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Numerical Investigation Baffle Position in Rectangular Tank to Reduce Sloshing Interface between Liquid and Gas Phase

Fereydoon Pavir[1*], Asad Mirahky[2] and Mohamad Reza Ansari[3]

[1]Mechanical Engineering Faculty, Sharif University of Technology, Tehran, Iran; pavir@mech.sharif.ir
[2]Faculty of Mechanical Engineering, Tarbiat Modares University, Tehran, Iran; a.mirahky@yahoo.com
[3]Department of Mechanical Engineering of Tarbiat Modares University, Tehran, Iran; mra_1330@modares.ac.ir

Abstract

Objectives: In this study, sloshing interface in the 2D and 3D tanks were investigated by Open FOAM software **Methods/Statistical Analysis:** The obtained results were in good agreement with experimental results. 2D and 3D results that were based on the first natural frequency excitement and ratio of A/L<0.1 (stimulation amplitude relative to the length of tank) were very close together. **Findings:** Rectangular tank with two phase such as gas and liquid was simulated with and without baffle under horizontal excitement in first natural frequency. The torque on the baffle, the height of the liquid in the FS and pressure on the wall of tank for different height of the baffle (installed at the bottom of the tank) were studied. Baffle was mounted in the bottom of the tank, height equal to half the initial height of the liquid. In Previous studies, baffles have been mounted at the liquid part on bottom of tank. In this study, in order to increase efficiency of baffles and reduce the torque exerted on it, baffles were installed in gas part on top wall and only tangent to the surface of liquid in first time. Installing baffles in the roof of tank reduce sloshing, because less torque entered on it in comparison with baffle on bottom of the tank. **Application/Improvement:** Installed baffles in top of the tank relative to optimum baffle in bottom decreased wave amplitude about 34 percent and exerted torque became half.

Keywords: Sloshing, First Natural Frequency, Baffle

1. Introduction

Sloshing of liquid free level in fluid mechanics is one of the important phenomena that is commonly used in designing of fluid-structure. Large industrial equipment including ships, satellites, rockets, tanks and fuel storage tanks directly linked with the phenomenon of sloshing[1]. Sloshing in the reservoir is one of the complex phenomena in fluid motion. The dynamic movement of the fluid in the reservoir which is limited by the walls, creates significant changes in the whole system of employment[2]. The waves that have been created in reservoirs can create risks of instability and damage to the structure. The amplitude of waves depends on, natural frequency, the excitation wavelength; height of the liquid, fluid's properties and the geometrical shape of the tank[3].

In[4] collected and developed analytical solutions to find out dynamic equations of liquid sloshing in order to extract the shape of free surface modes. In[5] collected a full reference of experimental results and analytic methods for sloshing phenomenon about sea Engineering. By[6] classified 2D and 3D sloshing, in rectangular tanks. This

*Author for correspondence

classification is based on the frequency and extent ratio of excitement and this classification does not include excitement around the first natural frequency. In[7] solved the issue using the analytical method and assuming the two-phase sloshing in the rectangular tank. In his research, the impact of the density of high phase on sloshing interface of gas and liquid was studied. He also obtained the results of transversal and random excitement by his proposed models. By[8] analytical method showed the wave height of liquid in a rectangular tank with different densities of gas phase. They developed the analytical solution for both the gas and liquid phase and showed that gas phase has significant impacts on the fluctuation between the two phases.

By[9] using finite element method simulated the sloshing in 2D and 3D tank. In this investigation, in addition to interface surface they also obtained the pressure in different parts of the tank's walls. Besides, they showed that in low excitement amplitude and far from the first natural frequency the result of the 2D and 3D are similar. By[10] using of computational fluid dynamic investigated the domain of interface waves of gas and liquid, frequency, in coming pressure to the walls, stability and also the impact of liquid sloshing on the walls of the tank. By comparing numerical results with different methods such as finite element, and finite volume method with the experimental results showed that the results of the finite volume method is more precise results than other methods.

In[11] used the 3D numerical simulation in order to solve the sloshing in rectangular tanks with baffle by means of spatial average NavierStockes equation and using LES. Finally, they showed that the numerical method can give results with high accuracy12 studied linear and non-linear behavior of interface sloshing of gas and liquid in rectangular tank numerically and analytically. In the low amplitude and frequency away from the natural frequency, numerical and analytical results are in a good agreement with the experimental results. In13 with the finite element method, made waves in the various excitements frequency and created resonant states that have been identified, by14 considering different Cases of gas phase density gained the formed waves on the surface of two phases by volume of fluid method and using OpenFOAM Software. They showed that by increasing density in gas phase the sloshing of gas and liquid interface will be reduced. In15 studied the generated waves on the fluid surface of liquid by placing the baffle in tank with the numerical and experimental method. Numerical results at excitement with frequency away of first natural frequency are in good agreement with the experimental results. By16 using the VOF gained the free surface of the liquid with baffle and without baffle. They showed that in the baffle case a layer of viscous is formed between the free surface and the top of the baffle, which lost the energy of the liquid fluid and prevent wave's rising. In17 experimentally demonstrated that baffles in a tank, significantly reduce the sloshing. This baffles by severing flow turbulence, reduces energy flow significantly.

Previous research has focused on controlling interface sloshing between liquid and gas by installed baffles on the bottom of the tank that the optimal location and size of the baffles have been neglected. In this research sloshing in the tank with different installed baffle's height has been studied, by increasing baffle's height the sloshing on the liquid surface decreased but importing force on the baffle increased. Here the torque on the baffle is calculated at different heights and the installed baffle on the floor of the tank is chosen with optimized height. The following location of installed baffle in order to further reduction of interface sloshing and tolerating less force has been studied.

2. Govern Equations

2.1 Continuity Equation and Navier-Stokes

The governing equations of the fluid's momentum transfer are NaviorStokes equations. To solve the equations of two phase flow, the momentum equations and the continuity equation has been treated similar to the single-phase flow except some parts which flow has different characteristic.

Continuity and momentum equations are presented as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\rho V + (\nabla \cdot \rho V V) = -\nabla P - \nabla \cdot \tau + \rho g \tag{2}$$

The incompressible fluid, equations (1) (2) are simplified as following[5]:

$$\nabla \cdot (V) = 0 \tag{3}$$

$$\rho \frac{DV}{Dt} = -\nabla P + \mu \nabla^2 V + \rho g \tag{4}$$

In equation 4, $V$is the speed term, P is the pressure term, μ is the dynamic viscosity and τ is the viscous stress.

To simulate the zone of liquid fluid and gas, the volume of fluid method is used which is shown in the following equations.

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \bar{u}) = 0 \quad (5)$$

$$\rho = \alpha \rho_l + (1-\alpha)\rho_g \quad (6)$$

$$\mu = \alpha \mu_l + (1-\alpha)\mu_g \quad (7)$$

α is a volume fraction and scalar parameter, this parameter is a value between 0-1. Cells with the value $0<\alpha<1$ define the gas and liquid interface. Density and viscosity can be obtained by equation of (6) and (7) for momentum equation. In the present study equations were discredited with finite volume method in OpenFoam Software. The coupling between the continuity and momentum equations was done by using the PISO method.

2.2 Numerical Solution

The integral equation in compressibility and non-compressibility were discredited by finite volume method. The coupling between the continuity and momentum equations was done by using the PISO. Flow turbulence is assumed with large eddy simulation model. In this research OpenFOAM software is used.

2.3 The Tank Geometry and Meshing

The tank was considered rectangular and two-dimensional Figure 1. The tank dimensions are L = 1.73m and H = 1.05m and the initial level of the static liquid is0.6m. We used water with density ρ = 1000 kg/m[3] as liquid phase and second phase is air with density ρ = 1.3 kg/m^3. The waves produced in interface by horizontal stimulation with x = A * sin (ω_ht) was generated. A is amplitude of stimulation and ω_h external excitation frequency of reservoir. To measure height of liquid and comparing with experimental results, the height of the liquid on the FS line was measured (Figure 1).

According to the measured fluid height on the FS line in experimental work and specify how the overall sloshing with interface volatility of the two–phase, grid independence tests were conducted using liquid height on the FS.

The tank is under the horizontal stimulation and we used three different grids for 2D rectangular geometry (Figure 1.) which were 52 × 86, 26 × 43, 17 × 27. Liquid height (h) on the FS using three different grids are shown in Figure 2. According to the results grid 26 × 43 was used.

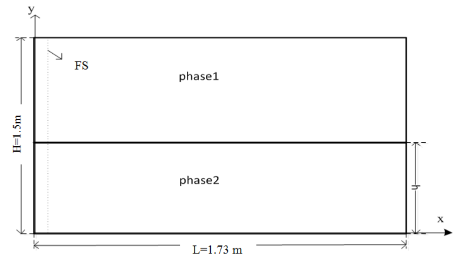

Figure 1. 2D tank geometry

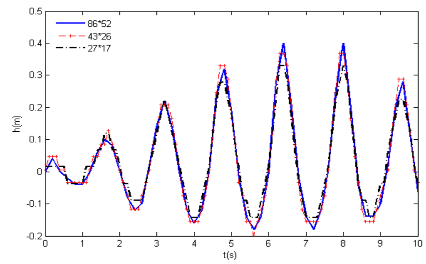

Figure 2 Liquid height in FS with different grids.

3. Results and Discussions

3.1 Results Validation

In order to validate the simulation conducted in this study, the numerical results with experimental results of[5] and analytical solution[12] to stimulate $x = 0.03 \sin(4.1817t)$ are compared in Figure 3. Numerical results are in good agreement with the experimental results of the present work so that the maximum error relative to the entire height of the tank is 9 percent. By approaching the stimulation frequency to the first natural frequency the analytical results get more distance from the real results, but there is a little error with numerical results in all cases. In this study in order to investigate the critical cases the stimulation frequency is equal to the first natural frequency.

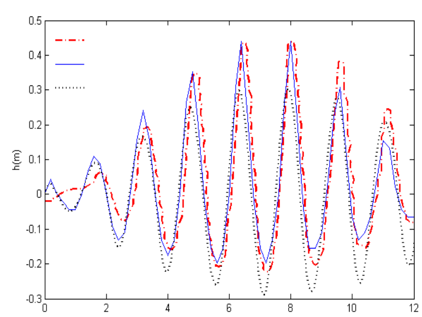

Figure 3. Liquid surface sloshing in FS

3.2 Comparison the Results of Two and Three-Dimensional Reservoir

3D tank similar to the 2D tank was examined by considering perpendicular Side to the screen of the required size 0.4m. The height of the liquid in FS line in two and three-dimensional tank in stimulation x = 0.03sin (4.1817t) is shown in Figure 4.

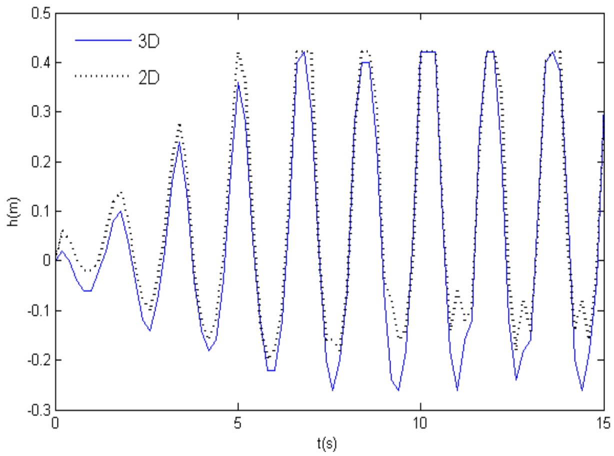

Figure 4. Liquid surface sloshing in FS for 2D and 3D reservoir.

In the first natural stimulation frequency and the amplitude of excitation, the result of two and three dimensional are the same and we can use two dimensional analysis for tank. In the tank stimulation with first natural frequency and stimulation amplitude relative to the length of tank less than 0.1 (A/L<0.1), results of two and three-dimensional are similar.

3.3 Comparing Results of Compressible and Incompressible Phases

By considering energy equation and using NavirStokes and continuity, gas phase is assumed as compressible. The results of the both compressibility and incompressibility for stimulation in the first natural frequency of tank are shown in Figure 5. Compressibility of gas phase in sloshing phenomena has no impact on the interface of two phases. The volume of gas and liquid fluid were Constant and temperature changing were negligible. So the incompressibility of fluid gas is a correct assumption.

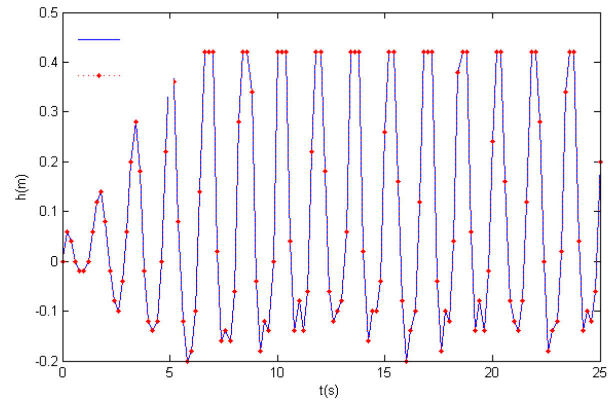

Figure 5. Free surface height of the liquid in the FS in the Compressible and incompressible cases

3.4 Force on the Baffle in Sloshing

In many reservoirs, controlling systems are considered for liquid surface sloshing. In some of controlling systems baffles are used in tank in order to reduce the interface sloshing of both phases.

The height of the baffle in tank is l_b which is in the middle of bottom on the horizontal side (Figure 6). In analytical solution the impact of baffle's tip is ignored, and for relatively slow flow the force which excreted on it is shown in equation8[17,18].

$$F_D = \frac{1}{2}\rho C_D l_b |u_r| u_r \tag{8}$$

Drag force (F_D) is preventing force on the baffle and Ur is the horizontal speed of flow in contact with baffle. One way to guess the drag coefficient is assuming the tank reflection as mirrored bottom which is used from flow crossing relationship on the vertical plane and fluid flow is considered unlimited. So the lengthen of plane is $2l_b$ considering the assumption that has been done, the drag coefficient is calculated into the below equation. KC is obtained from experimental results[19].

$$C_D = 8.0 * KC^{-1/3} \tag{9}$$

In the current research for studying force and torque on the baffle in Figure 6 under the horizontal stimulation x=0.03sin (3.7673t), the incoming pressure on the both sides was achieved in anytime step. The average importing pressure on both sides and the difference of pressure was calculated in any time steps. Indifferent baffle's height the average pressure differences on both sides has been shown in Figure 7. The positive pressure difference is in agreement with X and the negative pressure difference is in contrary with X. The pressure difference on the both sides of the baffle is reduced when the height of baffle increases. Also in the cases that the height of baffle is half of the liquid height by increasing baffle height the pressure difference is not reduced phenomenally.

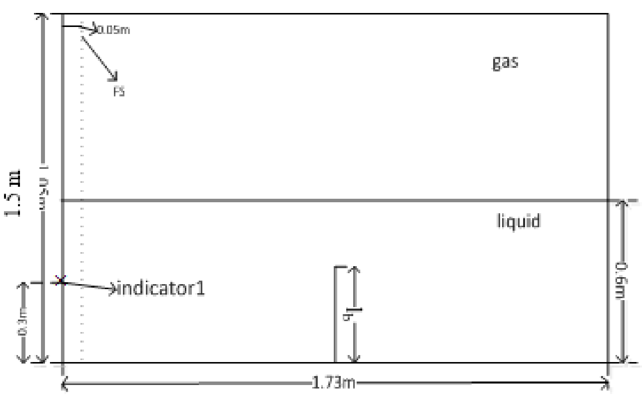

Figure 6. Tank geometry with installed baffle on surface

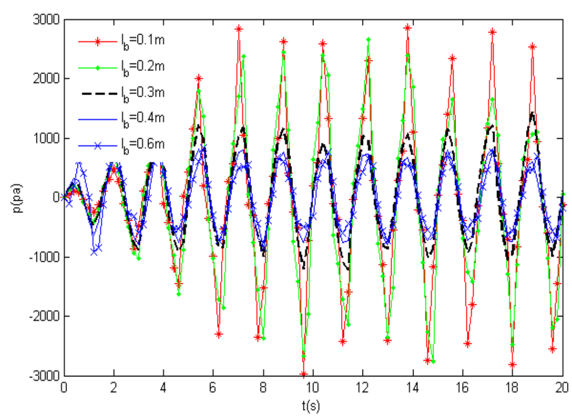

Figure 7. Difference pressure onto installed baffle on surface tank

By increasing the height of baffle from l_b=0.3m (baffle is as half as the height of liquid) to l_b=0.4m the changes in pressure difference is only 9 percent while for l_b=0.4m to l_b=0.6m pressure difference is approximately the same.

In the baffle with low height, the speed of crossing flow above the baffle is more and the pressure difference on the both sides is increased. Although by increasing the height of the baffle the pressure difference reduced but the surface of the baffle increased therefore the incoming torque and force on the baffle increased. The pressure difference on the both sides of baffle in the integral of baffle surface causes the importing force. The average of incoming force on the baffle in any time step was calculated. Based on the place of the force effect on the middle of the baffle the importing torque to the baffle is shown in Figure 8. As for increase in baffle surface and height of force effect point, importing torque on the baffle has a contrary process of pressure difference and torque is mostly related to l_b=0.6m.

However by decreasing baffle's height tolerate less torque but the aim of installing baffle is to reduce the interface waves' domain and reducing the pressure on the walls of tank which we will discuss (Figure 8).

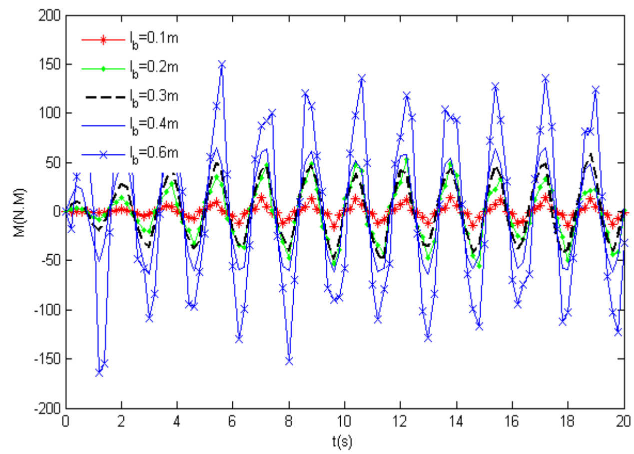

Figure 8. Importing torque onto installed baffle on surface

3.5 The Effect of Baffle on the Interface Sloshing of Two Phases

The effect of baffle with different heights (l_b=0.2; 0.3; 0.4; 0.6m) (Figure 6) on the interface sloshing and importing pressure on the walls for external stimulation x=0.3sin (3.7673t) was studied. In Figure 9, the liquid height in FS is compared in different cases with baffle and without baffle (l_b=0m). Without baffle the domain of the waves increased while with installing baffles wave's height significantly decreased and prevented waves from reaching to the ceiling of the tank. In Figure 10 importing pressure to the wall in the indicator 1 is compared in different heights of the baffle. Increasing the height of the baffle not only decreased the domain of the wave but also decrease the importing pressure onto the walls. By checking pressure on the other different points of the wall and ceiling of the tank we observed that increasing the height of the baffle reduces the importing pressure. Here it's sufficient to show the pressure in the indicator 1. In cases which domain height of formed waves in interface is lower than the half of gas phase 1st height, the waves unable to create instability in tank[5,4]. In Figure 9 from the height of the baffle l_b=0.3m onward, the domain of the waves are less than 0.2m (the 1st height of the gas 0.405m) which is a desirable area. In the height of the baffles in which waves domain is in desirable area the case l_b=0.3m, will tolerate the least torque. If the baffle has the half height of the fluid liquid it means that it's the most optimized case. For increase the height of the baffle more than l_b=0.3m the domain of the interface waves and importing pressure onto the walls will be reduced but, the torque on the baffle increased (Figure 10).

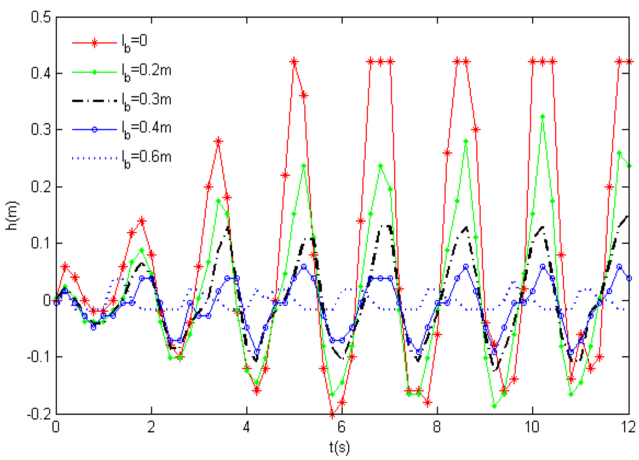

Figure 9. Liquid Fluid surface sloshing in FS for baffles different size in stimulation 0.03 sin(3.7673t)

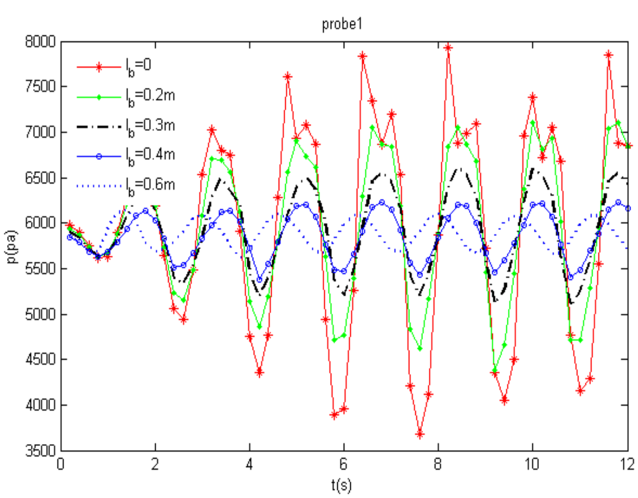

Figure 10. Importing pressure on indicator 1 for 0.03 sin(3.7673t)

By increasing the height of the baffle from 0.3m to 0.6m the pressure in the indicator 1 decreases about 8 percent, but the torque will be multiplied by 3.

3.6 The Optimized Baffle's Place in the Tank

In this research in order to control the interface sloshing and importing pressure on the tank's walls, baffle has been installed on the ceiling of the tank (Figure 11) and the end of the baffle is in contact with fluid liquid. Considering equation 11 the importing force on to the baffle depends on the fluid phase where the baffle has been installed. So by installing the baffle on the ceiling we expect that the importing force on to the baffle will be reduced.

The sloshing in the tank has been studied (Figure 11) by installing baffle on the ceiling under the stimulation of x=0.3 sin (3.7673t). The tank geometry with installing baffle on the ceiling equals to installed case on the surface, only the size and the location of installation will be different. The sloshing of the fluid liquid in FS line has been measured.

In Figures 12 and 13 respectively the height of fluid liquid in FS and importing pressure to indicator 2 (Figure 11) in two tank with installed baffle on the ceiling and bottom with l_b=0.6m have been compared. The most difference fluid liquid height in the two geometries is 0.02m. The height of the fluid liquid causes the same change in both cases. The domain of the wave in a tank with installed baffle on the ceiling is less than the waves' domain in another case with bottom baffle l_b=0.4m. The pressure of the indicator 2 in the tank with the baffle on the ceiling was reduced as much as the baffle on the bottom. Ceiling baffle as bottom baffle with height l_b=0.6 m tolerate least pressure difference.

The imported force to the baffle on bottom baffles was studied. Providing baffle on the bottom of the tank with half height of the fluid liquid plays the optimized role in order to reduce both the interface sloshing of the two phases and importing force to the baffle. Installing baffle on the ceiling of the tank reduced the sloshing domain and imported pressure to the walls just like bottom baffle at the height l_b=0.6m which reduced the sloshing and pressure to the least level. In each step the pressure difference has been calculated in order to study the pressure and the torque on the ceiling baffles as bottom baffles. In Figure 14 and 15 respectively the pressure difference and imported torque to the ceiling baffle and bottom baffle at height l_b=0.6m have been compared.

The baffle which was installed on the ceiling as we expected tolerated far less torque in comparison with surface baffle. The most torque which exerted on ceiling baffle is 40 N.m. This baffle in comparison with optimized baffle in bottom not only tolerate 34 percent torque less but also reduced the wave's domain in half. The baffle which installed on the ceiling not only reduces the sloshing but also reduces the imported force to the baffle on the ceiling of the tank. Ceiling baffle from the beginning of the stimulation prevents the soar of interface, and the sloshing with first natural frequency is completely quiet. In most cases the height of fluid liquid is more than the half of the tank and installed baffle on the ceiling of the tank causes reduction of used materials.

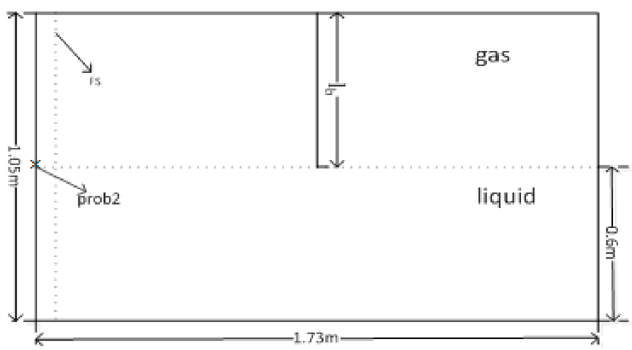

Figure 11. Tank geometry with installed baffle on ceiling

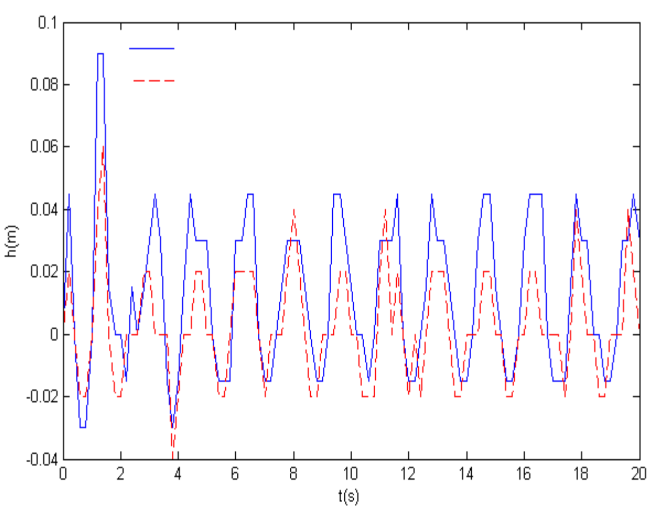

Figure 12. Liquid fluid sloshing with installed baffle on surface and ceil

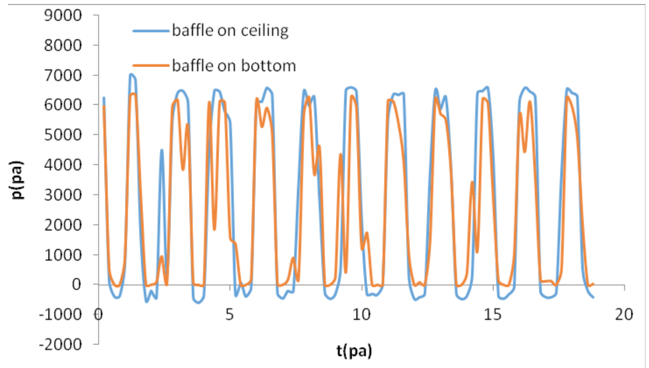

Figure 13. Importing pressure on indicator in contact with free surface in both tank dashed line surface baffle, filled line ceiling baffle

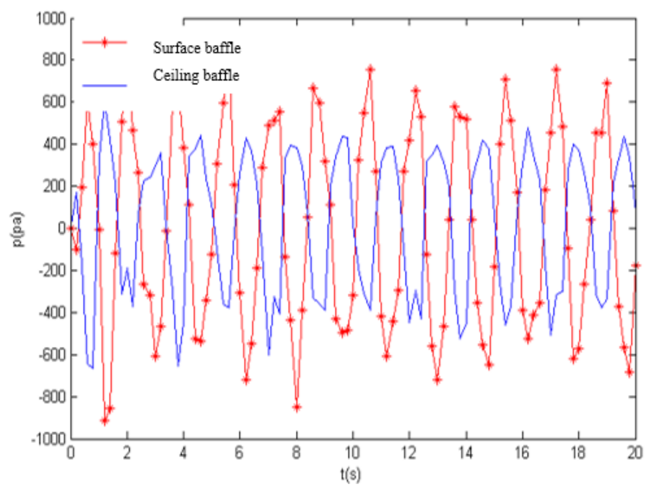

Figure 14. Importing pressure difference on surface and ceiling baffle (l_b = 0.6)

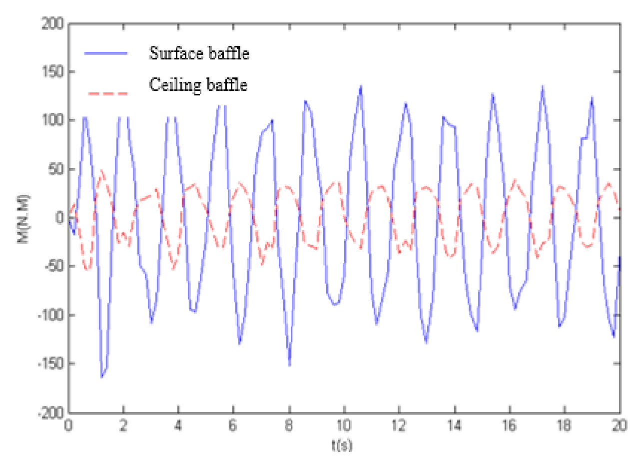

Figure 15. Importing torque on surface and ceiling baffle (l_b = 0.6)

4. Conclusion

The fluid surface sloshing in two dimensional and three dimensional tanks with baffle and without baffle has been simulated by OpenFOAM Software. Sloshing in two cases with assumption of being compressible and incompressible of gas fluid was studied. Incompressibility assumption of fluid gas in this issue is quite right. The installed vertical baffle on the bottom of the tank was studied in different sizes. Increasing the height of the baffle in the tank reduces the pressure difference on the both sides of the baffle but, the crossing section and the impacting place of the force increases and causes the increasing of importing torque to the baffle. The most importing torque in the bottom baffle is at the height 0.6m. The goal of the baffles are to reduce the interface sloshing and importing pressure to the walls which reduced by increasing the height of the bottom baffle. Baffle with the half height of the fluid liquid 1st height has the optimized case in tolerating torque and reduction of the imported pressure to the walls. By increasing the height of the baffle from 0.3m to 0.6m we reduce the pressure in the indicator 1 about 8 percent but the importing torque to the baffle was multiplied by 3. Baffle was installed on the celling of the tank in gas phase part which is in contact with liquid. The ceiling installed baffle as bottom baffles reduces the waves' domain and interface sloshing at height l_b=0.6m but, importing torque to it is less than half of the bottom baffle. Ceiling baffle comparing to optimized bottom baffle (l_b=03m) not only tolerates less torque by 34 percent but also reduces the domain of the waves to the half.

Notation

A external stimulation domain (m)
$\bar{F}$ Force (N)
h liquid fluid height
h_B baffle height
P pressure (kgm^{-1} s^{-1})
t time(s)
$\bar{u}$ Speed (ms^{-1})
g gravity(ms^{-2})
l_b baffle length(m)

Greek's notation

Ρ density (kgm^{-3})
μ Dynamic viscosity (kgm^{-1}s^{-1})
α volume fraction
φ potential function
η liquid surface sloshing (m)
ω_h Stimulation frequency (rad^{-1})

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