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Numerical Simulation of Air-core Vortex Using an Axisymmetric Boundary Condition

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Abstract: Accurate numerical simulation of liquid draining is important to study the physics fluid flow. However, liquid draining involves multiphase and rotational flows, where numerical simulation is expensive to accurately recreate these flow behaviors. Therefore, this paper presents a numerical method of liquid draining inside a tank using OpenFOAM by proposing an axi-symmetric boundary condition to reduce the computational cost and time. The axi-symmetric boundary condition shows an excellent and strong capability to simulate the liquid draining and simultaneously reduce the time and computational cost by 14 times as compared to the full cylinder mesh.

Keywords: Axi-symmetric boundary condition; Air-core; Draining tank; OpenFOAM.

Introduction

The use of Computational Fluid Dynamics (CFD) to predict and understand the dynamics of the liquid draining inside the tank has been well-established in the last thirty years (Lubinans Springer, 1967). One of the main advantages of using numerical method is the ability to model the geometry of the system with a wider range of scale and complexity (EPRI Technology Insights, 2014) (IAEA-TECDOC-1379, 2013). With the advanced progress in numerical solutions, the introduction of new higher order discretization schemes, accurate predictions can be obtained from the numerical method with less cost compared to the experimental work (Rechiman,Centero and Dari, 2014). Additionally, CFD has the capabilities to provide detailed information of the liquid flow structures and their behaviors.

In this study, a validation and verification study is performed using OpenFOAM (Open Field Operation and Manipulation) (Jasak, 1996). OpenFOAM is an open source CFD-toolbox software for various fluid flow processes (Robertson, Choudhury and Walters, 2015) (HG, 1998). There are many published studies that prove OpenFOAM's capabilities in simulating various flow problems such as computational heat transfer, fluid structure interaction, multiphase and high speed flow. However, only a limited number of studies are focused in the fields of the formation of an air-core vortex inside a draining tank (Ramamurthi and Thrakan, 1995) (Mcduffie and N.G, 1977)Therefore, the numerical simulation of a draining tank poses a challenge in the sense that it involves multiphase and rotational flows, where an extended computational period is required.

Most draining tanks exhibit one similar problem which is the formation of an air-core vortex. This problem can be observed during the draining process inside a cylindrical tank. Air-core vortex is one of the rotational motions of the liquid with air entering the vortex through its core (F. M. Sakri et al, 2015). Air-core vortex formation occurs when a dip is formed on the top surface of the liquid as the liquid level reaches a certain critical height, Hc (Basu et al, 2013). Then, the dip deepens as the draining process continues and the shape of the liquid surface becomes a long slender string. When the dip reaches the outlet of the tank, this is called air-core vortex (Hyun et al, 2012). This air-core vortex formation is escalated by the intensification of rotational flow during the draining process (Basu et al, 2013). When the core of the vortex reaches the bottom of the tank, the rate of liquid draining is decreased and the flow at the outlet nozzle is unsteady and highly rotational. The air-core vortex, if not properly controlled, can cause vibrations that will reduce the life and efficiency of the storage tank (F. M. Sakri et al, 2015).

The formation of air-core vortex involves a complex process. Thus, to accurately recreate the formation of air-core vortex in the numerical simulation, an appropriate treatment of the numerical setting is highly required (F. M. Sakri et al, 2016).The main objective of this paper is to provide a systematic numerical method to simulate liquid draining inside a cylindrical tank using an axi-

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symmetric boundary condition (wedge) under the CFD platform of OpenFOAM. Additionally, this study also revisits the fundamental physics flow of the generation of an air-core vortex. Comparisons between the simulation result with the previously published data by Park and Sohn (2011) and Jong Hyeon Son et al (2015) are also discussed to validate the capability of the axi-symmetric boundary condition and the numerical settings in simulating the liquid draining inside a tank.

Problem Geometry and Case Setups

A cylindrical tank of diameter *(D)* 90mm and length *(L)* of 450mm is partially filled with water. The initial height of the water measured from the bottom of the tank (h_o) is 350mm. A drain nozzle is located at the centre of the tank's bottom surface. The drain nozzle's diameter *(d)* is 6mm whereas its length *(l)* is 15mm. The top and bottom surfaces of the tank is open, i.e., in atmospheric condition. The fluid is drained downward naturally by gravity, g. This geometry is intentionally made the same as the experimental and numerical investigations of Park and Sohn(2011) for direct comparisons to the study. Figure 1 shows the schematic diagram of the problem geometry.

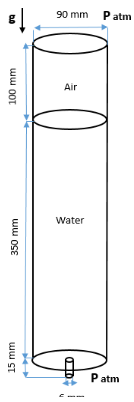


Figure 1 Schematic diagram of the draining tank (Park and Sohn, 2011)

In this study, two flow conditions are being simulated. The first condition is for the non-swirl cases where the liquid is drained from the stagnant condition. Comparisons between the full geometry (3D) and axi-symmetric boundary condition are discussed (2D). The second condition involves swirl cases where the liquid is initially rotated at the speed of 120 RPM before being drained out by gravity. Experimental and numerical comparisons between the previously published studies by Park and Sohn[15] are discussed.

Governing Equations

The conservation equations for mass and mometum for incompressible, transient and free surface flows are given as follow (Jasak, 1996)

$$\nabla . U = 0 \qquad (1)$$

$$\frac{\partial \rho U}{\partial t} + \nabla . \rho U U - \nabla . (\rho \Gamma_U \nabla_U) = S_U(U) + g + F (2)$$

Here, U is the local velocity at instantaneous time, ρ is the density, and Γ is the diffusion coefficient. The Direct Numerical Simulation (DNS) is employed and the temporal term is discretised using the first-order scheme.

Axi-symmetric Boundary Condition (wedge)

An axi-symmetric boundary condition is named as 'wedge' in OpenFOAM. This boundary condition is applied to two-dimensional axi-symmetric cases specifically for a cylindrical geometry. Since the tank with the cylinder geometry is adopted, the axi-symmetric boundary condition is reliable and applicable to this study. Figure 2 displays the configurations of axi-symmetric boundary condition in OpenFOAM. The figure shows a wedge with a small angle (<5^0) and 1 thick cell running along the plane of symmetry. This plane has been set as different patches of wedge types such as wedge patch 1 and wedge patch (Greenshileds, 2015).

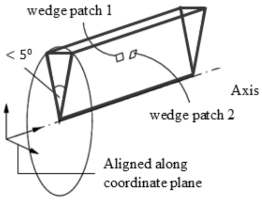


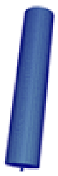
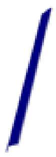
Figure 2 Axi-symmetric boundary condition in OpenFOAM[26]

Analysis and Discussion

Comparisons between full geometry model and wedge model

Table 1 shows the geometric comparisons between full cylinder and a sector of the cylinder for non-swirl liquid draining. 3-D numerical simulation with 3,303,750 cells is adopted in the full cylinder case. Meanwhile, 2-D numerical simulation with 44,050 cells is applied to the axi-symmetric case. Each case is simulated using 4 processors with 4.2 GHz of processing power. In the non-swirl cases, the time for draining completion obtained from both cases is exactly the same, i.e. 63s. However, full cylinder cases require 504 hours to complete the liquid draining. However, by adopting the axi-symmetricboundary condition, it takes only 36 hours. Thus, computational is 14 times faster than the complete geometry. Hence, the axi-symmetric boundary condition is chosen to be applied in the next stage.

Table 1 Comparison between full case and current axi-symmetric case

	Full Cylinder Case	Axisymmetric Case (wedge)
Geometry		
Number of cells	3 303 750	44 050
Processors	4	4
Machine	HP Z240 4.2 GHz	HP Z240 4.2 GHz
Drain time (non-swirl)	63 s	63 s
Computational completion time	504 hours	36 hours

Comparisons of the surface progression

The current simulations that are utilizing the axi-symmetric boundary condition are able to reproduce the liquid draining inside a cylindrical tank for both non-swirl and swirl cases. In non-swirl cases (Figure 3), the time for draining completion obtained from the current simulation is 63s, which is very near to the result obtained from the experiment by Park and Sohn(2011). The pattern of the draining time is also reflective in the numerical results obtained by Park and Sohn.

In swirl cases (Figure 4), the time for draining completion is longer than the non-swirl cases. Similar results are obtained from the numerical and experimental investigations of Park and Sohn(2011). The longer time for draining completion is due to the generation of the swirling flow. Swirling flow leads to the air-core being developed at the outlet, which reduces the draining rate. Consequently, the completion time forthe draining rate.Consequently, the completion time for the liquid draining is expanded as the effectiveness of the outlet section is decreased. The current

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simulation is able to recreate the phenomenon of air-core vortex and the drain time is shown in Figure 5.

The difference in the draining time completion between the numerical results of the current study and the experimental results by Park and Sohn for the non-swirl and swirl cases are 5s and 11 s, respectively. According to the Jong Hyeon Son et al(2015), the speed of water level is decreased after 10s in the experimental data of swirl cases since dips started to form. The numerical result of the current study also shows that the dip starts to generate around that time until the air-core vortex enters the outlet after 20s. In order to complete the liquid draining, the swirl case for the current study requires about 28s or 30% longer time than the non-swirl cases. This is due to the air entrainment into the outlet and thus the water level moves down slowly.

According to Park and Sohn (2011), the draining time can be expressed theoretically with the following equation:

$$t = \frac{\sqrt{h_0} - \sqrt{h}}{\sqrt{\frac{g}{2}}} \left(\frac{d_t}{d_n}\right)^2 \qquad (3)$$

Here, t is the draining time, h_o the initial water level, h the water level at a t time, d_t the tank diameter, d_n the nozzle diameter, and $g$gravitational acceleration. Equation (3) is derived with the assumption that the flow is irrotational and inviscid. Current simulation that employs the axi-symmetric boundary condition supports the theoretical value.

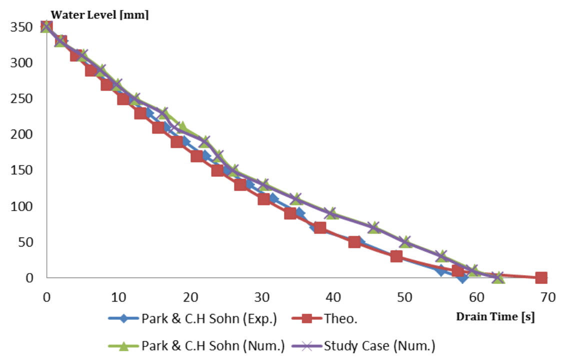


Figure 3 The comparison of draining time for the non-swirl case between published data by Park and Sohn (2011) (experiment and numerical), theoretical (Equation (3)) and current numerical study

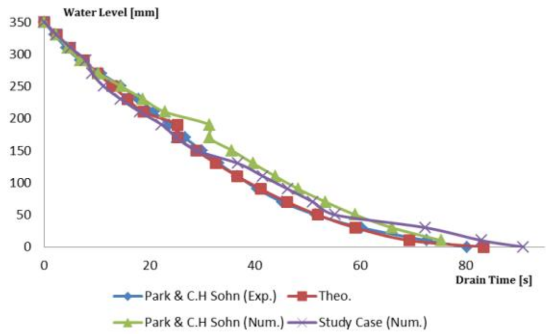


Figure 4 The comparison of draining time for the swirl case between published data by Park and Sohn (2011) (experiment and numerical), theoretical (Equation (3)) and current numerical study

Free surface progressions

Figure 5 shows the free surface progressions of the numerical simulations. At 0s, the free surface turns into a concave meniscus (paraboloid) shape. This phenomenon is known as adhesion. Adhesion occurs when molecules of water have strong attractions to the material of the tank than to each other. Thus, adhesion enables water to 'climb' upwards through the wall of the tank.

After the dip and air-core vortex are generated, the area on the free surface turns out to be flat except at the narrow center area. Around this center area, a large radial gradient of the free surface level is produced.

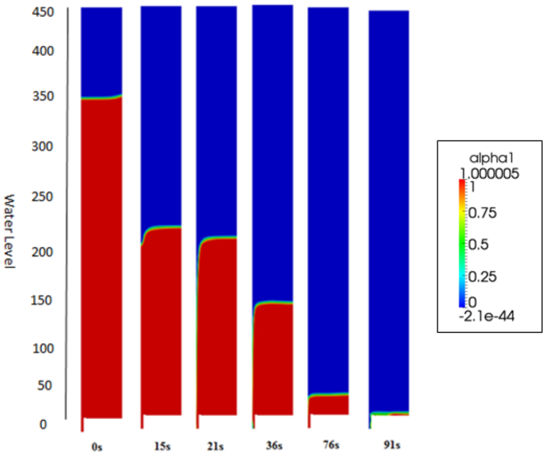


Figure 5 Free surface progressions and the generation of air-core vortex at 0-91s

Generation of air-core vortex

Figure 5 shows the generation of air-core vortex inside a cylindrical tank from 0s to 91s. A dip starts to develop on the free surface at the center of the tank at 15s. Then, it is instantly dragged downwards and quickly passes through the liquid inside the tank. When the dip is extended till the outlet of the tank at drain time 21s, air-core vortex generation is completed. At this time, the dip grows into a vortex with an air-core and the free surface generates a long and slender string shape that lengthens to the bottom of the tank, and is called a vortex (air-core) phenomenon. The dip forms the air-core on the surface as the level reaches a certain critical height, *Hc* which subsequently enters the outlet and is constantly continued until the draining is finished. When the core of the vortex reaches the bottom of the tank, the rate of liquid draining is decreased and the flow at the outlet nozzle is unsteady and highly rotational.

Velocity magnitude in a tank

Figure 6 shows the velocity magnitudeinside a draining tank from 0s to 91s. At 0s, the velocity magnitudeis the strongest at the sides of the wall, where its magnitude is similar to the initial rotation velocity at the wall. Hence, the velocity magnitude of the side wall is bigger than the others. When the tank stops rotating, the velocity of the fluids inside the tank is slowly reduced. Based on the experimental results obtained from Park and Sohn (2011), a boundary layer known as the Ekman spiral layer is observed inside the tank. According to the Ekman spiral suction flow, the top region of the liquid has a bigger velocity magnitudewhich is affected by the downwards flow and conservation of angular momentum.

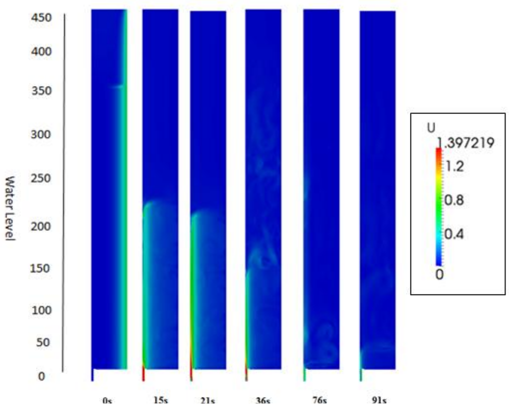
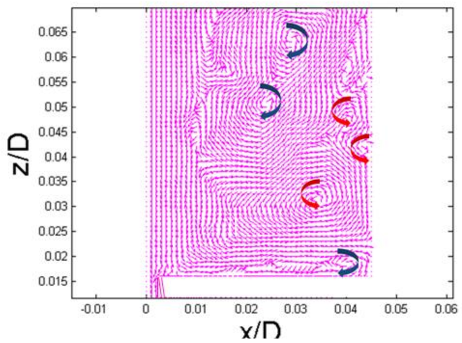


Figure 6 Progression of velocity magnitudedistribution at 0-91s

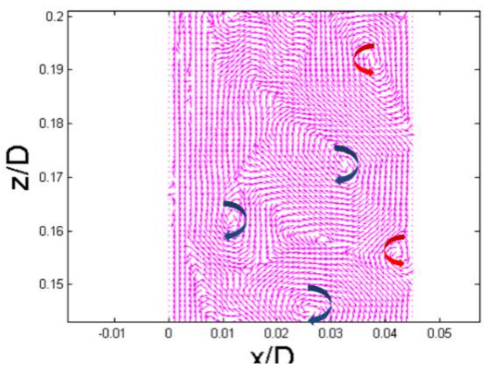
Velocity Vector in a tank

After the liquid starts to drain, as shown in Figure 7, a large axial flow is detected around the outlet region. At the same time, the vorticity is produced in off-centre areas and made multi-vortex structures that rotated with circumferential axis that grows more visibly over time. As shown in Figures 7(a) and 7(b), these flow structures are called Taylor vortices. According to Jong Hyeon Son et al. (2015), Taylor vortices are produced by two angular velocities which are inner and outer areas in the tank. The arrows in Figure 7 represent these velocities. The blue arrow with a clockwise direction represents positive values of angular velocity. Meanwhile the red arrow with a counter clockwise direction represents negative values of angular velocity. Besides, the axially rotating vortex in the central area is created by the conservation of angular momentum as the fluid particles move from the sides of the wall to the centre through draining. From this velocity vector plots, the toroidal vortex patterns are illustrated and is supported by the results obtained from Jong Hyeon Son et al. (2015). They are continually stacked from the bottom of the tank which axially swirls downwards in the narrow centre.

Figure 8 shows the velocity vector, vorticity and streamline distributions at drain time 21s. Although the vortex structures as shown in the figures are not axi-symmetric with their distributions and size being ambiguous, they showed a very similar flow pattern to the figure obtained by Jong Hyeon Son et al (2015). They stated that the chaotic vortex structures are caused by the strong axial flow in the tank centre. However, the pair of Taylor vortexes which rotates in opposite directions can also decelerate and accelerate the axial flow.



(a)



(b)

Figure 7 Close-up velocity vector distribution at a draining time of 21s: (a) at the outlet and (b) on the surface

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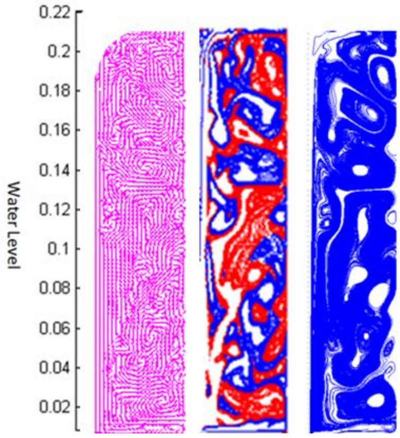

Figure 8 Velocity vector, vorticity and streamlines distributions at a draining time of 21s

Conclusion

In this study, the liquid draining inside the cylindrical tank was successfully investigated through the axi-symmetric (wedge) boundary condition in the OpenFOAM framework. The wedge boundary condition shows an excellent result of simulating the condition while simultaneously saving both time and computational efforts. From the comparisons of drain time plots, the OpenFOAM results for the non-swirl and swirl cases demonstrate very similar patterns and values to the results obtained from the numerical and experimental studies by Park and Sohn (2011). The ellipsoidal shape of the free surface and the generation of air core vortices were successfully recreated and is reflective of the results from Jong Hyeon Son et al. (2015).

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