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Parametric Study on the Effect of Baffles on Fuel Tank Sloshing

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Abstract

The present study describes the effect of position, sizing and configurations of the baffle on the dynamics of fuel tank sloshing. The 2D grid is made with the help of blockMesh option available in the OpenFOAM solver, for T-shaped baffles in rectangular tank at different locations. 3D case geometry and meshing is carried out with the help of a commercial solver ANSYS Workbench 2021 Academic version. Both 2D and 3D simulations are performed with the interFoam solver in OpenFOAM v8. The flow physics is simulated for dynamic motion of liquid container subjected to sinusoidal motion. The transient computations are performed by incorporating the interface tracking mechanism. The obtained results are validated with the benchmark results of Akyildiz et.al.

1 Introduction

Sloshing is the phenomenon observed for partially filled fluids in a container subjected to external excitation. Due to external excitation, the interface between fluids oscillates as a wave motion. This kind of situation arises in many applications such as petroleum transport by trucks, liquid containers on a ship, seismic excitation for chemical storage tanks. The oscillatory motion of interface has a low frequency and high amplitude. The oscillating fluids exert forces on the container walls which can cause issues such as unstable maneuver in petroleum transport trucks, structural failures of storage tanks. Thus to damp the sloshing phenomenon in partially filled fluid containers, baffles are used. Baffles are sheet metal components or parts situated inside of the containers in such a way that they effectively break the waves getting formed with sloshing motion. Baffles increase the turbulence in the container and also lead to formation of vortices at particular locations inside container. This helps in damping the energy of sloshing due to losses in vortex formation energy and turbulence. Thus based on the geometry of fluid container and fill level in the container, selection and positioning of baffles in container becomes of significant importance.

2 Problem Statement

The present study deals with the effect of baffles on liquid sloshing in a rectangular container. The objective of the present case study is to investigate -

1. Effect of fill level on sloshing
2. Effect of T shaped baffles in rectangular tank (2D)
3. Effect of T shaped baffles location in rectangular tank (2D)
4. Effect of other baffle configurations on sloshing (3D)

The problem statement considers the model geometry as below -

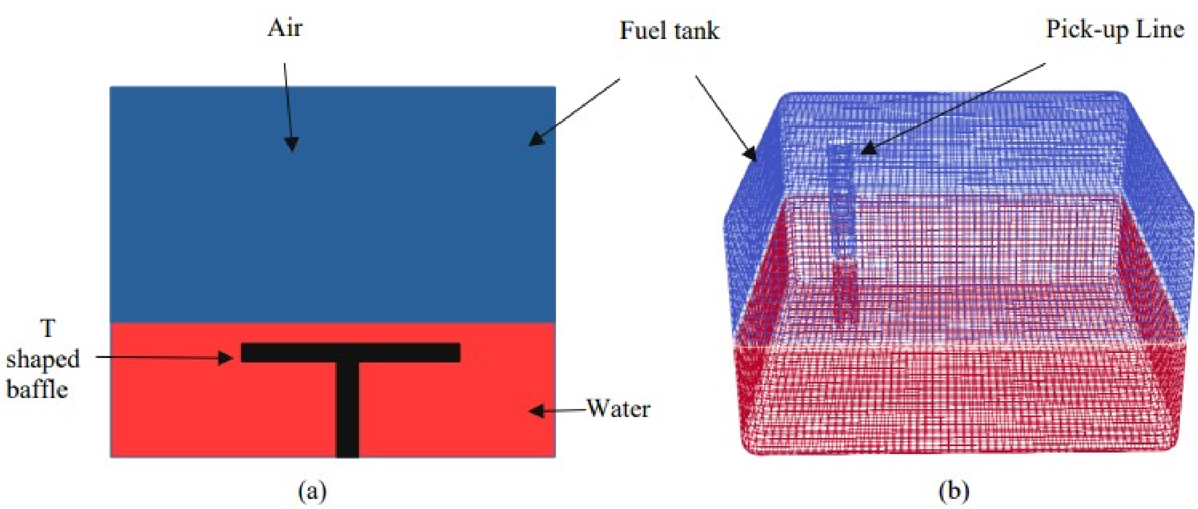

Figure 1. Partially filled fuel tank with baffles (a) 2D case and (b) 3D case

As shown in Figure 1, a partially filled tank with or without baffles is considered. The volume fractions of the tank filled with air and water, with centrally placed baffle is shown in Figure 1(a). The geometry and volume fraction in 3D case with fuel tank fitted with pick up line is shown in Figure 1(b). The effect of different fill levels of liquid(water or kerosene) with 25%, 50%, 75% fill levels is investigated.

3 Governing Equations

The solution to sloshing phenomenon consists of solving Navier-Stokes equations for two incompressible, isotropic fluids. The properties and boundary conditions at the interface are different than remaining flow-field of the container. For given problem, Navier-Stokes equations are as below -

1) Continuity Equation

$$\frac{\partial(u_i)}{\partial x_i} = 0 \tag{1}$$

2) Momentum Equation

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial[\rho u_i u_j]}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + f_{\sigma i} \tag{2}$$

Where, u is the velocity, g_i is gravitational acceleration, p is pressure, τ_{ij} is viscous stress and σ_i is surface tension.

The density is defined as

$$\rho = \alpha\rho_1 + (1-\alpha)\rho_2 \tag{3}$$

α = 1 inside fluid 1 with the density ρ_1 and

α = 0 inside fluid 2 with the density ρ_2 .

At the interphase between the two fluids α varies between 0 and 1.

The surface tension $f_{\sigma i}$, is modelled as continuum surface force. It is calculated as follows:

$$f_{\sigma i} = \sigma\kappa\frac{\partial\alpha}{\partial x_i} \tag{4}$$

κ is the curvature defined as,

$$\kappa = -\frac{\partial \eta_i}{\partial x_i} = -\frac{\partial \frac{\partial\alpha}{\partial x_i} / |\frac{\partial\alpha}{\partial x_i}|}{\partial x_i} \tag{5}$$

3) Volume Fraction Equation

$$\frac{\partial\alpha}{\partial t} + \frac{\partial(\alpha u_j)}{\partial x_j} = 0 \tag{6}$$

4 Numerical Aspects

4.1 Geometry and Mesh

The geometry consists of rectangular fuel tank with air and liquid as two phases. The simulation is run for air-water and air-kerosene in two cases.2D geometry consists of tank without and with T-shaped baffle centrally placed inside tank.The dimensions of 2D tank are 62 x 92 cm with baffle dimensions that can be varied from blockMesh file in OpenFOAM.The dimensions are referred from [2].

3D geometry consists of tank with and without baffles.Fuel pick up line is as shown in the image. In later cases, baffles are introduced in 3D tank geometry and simulated.The dimensions of the tank are 50 x 50 x 30 m with pick up pipe diameter 3 m as given by Singal et.al. [3]

For 2D geometry, Grid independence study was carried out with pressure at probe location in tank with grid refinements as shown in Figure 2.

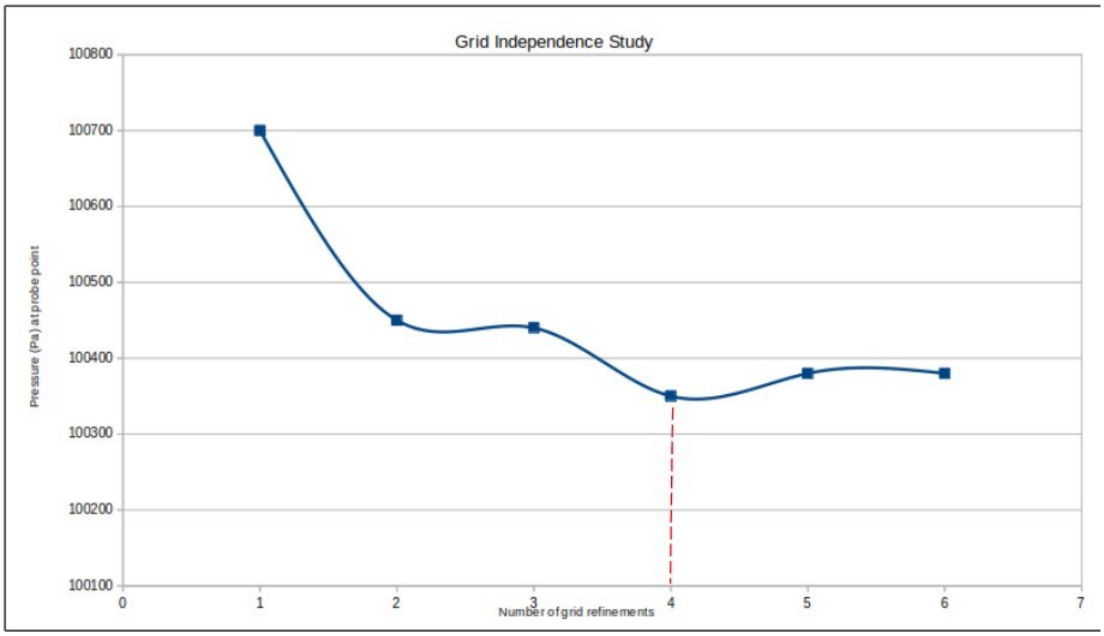

Figure 2. Pressure variation along diagonal line of tank vs no. of grid refinements

For 2D geometry, structured grid with quadrilateral elements was generated using blockMesh from OpenFOAM as shown in Figure 3.The mesh size of 15 divisions in Y and Z directions per block was selected as computationally effective mesh as further refinement creates some additional pressure which flattens out again with more refinement. 4th iteration of 15 divisions per block correspond to 56,250 mesh elements. The 2D tank with T-baffle flow domain was divided into total 9 blocks and then mesh sizing of 15 divisions was added to it. The division strategy is shown in Figure 3a.

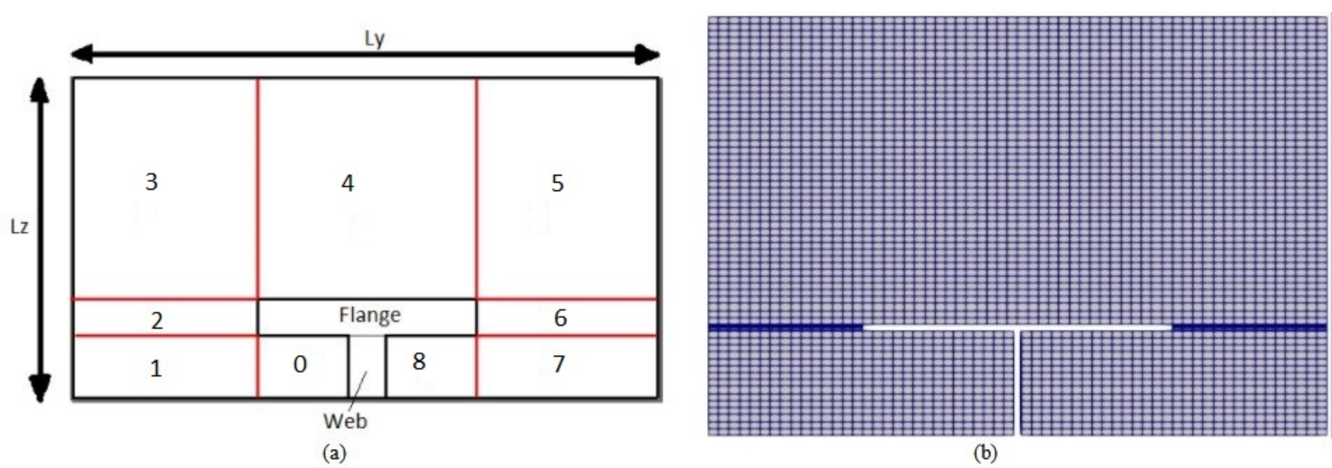

Figure 3. (a) Blocks division strategy for 2D tank with centrally placed T baffle (b) Mesh for 2D tank with centrally placed T baffle

for 3D geometry, Mesh was imported from ANSYS Workbench 2021 Academic with body fitted cartesian mesh used. The mesh with 98160 elements is shown in Figure 4.

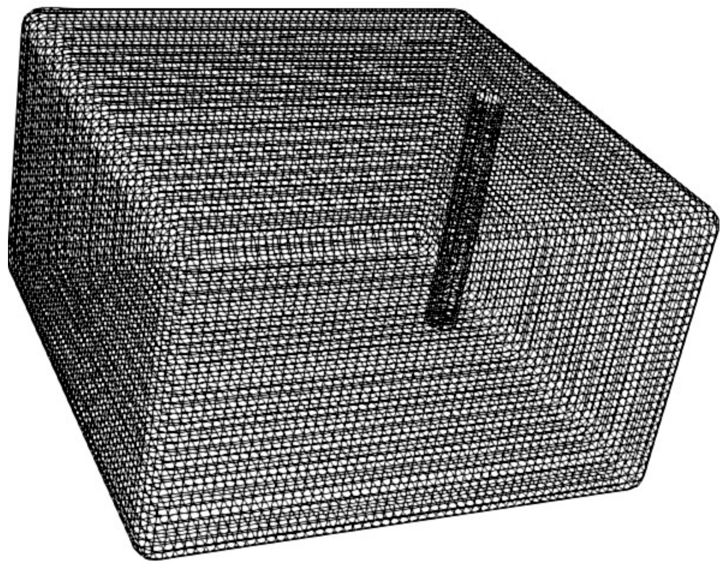

Figure 4. Mesh for 3D tank without baffles

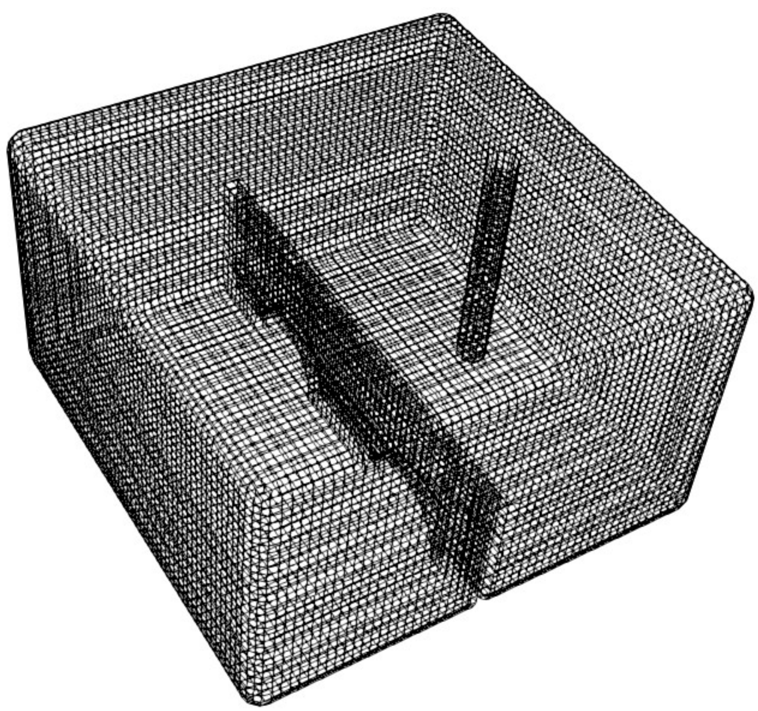

Figure 5. Mesh for 3D tank with baffles

4.2 Initial and Boundary Conditions

The problem is set up with following initial and boundary conditions.

a. alpha.water and alpha.kerosene They are used for setting up the volume fraction information of water and kerosene in the test cases. For water case, the volume fraction up to fill level is set up with setFieldsDict using boxToCell utility. The remaining volume fraction of the flow domain is set with air as fluid. Similarly the volume fraction is set up to different fill levels (25%, 50%, 75%) for kerosene case. Figure 6 shows the fill levels of tank with volume fraction of liquid(water/kerosene) by red color and volume fraction of air by blue color.

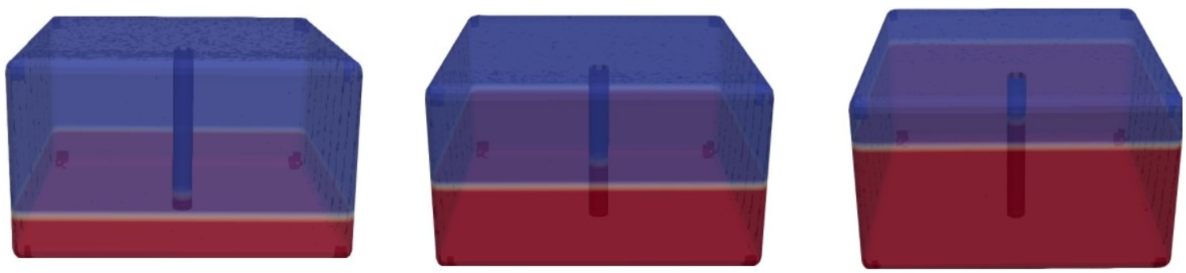

Figure 6. Different fill levels of tank partially filled with liquid

b. Velocity boundary condition

As discussed in [2], boundary condition for velocity at the walls can be implemented as either slip or no slip walls. The no slip boundary condition can be implemented when viscous effects are significant at the walls of the tank. When viscous effects are not significant free slip condition can be implemented. The present study incorporates no slip condition at walls to account for viscous effects as well if any. However inviscid assumption with free slip boundary condition can be implemented in the cases where viscous effects are not important.

c. Pressure boundary condition

The pressure file named p_rgh in OpenFOAM consists information about hydrostatic pressure in the cells. Initially the internal region of the flow domain is set to zero pressure. The walls of the flow domain is set to fixedFluxPressure which sets zero pressure gradient on the walls.

4.3 Numerical Solver

InterFoam is a transient solver used for solving Navier-Stokes equations for two incompressible and immiscible fluids in the present study. It uses Volume of fluid method with phase-fraction based interface capturing method. The fluid is considered as newtonian fluid with no phase change. It uses preconditioned conjugate gradient(PCG) solver for pressure correction and algebraic multigrid (GAMG) solver as pre-conditioner. For velocity, smoothSolver with GaussSeidel smoother was used. The solver uses PIMPLE algorithm which is combination of Pressure Implicit with Splitting of Operator(PISO) and SIMPLE algorithm. For time derivatives Euler scheme is used whereas for spatial gradients and divergences Gauss divergence schemes are used.

5 Results and Discussions

5.1 2D simulation base case validation results- Air-Water system

Case 1. Tank without baffles

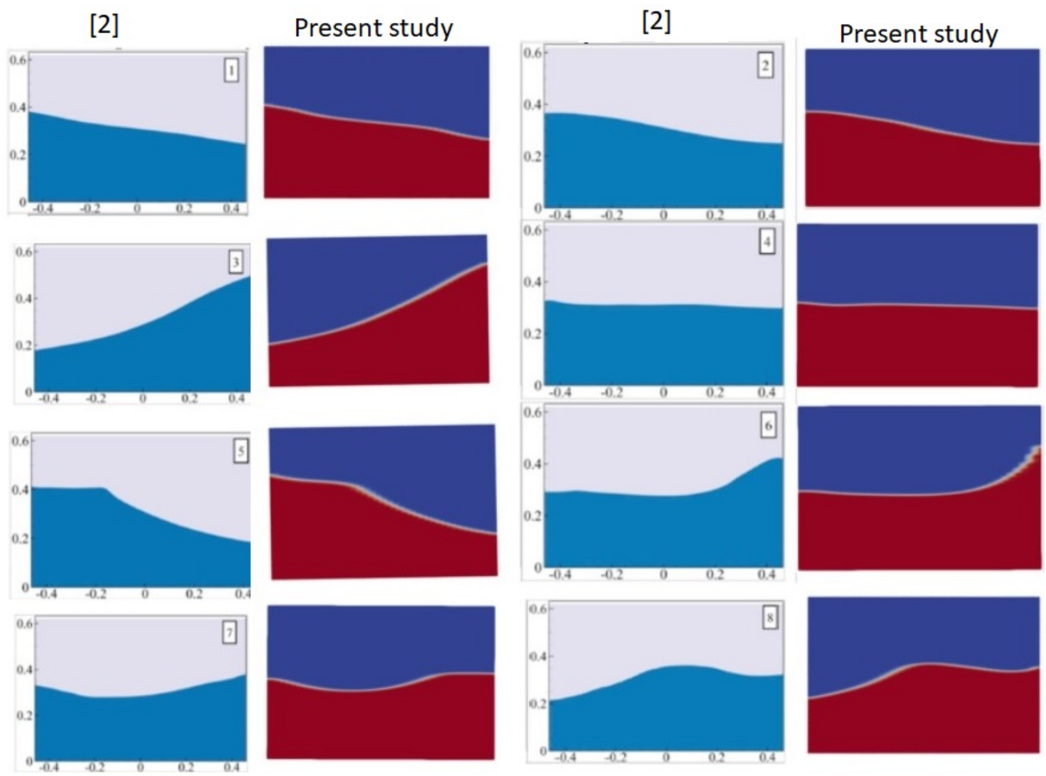

Figure 7. Free surface deformations at different sloshing phases (50 % filling depth, $\theta_0 = 8^\circ$) [2]

The results for tank subjected to sinusoidal motion with rotation angle of 8° and angular frequency ω = 3.3 rad/s are shown in Figure 7. The results for base case simulation in OpenFOAM agree closely to results given in [2]

The results shown are corresponding to time(seconds) as shown by marker on each image as -

(1) 0.48 (2) 0.95 (3) 1.43 (4) 1.90 (5) 2.38 (6) 2.85 (7) 3.33 (8) 3.80

The wave motion of interphase can be seen from the phase fraction snapshots at these time intervals as shown in Figure 7. For the case of T-shaped baffle tank with baffle height to fill height ratio of 0.5, Figure 9 shows effect of baffle location on sloshing phenomenon. Shifting the T-shaped baffle near to the corner location increases the energy loss from sloshing motion due to formation of vortices and more breaking of the wave formation.

The snapshots shown in Figure 9 correspond to time(sec) as (1) 0.48 (2) 0.95 (3) 1.43 (4) 1.90 .

From snapshots 3 and 4 it can be seen that the wave breaking tends to shift towards the location of the baffle.

Case 2. Tank with centrally placed T-shaped baffle

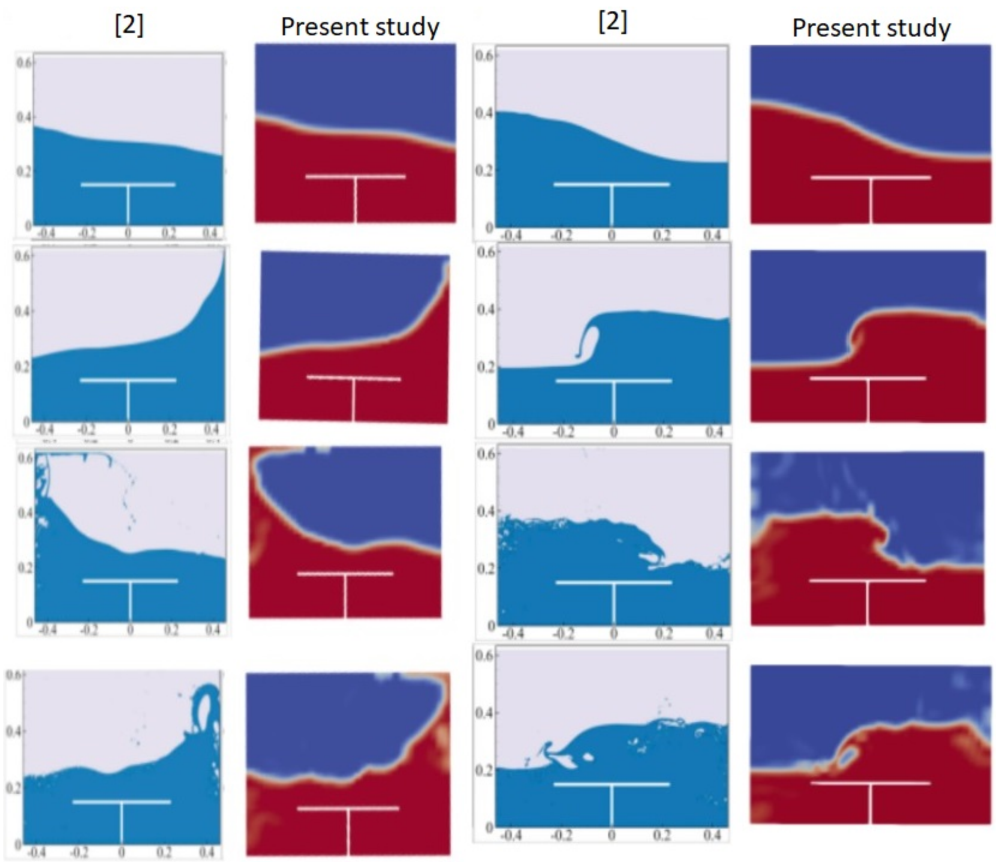

Figure 8. Free surface deformations at different sloshing phases (50 % filling depth, θ_0= 8°, hb/h = 0.5) [2]

Case 3. Tank with T-shaped baffle near one end

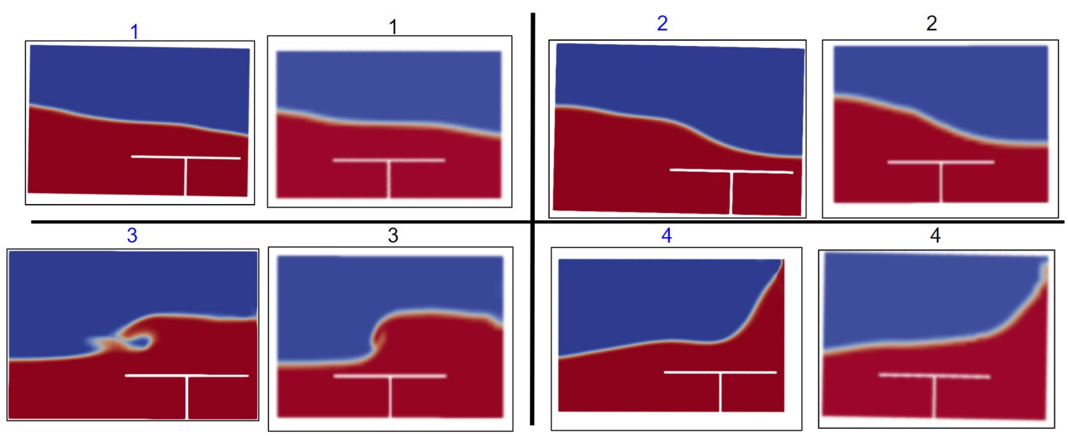

Figure 9. Effect of baffle location on sloshing - near corner placed baffle vs. central baffle

Case 4. Effect of baffle sizing on sloshing

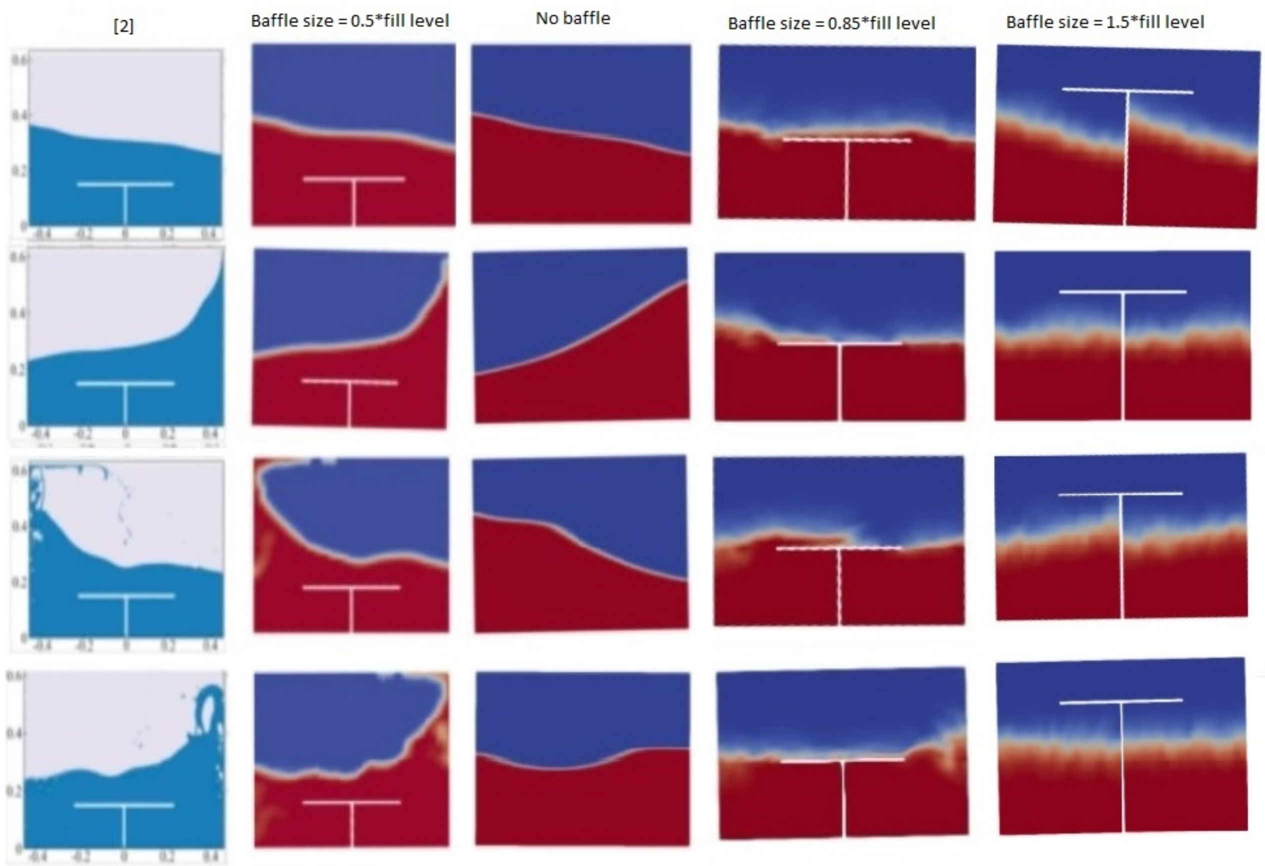

Figure 10. Comparison of sloshing with size of baffle

The results shown in Figure 10 correspond to time intervals of 0.48, 0.95, 1.43 and 1.9 seconds. The comparison is done for centrally placed T-shaped baffle, no baffle case and centrally placed T-shaped baffle of bigger sizes. When size of the baffle is more than 85% of the fill level, the baffle becomes more effective in terms of damping the sloshing phenomenon. In case of baffle size 150% more than fill level, the sloshing observed is less however the tank acts as with two compartments in this case.

The sloshing is damped overall however the free surface breaking phenomenon in individual compartments is not observed due to absence of baffle in that region. This is because the baffle is able to break the wave formation more easily than baffle of small size. The results are in good agreement with the effect of sizing of baffles as suggested by Akyildiz et.al. Also it is observed that pressure at probe location is more in case of baffle of bigger size as seen from Figure 11. Figure 11 shows pressure at probe location for baffle of size 0.85 times fill level and for baffle of size 1.5 times fill level. The fill level is this case is 0.5 times the total height of tank. It is observed that with increased baffle size than fill level, the pressure at probe location is rising. This can be attributed to reduction in formation of vortices and wave breaking as the baffle tips are at higher location than the fill level.

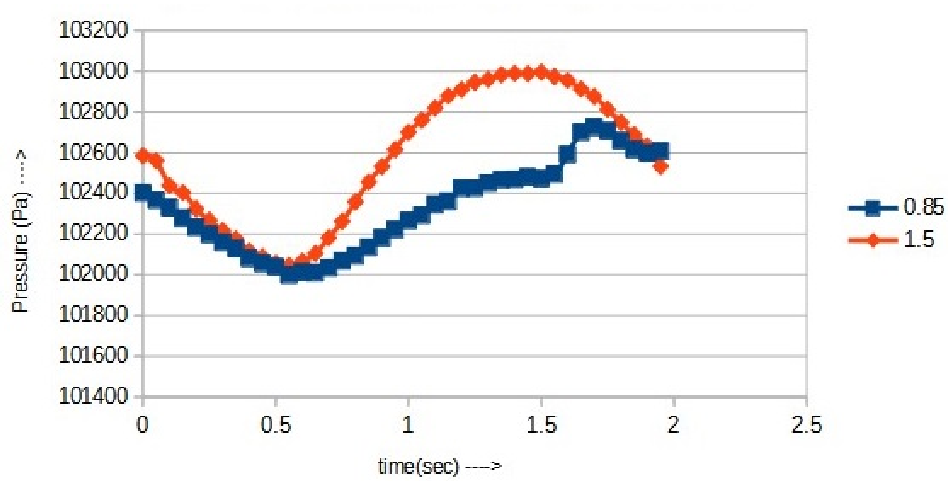

Figure 11. Comparison of pressure at probe location (0 0.46 -0.25) vs time

5.2 3D simulation results - Air-Kerosene system

Figure 12 shows effect of fill level on fuel tank sloshing. As shown in the figure, 4 cases of tank filled up to 25%, 50%, 75% and 50% with baffle are shown. The snapshots at time intervals of 0, 0.5, 1.0 and 1.5 for volume fraction of kerosene-air system are shown. It is seen from the snapshots that at a particular time instant, kerosene is spreading and forming more vortices in higher fill level than lower fill level cases. For the case of 50% fill level, the baffles are significantly reducing the sloshing on the walls as compared to the case of 50% fill with no baffles.

As seen from Figure 13, pressure is higher for more fill level of the tank subjected to rotational motion. The pressure decreases with decrease in the fill level at probe location of (-24 0 -15). The effect of baffles in reducing the pressure amplitude at the probe location is verified from the Figure 13.

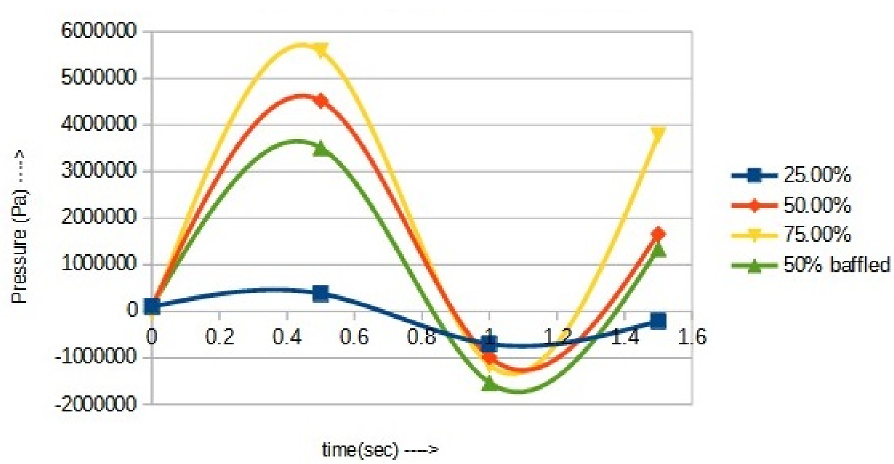

Figure 12. Effect of fill level on pressure variation with time

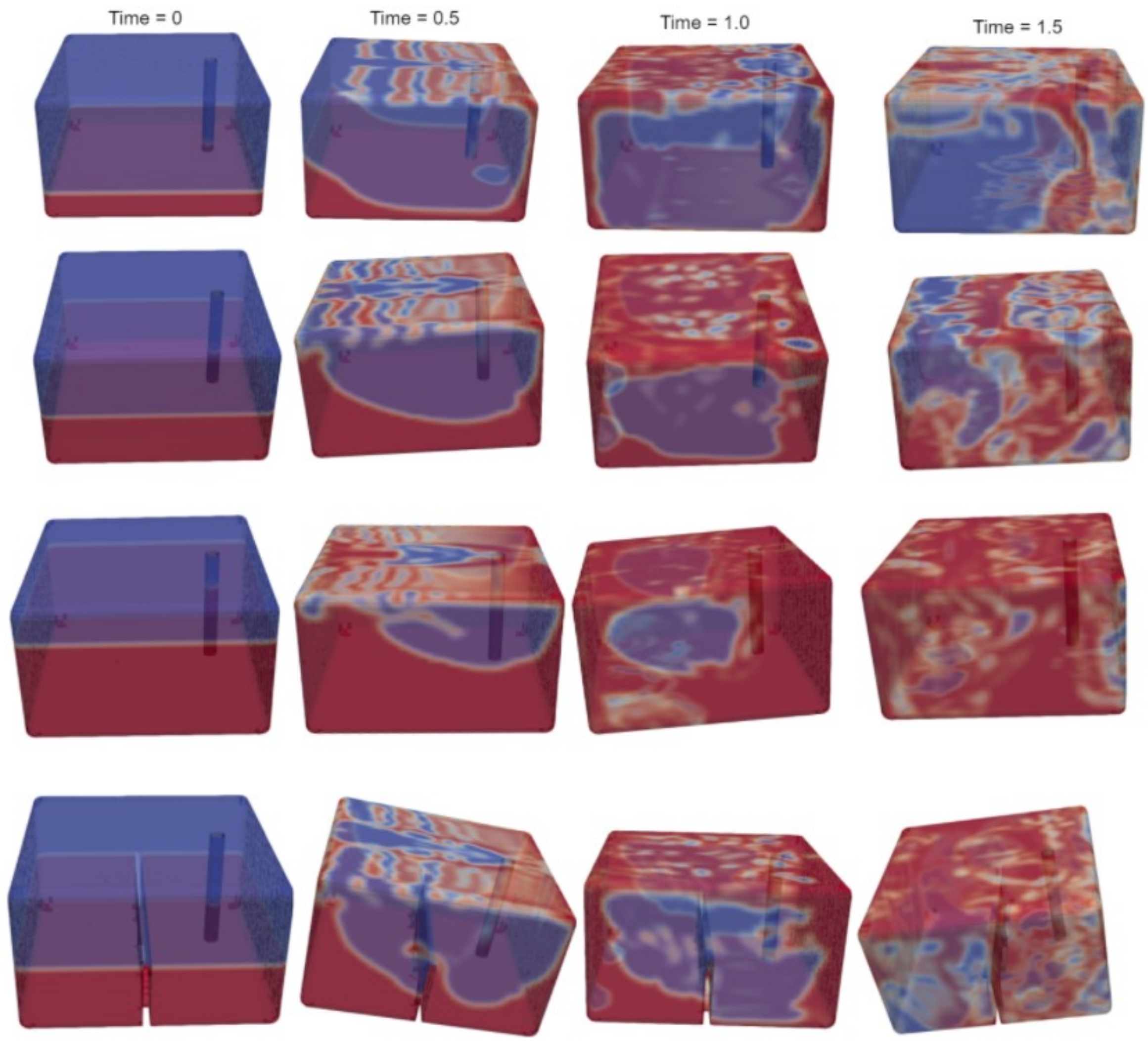

Figure 13. Effect of fill level on sloshing

Conclusions

It can be concluded from the present study that baffles reduce the sloshing phenomena occurring inside container subjected to motion by loss of energy due to formation of vortices. This loss of energy favors in breaking the wave motion occurring inside the liquid container thereby damping the sloshing phenomena. It is observed that wave breaking shift towards the direction of baffle location more. This information can be used in deciding the pick-up line location so as to ensure that pick up line remains filled. The effect of size of baffle is seen from Figure 10 and 11 indicating more sloshing pressure in case of bigger size baffles.

The baffles size as seen from Figure 10 has a critical value at which it gives minimum sloshing to a particular fill level. As suggested in [2], this size is greater than 0.8 times of the fill level. The results of present study agree with this argument. Thus efforts might be put in a variable size baffle which adjust its size based on the fill level of liquid in the tank. However this can be considered as the future scope of the current study. The effect of fill level is observed from Figure 12 and 13 which indicate that sloshing is dominant in case of more fill level of the tank and it is reduced with introduction of the baffle.

References

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