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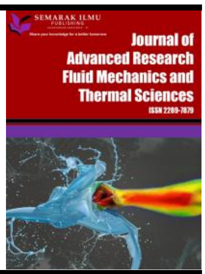

Hydrodynamics Analysis on Liquid Bulk Transportation with Different Driving Cycle Conditions

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ABSTRACT

Liquid bulk transport is one of the most important modes of fluid package transport, whether by sea or land. Flexitank has recently attracted the attention of shipment companies as an alternative method of fluid transportation due to the benefits of cost effectiveness, large shipping capacity, environmental friendliness, and quick loading/unloading time. However, the industry reports some cases regarding the leakage of the flexitank during transportation. While the hydrodynamic behaviour of the flexitank during transportation may influence the tank surface leakage issue. Thus, this study aims to determine the suitable filling volume capacity on flexitank by using Computational Fluid Dynamics (CFD). Hydrodynamics performance such as wall shear stress, volume fraction, dynamic pressure, and slosh force will be analyzed on different filling volume capacities and driving cycles. The filling volume capacity analyzed in this study are 5%, 10%, 15% more, or less than the reference capacity, 24000 L, based on different driving cycles: city-suburban and freeway. The results indicate that varying the fill level capacity of the tank affected the liquid sloshing behaviour and hydrodynamic performance of the tank. The highest wall shear stress (WSS) occurs at a filling volume capacity of -15 % because it is increasing the wall shear stress by 80% (city-suburban) and 35% (freeway) than the reference value. Following that, both speed profiles with a +10 % filling volume have the dynamic pressure, reducing it by 60% (city-suburban) and 47% (freeway) compared to the reference value. Thus, the filling volume of +10% is recommended to be suitable for the flexitank. Hence, this study benefits liquid bulk transportation by increasing fill level capacity and optimizing hydrodynamic performance.

Keywords:
Bulk liquid; Computational Fluid Dynamics (CFD); driving cycle; flexitank; hydrodynamics; sloshing; transportation

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1. Introduction

Most of the people have all come into encounter with liquid bulk cargoes in some way or another at some time in daily lives. Without relying on those every day, from gasoline to power automobile to fruit juices and cooking oil for use at home, it would be challenging to carry the daily lives [1]. These liquid cargoes, including crude oil, liquefied natural gas, and chemicals, are not packaged, bagged, or manually stored. Despite this, they are put into and sucked out of a Parcel Tanker's huge tank areas, referred to as the holds [1].

Ocean tankers are one of the oldest forms of merchant ships, with the demand for these vessels deriving from the globally dispersed distribution of natural oil reserves and liquid chemicals. Oil tankers are the most prevalent ocean tankers operating at sea [2]. However, ocean transportation is a time-consuming mode of transportation, and it might take up to months for products to be delivered [3]. Besides, an ocean tanker is a reusable tank; abundant transfers raise the risk of product contamination.

A standard ISO tank container is ideal for transporting bulk liquids, gases, or pressured dry bulk through road, rail, or sea [4]. The tank container is constructed entirely of low-carbon steel and stainless steel. A standard tank typically holds 25,000 litres and has a gross weight limit of 36 metric tonnes [5]. Tank containers also can be reused as it is reusable. Despite that, incurring costs for the cleaning after unloading will need to be bare by the shippers. Besides, the risk of contamination will also be high if the cleaning work is inefficient due to the abundance of load-unload [6].

Intermediate bulk containers (IBCs) are reusable industrial containers used to transport and store bulk liquid and granular goods such as chemicals, food components, solvents, and medicines [7, 8]. It is the lowest cost compared to other tanks. However, the cost for packaging is higher if compared to flexitank. Consequently, there is a possibility of contamination during the transportation of the products. This type of tank would result in a high operating cost in liquid bulk due to the time required to load and unload items. Additionally, it is tough to handle in terms of logistical space [9]. Flexitank is a pillow-style tank contained within a dry container that is advised for items susceptible to air exposure, such as latex, and for long routes where lower capital expenditures result in cost savings. A flexitank may carry between 10,000 and 24,000 litres, while the most common sizes are 16,000, 18,000, 20,000, 22,000, and 24,000 litres. Generally, larger capacity models are chosen; nevertheless, product density must be calculated for model selection and flexitank capability [10]. Flexitank has become famous among industry players because of its lightweight [11]. Flexitank is a one-way transportation method as the flexibags is not reusable, making the contamination risk of products low [11].

Flexitank available in the market claimed that the maximum capacity is 24000 L. However, there are cases reported by the industry on the leakage incident. The well-known issue in shipping liquid is the sloshing effects. It may be because the filling volume for flexitank is not suitable. Therefore, this study aims to analyze the hydrodynamics performance on different driving cycles and determine the suitable filling volume capacity on a 20ft container.

This study focused on flexitank for liquid transportation and 20ft shipping container as the model for CFD simulation. The size of the container and the flexitank capacity used for this study are according to the specifications given by MY Flexitank Industries Sdn. Bhd. [12]. CAD software is utilized to create the geometry, and the capacity liquid for the simulation was set for 5 %, 10 %, 15% less or more than the standard capacity of the volume in the flexitank according to the guidelines used by the Container Owner Association (COA). This simulation also was run in longitudinal motion according to the speed profile of the city-suburban and freeway driving cycle. Analysis and data establishment on hydrodynamic of flexitank sloshing effect were obtained from CFD SolidWorks flow simulation only.

2. Methodology

The primary goal of this research is to analyze and explore the sloshing effect of a flexitank in term of the volume fraction, wall shear stress (WSS), dynamic pressure and sloshing force using CFD. The flexitank design was created with computer-aided design (CAD) SolidWorks 2019 and then analyzed with flow simulation in SolidWorks 2019.

2.1 Geometrical Modelling

The dimensions of the 20ft container used in the simulation, such as the height, width, and length, are shown in Table 1, and Figure 1 shows the geometry drawing.

Table 1
Dimensions of the 20ft container

Description	Specification	
	Outer (mm)	Inner (mm)
Length (L)	6096	5892.8
Height (H)	2590.8	2387.6
Width (W)	2438.4	2362.2

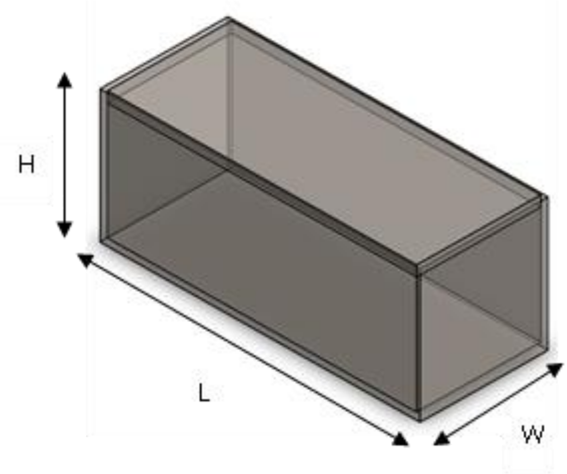


Fig. 1. Tank geometry used in this study

2.2 Filling Volume

The variation of filling volume that were used in this study simulation setup is as shown in the table below. The reference capacity was used as the benchmark for the analysis in this study.

Table 2
Filling volume

Fill level	Capacity (L)	Fill depth (mm)
-5%	20400	1465.52
-10%	21600	1551.73
-15%	22800	1637.93
Reference	24000	1724.14
+5%	25200	1810.35
+10%	26400	1896.56
+15%	27200	1954.03

2.3 Speed Profile

The speed profile used in this study is based on the driving cycle of city-suburban and freeways. However, due to computational limitations, this study cannot run the simulation based on the actual speed profile and the total time on the driving cycle speed profile, which is the 1680s [13]. Therefore, to make this study possible, a new speed profile was developed, implying the origin speed profile [13] as shown in the figure.

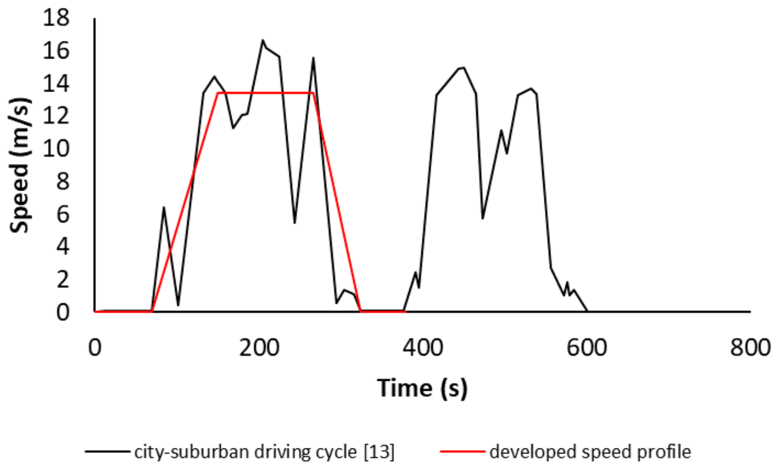


Fig. 2. City-Suburban speed profile

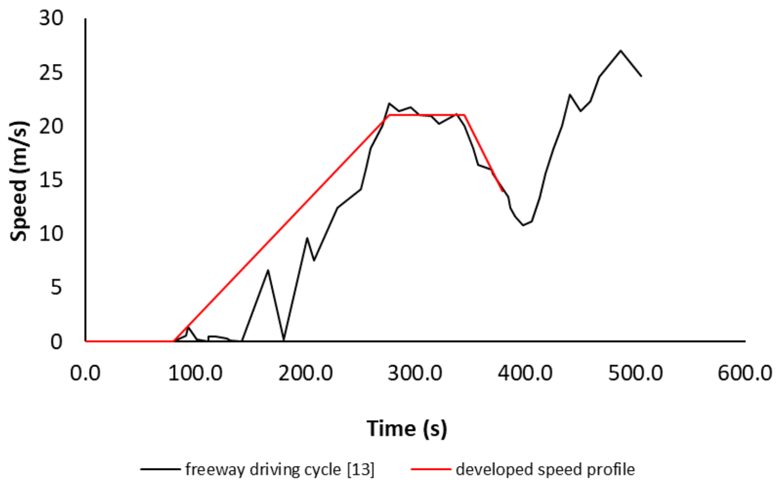


Fig. 3. Freeway speed profile

2.4 Simulation Setup

A computational domain for the geometry was generated automatically. Using a finite volume method, the geometry can be simulated using SolidWorks Computational Fluid Dynamics (CFD) flow simulation tools. First, the model's initial state was established. Next, physics is defined in the internal domain for this investigation. The total analysis time was set to 379 s following the speed profile used. Besides, the output time step was set to 0.01 s to achieve better accuracy result and shorter solution time. This study defined two types of fluids: gases (air) and liquids (water). The boundary condition is one of the most crucial aspects that must be revised to acquire correct results. The computational domain surrounding the model represents the actual size of the container. The initial and final velocity parameters, for example, must be revised and defined accurately. This study's numerical setup can simplify the boundary conditions, as shown in Table 3.

Table 3
Details of boundary condition

Software	Type of tank	Velocity	Capacity	Type of flow
SolidWorks 2019	Flexitank container	City-suburban – 13 m/s Freeway – 21 m/s (Refer to speed profile)	(Refer to fill level capacity)	Transient state

Next is the meshing process. Meshing comes after design modelling; it is a term that refers to the process of discretizing a model into a finite number of elements [14]. It is the most critical step in the analysis of a flow simulation which requires mesh quality validation or grid impendence study setup to obtain proper meshing size and meshing elements counts throughout the process [15]. The mesh quality dictates the correctness of the outcome. Figure 4 illustrates how the mesh is formed. Due to the model's simplicity, it was meshed using the hexahedron approach. The mesh was generated automatic under global meshes.

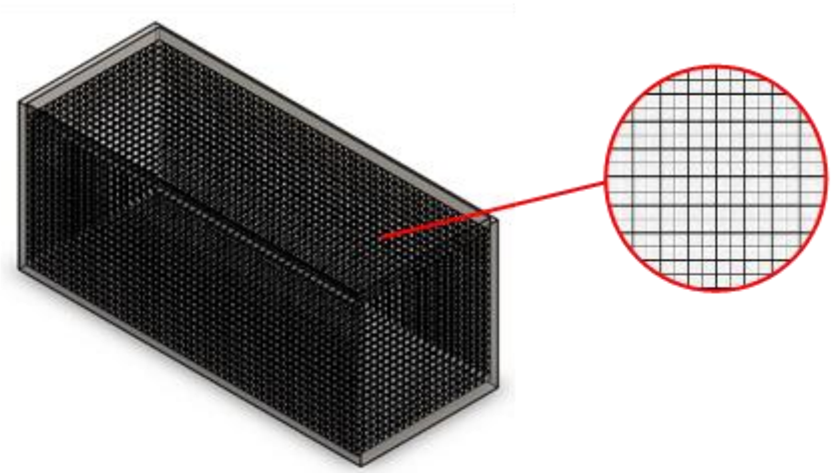


Fig. 4. Geometry meshing

2.5 Governing Equation

The key governing equations that dictate the physics of fluid mechanics and thermal sciences and are used in computational fluid dynamics (CFD) research are continuity equations, Navier-Stokes equations, and energy equations [16]. Before beginning the simulation, it is necessary to establish the conversion laws applied to the actual flexitank [17].

Conservation of mass - the amount of mass in the system remains constant; equal amounts of mass enter and leave the system's control volume.

$$Continuity\ equation: \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

Conservation of Linear Momentum - the relationship between the system's pressure, viscous forces, and momentum. These equations are also known as the Navier-Stokes equations.

$$pg_x - \frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) = p\frac{du}{dt} \tag{2}$$

$$pg_y - \frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) = p\frac{dv}{dt} \tag{3}$$

$$pg_z - \frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) = p\frac{dw}{dt} \tag{4}$$

Conservation of energy - energy cannot be created or destroyed within the system.

$$pc_p\frac{dT}{dt} = k\nabla^2 T = \Phi \tag{5}$$

where p is density, g is gravity, μ is dynamic viscosity, Φ is the viscous dissipation function, k is thermal conductivity, T is temperature, c_p is specific heat and t is time.

Reynolds-averaged Navier-Stokes (RANS) equations are time-averaged fluid flow equations mainly used to represent turbulent flows. Turbulence's features provide approximate time-averaged solutions to the Navier-Stokes equations [18]. A limitation of most RANS solvers is their underlying inability to deal with highly divided flows, as manifested in numerous logical structures [19]. The nonlinear Reynolds-averaged Navier-Stokes equations cannot be solved analytically. The RANS method divides the instantaneous velocity and pressure into two components: fluctuating and average, Eq. (6) and Eq. (7).

$$u = \frac{1}{T}\int_0^T u dt \tag{6}$$

$$\begin{aligned} p &= \bar{p} + \acute{p} \\ u &= \bar{u} + \acute{u} \\ v &= \bar{v} + \acute{v} \\ w &= \bar{w} + \acute{w} \end{aligned} \tag{7}$$

From the Navier-Stokes equation, inserting Reynolds decomposition will result in the continuity equation giving the new fluctuating terms, Eq. (8) and Eq. (9).

$$\frac{\partial \bar{u}}{\partial x}+\frac{\partial \bar{v}}{\partial y}+\frac{\partial \bar{w}}{\partial z}=0 \tag{8}$$

$$pg_x-\frac{\partial \bar{p}}{\partial x}+\frac{\partial}{\partial x}\left(\mu\frac{\partial \bar{u}}{\partial x}-p\bar{u}^{\,2}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial \bar{u}}{\partial y}-p\acute{u}\acute{v}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial \bar{u}}{\partial y}-pu\acute{v}\acute{w}\right)=p\frac{d\bar{u}}{dt} \tag{9}$$

New unknown terms known as Reynolds stresses [17] now exist, which cause a closure problem resulting in these stresses having to be modeled to get a closed system on equations. It is done by introducing turbulence models.

3. Results and Analysis

3.1 Mesh Quality Validation

Mesh quality validation is required to have the best mesh level of refinement where mesh doesn't have any influenced on the results. In other words, optimum mesh quality to achieve acceptable results by saving computational cost in terms of memory and time for the simulation [20]. Mesh quality validation was carried out from the 1st level of refinement until the best level. The best level of refinement is defined as the condition where there is no more increase of cell number, or specifically, the number of cells has been constant, as shown in Figure 5. The figure shows a mesh quality of force versus the level of refinement. Based on the plotted graph, there are slightly different sloshing force values with an average relative error below 1 % in force from the level of refinement between 2 to 3. In addition, the number of cells for 2nd level of refinement is 6800000 which is same as 3rd level of refinement. Thus, the 2nd level of refinement will be set as the best level for the mesh quality for this study.

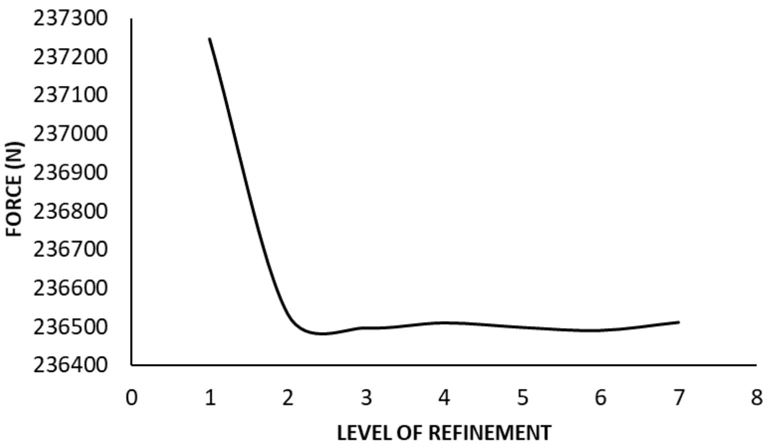
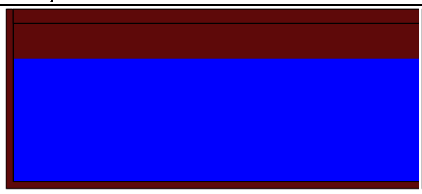
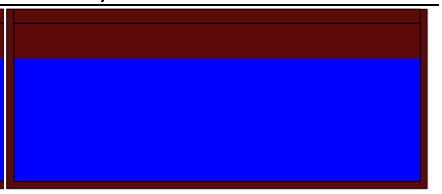
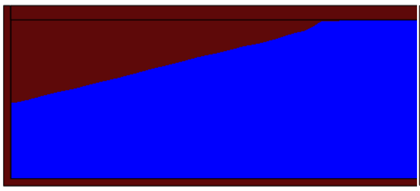
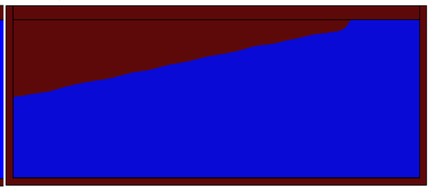
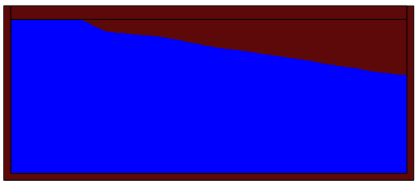
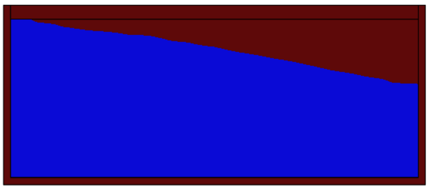


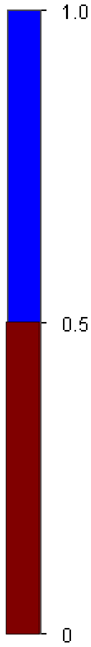
Fig. 5. Results for different level of mesh refinements

3.2 Volume Fraction

Table 4 shows the volume fraction contour generate from the CFD analysis on the sloshing behavior of the liquid. The contour shows the liquid hit the back and the top of the walls as it is sloshing during accelerating at t = 100 s and hit the front and top of walls during decelerates or braking at t = 300 s. Iacob *et al.,* in his study also found that the liquid hits front of the tank during simulated under sudden stop condition [21]. From the contour when the flexitank is partially filled, the liquid’s center gravity will shift as the vehicle that carry the flexitank move towards the motion of the speed profile. Hence, this shows that leakage is possible to occur at the top of the flexitank as the liquid slosh frequently hits at the top. Parameters like wall shear stress may contribute to the leakage of the flexitank.

Table 4
Volume fraction

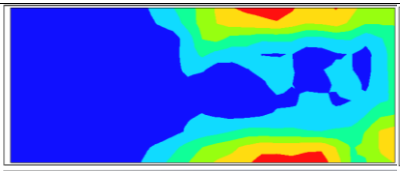
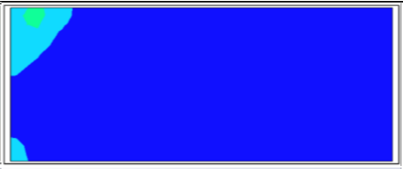
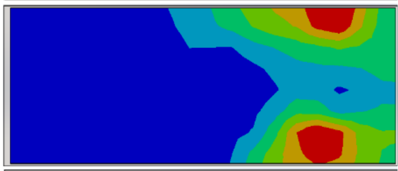
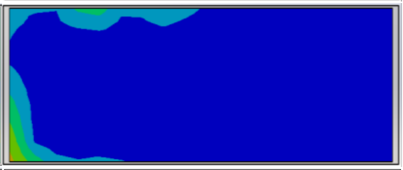
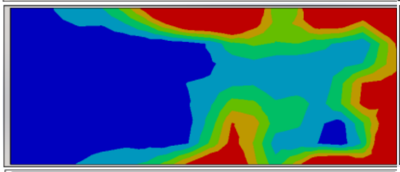
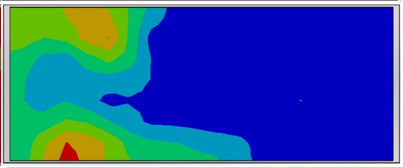
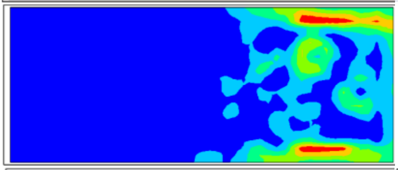
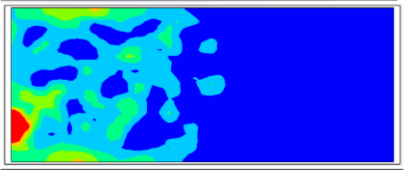
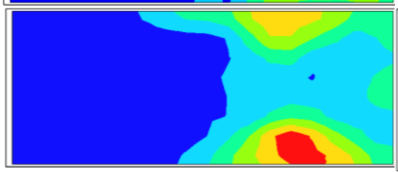
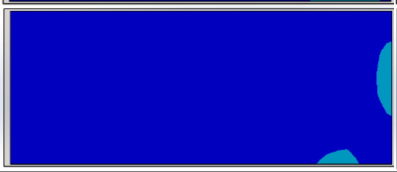
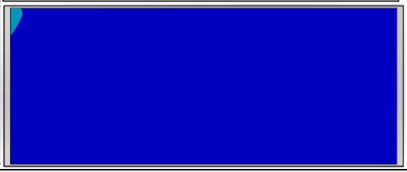
Condition	City-suburban	Freeway
T = 0s Stop	 0 m/s	 0 m/s
T = 100s Acceleration	 13 m/s	 21 m/s
T = 300s Deceleration	 10 m/s	 19 m/s
	←	Direction of motion

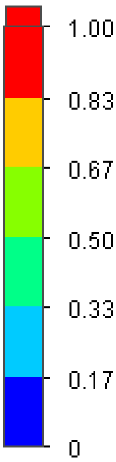
Volume Fraction


3.3 Wall Shear Stress (WSS)

The presence of water in the container causes it to contact with the wall's surface and produce friction indirectly create wall shear stress [22]. Wall shear stress (WSS) is a tangential force caused by system friction and fluid movement [23]. Figure in Table 5 indicates the phenomenon of the wall shear stress (WSS) that occurred at the top of the flexitank based on the speed profile of the city-suburban driving cycle during accelerates at 140s and decelerates at 330 s. It can be seen from the contour shown in the figure in the table decreasing the fill level led to increasing the shear stress at the top of the flexitank. The sloshing behavior is more violent with a lower fill level than the higher fill level. Thus, the speed of the liquid flow that hit the top of the wall increase and resulting to higher wall shear stress. The red region contour indicates the maximum shear stress. As can be seen in the table, the minimum fill level -15% has the reddest region with the value of 0.1775 Pa and 80% worse than the reference, while the maximum +15% has no red region with the value of 0.0301 Pa and 70% better than the reference value. It shows that shear stress increases when the fill level decreases due to the rigidity of the liquid in the flexitank.

Table 5
City-suburban WSS contour

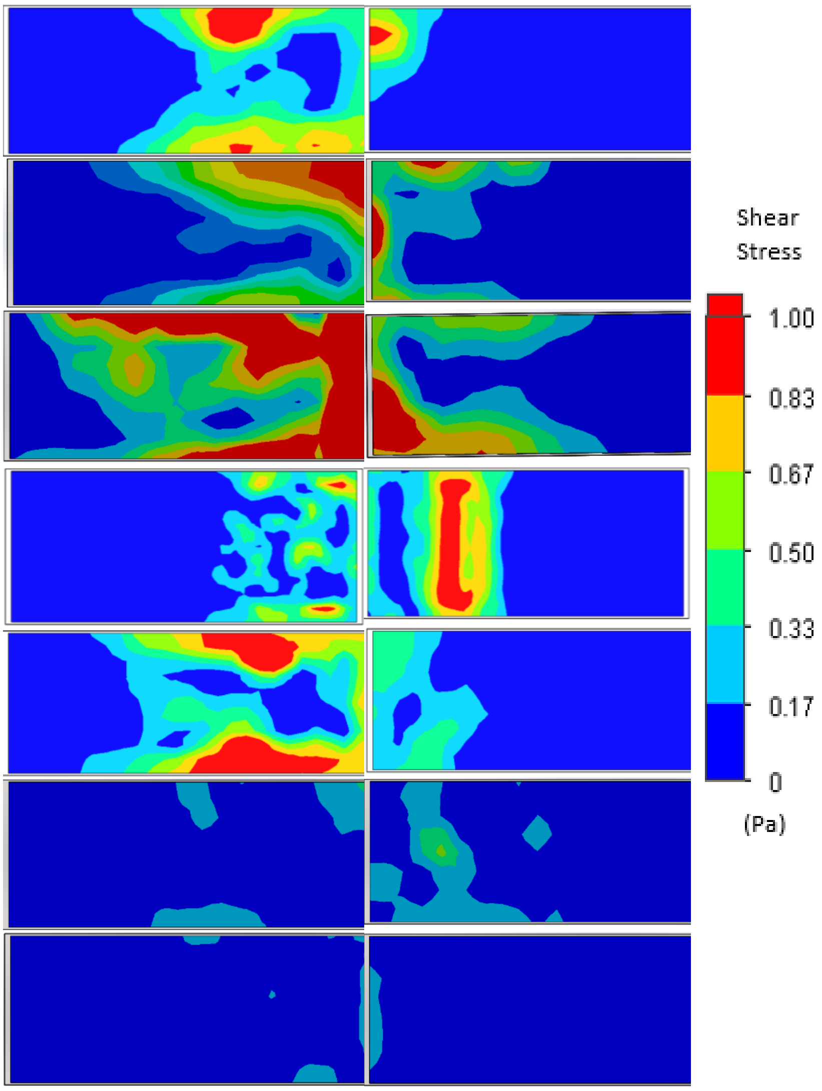
Capacity	Accelerate	Decelerate
-5% (20400L)		
-10% (21600L)		
-15% (22800L)		
Reference (24000L)		
+5% (25200L)		
+10% (26400L)		
+15% (27200L)		



Based on Table 6, the shear stress contour at the top of the flexitank can be concluded to have the same trend as the contour at the city-suburban driving cycle. Increasing the filling volume will decrease the shear stress. The figure also shows that the highest shear stress occurred at the filling volume of -15%, where the value of its' wall shear stress is 0.1585 Pa which is 35% worse than the reference filling volume's shear stress 0.1177 Pa. This study is being analyzed during accelerating at the 150 s and decelerating at 373 s. The contour also shows that shear stress at the top is higher during acceleration than during decelerating based on the red contour region distribution. It occurred due to the flow speed of the liquid that hit the top of the wall is higher during accelerate compared to decelerate.

Table 6
Freeway WSS contour

Capacity	Accelerate	Decelerate
-5% (20400L)		
-10% (21600L)		
-15% (22800L)		
Reference (24000L)		
+5% (25200L)		
+10% (26400L)		
+15% (27200L)		



3.4 Sloshing Induced by Driving Cycle Motion

The plotted graph in Figures 6 and 7 show the dynamic pressure variation of different filling volume over time. The reference capacity (24000 L) has the maximum dynamic pressure value for 1325 Pa for city-suburban and 1695 Pa for the freeway. The highest dynamic pressure was recorded at the filling volume of -10%. This phenomenon will be resulting to higher liquid impact to the walls during sloshing. If the pressure impact reached approximately to the critical pressure range of the tank material, it will cause structural damage [24]. Thus, it is also may contribute to the worn of the flexitank. Next, the graph also shows that the fill level capacity of +10% has the lowest dynamic pressure for both driving cycle conditions. This is because, when increasing the filling volume, the liquid slosh less violent compared to decreasing the filling volume. Hence, this analysis shows that filling volume of +10% is better as it is sloshing with lower dynamic pressure and will resulting to the lower liquid impact.

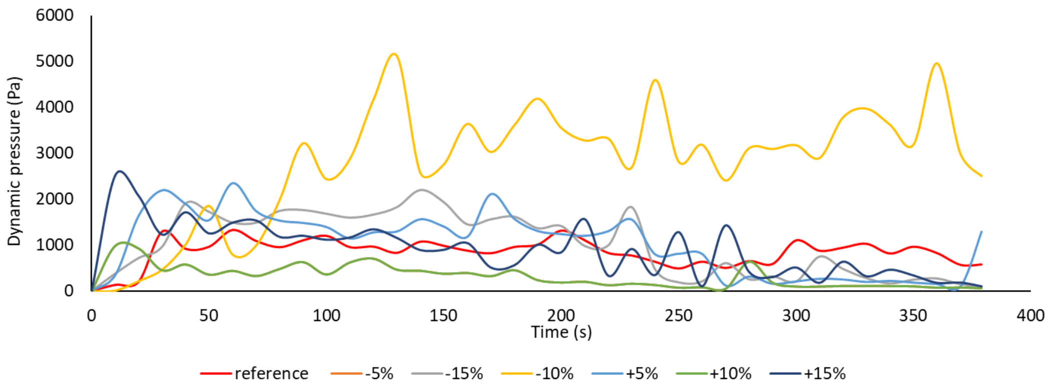


Fig. 6. City-suburban dynamic pressure vs. time

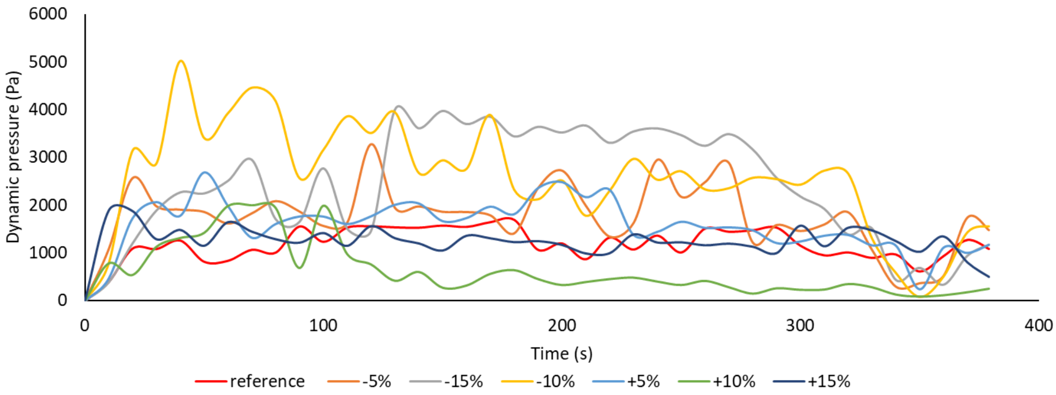


Fig. 7. Freeway dynamic pressure vs. time

3.5 Sloshing Force on Top of the Tank

Figure 8 and 9 show the plotted graph of slosh force versus time. The trend shows that the sloshing forces increase when the filling volume decreases from both graphs. It is occurred due to the sloshing behaviour differences, when the filling volume decrease the behaviour of the liquid sloshing is more violent thus increasing the sloshing force compared to when the filling volume is increasing. This also found by J. A. Romero *et al.,* in his study he reveals important reductions in average sloshing forces with increases in fill levels [25]. From the graph in Figure 8, plotted slosh force is higher at the range (266 s -379 s) than the plotted at the range (0 s -150 s); this occurred due to the deceleration time experienced by the flexitank being shorter than the acceleration time. For the graph in Figure 9, the slosh force is higher during acceleration at the range (0 s -276 s) than the slosh force during deceleration that can be observed at the plotted graph range (344.6 s -379 s). It is affected by the motion experienced by the flexitank, which is the city-suburban and freeway driving cycle. It also demonstrates that slosh force increases in magnitude as the flexitank's excitation level increase. As stated by Mengmeng Han *et al.,* in his finding, higher filling volume leads to a larger increase in the inertia effect [26]. Hence, the filling volume capacity of +15% is the best because it has the lowest slosh force, 27% (city-suburban), and 14% (freeway) better than the reference slosh force.

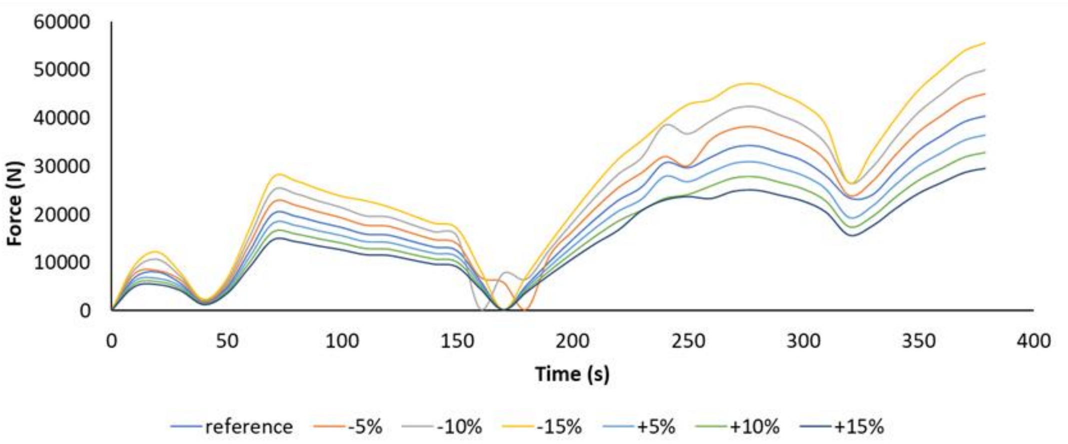


Fig. 8. City-suburban sloshing force vs. time

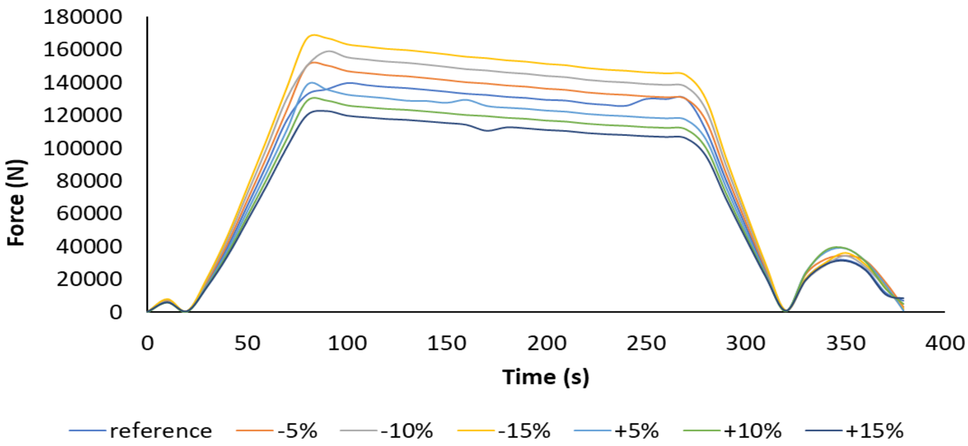


Fig. 9. Freeway slosh force vs. time

3.6 Suitable Filling Volume

After considering the hydrodynamic performance analysis in this study, the suitable filling volume can be determined. The determination is being made by using the method of concept screening and scoring. The (+) indicates that the parameters value achieved are acceptable as it has the lower percentage difference compared to the reference's parameters value while (-) indicates as it is not acceptable as its' percentage difference is higher than the reference. The concept screening and concept scoring are presented in the table below.

Table 7
Concept screening (Freeway driving cycle)

Criteria / Concept	Wall Shear Stress (WSS)	Dynamic Pressure	Sloshing Force	Sum +'s Sum 0's Sum –'s	Net score	Continue?
24,000 L (Reference)	0	0	0	0 3 0	0	NO
20,400 L (-5%)	-	+	-	1 0 2	1	NO
21,600 L (-10%)	-	-	-	0 0 3	-3	NO
22,800 L (-15%)	-	-	-	0 0 3	-3	NO
25,200 L (+5%)	-	-	+	1 0 2	-1	NO
26400 L (+10%)	+	+	+	3 0 0	3	YES
27,200 L (+15%)	+	-	+	2 0 1	1	YES

Table 8
Concept screening (City-Suburban driving cycle)

Criteria / Concept	Wall Shear Stress (WSS)	Dynamic Pressure	Sloshing Force	Sum +'s Sum 0's Sum –'s	Net score	Continue?
24,000L (Reference)	0	0	0	0 3 0	0	NO
20,400 L (-5%)	-	+	-	1 0 2	-1	NO
21,600 L (-10%)	-	-	-	0 0 3	-3	NO
22,800 L (-15%)	-	-	-	0 0 3	-3	NO
25,200 L (+5%)	-	-	+	1 0 2	-1	NO
26400 L (+10%)	+	+	+	3 0 0	3	YES
27,200 L (+15%)	+	-	+	2 0 1	1	YES

Table 9
Concept scoring

CONCEPTS					
		26,400 L (+10%)		27,200 L (+15%)	
Selection criteria	Weight	Rating	Weighted Score	Rating	Weighted Score
Wall shear stress (WSS)	50%	4	2	5	2.5
Dynamic Pressure	30%	5	1.5	2	0.3
Sloshing Force	20%	4	0.8	4	0.8
Total Score		4.3		3.6	
Rank		1		2	
Develop?		YES		NO	

From the concept screening and scoring above, it can be considered that the suitable filling volume is +10 %, as its' scores indicate that it is better than the reference values of all the parameters.

4. Conclusions

In this study, the hydrodynamics performance due to different driving cycles was analyzed. The determination of suitable filling volume capacity of flexitank on 20ft container was accomplished in this study which is + 10%, 26,400 L. Computational fluid dynamics (CFD) analysis is performed on the different filling volume capacity and different driving cycles, city-suburban, and freeway, by using SolidWorks 2019 software to analyze the hydrodynamics performances of sloshing forces, dynamic pressure, volume fraction and wall shear stress. It was ascertained that increasing the filling volume will decreasing the wall shear stress and sloshing force. While, for the dynamic pressure the lowest was achieved on the filling volume of +10%. The predictions of volume fraction, wall shear stress (WSS), dynamic pressure and slosh force ought to help engineers to improve the hydrodynamics design application.

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