Numerical simulation of the influence of baffles on the impact force of heavy-duty tanker

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Abstract. The impact force of heavy-duty tanker is simulated and analyzed under liquid sloshing. Based on the finite volume method, the free liquid level capture technology (VOF) is used to establish a numerical calculation model for the sloshing analysis of heavy liquid tank trucks. FLUENT, a fluid simulation software, is used to simulate the impact of liquid on the front head of liquid tanker when the braking acceleration is 0.981 m/s², and the filling ratio is 0.5. The influence was studied that the number of rectangular baffles brings the changes of the impact force of the front head of the liquid tanker. The research provides a reference for the optimization design of baffles in heavy oil tanker manufacturers in the future and also validates the rationality of baffle set in the latest national standards.

1. Introduction

With the development of China's economy, the demand for cargo transportation is growing. There are many flammable liquids which are highly corrosive, and 80% of the liquid cargo is transported by road tankers [1]. Due to the heavy load and low cost of liquid tanker transportation, the Chinese market will become the largest growth market in the world by 2020 [2]. Heavy-duty vehicle containers are commonly used for liquid cargo transportation. They are usually made of carbon steel, and they can also be made of FRP, stainless steel, etc., but they must have a certain material strength. According to the standard of "Safety Technical Supervision Regulations for Pressure Vessels", liquid tankers are classified as III pressure vessels, the most dangerous type [3]. Because of the danger of transporting goods, once a leakage accident occurs in the transportation project, it is easy to cause major property damage, environmental pollution which may even threaten personal safety. The sloshing of the liquid has the greatest impact force on the tanker during the braking and starting of the tanker. Installing baffles are an effective method. The sloshing of the liquid is a complicated liquid movement process, which has a great influence on the safety of the vehicle.

Along with the extensive use of vehicle containers, domestic and foreign researchers have conducted a series of studies on the sloshing of liquid during driving. Domestic researches on vehicle-mounted containers can be traced back to the Arbitrary Lagrange-Euler equation derived by
Zhaolin Wang [4] a Professor of Tsinghua University, which is used to describe the relationship between fluid mechanics equations and kinematics. It has a great reference value for the study of liquid sloshing. Xiaodong Wang [5] simulated the dynamics of the tanker semi-trailer vehicle model. When the liquid filling coefficient is 0.5, the stability of the vehicle is the worst when turning. Also, Vaibhav Singal [6] found that the shunting phenomenon caused by the baffle is the main reason for the liquid to weaken the impact force of the container.

In summary, although there are many references on sloshing analysis and the driving stability of the tanker, there are few studies on the sloshing effect of liquid containers with the different number of baffles. Therefore, this paper focuses on the anti-sway effect of the number of baffles of heavy-duty liquid tankers on the braking process. Under the premise of liquid sloshing analysis, the heavy-duty liquid tanker is simulated and analyzed under the braking condition by establishing the actual heavy-duty tank truck model and the common rectangular baffles model. By comparing the impact of liquid sloshing on the impact force of the front head during the braking process of the tanker with different numbers of baffles, the reasonable number of baffles is obtained.

2. Comparative analysis of theoretical and numerical models

To verify the accuracy of the method, a cylindrical tank is established that has both experimental and analytical solution [7]. For cylindrical tanks, the calculation method of the natural frequency of internal liquid sloshing is generally based on the traditional linear theory formula [8], as is shown in equation (1).

\[ f_{mn}^2 = \frac{g\lambda_{mn}}{R} \tanh\left(\frac{\lambda_{mn}}{R} h\right) \]  

\( f_{mn} \) is the nth natural frequency of the cylindrical cavity liquid, where R is the radius of the cylindrical cavity. \( \lambda_{mn} \) is the root of the first derivative of the Bessel function, m and n are positive integers (representing the modes along axial and radial directions, respectively frequency number). h is the filling depth. The tank body has a radius of 2000 mm and a height of 4000 mm. The liquid filling ratio is \( h/H \). The structured grid is divided into tank fluid domains with a total of 95,800 elements. The cylindrical tank body satisfies the condition of rigidity and non-deformation. Internal liquids are air and water phases. The liquid is initially stationary. At \( t = 0s \), the liquid begins to accelerate with \( a=2m/s^2 \) for 0.5s. Then the liquid begins to slosh freely at its natural frequency. Fig. 1 is the curve of the impact force of the wall surface of the cylindrical cavity and Fig. 2 is the frequency map which is obtained by fast Fourier transform.

**Figure 1.** impact force changes at \( r=0.25 \).

**Figure 2.** Free sloshing frequency at \( r=0.25 \).
The first-order sloshing frequency of the liquid calculated by equation (1) is compared with the numerical solution calculated by numerical simulation. The comparison results are listed in Table 1:

| Filling ratio r | Theoretical solution | Numerical solution | Relative error |
|----------------|----------------------|--------------------|---------------|
| 0.25           | 0.408                | 0.385              | 5.6%          |
| 0.5            | 0.466                | 0.439              | 5.8%          |
| 0.75           | 0.476                | 0.440              | 7.6%          |

Since the maximum error is less than 5.8%, it can be assumed that the model settings and calculation settings are correct.

3. Simulation analysis of liquid sloshing of heavy liquid tanker

3.1 Liquid tanker model establishment A subsection

A heavy-duty tanker is taken as a typical research object with parameters as follows: tanker length 10500mm, front-end length 3000mm, rear end length 6500mm, front end diameter 2000mm and rear end diameter 2200mm. The wall thickness is 10mm, the material is steel, and the filling liquids are water and air. The baffle adopts the common rectangle baffle on the market, whose area accounts for 56% of the cross-sectional area.

3.2 Grid model and solution settings

The total number of elements is 1034337, and the number of nodes is 2130623. Fig. 3 is the tanker model and Fig. 4 is the 50% filling ratio model. VOF method is used to track free surface. The basic variable pressure is located at the center of the element and velocity is located at the surface of the element. The conservation equation is solved by a linear discrete separation method. The momentum equation is discretized by the second-order upwind model and volume weighting method. The boundary conditions are non-slip boundary conditions and wall boundary conditions. The tanker is assumed to be a rigid body, and the liquid phase is divided into water and air. For ease of calculation, the first phase is a gas phase and the second phase is the water phase (Fig. 4). The working conditions are set to withstand gravity acceleration and braking acceleration (9.81m/s²) and last for 2 seconds. The iteration step is 0.0001s.

![Figure 3](image1.png) **Figure 3.** Liquid grid model of liquid tanker.

![Figure 4](image2.png) **Figure 4.** The mixed model of liquid filling ratio of 0.5.
3.3 Influence of the number of baffles on the impact force of the front head

Table 2 shows the impact force data of the front head of the tank car with different numbers of baffles.

| Number of baffles | Maximum impact force(KN) | Time(S) |
|-------------------|---------------------------|---------|
| 0                 | 937                       | 0.86    |
| 2                 | 758                       | 0.47    |
| 3                 | 806                       | 0.47    |
| 4                 | 656                       | 0.47    |
| 5                 | 643                       | 0.46    |
| 6                 | 703                       | 0.47    |

Comparing whether there are baffles, the maximum impact force is obviously reduced, but the maximum impact force is not reduced as the number of baffles increases. It is found that the maximum impact force of tank with five baffles is the smallest and the maximum impact force is reduced by 293,616 N, which is lower than that with no baffle by 31.4%. The volume of the heavy-duty liquid tanker is 40 m³ in this paper. According to the national standards, the volume between baffles can be increased to 7 m³ because the tanker is larger than 25 m³. The volume between baffles is 6.67 m³ when five baffles are installed. The results verify the rationality of the national standards.

![Fig. 5](image-url)  
(a) impact force changes at n=0 2 3 4 5 6  
(b) impact force changes at n=0 5

**Figure 5.** Comparisons of Impact Forces on Front Heads of the Different number of baffles.

Fig. 5 shows the fluctuation of the impact force of the front head of different number baffles. Comparing the impact force of five baffles with no baffle, for tank with no baffles, the time is 0.83s (the time point is from 0.65s to 1.48s) that the force exceeds the 300KN, the time is 0.53s (from 0.72s to 1.25s) that the force exceeds the 400KN; for the tanker with five baffles, the time is 0.30s (the time point 0.44s to 0.58s, 1.56s to 1.72s) that the force exceeds 300KN, and is lower than the force of no baffle by 64%; the time is 0.09s (time point from 0.44s to 0.53s) that the force exceeds 400KN, and is less than the force of no baffle by 83%. It is easy to find that the installation of the baffles can greatly reduce the impact force caused by the liquid on the front head of the tanker. Through comparison of the impact force of the five-baffle tanker and the six-baffle tanker (Fig. 5 (a)), the former is stronger than the latter before the first isolation chamber is filled. The reason is that the six baffles have the more ability to prevent the liquid of the tanker to flow to the front of the tanker. The secondly liquid forms the superposition effect. The superposition effect of the secondly liquid of the tanker with six baffles is stronger than the liquid of the tanker with five baffles. This is the reason why the maximum impact force of the latter is greater than the former.
Fig. 6(a-f) show the liquid phase of the five baffles and the liquid phase of no baffle. For the tanker with five baffles, it can be seen that the baffles have a significant flow blocking effect (Fig. 6(a)), and the baffles buffer the impact of the liquid on the front head by the shunting. It can be observed from Fig. 6(e) that all the liquid has flowed to the front when the time is 0.86s. This time coincides with the maximum impact time of the tank car with no baffle at 0.86s. At 2s, all the liquid flows to the front of the tanker in the tank truck whether there are baffles. By analyzing and comparing the impact force of the front head of a tanker with five baffles and with no baffle (Fig. 6 (a-f)), the impact force of the front head of a tanker with five baffles is greater than that of the front head with no baffle because the liquid continues to flow to the front of the tank in the tanker with five baffles after 1.56s (Fig.5 (b)).

4. Conclusion
The maximum impact force is significantly reduced when the baffles are installed. The maximum
impact force does not decrease with the increase of the number of baffles because of the impact superposition of the diversion fluid. Installing a reasonable number of baffles can greatly shorten the duration of larger impact force and reduce the maximum impact force. The baffle reduces the impact of the liquid on the front by shunting. Therefore, the installation of a reasonable number of baffles can improve the safety of the fuel tank and the driving stability of the tanker.

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