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Optimal Baffle Design for Kuwait's Next-Gen Hydrocarbon Truck Tanks to Minimize Internal Wave Formation

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***Abstract* -** This research paper is concerned with the phenomena of internal wave formation or in other words internal sloshing inside liquid vessels, such as tanker trucks during any change of velocity. The paper has started by clarifying the importance of such topic regarding Kuwait as an oil industry that depends on constant transportation of fossil fuel derivatives. Notably, this isn't isolated to fossil fuel, but farming sectors depend on constant transportation of water via tankers to provide ground irrigation for crop production. Also, this report has illustrated the adverse effects of improper mitigation and safety standards for transporting liquids as the internal fluid will constantly shift under and acceleration. Effectively under emergency breaking the force of the liquid and stored momentum will adversely impair braking distance and leads to change of centre of mass in case of making turns. Moreover, the first step of this project is to effectively study the problem at hand by defining existing outcomes that could have been avoided with proper mitigation methods as to protect the driver, public and environment. Continuing, the goal of this research is to study current design in Kuwait and conduct a case study to see the effects of altered baffle geometry. This paper initiated its design process by validating its CFD software via an existing academic paper to reproduce its results prior to conducting field visits to manufacturing sectors in Kuwait. The goal was to obtain an initial benchmark design to create in SolidWorks Flow then iterate the internal baffles design and obtain improved results. Where the final designs illustrated an improvement up to 83.4% for dynamic pressure. This paper has started to conclude that more design is desired to further reduce internal sloshing and improve safety as existing constraints of time and prior knowledge on this topic.

***Keywords*:** Kuwait oil and gas, Sloshing, Optimal design, Baffle Systems, Oil transportation, Tanker trucks.

1. Introduction

Kuwait as an oil industry relies heavily on liquid transportation for its primary resources and for outward exports. The use of truck tanks as transportation method is very crucial to transport large amounts of oil across the country [1]. Fuel oil transportation in Kuwait faces a unique challenges and factors like Kuwait's climate, road system, traffic patterns, and transportation regulations. Understanding these elements is essential to creating solutions to reduce internal fuel sloshing and improve tanker truck operations safety. There are numerous reasons that contribute to truck accidents in Kuwait. The main two reasons are heavy braking, collision and rollovers. In august 2020, a fuel tanker truck carrying 36000 Liters of diesel rolled over and caught fire on Jahra Road [2]. Another rollover accident happened in March 2019 involving a gasoline truck tank on king Fahad road, and the driver suffered from injuries but there was no gasoline ignite [3]. A fatal collision in March 2025, resulting in the

Figure 1: Tanker truck rolled over in Jahra Road, Kuwait [2]

Figure 2: Wrecked sedan and damaged water tanker truck are seen following an accident reported at Wafra Road. [5]

causality of the driver [4]. Another collision in January 2017 of a water tanker truck and a sedan car on the Wafra road resulting in the death of the sedan driver and the injury of the truck driver [5-8].

To start, internal sloshing is an event that occurs due to movement of fluid that has free space in a bounded container after any change in speed [6]. Kuwait and many countries depend on liquid transportation that encompasses hydrocarbons, water, chemicals and food products throughout the country. Such aspect is vital for Kuwait due to the dependence on fossil fuels and notably for water tankers to reach agricultural sectors for ground aggregation and ensure food security is maintained. Firstly, to provide background on the topic of sloshing, in the middle of the 20th century specifically in the 1950s and 1960, sloshing liquid inside nearly filled tankers was majorly studied towards aerospace [7]. This was achieved by experimenting with different tank vessel geometries to examine the effects of internal wave formation on overall stability [8]. The studies evolved in the late 1970s, where researchers tried to determine the consequences of sloshing in nearly filled containers [7]. Hence, this paper will consider lowering the longitudinal slosh mainly due to current time constraints. However, lateral slosh can affect stability of the truck but is a future topic of research for this project.

Figure 3: Fuel tanker accident on Kuwait's Jahra Road in 2020 [10]

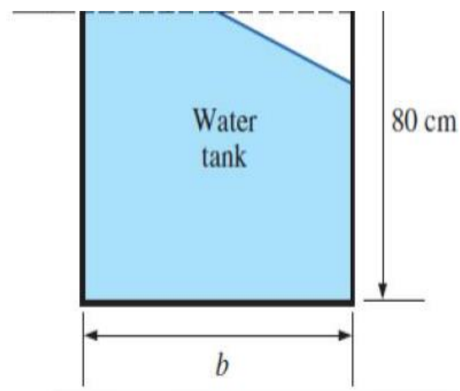

Figure 4: Illustrates how fluid rise occurs due to acceleration and is affected by base length [11]

2. Modelling and Analysis

Furthermore, during this project extensive background research was conducted and this encompassed many existing reports, academic journals and statistical data, as to provide a stable general foundation before pursuing further. Firstly, manual calculation is provided as example, where initial speed to be (90 Km/h) or (25 m/s) with 10 seconds for a complete stop. To obtain deacceleration value, its simply velocity is divided by time, (25 m/s/10s) and this translates to (2.5 m/s^2). The angle can be found by the below equation prior to being used in equation 2, (az) is taken as (0) on an ideal flat road.

$$Tan\theta = \frac{a_x}{g + a_z}, \rightarrow \qquad \theta = ArcTan\left(\frac{25}{9.81}\right) = 14.3^o \tag{1}$$

$$0.5 * \left(Base * Tan\left(\frac{14.3Pi}{180}\right)\right) = Liquid\ Rise. \tag{2}$$

Therefore, in theory if the container was sealed as a tanker or truck would have been and the liquid could only rise at Y distance, but the rise should be higher this would translate to increased forces on the struck wall. This can possibly compromise the integrity of the tank and cause issues such as losing control if the truck is steering. Essentially, this means decreasing the base will result in reduced rise and forces on the wall. This can be achieved in one way by incorporating baffles and compartments to have lower base length for each subsection and increase acceleration time, as to provide a gentler mass shift and reduced turbulent forces internally [9] & [12].

3. Simulation Model

Furthermore, the design of the simulation by Liquan Lu et al was based on water and a total of 500 iterations with a time step of 0.01s. Thus, giving out a total of 5 seconds of simulation with the tank design being a cylinder with a radius of (0.3m) and (1) meter length. The filling was varied between run but for the validation, this report replicated the design with 50% fill amount. Additionally, the case scenario was an acceleration pulse of $5m/s^2$ for a duration of (0.1s) in the lateral direction to study the toque on longitudinal direction. The design was strictly replicated in SolidWorks as per the information provided on the aforementioned paper. Notably, as shown in Figure 4, the simulation was conducted with the global goals in SolidWorks Flow being torque on (x-axis) and the acceleration on the (z-axis) with a total simulation time of (5s). The results were obtained and compared to the 50% results from the research paper. The below Figures 5 showcase the results obtained by Liquan Lu et al at time (0.3s) on their simulation and actual testing [14].

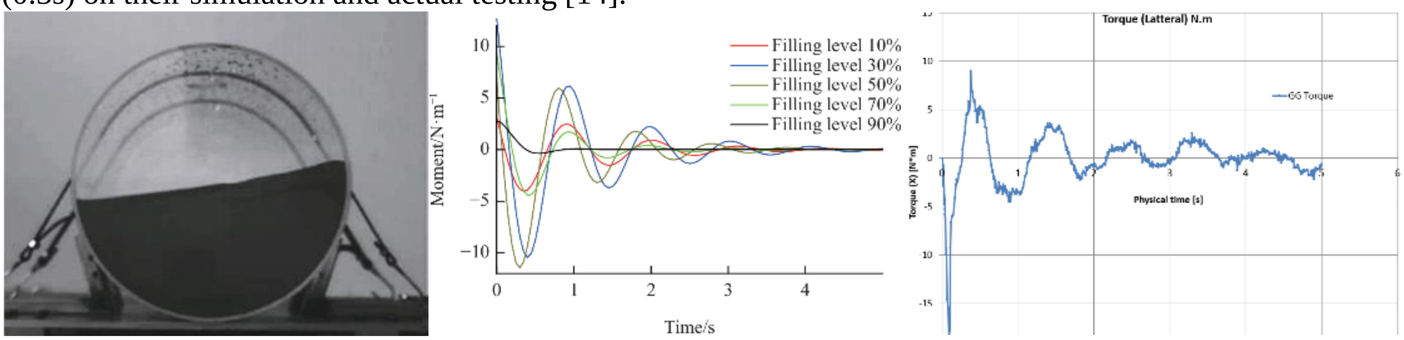

Figure 5: Physical test by Liquan et al at 0.3s, & torque graph (Right blue graph) Output obtained [14]

Continuing, the results obtained from our simulation have successfully replicated the positions of the flow at the same snapshot of time (0.3s) as the report being followed and with the same trend in the torque graph at 50% fill. Therefore, the results show that our software works as expected and will illustrate the results of incremental improvements in tank design.

Figure 6: the oil tanker benchmark with built in baffles, Mula company Kuwait.

A visit to the manufacturing sector in Kuwait responsible for tanker trucks was done to discuss the tank design used for the following simulations and to discuss the design goals for internal separators. The goal of the visit was to thoroughly learn about the manufacturing process, designs and to discuss the simulation study with Mula engineers. The dimensions will be taken as an ellipse with D1 = 2.4m, D2 = 1.8, L = 10.7m with thickness of and this was based on benchmarking data after discussing the project with Mula engineers in addition to research. The calculations ensured that the total volume will be at the designated volume of 36000 liters Additionally, supports will be studied based on (8mm) thickness to study the effects of sloshing on the tank attachment to the chassis.

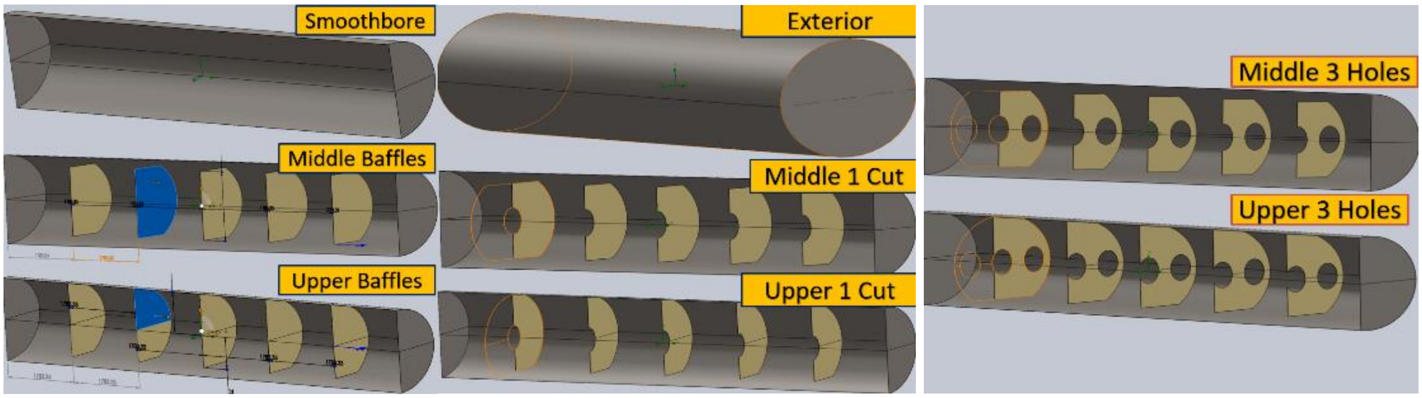

Figure 7: All 7 designs simulated for this research project with the variable being internal baffle design

Table 1: Boundary conditions used in SolidWorks 2024 Flow

Time Interval (second)	0.01
Total Simulation time (second)	60
Fluids (Internally):(Internal Simulation)	Propane + Air (50%/50%)
Overall Temperature (Celsius)	40
Tank fill (litters) 50% fill of 36000 Litters	18000
Velocity (Range) (kmph) in X-axis only (longitudinal)	(0 to 100 in 20s), (100 to 0 in 17s) Graph below (Fig 12)
Number of Baffles, Offset from center (1.7833m)	0 or 5

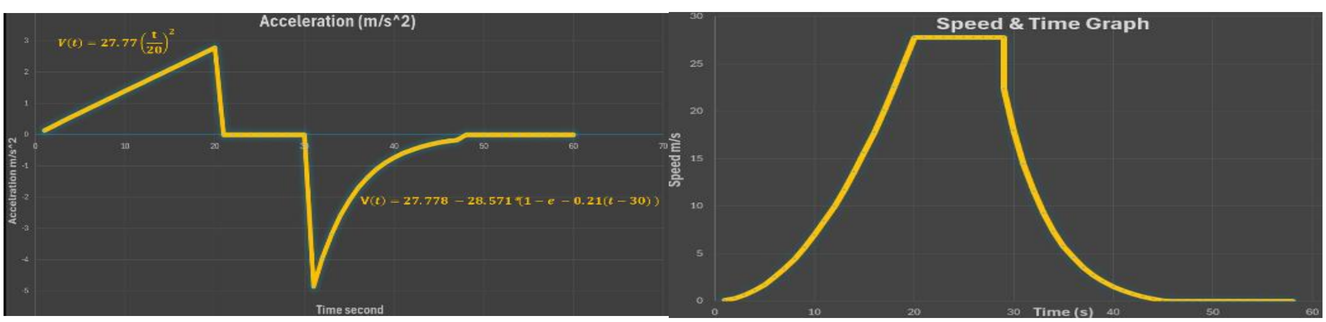

Figure 8: Acceleration and speed graphs used for this 60s simulation

4.Result and Discussion

The simulations were conducted with the design variable being internal baffle design. A total of 7 designs were selected to be presented and due to the limitation of number of pages only 3 will be visually provided with a table providing the values for the other designs in the Figures 9-10. Additionally, the first design was to be a smoothbore with no passive mitigation methods. This will be used in comparison to the other designs for better illustration on overall improvement and reduction towards internal sloshing forces. The order of the results will be smoothbore, middle welded baffles with 1 cuts and upper welded baffles with 3 cuts. Notably the supports were simulated under the load of smoothbore design, and this resulted in factor of safety of 2.53

while having 50% fill. The issue with such aspect is notably that any additional experienced forces or complete fill may result in sudden and cataphoric failure. And during discussion with Mula engineers they mentioned support thickness range from 6 to 8 mm. Simulations with 6mm have illustrated a factor of safety of roughly (1.76). (1.76). Such value isn't ideal for safety concerns and with internal baffles to absorb liquid sloshing the expected expected FOS is to increase.

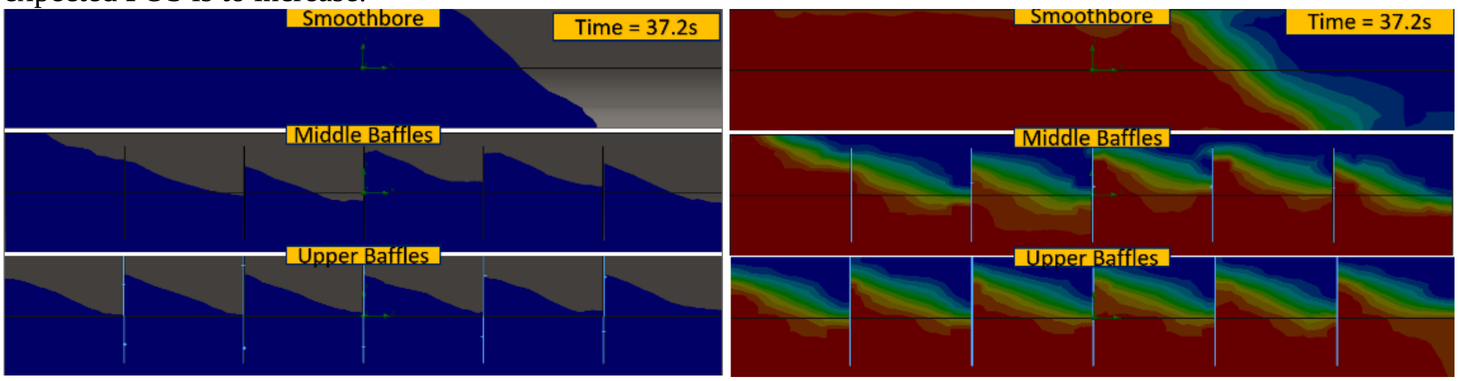

Figure 9: Fluid motion during braking at (37.2s) with heat map of propane volume fraction (Red = 100% propane, Blue = 100% Air), For the first 3 designs (Smoothbore, Middle Baffles & Upper baffles)

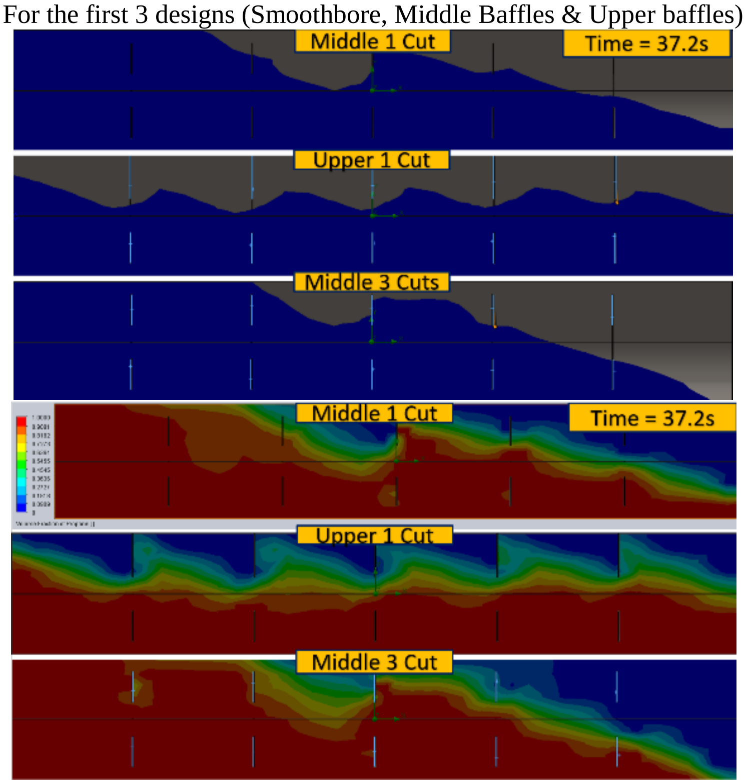

Figure 10: Fluid motion during braking at (37.2s) with heat map of propane volume fraction (Red = 100% propane, Blue = 100% Air), For the second 3 designs (Middle baffles 1x Cut, Upper Baffles 1x Cut & Middle baffles 3x Cuts).

Approaching the final design of this project and this was landed as final due to its improvements compared to smoothbore tanker. However, this doesn't translate to it being the absolute best because as mentioned earlier the constraints and limitations following this project affected its scope. Nevertheless, more designs will be tackled in the future, and they will be based on this data and further discussion with manufacturing engineers. The final design was based on the middle welded with three cuts but to alter the design as to close the upper gap and prevent fluid flow over the baffles. This design is denoted as upper welded baffles with three cuts, and this baffle design retains a 20cm gap

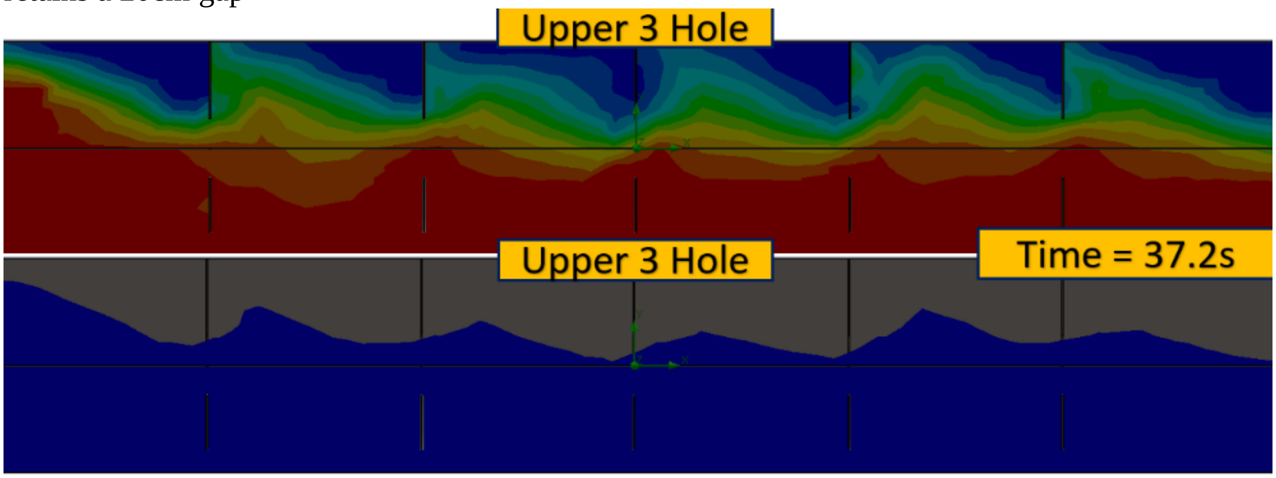

Figure 11: Simulation results for upper 3 cuts and heat map for propane volume fraction vs air (Red = 100 propane, blue = 100 Air).

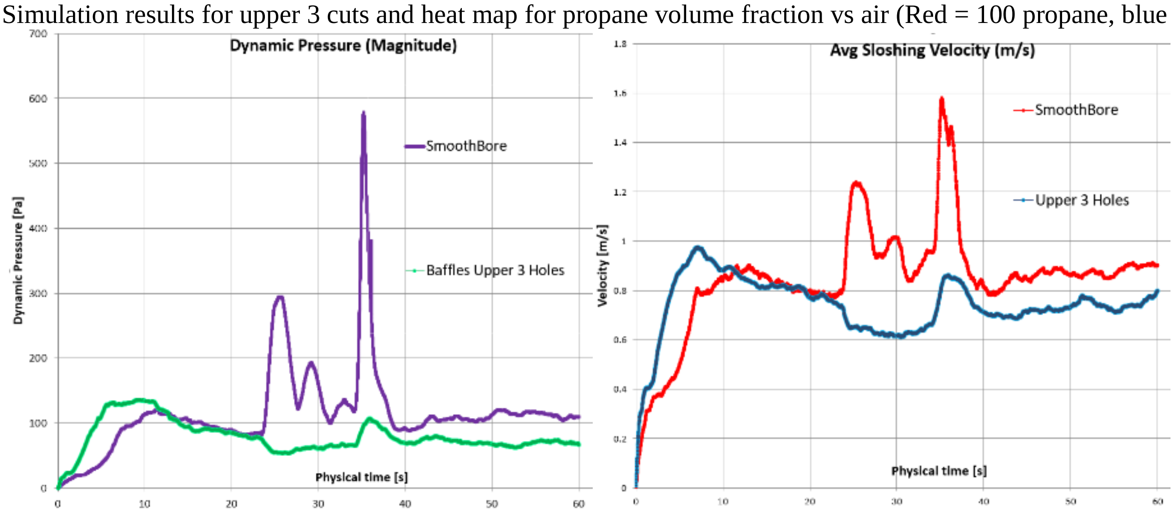

Figure 12: Dynamic pressure and Avg sloshing velocity comparison between smoothbore and final design

Finally, the two above Figures 11-12 show the upper 3-hole design baffles with the highest reduction to internal sloshing via a significant drop in dynamic pressure and average fluid surface velocity. This was a drop from roughly (575 Pa dynamic pressure to 95, 83.5% reduction) and (1.58m/s to 0.8m/s average surface velocity, 49.4%). The improvement here is expected to translate to improved control during emergency braking, reduced stopping distance and significantly contributing to safety for the driver and public. Notably, the data below will overlay all designs against each other with incremental improvements.

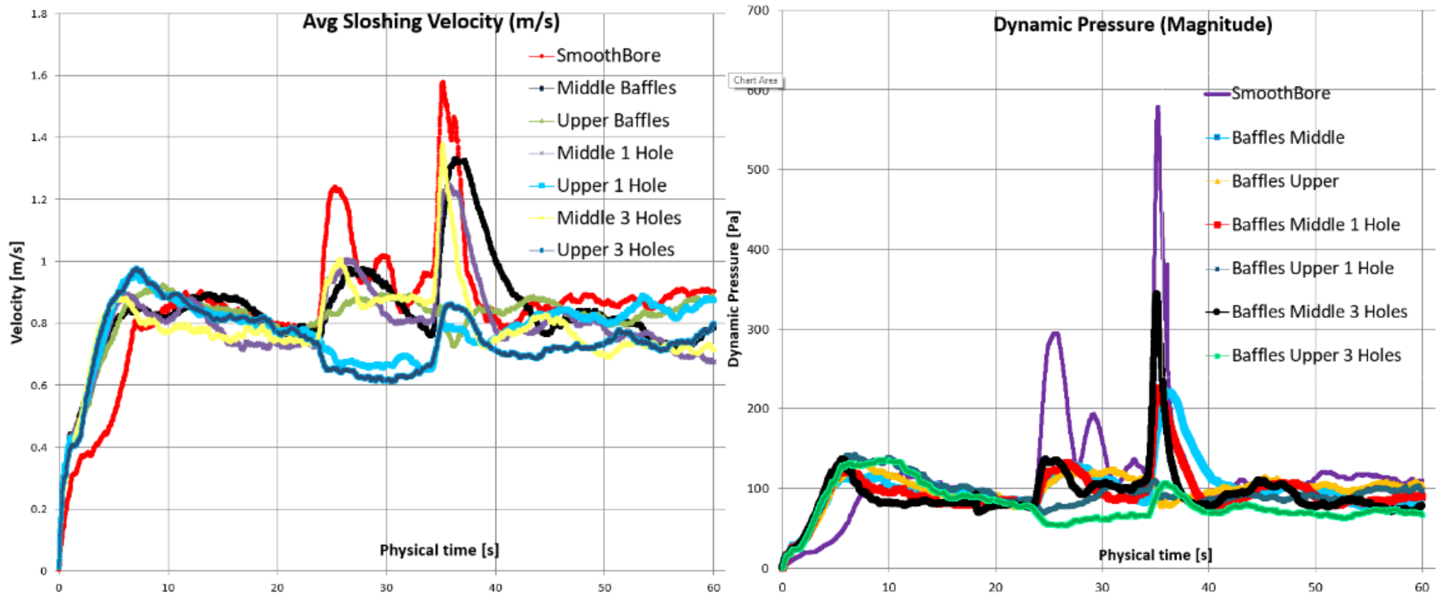

Figure 13: Average velocity & Dynamic pressure data graphs overlayed for all 7 designs

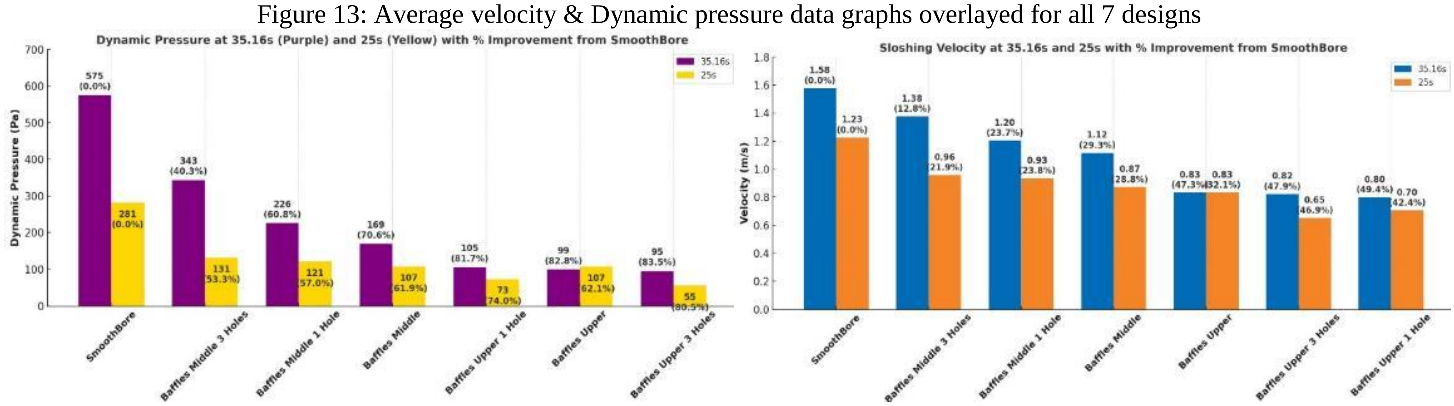

Figure 14: Dynamic pressure & Average velocity data as bar chart with percentage reduction compared to smoothbore tank

In summary, the simulation section with all 7 designs presented has clearly indicated that integrating geometrical mitigation methods or in other words baffles to absorb the internal wave formations has contributed to a significant reduction in dynamic pressure of (83.5% from 575 to 95 Pa) and (49.4% reduction in avg liquid velocity from 1.58 to 0.8m/s). Effectively, the results have illustrated that internal separators with optimized shape leads to a large reduction in internal sloshing and this will directly translate to improved safety for truck drivers, public and environment during road operation. Such an aspect is expected to manifest via the improvement of braking distance, reduced induced forces by the fluid during any acceleration and overall enhancement to tanker control during operation.

5. Conclusion

In conclusion, this research paper is concerned with the safety concerns of transporting liquids in a sealed container due to the internal wave formation, which is better known as internal sloshing. This happens mainly due to the change in speed throughout road operation and improper mitigation methods could lead to disasters. The goals of this research were to contribute to the design of tank vessel used on tanker trucks by conducting a case study. This was initially done by validating our software by repeating an existing academic paper and gaining the same result. Prior to being on contact with the Mula to help us gauge a benchmark design of an average tanker seen in Kuwait.

Finally, the results showcased a significant reduction of 83.5% in dynamic pressure and 49.4% in average fluid surface velocity. Where ultimately the best design was with three (0.25m) holes spaced at (0.8m) between the centre of the tank and sealed upper welding to prevent fluid from flowing over them.

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