Numerical study of the liquid sloshing in the cylindrical tank with baffles

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Abstract. Many kinds of dangerous chemicals, like liquefied natural gas etc., are stored or transported in liquid state by pressure vessel. Liquid sloshing will occur in many scenarios such as during the geological disasters, and the transit operations. Sloshing might lead to large deformation or even damage to containers, causing serious safety threats. In this study, the sloshing phenomenon in a cylindrical tank with four baffle shapes are investigated. The volume-of-fluid (VOF) method is used to track the distorted and broken free surface. Fluid movement phenomenon in tank with different baffles is observed. The effect of four different baffles shapes is compared, impacting force on tank and baffle walls which induced by liquid sloshing is analyzed. Baffles openings affect the impact forces on the tank and baffle walls. More number of baffle orifices, liquid distribution is more even in sections of the tank. Maximum force value of y direction occurs as the liquid climbs up the tank ceiling. Reasonable number and position of baffle openings can increase the stability of the tank during driving. For this simulation method, more validation with experimental data is necessary, the same size of tank and four baffle shapes will be tested on the shaking platform.

1. Introduction

Liquid sloshing in partially filled tanks is widely observed during the pressure vessel, which might lead to large deformation or even damage to containers, causing serious safety threats[1-2]. When the frequency of the external excitation nears the natural frequency of the fluid in the tank or the amplitude of the excitation is very big, a violent vibration may occur and a large impact pressure on the tank will cause structural damage. Baffles inside the liquid tanks are effective to prevent violent free surface fluctuation [3].

Many researchers investigate the liquid sloshing in a baffled tank theoretically, experimentally and numerically. Miles [4] analyzed the damping caused by a ring baffle via analogy to the drag force that a flat plate exerts on an oscillatory flow. Laura Battaglia [5] numerically and experimentally studied three-dimensional sloshing problems, presented data obtained from a forced sloshing experiment that are specifically devoted to 3D free surface behaviour. Liting Yu [6] experimentally investigate of parametric sloshing in a tank with vertical baffles. Y.kim [7] simulated sloshing flows with impact load, a concept of buffer zone seems to be very useful when the fluid generates an impulsive pressure on the tank ceiling.
Baffle with orifice can allow the lower surface liquid to pass through, thus attenuating the impact forces on the baffle. Younes [8] conducted an experimental study of the hydrodynamic damping provided by using vertical baffles with orifice in partially filled rectangular tanks; they pointed out that the size, location, number, and drilling holes of the vertical baffle significantly influence the hydrodynamic damping. Panigrahy [9] developed a slosh experimental setup with a degree of freedom (DOF) of horizontal motion to estimate pressure distribution on tank walls and surface elevation variation in a tank with drilled orifice baffle. Mi-An Xue [10, 11, 12] simulated sloshing phenomena in tank with multiple baffles.

Due to the vortex generated in the fluid, even the baffle can reduce the sloshing effect by dissipating kinetic energy, but the damping mechanism of the baffle is not fully understood. The shape of the baffle needs to be designed using numerical model simulation or experiment. The study of liquid sloshing in storage tanks with baffles is still necessary.

A numerical model with CFD has been developed to study three-dimensional (3D) liquid sloshing in a tank with vertical baffles. The volume-of-fluid (VOF) method is used to track the distorted and broken free surface. The effects of four different baffles shapes are compared and analyze force induced by liquid sloshing. Study different baffle shapes give useful reference to designer.

2. Physical model
Model tank and four type baffles show in fig1. Length of the cylindrical tank is 1.2m, and diameter is 0.5m, thickness of the baffles is 6mm, distance between two baffles is 0.4m. The space in tank is divided into three connected parts. Vertical distance from the center of tank model section to bottom edge of baffle is 0.16m, diameter of center opening hole is 0.1m.

When a tank is partially filled with liquid, sloshing is prone to occur under external accelerations[13]. In this study, Initially the tank is static, and then 0.2g acceleration along Y-coordinate lasts 1s, remove acceleration, tank model drives at a constant speed.

3. Solution setting
About 915460 polyhedral cells are generated by using Fluent Meshing for the whole geometry. For the transient calculation of the fluid domain, the direction of gravity is the positive direction of the X coordinate. VOF method is applied. The turbulence model is Realizable k-ε, the SIMPLE algorithm for the velocity-pressure coupling, and the pressure in the discrete format is PRESTO.

The Volume of Fluid (VOF) technique is employed for tracking the interface between the two fluid (air and water) during simulations. The governing transport equation for the phase fraction ($\alpha$) is

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

Where, $\alpha$ represents the volumetric fraction between air and water, which is taken as 0 for air, 1 for water and in between 0 and 1 at the interfaces.
4. Results and discussion

4.1. Liquid sloshing in baffled A tank with time series
The simulation results of two phase distribution on cross section and free surface at the 0.2s, 0.5s, 0.6s, 0.8s, 1.0s of moving tank with 0.5 liquid filling ratio show in Fig2, as 50% of the tank space is filled with water and the constant acceleration. It can be seen the liquid in the tank changes the flow direction, and air moves from top of the tank to bottom. The sloshing water hit the ceiling of the tank between 0.5s and 0.6s. The sloshing contains broken free surface and strong turbulence, plunging wave is formed that generates many water droplets when the free surface is tiny broken.

![Fig. 2 Two phase distribution on cross section and free surface at the 0.2s, 0.5s, 0.6s, 0.8s, 1.0s of moving tank with baffle A](image)

4.2. Liquid sloshing in baffled BCD tank at 0.5s and 0.6s
From Fig.3, the comparisons of two phase distribution on cross section and free surface at 0.5s, 0.6s of moving tank with baffle B, C and D. It is shown that the effectiveness of different baffles on reducing liquid sloshing amplitude is no apparent difference in this small tank model. More number of baffle orifices, medium distributions are more even in sections of the tank.

![Baffle B at 0.5s, Baffle C at 0.5s, Baffle D at 0.5s](image)
Fig. 3 Two phase distribution on cross section and free surface at 0.5s, 0.6s, of moving tank with baffle BCD

4.3. Impact force on the tank wall and baffle wall

Fig. 4 shows the time histories of force along y direction on walls, which are tank rear head, front head, baffle1-1 wall, baffle1-2 wall, baffle2-1 wall, baffle2-2 wall. It can be seen from the figure when the tank starts to move, an acceleration of impulse exists, it can be clearly seen that the force along Y axis on the tank wall maintain small, and then increases in negative y direction, and then rapidly reaches a maximum value in positive y direction as the liquid climbs up the tank ceiling. The impact forces decline to zero range later. The time for the maximum force acting on rear head, front head, baffle 1-1 and baffle 2-1 is relatively consistent, all around 0.55s, and they increase and decrease sharply in an instant. The maximum force on baffle 1-2 and 2-2 occurs before the liquid reaches the top of tank, and the direction of the force changes about 0.55s. According to the force analysis in the fig.4 that the comprehensive force of baffle C is relatively small.

Perfected baffle depends upon the orifice size, number, location and excitation frequency, baffles openings affect the impact forces on the tank and baffle walls. Reasonable number and position of baffle openings can increase the stability of the tank during driving.
5. Conclusions
In this study, three-dimensional characteristics of sloshing in cylindrical tank with four baffle shapes are analyzed. The volume-of-fluid method is used to track the distorted and broken free surface.

More number of baffle orifices, liquid distribution is more even in sections of the tank. Maximum force value of y direction occurs as the liquid climbs up the tank ceiling.

Perfected baffle depends upon the orifice size, number, location and excitation, comparison of baffle shapes effects give useful reference to pressure vessel designer.

For this simulation method, more validation with experimental data is necessary, the same size of tank and four baffle shapes will be tested on the shaking platform. Moreover, the simulation should be extended to more complicated tank geometry and baffles.

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References
[1] Faltinsen, O.M., Timokha, A.N., 2009. Sloshing. Cambridge University Press.
[2] Ibrahim, R.A., 2005. Liquid Sloshing Dynamics: Theory and Applications. Cambridge University Press.
[3] Ibrahim, R.A., 2005. Liquid Sloshing Dynamics: Theory and Applications. Cambridge University Press, New York, USA.
[4] J.W. Miles, Ring damping of free surface oscillations in a circular tank, Journal of Applied Mechanics. 25 (1958) 274–276.
[5] Laura Battaglia, Mareela Cruchaga, et al. Numerical modelling of 3D sloshing experiments in rectangular tanks [J].Applied Mathematical Modelling,2018,7,59: 357-378.
[6] Liting Yu , Mi-An Xue. Experimental investigation of parametric sloshing in a tank with vertical baffles. Ocean Engineering.213.2020.
[7] Y.Kin, Numerical simulation of sloshing flows with impact load. Applied Ocean Research. 2001, 23:53-62
[8] P.K. Panigrahy, U.K. Saha, D. Maity, Experimental studies on sloshing behavior due to horizontal movement of liquids in baffled tanks, Ocean Engineering, Volume 36, Issues 3–4,2009
[9] Younes Beygi Khosrowshahi, Ali Baradar Khoshfetrat, Zahra Abolghasemi, Karim Shams Asenjan, Performance evaluation of a proliferation chamber with external stirred conditioning tank for expansion of a suspendable stem cell model, Process Biochemistry, Volume 50, Issue 7,2015, Pages 1110-1118.
[10] Mi-An Xue, Pengzhi Lin, Numerical study of ring baffle effects on reducing violent liquid
sloshing, Computers & Fluids, Volume 52, 2011.

[11] Mi-An Xue. Numerical Simulation of Sloshing Phenomena in Cubic Tank with Multiple Baffles. Journal of Applied Mathematics. 2012.

[12] Mi-An Xue, Yichao Chen, Jinhai Zheng, Ling Qian, Xiaoli Yuan, Fluid dynamics analysis of sloshing pressure distribution in storage vessels of different shapes, Ocean Engineering, 192, 2019.

[13] Dongming Liu, Pengzhi Lin. "Three-dimensional liquid sloshing in a tank with baffles", Ocean Engineering, 2009.