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IMPACT OF DIFFERENT BAFFLE HOLE SHAPES TO DAMP SLOSHING EFFECTS

İbrahim Arda[1,2], Yılmaz Barış Erkan[3,4] and Tolga Vergün[5,6]
University of Turkish Aeronautical Association
Ankara, Turkey

ABSTRACT

This study investigates the impact of different baffle hole shapes to damp sloshing effects. For this purpose, a representative fuel tank model partially filled with liquid water is drawn within the DesignModeler of ANSYS and five different hole shapes are chosen to analyse the effects of pressure on tank walls. The cross sectional area of respective holes are kept identical and the tanks are subjected to sinusoidal angular velocities to perform roll and yaw motions. As these motions cause liquid waves to hit on tank walls, the flow enters into the turbulent regime. Hence, ANSYS Fluent CFD solver with Reynolds Averaged Navier-Stokes (RANS) realizable $k - \varepsilon$ *is implemented during the simulations. Consequently, simulation results are presented and compared.*

INTRODUCTION

Sloshing is a phenomenon which corresponds to free surface elevation in two phase flows. Slosh dynamics are exceedingly observed when a partially liquid filled solid container is exposed to motion. This phenomenon has both advantages and disadvantages for different ways of usage. Partially liquid filled tanks occasionally have been used to damp destructive effects on buildings such as those due to earthquake. In such cases, the higher the acceleration amplitude the easier it is for the system to damp destructive effects, since the energy dissipation will be higher [Banerti and Samanta, 2011]. On the other hand waves generated by sloshing motion may pose as a disturbance to the stability of the system. Vehicles that are able to quickly accelerate such as jets, rockets or satellites experience the effects of sloshing. Sloshing might be extremely important for space missions such that they may determine the success of the mission by having a potential to damage the attitude control system of the satellites [de Souza and de Souza, 2014]. Sloshing can also be used to passively stabilize the satellites by damping the nutation of the spinning spacecraft [Kang and Lee, 2008].

Baffles are mainly used to compensate the sloshing effects on the structure. Eswaran et al. published

[1] Rsc. Asst. in Astronautical Eng. Department, E-mail: iarda@thk.edu.tr
[2] MSc Student, METU Physics, E-mail: ibrahim.arda@metu.edu.tr
[3] Rsc. Asst. in Astronautical Eng. Department, E-mail: yberkan@thk.edu.tr
[4] MSc Student, METU Mechanical Eng., E-mail: baris.erkan@metu.edu.tr
[5] Rsc. Asst. in Aeronautical Eng. Department, E-mail: tvergun@thk.edu.tr
[6] MSc Student, ITU Aeronautical and Astronautical Eng., E-mail:vergun19@itu.edu.tr

their study which is focused on baffle effect [Eswaran, Saha and Maity, 2009]. They showed that there are drastic differences regarding the dynamic pressure and the free surface elevation for cases with and without baffle.

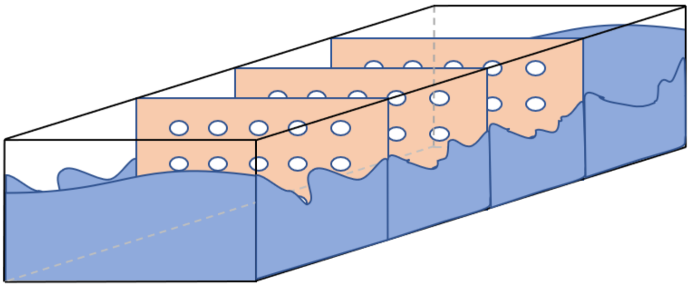


Figure 1: A sample container with baffles.

Baffle height, baffle thickness and baffle material are the main parameters that are examined in the literature in order to reduce the sloshing effects. The study of Liu and Lin focused on the effect of baffles on the sloshing by comparing the cases without baffle, with horizontal baffle and with vertical baffle [Liu and Lin, 2009]. As a result of their study, vertical baffle is a more effective tool in reducing the sloshing amplitude compared with horizontal baffle; but in general presence of baffle has a significant damping effect. Jung et al. focused on the vertical baffle height on the liquid sloshing [Jung, et al., 2012]. As a result of their study, the vortex generated by the flow separation from the baffle tip becomes weaker and smaller with increasing baffle height, leading to a diminished damping effect of the tip vortex on the liquid sloshing. In this regard, the study of Liu and Lin and the study of Jung et al. are in good agreement, therefore, their work are the perfect candidates to understand the trend of baffle effects. Various baffle hole shapes and their effects on the sloshing as well as the maximum pressure attained on the tank walls are examined thoroughly in this paper.

METHOD

Volume of Fluid (VOF) method is used during computation process with Reynolds Averaged Navier-Stokes (RANS) realizable $k-\varepsilon$. VOF method is a surface tracking method that calculates free surface at each time step and it is efficient in solving the problems which deal with the shape of the free surface. The fluid motion is governed by the continuity and the Navier-Stokes equations

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

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho(\vec{u} \cdot \nabla)\vec{u} = -\nabla p + \mu \nabla^2 \vec{u} + \rho \vec{g} \tag{2}$$

The volume inside the tank is partitioned into liquid and air. Also, the entire volume is discretized into individual cells. In each cell, volume fraction is used to rearrange continuity and momentum equations. Volume fraction in each cell is defined as [ANSYS Inc., 2013]

$$\alpha_i = \frac{V_i}{V_t} \tag{3}$$

where V_i corresponds volume of i^{th} phase in each cell and V_t corresponds total volume of the cell. Due to the discretization, density and viscosity terms in eq. (2) are rewritten with a summation:

$$\rho = \sum \alpha_i \rho_i \qquad \mu = \sum \alpha_i \mu_i \tag{4}$$

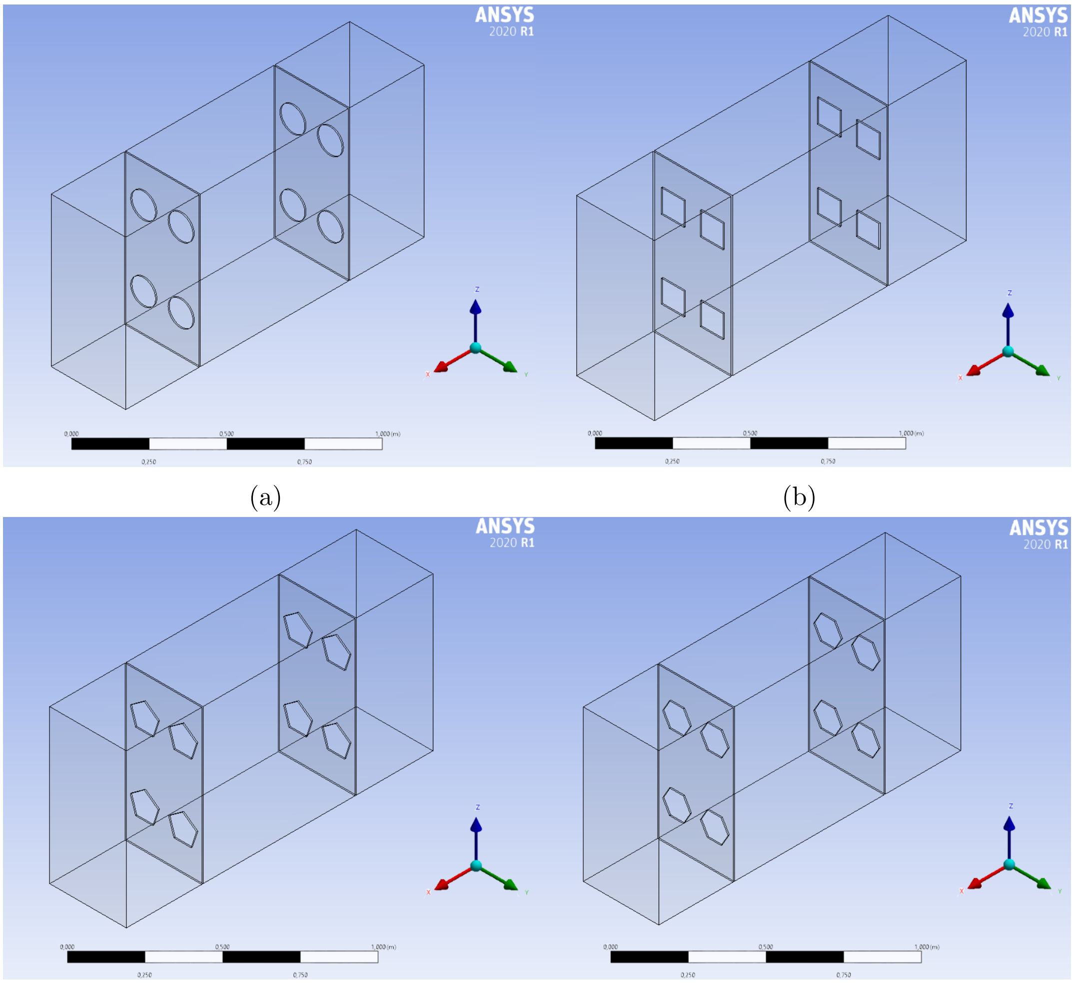
Equation (3) together with eq. (4) are substituted into eqs. (1) and (2) to yield

$$\frac{\partial}{\partial t}\left(\sum \alpha_i \rho_i \vec{u}\right) + \nabla \cdot \left(\sum \alpha_i \rho_i \vec{u}\vec{u}\right) = -\nabla p + \nabla \cdot \left[\sum \alpha_i \mu_i (\nabla \vec{u} + \nabla \vec{u}^T)\right] + \sum \alpha_i \rho_i \vec{g} \quad (5)$$

As the liquid wave interacts with the walls of container and baffles, the flow becomes exceedingly turbulent. Therefore, to obtain a more precise result, utilization of a turbulent modeling is inevitable since otherwise the model would predict fictitious free surface profiles [Liu, et al., 2016]. Thus, $k-\varepsilon$, a commonly used turbulence model, is associated with the main relation, eq. (5).

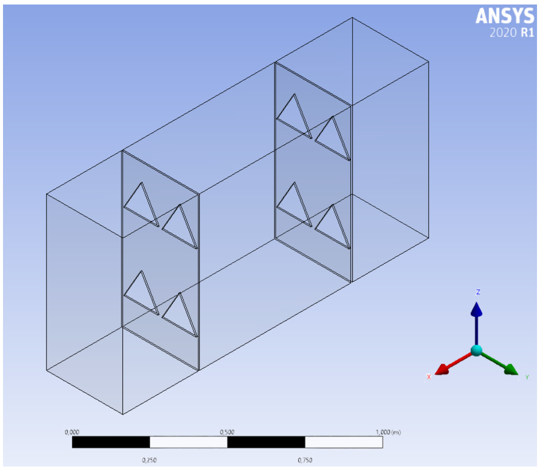
MODEL

Various analyses for different baffle hole shapes are considered for a tank with dimensions 1.2 m, 0.3 m, and 0.6 m respectively in x, y, and z directions [Arora and Vasudevan, 2017]. In this context, five different baffle hole shapes are utilized as shown in Figure 2. The relevant dimensions for these geometries are given in Table 1.



(a) (b)

(c) (d)



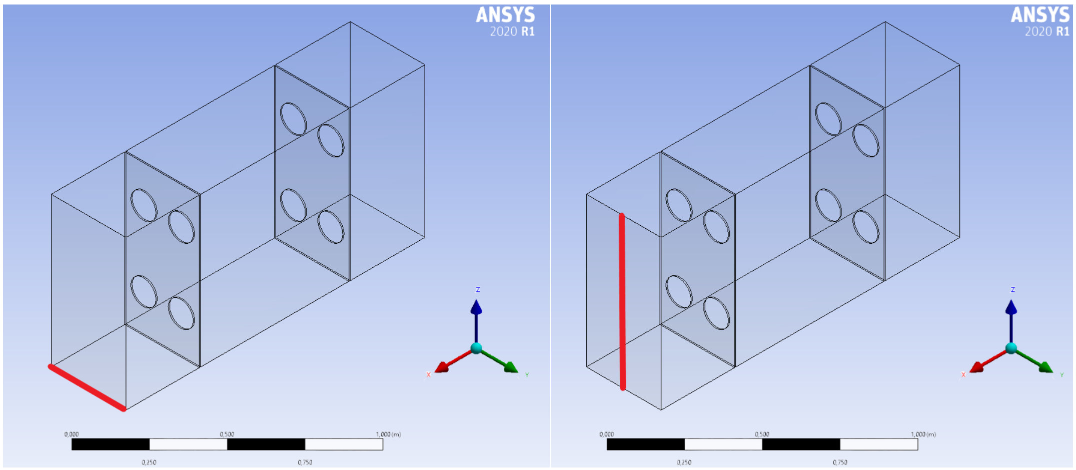
(e)

Figure 2: Geometries with (a) circle hole-shaped, (b) square hole-shaped, (c) pentagon hole-shaped, (d) hexagon hole-shaped and (e) equilateral triangular hole-shaped baffles.

Table 1: Diameter or length of different baffle hole shapes

Hole Shape	**Diameter or Length(m)**	**Cross Sectional Area(m^2)**
Circle	0.1000	0.00785
Hexagon	0.0550	0.00786
Pentagon	0.0676	0.00786
Equilateral Triangle	0.1350	0.00789
Square	0.0886	0.00785

Once the tank models are defined, 50% of the tanks are filled with liquid water and the tank is excited to undergo roll and yaw motions with sinusoidal angular velocities. Velocity expression is defined with $Asin(2\pi t/T)$ and the rotations are performed about the rotation axes illustrated in Figure 3 for roll and yaw . Here, the amplitude of the rotational speed is represented with A while the period is denoted with T. These parameters are taken as 0.175 rad/s and 1.94 sec, respectively [Arora and Vasudevan, 2017].



(a) (b)

Figure 3: Rotational motion is applied around the axes shown with red lines. (a) Roll motion, (b) yaw motion.

RESULTS AND DISCUSSION

To compare the impact of the five baffle shapes of the liquid pressure on the tank walls, analyses are conducted for 50% tank fill level for roll and yaw motions. The periodic motions are observed for approximately 2.5 periods. The maximum pressure on the tank walls for each time step is illustrated in Figure 4 for roll motion, and in Figure 5 for yaw motion. Global maxima of pressure values (i.e., maximum pressure throughout the entire motion), on the other hand, are illustrated in Table 2 for roll and yaw motions.

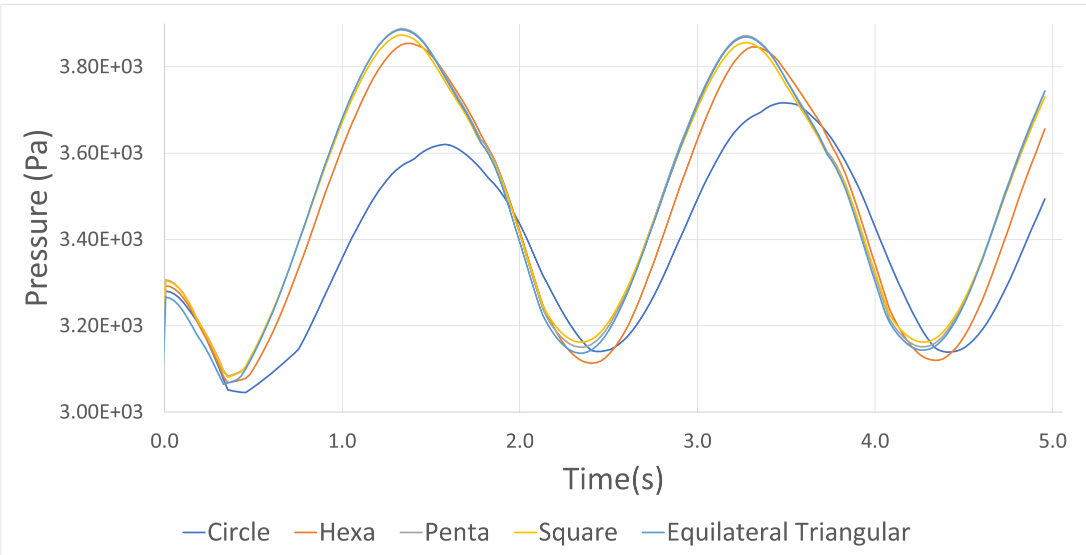


Figure 4: Comparison of maximum pressure occurring on tanks for roll motion.

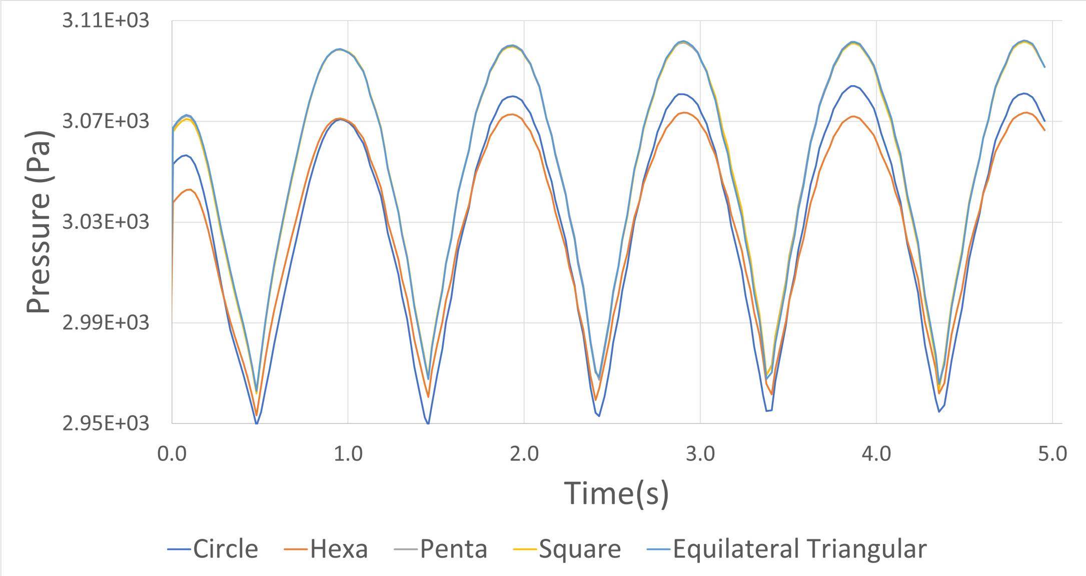


Figure 5: Comparison of maximum pressure occurring on tanks for yaw motion.

In the light of the results given in Figure 4 and Figure 5, small pressure variations are observed for the five different hole shapes. From Table 2, it is clearly observed that circle hole-shaped tank has the lowest global maximum pressure signal during roll motion while hexagon hole-shaped tank has the lowest global maximum pressure signal during yaw motion. When the results are analyzed in conjunction with roll and yaw motions, the tank with circle hole-shaped baffle offers the best lowest maximum pressure signal that is followed by the tank with hexagon hole-shaped baffle, while the tank with pentagon hole-shaped baffle appears to be the worst in this comparison.

Table 2: Global maximum pressure in the tank for various baffle hole shapes

Hole Shape	**Max. Pressure for Roll(Pa)**	**Max. Pressure for Yaw(Pa)**
Circle	3716.57	3084.05
Hexagon	3854.34	3073.47
Pentagon	3888.34	3102.08
Equilateral Triangle	3886.26	3102.07
Square	3873.60	3101.65

CONCLUSIONS

In this study, 5 different hole shapes are considered to investigate global maximum pressure signals on tank walls. Throughout this study, $k - \varepsilon$ turbulence model is preferred [Liu, et al., 2016]. By doing so, turbulent kinetic energy and turbulent dissipation is taken into account. It is observed that the lowest global maximum pressure signal is occurred in circle hole-shaped tank while the highest global maximum pressure signal is occurred in pentagon hole-shaped tank.

Even though the pressure amplitude for the circular hole is distinctively less than that of other four shapes, it is required to conduct analyses for different parameters with different container filling levels since the results in Figure 4 and Figure 5 are rather close to each other, especially for the tanks with hole shapes other than circle.

It is common in aerospace industry that weight is one of the major problems. Therefore, these results might be transferred into a tank structure and the factor of safety can be investigated as a future study. In order to achieve higher factor of safety, the system can be designed with lighter materials or with different topology options to decrease the total weight.

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