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RESEARCH ARTICLE - ENGINEERING

Numerical Simulation of a Partly Filled Rectangular Tank with Fuel Oil

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Abstract

Sloshing refers to a certain kind of fluid movement that changes as it progresses. It possesses properties that are both nonlinear and exceedingly unpredictable, and these properties affect the tank wall. This effect may lead to structural wear, which in turn can cause the tank to fail. Benzene and gasoil liquids are used to test the effect of sloshing liquid and accompanying pressure on the wall tank caused by the baffles in partially full fluid tanks. To attain this, modeling of the interaction between fluid and structure is justified using the finite element analysis while the ANSYS Fluent is used to do the simulation. Specifically, the analysis enables us to anticipate the pressure that is being exerted on the shield, the influence of sloshing on the grounding point forces, and the size of the sloshing waves. The pressure distribution over time indicates a reduction of pressure on the tank wall as a result of utilising a vertical baffle if compared to the case of a tank wall without a baffle. The usage of vertical shields allows for around 20% of the greatest contact energy to be deflected, which is attributed to the potential of generating turbulence and vortices by the baffle.

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Keywords: Sloshing; Tanker; Partially Filled; Fluid Dynamics; VOF; UDF.

1. Introduction

Sloshing is a typical phenomenon that occurs when a partially filled tank of liquid is vulnerable to movement or disturbances. When the tank is moved, the liquid inside it moves with it, causing waves to slosh back and forth. The movement of the liquid can generate dynamic forces and moments that can compromise the tank's stability and safety [1]. In the worst case, a wave could break, a mixture of liquid and gas could form, or there could be air bubbles at every point. The swirling is a very complicated process from a hydrodynamics point of view. To understand the swirling, both computer simulations and real-world experiments should be utilised [2]. The utmost significant difficulty that can happen with sloshing is that the tank walls can get hit with a lot of force. In particular, the tank can be damaged by increasing waves. Standing waves are the most concerning thing that can be seen at the top of the tank [3, 4]. The behavior of liquid in a partially filled tank is determined by several parameters, including the form and size of the tank, the kind and volume of liquid, and the frequency and amplitude of external shocks. Proper design and analysis of tanks subject to sloshing are required to ensure structural integrity and safety [5].

There has been a lot of research on the sloshing caused by ocean waves and how it relates to the movement of ships like oil and gas trucks [6–8]. Most people are familiar with the sloshing that happens in road and train cars when they speed up, slow down, or turn. The rapid acceleration of the car can cause temporary sloshing in the tank. This sloshing would last for a while even after the external excitation stopped. Indeed, liquid sloshing is often a bad thing that can increase the chance of a rollover and make the car harder to control [9–11]. Pandit and Biswal [12] studied the forced shaking of a two-dimensional, rigid, rectangular partially filled tank. A Finite Element (FE) code in two dimensions is used to figure out how sloshing works. The results of the same amount of liquid with fixed dimensions of the tank were compared when it is excited in a harmonic way with amplitudes of 5 mm and 10 mm. Higher excitation values cause the liquid in the container to move more, which increases the dynamic reaction.

Yu et al. [13] investigated the stability of the circular tank at various fill levels. A novel automobile crash model discovered the solutions for the moving mass center of liquid in a tank with modified circular cross sections. Nonlinear external excitation is used to make a liquid sloshing model of a partially filled tank. The Euler transform 6-DOF motion equation of the tank was used. The nonlinear mathematical models of liquid

Nomenclature & Symbols

VOF	Volume of Fluid	g	Gravity Acceleration
UDF	User-Defined Function	NS	Navies Stokes
FE	Finite Element	RANS	Reynolds Averaged Navies Stokes
CFD	Computation Fluid Dynamic	ρ	Density
L	Length	μ	Dynamic Viscosity
h	Height	τ	Shear Stress
u	Fluid Velocity Vector	α	Volume Fraction
t	Time	ω	Natural Frequency
C	Coefficient of Surface Tension = 0	β	Frequency of Excitation
k	Curvature of the Interface	P_d	Dynamic Pressure

swirling and the vehicle motion equation were shown to precisely represent the dynamic behavior of a tank truck in Turing. Cui et al. [14] demonstrated how liquid fuel sloshes around in the spaceship system using a similar pendulum model. The lagrangian method was used to make a dynamic model of how liquid moves when it is shaken in both directions. Analytical and numerical results are depicted in the form of phase diagrams, frequency-response curves, and time histories of sloshing motion and sloshing force to show the influences of key parametric resonance, sub-resonance, and non-resonance conditions on sloshing motion separately.

Zhang et al. [15] studied how a partially filled liquid tank travels in regular waves using both experiments and computer models. The authors studied different heights and lengths of waves in the wave tunnel. A PIT 3D motion capture system is used to track how the liquid tank moves. The volume of fluid (VOF) method and the overset meshes methodology were used to solve the multi-phase flow during liquid swirling. The results indicated that the frequency of the most severe liquid churning is lower than the frequency of the liquid tank itself. A viscous fluid flow model with the Navier–Stokes solver was used by Wang et al. [16] to study how vertical and horizontal staggered tanks respond to random external excitations that cause them to move. The sloshing reaction to irregular excitations is thought to have a three-phase variation. These are the first-order natural period controlling stage, the second-order natural period controlling stage, and the transitional stage in between. Samples of large free surface amplitudes gave smaller standardized sloshing than samples of small free surface amplitudes.

Computer simulations were utilised by Barabadi et al. [17] to determine whether floating foams might be used to prevent water from flowing in a rectangular tank. A harmonic vibration causes the water in the tank to move around. The Arbitrary Lagrangian-Eulerian method (ALE) in the commercial program ABAQUS is used to run numerical models in 3D. The impacts of plastic foam density on lowering the height of waves were investigated to be insignificant. Doubling the density of the foam reduces the maximum kinetic energy by 9.68% while triplicating the density of the foam causes a reduction of the maximum kinetic energy by 29.03%. The influence of nonlinear shields on hindering the movement of water was studied by Raja and Ponnusamy [18]. The Volume of Fluid (VOF) method was used to carry out numerical studies in two dimensions with horizontal acceleration. The nonlinear baffles were utilised with different amounts of fill, different frequencies of excitation, and different depths of submergence. The influence of change in the baffle factors, such as the baffle volume, the number of baffle cycles, and the angle of the baffles was also assessed. Of all of the nonlinear baffles that were looked at, the negative amplitude cosine baffles with a 2 cm wave amplitude set at 0.02 m submergence depth stopped churning the best. A set of experiments were conducted by Korkmaz and Güzel [19] to study how waves hit the side walls of a rectangular tank that was moving in a harmonic sway motion with and without a hydrophobic coating. The findings showed that the features of the solid surface have a strong effect on the height of the open surface, the formation of waves, and the spread of pressure. Particularly, big changes have been found around the resonance frequency. This is ascribed to the dominant radial flow and changed waveform, which reduces the peak pressure that stimulated more water to move inside the tank due to the hydrophobic effects.

Referring to the above-revised studies and up to the authors' knowledge, the effect of sloshing liquid on the wall tank with and without a vertical baffle has not been thoroughly analyzed in the open literature. Thus, this study aims to fill this gap by utilising the Computation Fluid Dynamic (CFD) technology to investigate the issue of rectangular tanks sloshing in two dimensions. In this regard, benzene and gas oil will be employed as two liquids to determine the impact of sloshing liquid and associated pressure on the wall tank under the effect of the baffles. The distribution of density, velocity, and pressure will be analysed with and without a baffle. The significance of this study could be helpful to understand the actual physical phenomena and study the behavior of liquid under the effect of excitement load using UDF in the ANSYS program.

2. Physical Model

In this research, a moving vehicle is a rectangular tank of 1.2 m and 0.5 m in length (L) and height (h), respectively. Fuel with physical characteristics of density (ρ) and viscosity (μ) 950 kg/m^3 and 0.0687 kg/m s, respectively, is partly poured into the tank. It is believed that liquid is immobile, opaque, uniform, and illogical. It is assumed that the boundary is rigid and that sloshing alone is responsible for the pressure variations on the wall—tank wall bending will affect the frequency of sloshing naturally. The location of the free liquid fuel surface within the tank is shown in Fig. 1 when the vehicle experiences external excitations [20].

Baffles were added within the rectangular tank to lessen sloshing and restrict the impact produced. The baffle is positioned within the tank parallel to the side wall and measures 0.02 m by 1 m.

3. Mathematical Formulation

This section provides a mathematical model and several liquid-sloshing solutions. The sloshing liquid flow and its free surface motion are included in the mathematical models. The governing equations for sloshing are solved using a well-known CFD method and VOF as the interface capture method based on phase fraction. The air-fuel contact and ensuing wave motion are tracked using the VOF model. The continuity, momentum, and phase equations are correspondingly stated in the following correlations [21–24]:

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

$$\rho u/\partial t + \nabla.(\rho u u) - \nabla.\tau = C\kappa\nabla\alpha - gh\nabla\rho - \nabla P_d \quad (2)$$

$$D\alpha/Dt = \partial\alpha/\partial t + \nabla.(\alpha u) = 0 \quad (3)$$

ρ is the density, u is the fluid velocity vector, τ is shear stress, C is the coefficient of surface tension = 0, κ is the curvature of the interface, α is the volume fraction, g is the gravity acceleration, h is the fuel depth in the tank, P_d is the dynamic pressure. The phase contact and free surface are monitored using shear stress. The two densities of fluids (ρ_1, ρ_2) can be estimated using the volume fraction as stated below

$$\rho = \alpha\rho_1 + (1-\alpha) \times \rho_2 \quad (4)$$

Eq. 5 can also be used to calculate the dynamic viscosity of the two fluids, (μ_1, μ_2), using the volume fraction.

$$\mu = \alpha\mu_1 + (1-\alpha) \times \mu_2 \quad (5)$$

The liquid quality per domain volume unit can represent the phase function coefficient (α). If α is 1, then liquid has filled the cell. However, if α is 0, the compartment is completely air-filled.

Eq. 6 is the analytical formula to predict the natural frequency of sloshing of the liquid [25]

$$\omega_0 = \sqrt{g\frac{\pi n}{L}\ \tanh\left(\frac{\pi n}{L}h\right)}, \qquad n = 1,2,3 \quad (6)$$

The frequency of excitation (β) is a dimensionless frequency, which can be expressed as the division of excitation frequency (ω) to the natural frequency

$$\beta = \frac{\omega}{\omega_0} \quad (7)$$

n is the mode number.

In the current investigation, the direction of sloshing runs parallel to the length of the tank, and the vertical work is conducted by simple harmonic oscillation with three dimensionless frequencies of β= 0.7, 0.9, and 1.2. The excitation amplitude is initially applied as A= 0.05 m, and the wave elevation histories periods along the tank wall are presented and analysed in the result section. The smooth waves can then be produced by setting the proper frequency and amplitude. The tank incentive is expressed in the following formula

$$x = A\sin(\beta\omega_0 t) \quad (8)$$

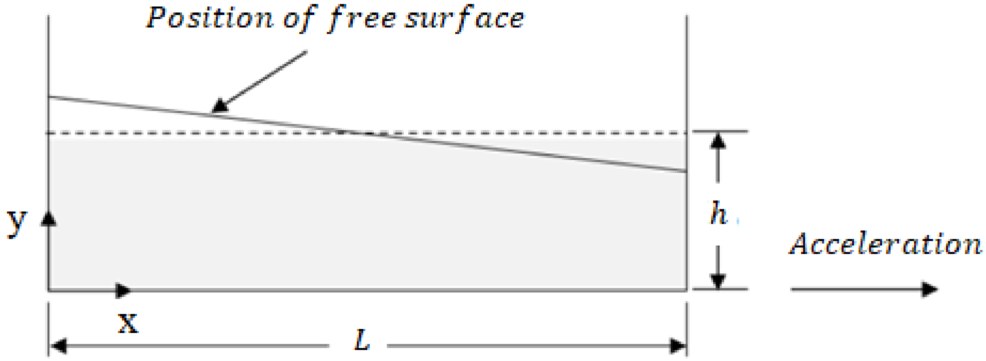

Fig. 1. Extension of liquid tank-free surface

4. Numerical Model

The basis solver is the CFD code Fluent 17.2, which is appropriate for solving compressible and incompressible fluid flows for Navies Stokes (NS) equations in both 2D and 3D as well as Reynolds Averaged Navies Stokes (RANS) equations. The fluid governing equations are examined and determined using the finite volume approach using the Fluent base solver, which then used RANS and the VOF methodology to follow the free surface movement. The body force weight scheme used pressure interpolation, and the second-order upward technique is used to discretize the momentum equation. Convection and diffusion fluxes across the faces of the control volume are calculated using the Pressure Implicitly with Sloshing Operators (PISO) method [26].

The function of the momentum source is incorporated into the x-momentum equations by utilising the macro of the UDFs in the software Fluent, which is utilised to apply the dynamic mesh approach to applying wave generation in the tank [27]. The grid size and temporal grid size had an impact on the computational findings for the instance of a no-slip boundary with smooth boundary conditions.

4.1. Procedure of UDF

The Fluent program can import user-defined functions (UDF) to give the common functions. The beginning circumstances, boundary conditions, or material attributes employed in a particular issue can all be specified. The UDF is written in the C programming language using visual express compilers. The Fluent program [28, 29] can successfully design several sorts of macros that can be applied in UDF code, including macros that describe liquid flow in tanks.

4.2. Validation of the numerical method

The numerical approach is validated by investigating the CFD's ability to predict the dynamics of the fluid-free surface under external excitations in the moving container. Using the same sloshing model as presented in [30, 31], the experimental findings are compared against the CFD results in terms of fluid flow visualization. The tank is filled to 80% capacity for the experiments. For the same fill levels, numerical predictions are also made for the liquid's free surface elevation profiles. Figs. 2 and 3 show the time histories of the height of the open surface at the tank wall as it reaches its maximum height with and without baffles, respectively. The CFD and experimental findings are found to be in excellent agreement.

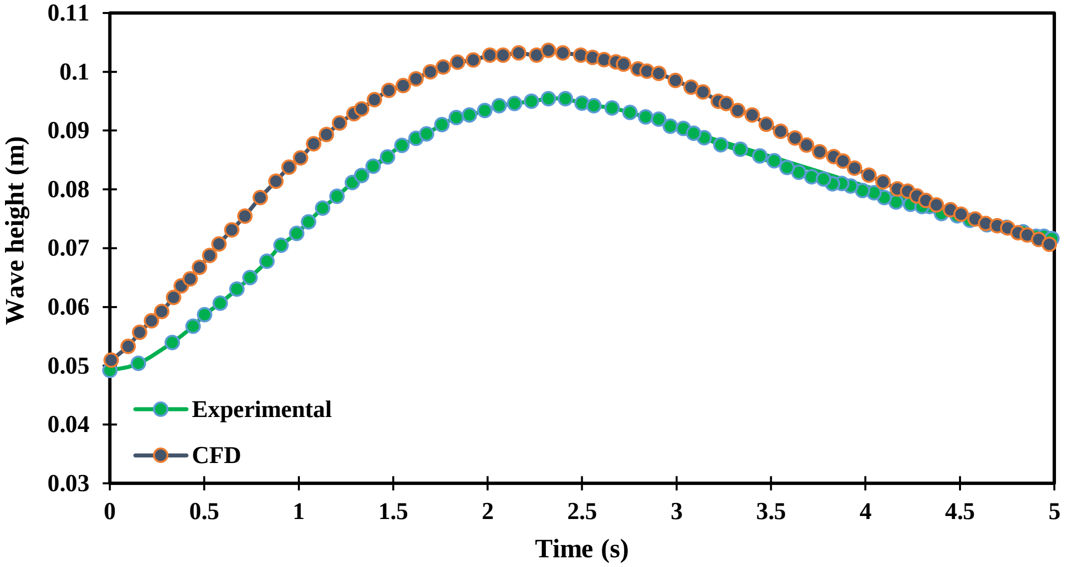

Fig. 2. Right wall tank liquid surface elevation without baffle

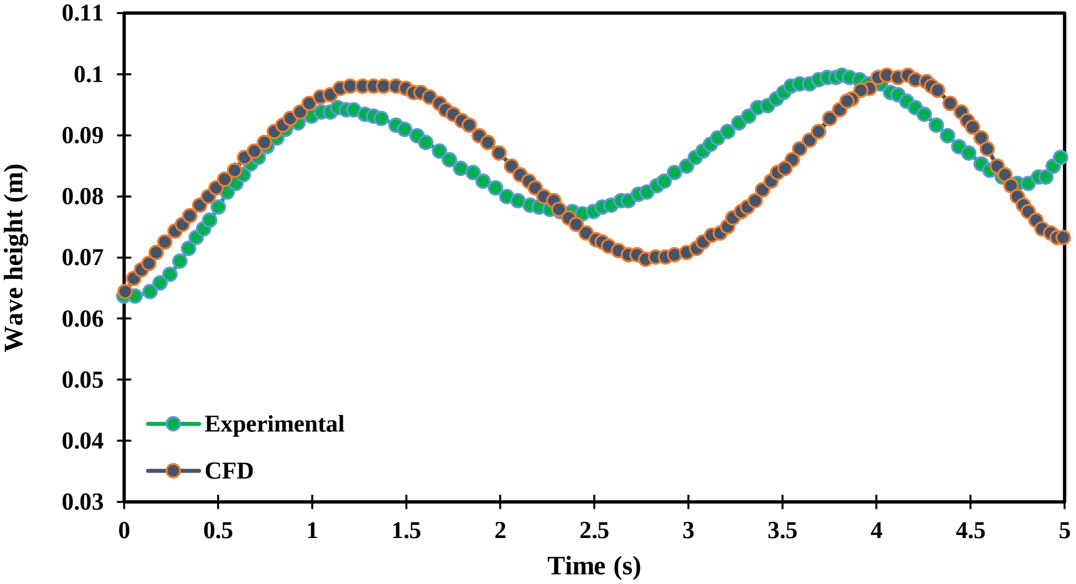

Fig. 3. Single baffled tank liquid surface elevation at the right wall

5. Results and Discussion

This section introduces the results of the interaction between fluid and structure in partially filled fluid tanks. Specifically, the intention is to focus on presenting the sloshing phenomenon and the estimated pressure that is put on the baffle via the analysis of finite elements. It should be noted here that sloshing has an influence on the anchoring point forces and the amplitude of the sloshing wave. To simulate the impulsive pressure that is magnified by the wall and the sloshing effect, the phenomenon of coupling was used. The supplied data generate pressure distributions as well as graphs that demonstrate how the pressure at the tank baffle varied over time. Indeed, the software ANSYS Fluent is used to conduct the simulation.

5.1. Contours of density, velocity, and pressure

Eighty percent of the tank is full with two liquids of benzene and gasoil, which is referred to as the filling ratio. Using the ANSYS, Fig. 4 shows the reconstructed free surface location of benzene using the VOF approach. This position is shown as the density of benzene during the excitation. The liquid is returning to the tank via both the back and front walls, according to the findings. Because the liquid rises just a short distance, it will eventually return to its original free surface. However, there is no substantial pressure coming from the surface, implying a negligible impact on the tank's walls. As a result, the threat posed by the sloshing action is overlooked.

Figs. 4 and 5 illustrate the interaction between benzene (red region) and air (blue region) in the wave tank for 2 seconds. This interaction demonstrates the capability of the proposed numerical model to produce regular waves.

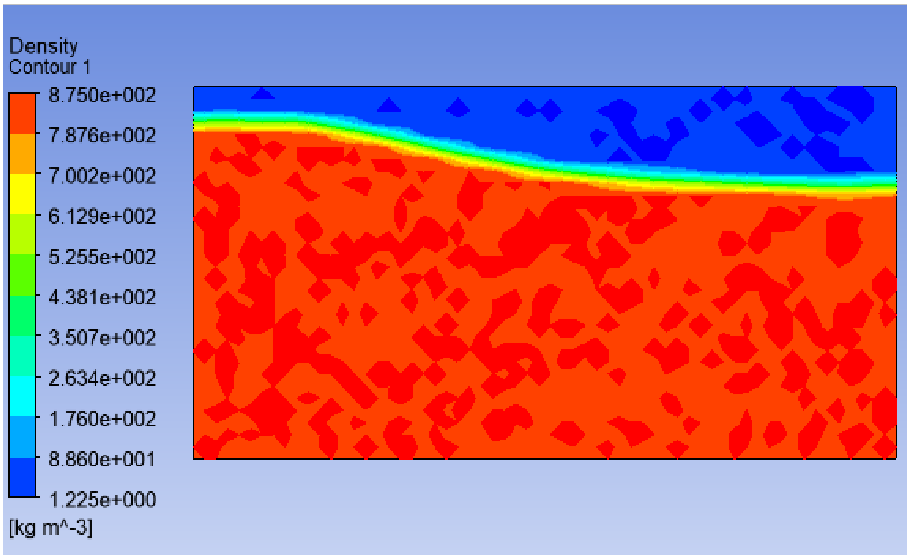

Fig. 4. Benzene density contour without a baffle

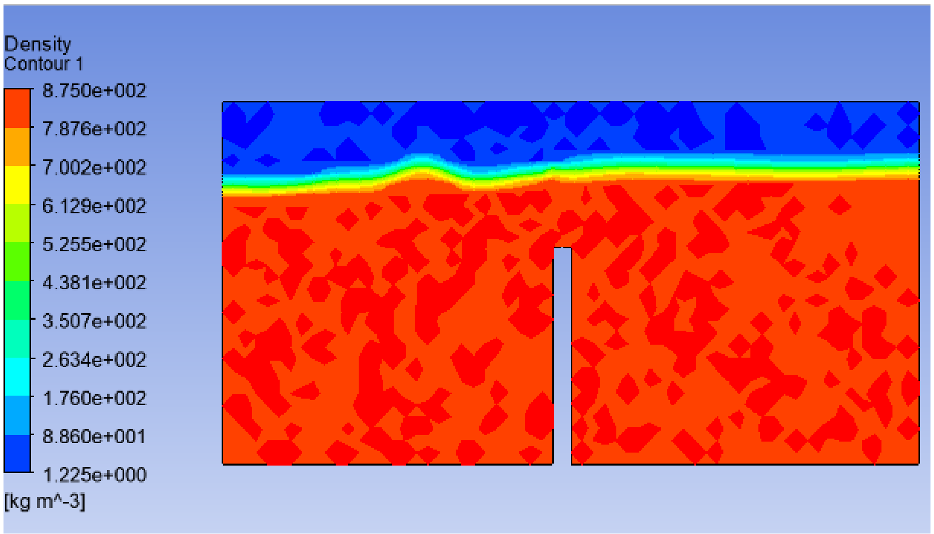

Fig. 5. Benzene density contour with a baffle

Fig. 6 depicts the velocity vectors and associated fluid flow direction. During excitation, benzene causes air to travel in its direction. A circulation area is created, deformed, and moved irregularly in the tank. Unlike the first tank without a baffle, the fluid behaves similarly in an additional tank with a baffle (Fig. 7).

Figs. 8 and 9 depict the contour of pressure distribution on the wall tank in two scenarios: with and without a baffle. Indeed, in the case of a tank equipped with a baffle, it is conceivable to conclude that the pressure value has decreased due to a decrease in kinetic energy.

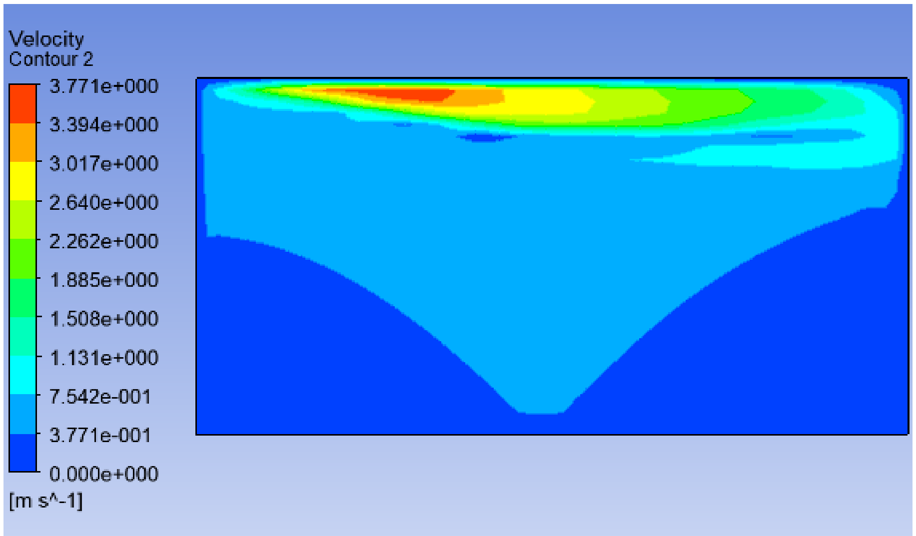

Fig. 6. Benzene velocity profile without a baffle

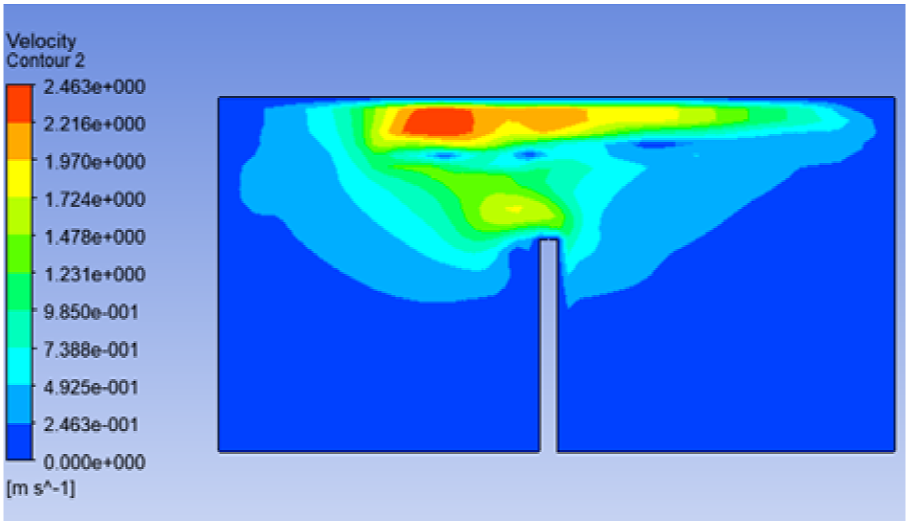

Fig. 7. Benzene velocity profile with a baffle

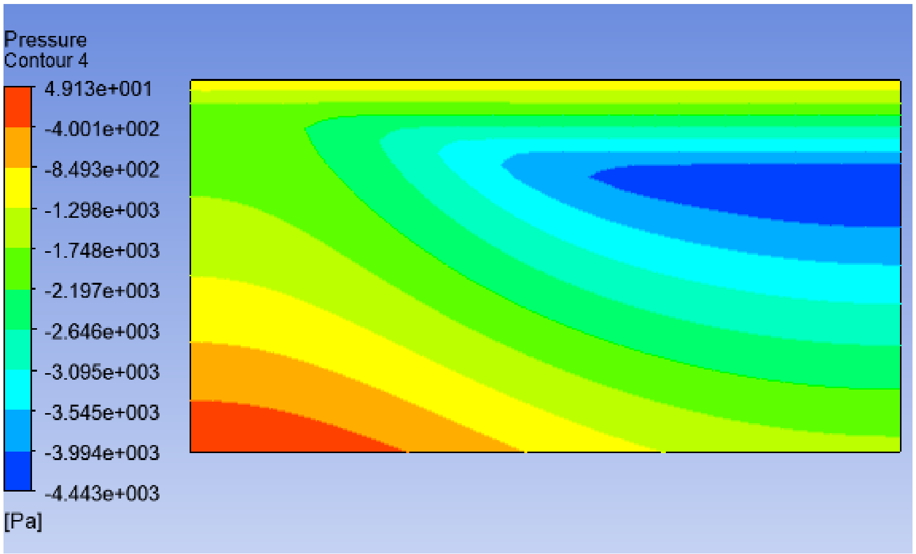

Fig. 8. Benzene pressure contour without a baffle

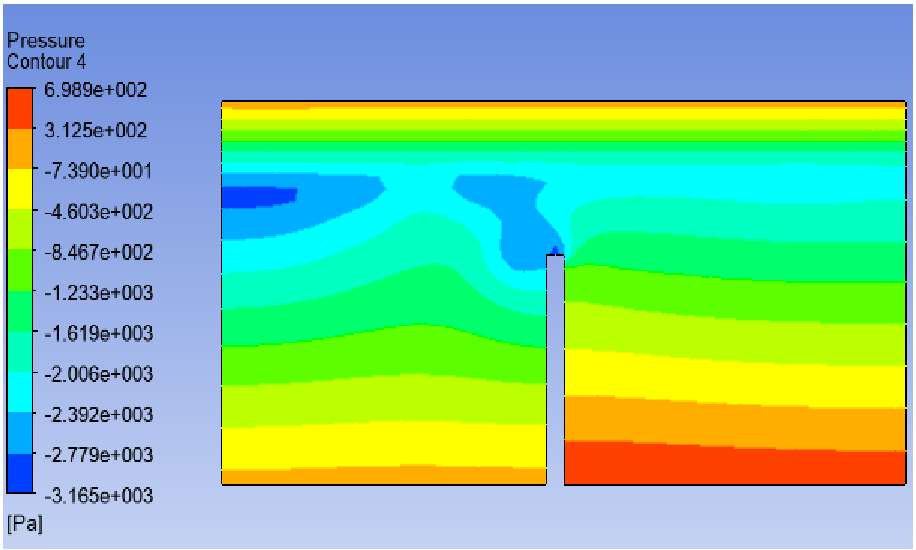

Fig. 9. Benzene pressure contour with a baffle

5.2. Evaluation of time histories of the velocity for both baffled and un-baffled tanks

Baffles are installed in the tank to absorb the kinetic energy of the liquid and inhibit the motion of the wave and therefore limit the liquid sloshing of a partially filled tank. The height of the vertical baffle is responsible for affecting the height of the liquid-free surface in the level that is only half filled.

Figs. 10 and 11 show, respectively, the velocity and pressure that are being exerted on the wall of the tank. The use of baffles demonstrates that the motion of the free surface waves is constrained, and this results in a reduction in the characteristic's length. This in turn results in a reduction in the amplitude of the free surface motion. Because of the usage of vertical baffles, over 20% of the maximum effect of pressure is minimized. Because of their sharp edges, baffles can induce turbulence and vortices, causing violent energy to be reflected and the fluid to be unable to ascend.

5.3. Evaluation of time histories of the pressure and velocity for the benzene and gasoil

Fig. 12 illustrates the pressure distribution along the tank wall while holding various liquids (benzene and gasoil, respectively). It is possible to notice that the pressure is different at the wall of the tank. This is because the density of the liquid is not consistent throughout the tank, which affects how pressure is distributed. The same pattern can be seen with the velocity distribution in Fig. 13.

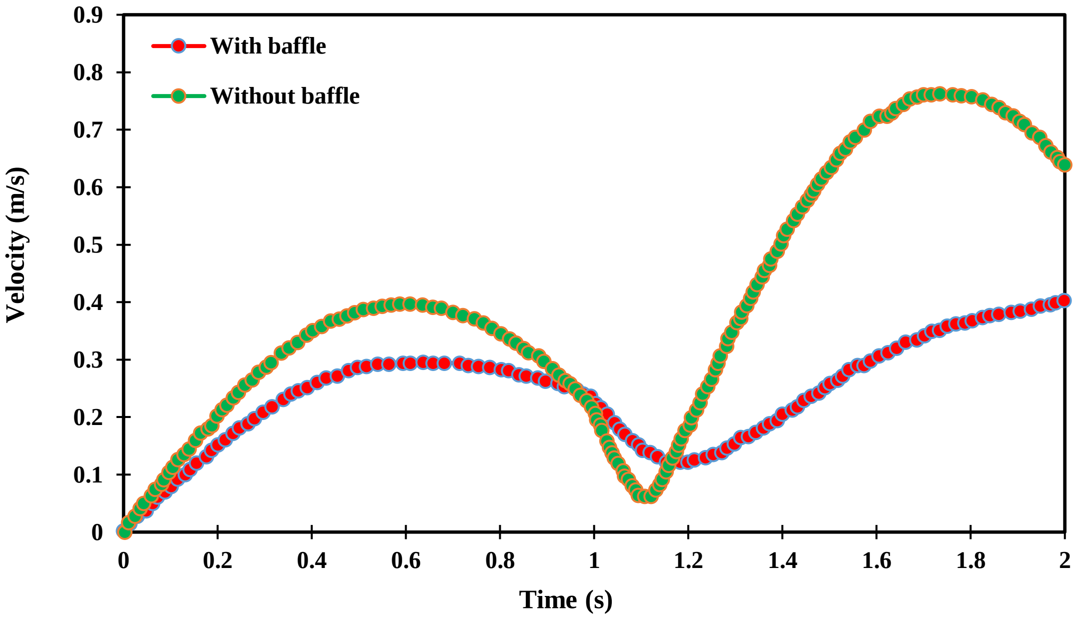

Fig. 10. Comparison of baffled and un-baffled tank velocity time histories

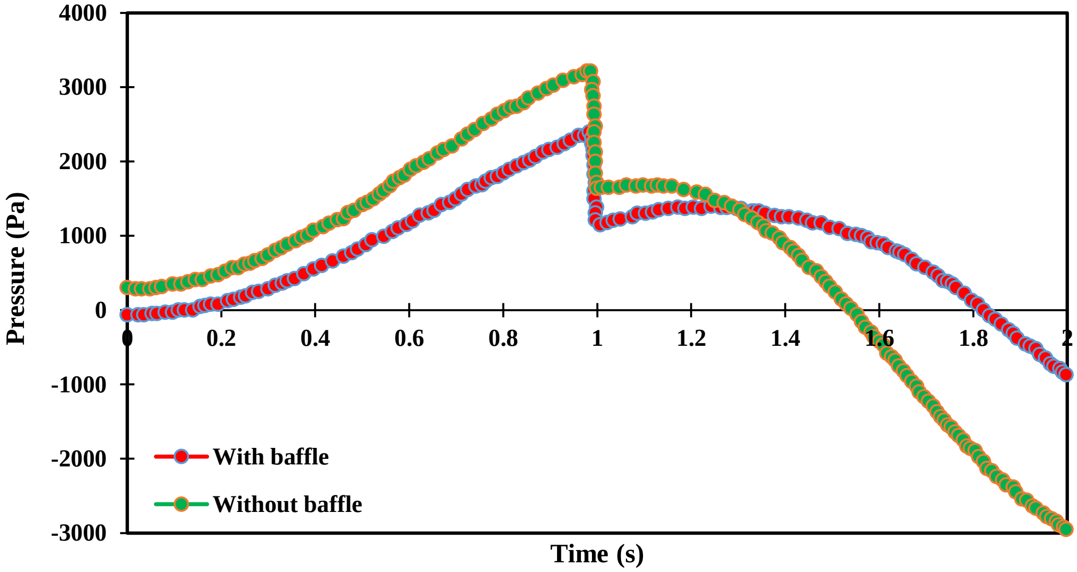

Fig. 11. Comparison of pressure time histories for baffled and un-baffled tanks

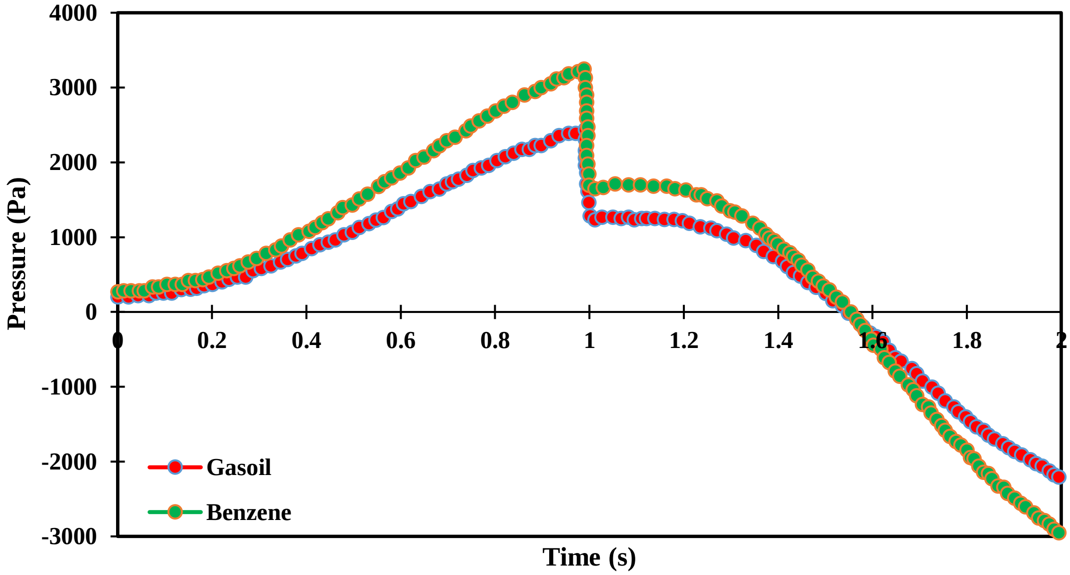

Fig. 12. Benzene and gasoil pressure time histories

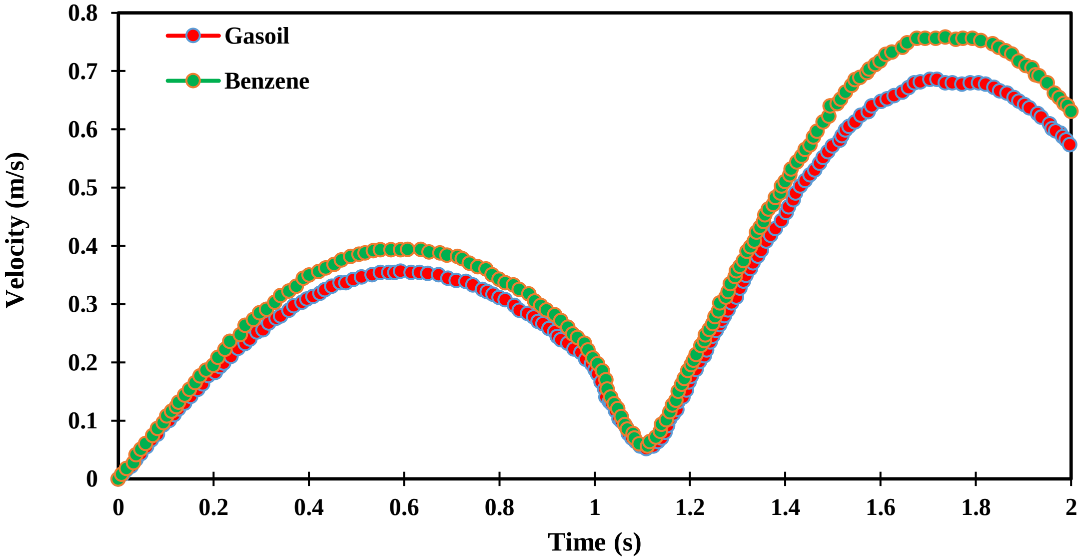

Fig. 13. Benzene and gasoil velocity time histories

6. Conclusions

The current study focused on liquid sloshing in rectangular tanks under external excitations. A system coupling was employed to integrate the solid and fluid domains. The dynamic mesh approach was used for mesh renewal after the success of the two-dimensional numerical tank with baffles. According to the contour of pressure distribution on the wall tank with and without a vertical baffle, the pressure value was lower due to a decrease in kinetic energy when a baffle was used. More importantly, vertical baffles can reduce approximately 20% of the maximum impact pressure.

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