular cross section without suppressor (case: WOTS) and with suppressor (case: WS) after imparting rotation to the liquid in the tank. Studies are carried out when there is no draining and with draining. The flow field is visualized both in horizontal and vertical planes under different conditions.

2. Experimental Arrangement and Procedure

An acrylic tank (test tank) with circular cross section is utilized; the circular test tank is shown in Fig.1a. The liquid used is water at room temperature. The test tank is enclosed by another larger square tank and the space between the two is filled with water. This was needed to light the entire cross section of the circular test tank by the laser sheet while photographing. Rotation is imparted to the liquid in the container by controlled stirring (with the drain port closed by a rubber stopper) using varying number of revolutions of the stirrer over a constant period of time (Gowda et al. 1996a, b). The stirrer is a hollow tube of 18mm diameter with a wall thickness of 0.5mm made of PVC and 500mm long. It is introduced into the tank so that the lower tip is slightly above the bottom of the tank and the revolutions are imparted manually. To check the reliability of the results obtained the experiments are repeated several times. The dish-type suppressor (Fig. 1(b)) is made of brass with suitable mesh size (Gowda et al. 1996b). The dimensions are such that the dish can be pushed down the tank and made to occupy the position at the bottom. The position of the suppressor at the bottom of the tank is shown in Fig. 1(a).

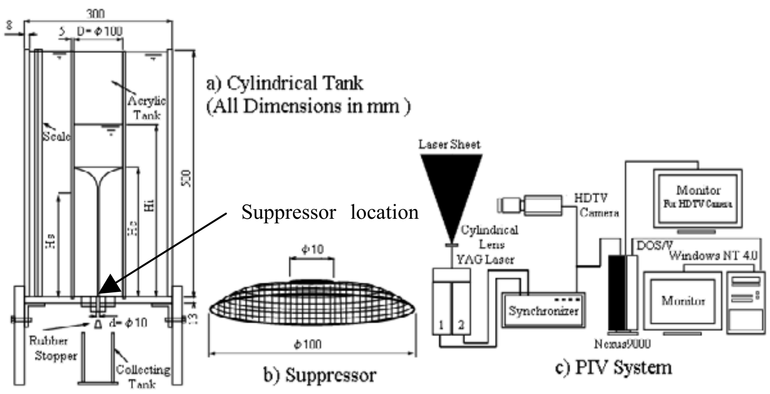

Fig. 1. Experimental arrangement.

The PIV technique is well documented in Adrian 1991. The system used in the present investigation is the same as described in Senoo et al. 2000 (nexus9000). For flow visualization two YAG lasers (Continuum) are used for a source of a light sheet (Fig. 1(c)). The tracers passing through the light sheet are visualized. In the present study, in order to visualize the flow patterns, the laser sheet is made to pass through the tank in horizontal planes at various values of height H_s (Fig. 1(a)) and in a vertical plane through the axis of the test tank. The flow patterns are recorded by a HDTV camera (B/W XCH-1125-SONY) through the lens (Manual-iris lens-SONY and Micro-Nikkor 55mm-NIKON). The HDTV camera is connected to YAG lasers by a synchronizer (Fig. 1(c)). The synchronizer controls the flash intervals of the laser sheet. Flash intervals of 3ms for the horizontal plane and 15 ms for vertical plane are used to record the movement of the tracers. The tracers are white polystyrene particles with a specific gravity of about 1.03, whose sizes are about 35-75μm.

After imparting rotation, the rubber stopper is removed and the draining is started. The results are obtained keeping the same initial height of water, H_i=350 mm for all runs. This was chosen so that the critical height H_c and the time of draining can be conveniently measured. While imparting rotation, YAG lasers are started to produce light sheet for horizontal and vertical planes. After imparting rotation, the time dependent behavior of the flow pattern is recorded by HDTV camera located normal to the laser sheet. The flow patterns are captured for obtaining the velocity vectors by means of the flow analysis software in the host computer. However, the results that are produced by the flow analysis are not seen in color. Micro AVS is used for making the final flow visualization so that the magnitude of velocities are clearly seen in fine color. For this purpose a special program was written and utilized.

3. Results and Discussion

As mentioned earlier, the rotation imparted to the liquid is quantified by controlled stirring of the liquid in the container by a stirrer. To study how the critical height varies when the draining is started after giving the rotation and waiting for different intervals of time, experiments were conducted for 60, 90 and 120 rpm. At each rpm, as the delay time increases lower critical heights are obtained. However, there is not much change in the variation of the critical height (H_c) for higher rpms as time elapses. Also, beyond 50s, there is very little change in the critical height (H_c) for all rpms. Hence, in the present study, all the results are obtained at 90 rpm (corresponding peak vorticity of about 18 rad/s) and up to 50s time interval.

3.1 Results without draining

As the main objective is to understand the changes in the flow field brought about by the presence of the suppressor, considerable attention is focused on the results obtained without draining. In all the results presented, the case without suppressor is indicated as WOTS and the case with suppressor as WS. As mentioned earlier, the flow visualization results are obtained in the horizontal plane (at H_s = 50,100,150,200mm) and in the vertical plane at t=3,5,10,15,20,30,40 and 50s. Typical results are presented and discussed below.

a) Horizontal plane

The velocity vectors at various intervals of time t in only one horizontal plane i.e., H_s=50 mm are shown in Fig.2. It is typical of the results at various horizontal planes. It is pointed out that the time t refers to the intervals of time after which the photographs are taken after giving the rotation; in effect, the photographs at various time t show how the flow field is changing with time after rotation is imparted to the fluid in the tank. Considering the results in Fig.2, it is seen that there are clear differences in the magnitude of the velocity vectors across the cross section and the decay rate with time between without suppressor (WOTS) and with suppressor (WS) cases. At t=3s, in the case WS, there is a region of high rotational velocities which extends over nearly 50% of the cross section in the outer periphery. There is a central core of much reduced velocities. With time, there is a decay in the velocity magnitude and at t=15s, velocities are reduced very considerably compared to t=3s. This decay process continues with increase in time.

When the results for the WOTS case at corresponding time intervals are considered, there are striking differences. At t=3s, the magnitude of the velocity vectors are almost the same over the entire cross section with very small core at the center. This is much different from that for the WS case at the same t=3s. Further, without suppressor (WOTS), the decay of the velocity magnitude occurs at a much gradual rate compared to the WS case as can be made out by the color code. At t=15s, the velocities are comparable to those at t=3s whereas this is not so for the case with suppressor (WS). As t increases further (t >15s), the magnitude continues to decay, but at a lower rate.

At higher values of H_s i.e. H_s=200mm, it is seen that qualitatively the trend in the magnitude of the rotational velocities and the general pattern of distribution remains the same.

b) Vertical plane

In the vertical plane (Figs. 3 & 4), the flow structures are quite different for the WOTS and WS cases. Compared to the WOTS case, the flow field in the WS case is more orderly.

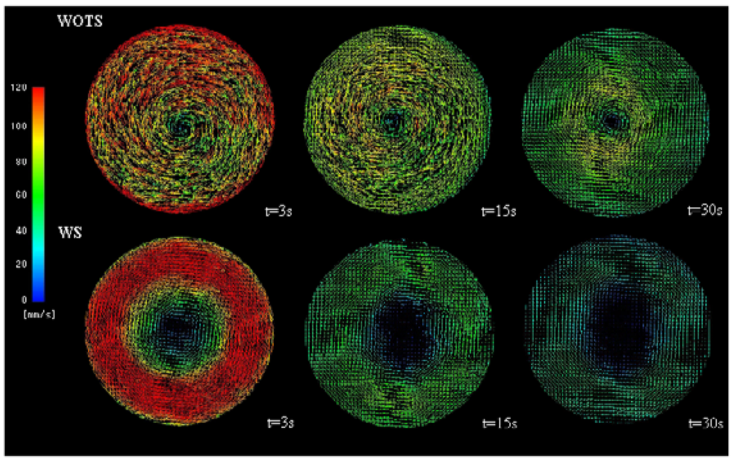

Fig. 2. Velocity vectors in horizontal planes : RPM =90 & H_s=50mm (without draining : t=3s ,15s & 30s).

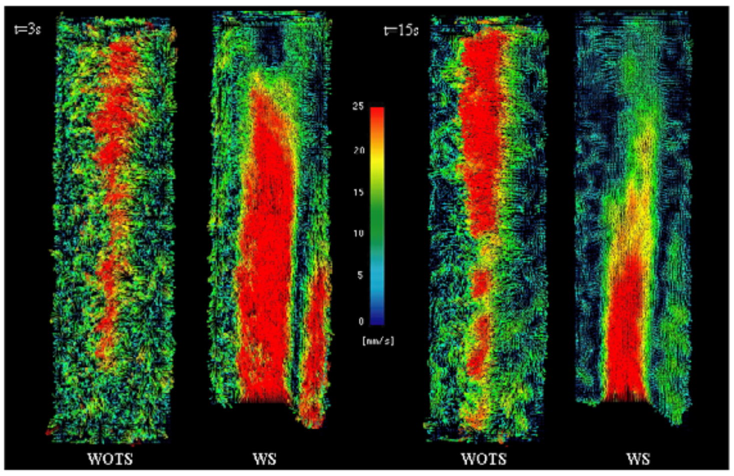

Fig. 3. Velocity vectors in vertical plane : RPM =90 (without draining : t=3s & 15s).

In the latter case, there is a strong jet-like upward flow from the bottom at the center extending to nearly 40% of the tank diameter. The width of this region remains constant up to about 50% of the height beyond which it starts decaying. The flow field outside the central core is seen to be different above and below the mid height. Below the mid height, a clear downward flow is seen near to the wall forming an approximately annulus region. Between this annulus and the central core there is random movement seen with vortical structures. These appear to entrain fluid from core to annulus, and vice versa. In the upper half, the outer annulus becomes very narrow and downward velocities are much weaker (as seen from color code). Interestingly, there is a strong movement in the horizontal direction in the upper half. This interacts with the central upward core reducing its strength. With increasing time (Fig. 4), the velocity magnitude starts decaying in the core region and at t=50s, the decay appears to be almost complete. There is continuity in the decay process.

However, without suppressor (WOTS), the flow patterns are quite different. The flow is much disorganized. At t=3s (Fig. 3), there appears to be a small core region at the axis with higher velocities. With increasing time, this central core is seen to extend and it has a conical shape widening from bottom to top. Beyond t=15s, there appears to be decay in this core but very gradually. Even at t=30s (Fig. 4) the decay is much less compared to the WS case. Thus it is seen that the structures of flow in the vertical plane also are different for the cases without and with suppressor.

3.2 Results with draining

In this case, once the draining is started for the WOTS case, a dip is formed which extends almost instantaneously to the bottom of the port forming a vortex. It is pointed out that with draining, the level of water in the tank is decreasing and hence, the height H_s at which the visualization can be made is limited with increasing t. This is also the case for the experiments with suppressor. The results are obtained at t=3,5,7 & 9s. The velocity vectors without draining at various intervals of time t in the horizontal plane at H_s=50 mm only are shown in Fig.5. From the figure, it is seen that there are clear differences in the magnitude of the velocity vectors across the cross section and the decay rate with time between the WOTS and WS cases similar to that for without draining. At t=3s (Fig.5a) in case WS, there is a region of high rotational velocities which extends over nearly 50% of the cross section in the outer periphery. There is a central core of much reduced velocities. With time, there is a decay in the velocity magnitude and at t=9s, velocities are reduced considerably compared to t=3s.

When the results for the WOTS case at corresponding time intervals are considered, there are striking differences. At t=3s, there is a region of high rotational velocities which extends nearly over 40% of the cross section in the outer periphery. There is a region of much reduced and random velocities which extends nearly over 60% of the cross section in the central core. This is much different from that for the WS case at the same t=3s. Further, without suppressor (WOTS), the decay of the velocity magnitude occurs at much gradual rate compared to the case WS as can be made out by the color code. For the WOTS case, the velocities at t=9s are comparable to those at t=3s whereas, this is not so for the case with suppressor (WS).

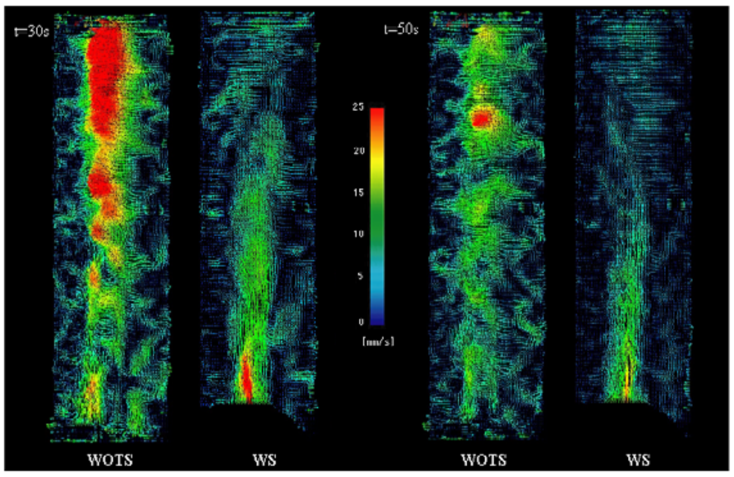

Fig. 4. Velocity vectors in vertical plane : RPM =90 (without draining : t=30s & 50s).

4. Concluding Remarks

The introduction of the suppressor into the tank results in lower rotational velocity magnitudes at different levels compared to the case without the suppressor. Further, there is a higher decay rate with time of the rotational velocities with the suppressor present. The presence of the suppressor is seen to give a strong jet-like flow near the bottom of the tank. This occurs just after imparting rotation. Probably the above changes in flow field are responsible for the prevention of vortex formation when draining is started with the suppressor in the tank. However, the exact mechanism by which the suppressor prevents vortexing is not yet clear. A tentative explanation is that the suppressor is probably acting like a source of roughness which prevents the occurance of very low pressures at the core of the vortex. Further, the suppressor in general appears to 'kill' or 'dissipate' vorticity imparted to the fluid. The results apply only to the configuration investigated.

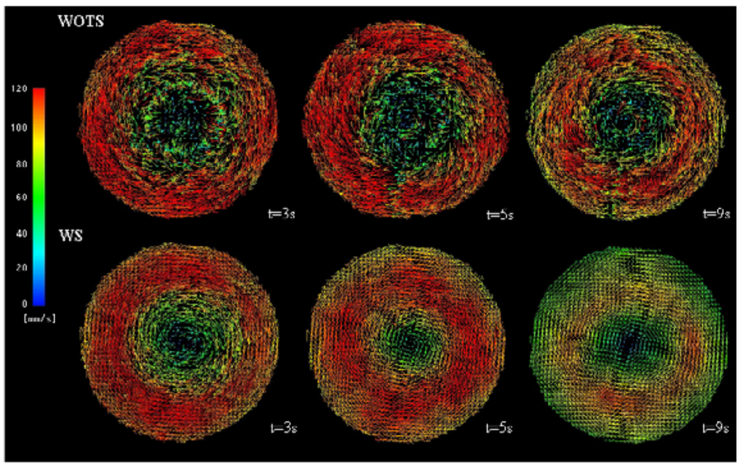

Fig. 5. Velocity vectors in horizontal planes : RPM =90 & H_s=50mm (with draining : t=3s ,5s & 9s).

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