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Hydrodynamic Performances on Flexitank Package for Bulk Liquid Transportation Subjected to Ship Motion Using CFD

Mohammad Aizal Almazan Jamil[1], Nofrizalidris Darlis[1]*,

[1] *Faculty of Engineering Technology, University of Tun Hussein Onn Malaysia, Education Hub Pagoh, 84600, MALAYSIA*

*Corresponding Author: nofrizal@uthm.edu.my
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Abstract

Bulk liquid transportation can be used to transport various useful materials overseas via sea transportation. There are a lot of ways to transport liquid in bulk overseas and using flexitank is one of them. However, transporting useful liquids such as water, latex and crude palm oil (CPO) could cause a sloshing phenomenon to happen which potentially could cause flexitank to be damaged. This problem could be address by determining the critical parameter on ship motion for flexitank problem. Besides, with the usage for computational fluid dynamics (CFD) software such as Ansys Fluent, the boundary conditions such as fluid density, filling volume and roll angle of ship motion could be applied. In this case, the fluid density that was chosen is 997 kg/m^3, 890 kg/m^3 and 950 kg/m^3 which are water, CPO and latex respectively. Moreover, the targeted filling volume of the flexitank was reference, +1%, +2%, and +3%. This means the chosen filling volume was 21,000 L, 21,210 L, 21, 420 L and 21,630 L respectively. Furthermore, by using CDF software such as Ansys Fluent, hydrodynamic performances such as pressure distribution, sloshing force and wall shear stress could be obtained. In addition, these hydrodynamic performances could be applied to determine the suitable filling volume for water, CPO and latex as filling fluid inside flexitank respectively. Thus, it is recommended to choose 2% as a suitable filling volume for water and CPO while 1% for latex.

1. Introduction

Bulk liquid transportation is a process where the liquid is transported in a huge amount at a time [1]. There are various ways to carry the liquid either by using ISO Tank, Intermediate Bulk Container (IBC), drums and barrels and even flexitanks. Each of these tank containers has its own unique advantages. For example, ISO Tanks can last up to 35 years [2]. On the other hand, IBC are installed with nozzles and valves which allows it easily to be emptied [3]. Next, drums and barrels are designed with multiple types of material such as plastic, steel and fiber [4]. Lastly, flexitank which has a lot of variety in size that could have a volume as low as 1,000 liters and as high as 100,000 liters [5]. However, this study focuses on the flexitank package as bulk liquid transportation.

Bulk liquid transportation can be carried out via land or sea transportation. This study only focuses on sea transportation rather than land transportation. This means that ship motion should be considered in this study. There are two different types of ship motions which are translational and rotational ship motion. This is because in an open sea, ships are subjected to many forces in all directions [6]. Translational ship motion is a movement that the related to lateral movement on respective axis while rotational ship motion is a movement that rotates on respective axis [7]. However, roll ship motion is the most critical ship motion that is categorized in rotational ship motion. Rolling motion can be described as a tilting motion of the ship [8]. Roll ship motion has a certain angle limit before the ship starts to capsize. In this case, since this study focuses on ship that are used to transport cargo, the roll angle limit is 30˚ [9]. So, the targeted angle for roll motion are 5 ˚, 10 ˚, 15 ˚, 20 ˚, 25 ˚ and 30 ˚. Besides, the critical angle for roll ship motion is 30˚ where the ship reach its maximum angle before capsizing. A more detailed roll motion profile will be discussed in the next topic.

Next, flexitank can be used to transport non-hazardous liquid. This includes both edible and non-edible liquids. Some of the non-edible liquids are printing ink, natural latex, crude oils, paints and lubricants. On the other hand, the food-grade liquid, which is edible are coconut oil, palm oil, liquid sugar, fish oil, corn-syrup and milk [10]. In this study, water, crude palm oil (CPO) and latex will be used as the filling fluid inside the flexitank. In addition, the volume of flexitank that are used in this study are reference volume, +1%, +2% and +3% which are 21,000L, 21,210L, 21,420L and 21,630L respectively.

Lastly, the hydrodynamic performances that could be obtained from this study are pressure distribution, sloshing force and wall shear stress. Hydrodynamic performance results are important to determine the suitable filling volume for each different fluid density.

2. Methodology

The goal of this study is to analyze and explore hydrodynamic performances such as pressure distribution, sloshing force and wall shear stress via CFD. The flexitank model are designed by using the SolidWorks 2022. Once the flexitank are designed, the model then will be applied by CFD to generate the desired results. Figure 1 below shows the flowchart of the CFD simulation setup.

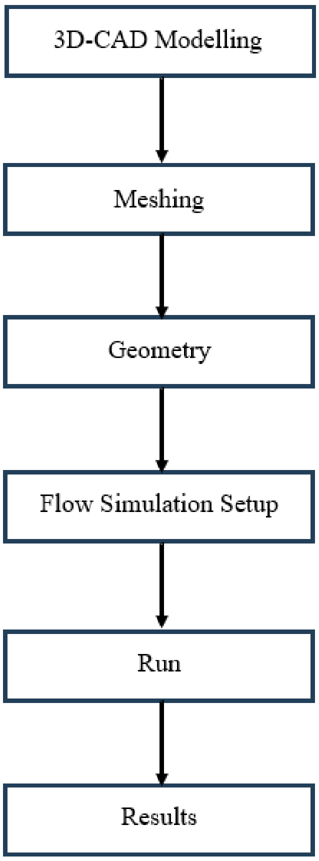


Fig. 1 *Flowchart of CFD simulation setup.*

2.1 Geometrical Modelling

SolidWorks 2022 was used to design the geometry of the flexitank. Since there are multiple filling volumes, the dimensions of the flexitank would be different. Figure 2 below shows the geometry of the flexitank. Even though the flexitank has different volume, its width and length are fixed causing only changes in height according to the volume. Table 1 below represents the detail of the dimensions of flexitank.

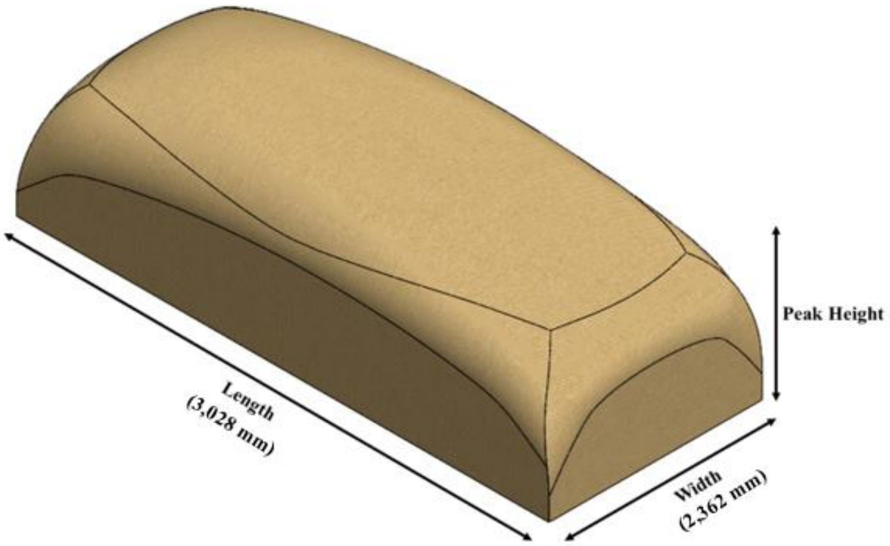


Fig. 2 *Geometry of flexitank.*

Table 1 *Flexitank detail according to filling volume.*

Filling Volume	Capacity (L)	Peak Height (mm)
Reference	21,000	2,223
+1%	21,210	2,244
+2%	21,420	2,255
+3%	21,630	2,264

2.2 Roll Motion Profile

It is necessary to understand the roll motion profile before starting the simulation. It is mentioned that roll ship motion is a rotational motion of the ship at the longitudinal axis [8]. Rotational motion means that there was change in angles involved. In this case, change of angles at the longitudinal axis. It is also mentioned earlier that the roll angle can reach up to 30˚. This means that the ranges of angles that will be carried out in this study is from 0˚ to 30˚ [9]. Figure 3 below shows the roll motion profile of 5˚, 10˚, 15˚, 20˚, 25˚ and 30˚.

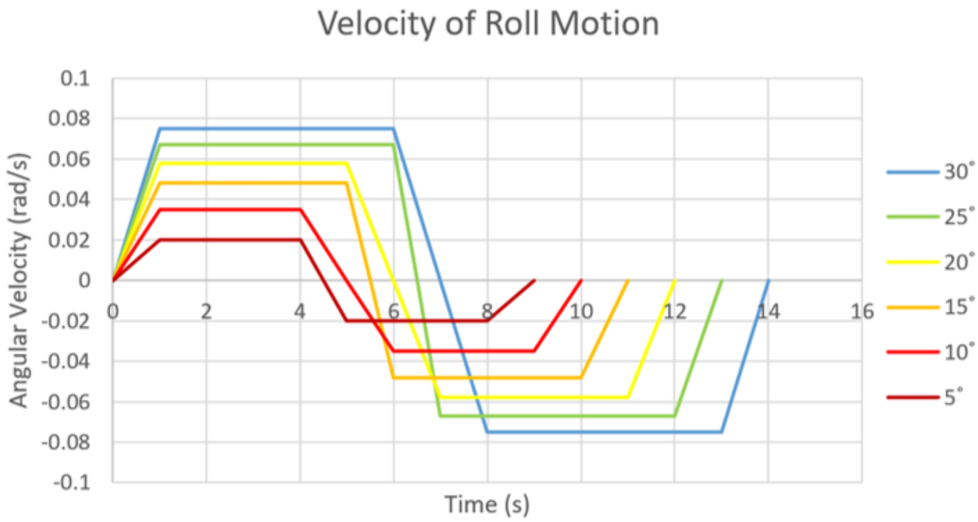


Fig. 3 *Roll motion profile of different angular velocity.*

2.3 Geometry Meshing

Meshing is important as it determines the accuracy of the results that were generated from the simulation. However, the higher the quality of the mesh, the closer the results to have significant change between the previous mesh quality. Other than that, the higher the mesh quality, the longer the time taken to run the simulations. So, it is important to determine the optimum mesh quality to get the best results while using the most efficient time. Table 2 below represents the mesh quality of the flexitank.

Table 2 *Three levels of mesh according to its face element*.

Parameters	Coarse	Medium	Fine
Face element size (mm)	35	30	25
Growth rate	1.2	1.2	1.2
Defeature size (mm)	0.1	0.1	0.1
Total elements number	1,310,000	1,940,000	3,020,000
Total nodes number	241,000	355,000	548,000

In determine the best mesh quality, grid independence method is needed. Further discussion on grid independence test will be carried out in the next topic.

2.4 Numerical Analysis of Hydrodynamic Performances

Before running the simulation, setting up boundary conditions is important so that the desired result could be obtained. Figure 4 below represents the selections of boundary conditions according to its domain.

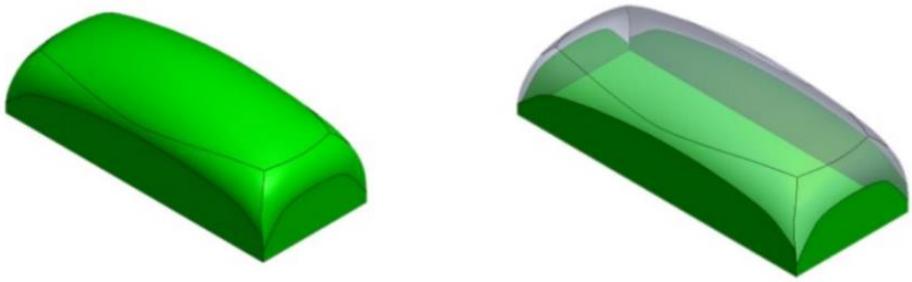


Fig. 4 *Boundary conditions of fluid domain (left) and fixed support (right).*

The left figure shows the green zone represents fluid domain while the outside surface represents the fluid wall. On the right figure, the green zone represents the fixed support.

3. Results and Discussion

This topic will discuss the results of grid independence test, effect of critical ship motion, pressure distribution, sloshing force and wall shear stress that was obtained from the CFD simulations.

3.1 Grid Independence Test

Grid independence test is important to determine the optimum mesh quality in order to generate accurate results within a reasonable time. Grid independence test is a process that can be used to determine the optimal grid condition to obtain the results via smallest number of grids [11]. Figure 5 below shows the grid independence test of different mesh qualities.

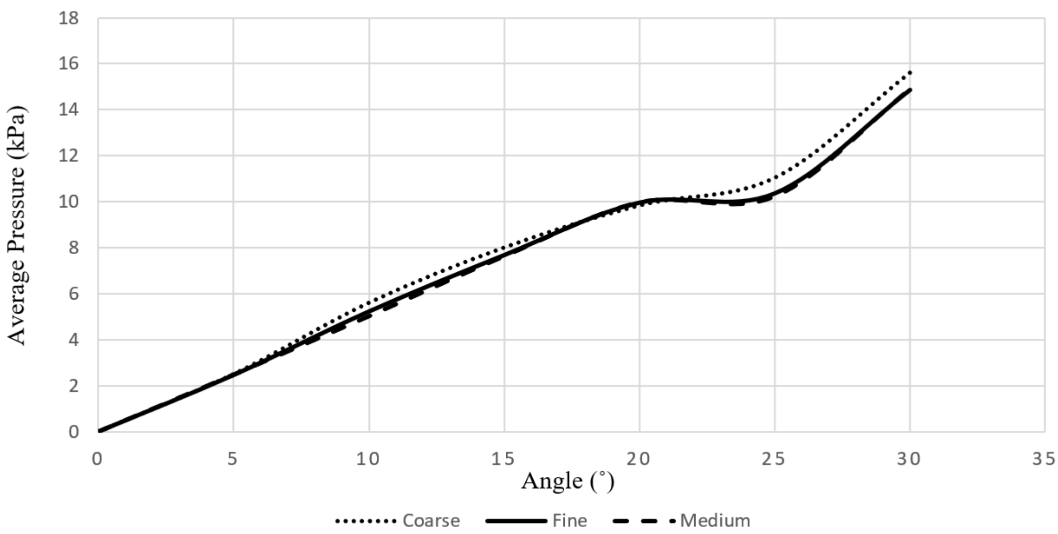


Fig. 5 *Grid independence test different mesh qualities.*

From the Figure 5 above, the most optimum mesh quality is the medium mesh. This is because the relative error between the fine and medium mesh is only 0.53% which is very small. So, the study was carried out using the medium mesh with 355,000 nodes.

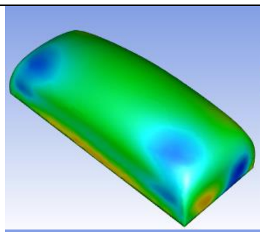
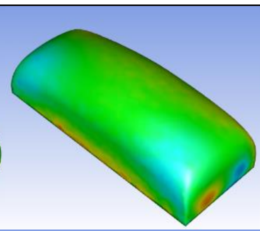
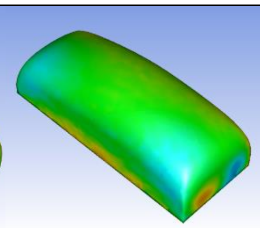
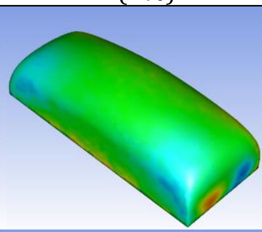
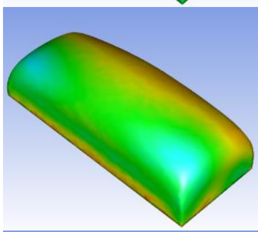
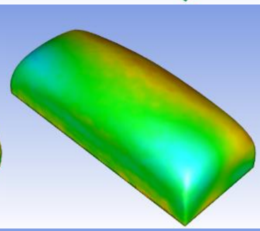
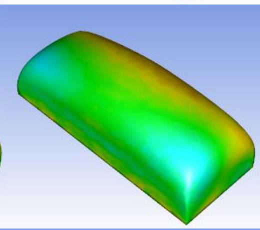
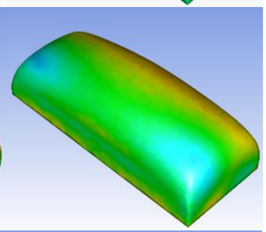
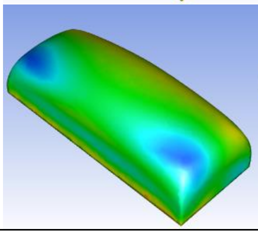
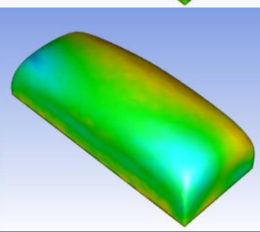
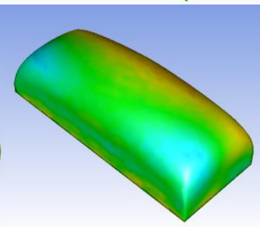
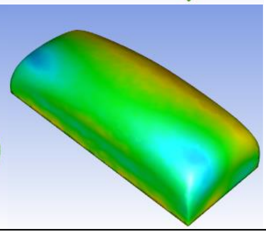
3.2 Hydrodynamic performances of Flexitank

The hydrodynamic performances include the effect of critical ship motion, pressure distribution, sloshing force and wall shear stress.

3.2.1 Effect of Critical Ship Motion

In this study, the effect of different filling fluid subjected to critical ship motion will be carried out according to the multiple filling volume. The critical ship motion is when the ship reach to its maximum roll degree before capsizing. From the previous study, it was stated that the maximum roll angle before capsizing is 30˚. Once the ship reaches to critical roll degree, the sloshing phenomenon will occur the most and would become more severe. This is due to the Table 3 shows the pressure distribution of different filling fluid density with multiple filling volume at 30˚ of ship roll motion.

Table 3 *Pressure distribution of different fluid density with multiple filling volume at 30˚ ship roll motion.*

Fluid Density	Filling Volume			
	+1.0%	+2.0%	+3.0%	Reference (0%)
Water				
CPO				
Latex				

From the Table 3, the difference in pressure distribution contour become more obvious. This is because once the ship roll angle reach 30˚, the sloshing effect inside the flexitank become stronger. The sloshing effect become stronger because of large amount of inertia cause by high angular velocity. With this information, by reducing the angular velocity, it can help to reduce the sloshing effect and at the same time lower the possibility of damaging the flexitank.

When compared with roll motion angle of 5˚ to 20˚ the sloshing effect are way weaker. This can be proved by the pressure distribution contour that almost look identical in colour and pattern for 5˚to 20˚. This is due to the lower inertia caused by the low angular velocity of roll ship motion. As a result, there are no significant changes in pressure distribution contour as each of the angular velocities for 5˚ to 20˚ gives lower inertia compared to angular velocity of 30˚.

3.2.2 Pressure Distribution on Flexitank

Based on the Figure 6 below, the pressure distribution of water to flexitank increases as the angle of roll motion increases. This increase in pressure is the result of the inertia created by the roll motion. Figure 6 also represents all the graph for the filling volume of water inside the flexitank. The reference filling volume of water has the highest pressure produced then followed by the 3% filling volume. On the other hand, when the filling volume is 2%, it produced the lowest pressure all the way from 0˚ to 30˚. On average, the pressure of reference filling volume is the highest with 8.72 kPa while the lowest is filling volume of 2% with 5.53 kP. Water has the lowest viscosity compared to CPO and latex. This means that the molecules inside the water can move easily causing fluid resistance to flow is low. Small change in volume and velocity can give more affect to the pressure compared to CPO and latex. This is one of the reason pressure graphs for water is more dispersed than CPO and latex based on different filling volume. In addition, water as a filling fluid is able to produce the highest maximum pressure of 14.90 kPa compared to CPO and latex which are lower because of its low viscosity. Even though the is only extra 2% of filling volume from the reference, which is 420 L, on average, there are 36.58%

changes in average pressure. Since water has low viscosity, this means slight change in volume would give huge effect to the changes in sloshing effect.

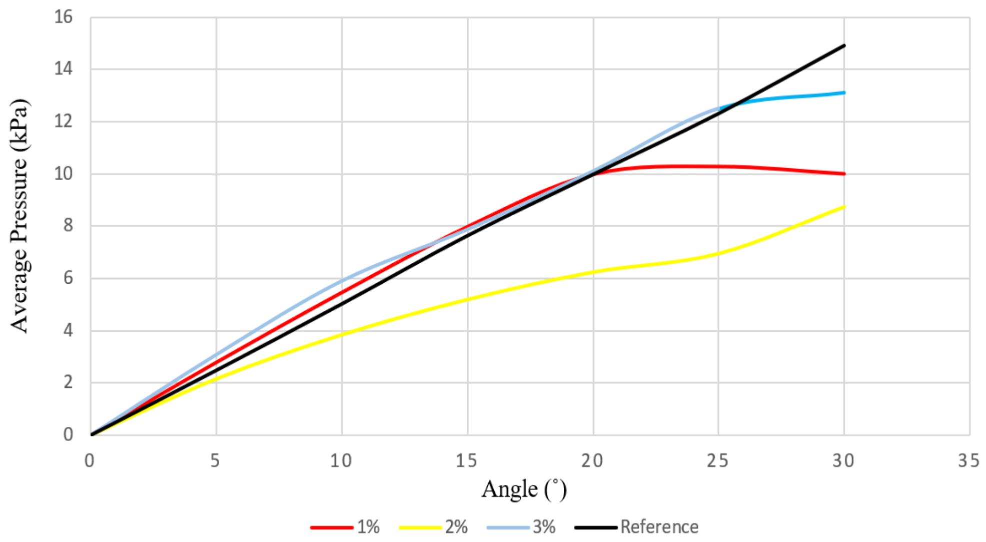


Fig. 6 *Average pressure of water.*

Figure 7 below shows the pressure distribution of CPO as filling fluid inside the flexitank. The average pressure of latex to flexitank increases as the angle of roll motion increases. From the Figure 7, the difference of pressure for 1%, 2%, 3% and reference filling volume is almost similar from 0˚ to 30˚. This is due to the CPO that have the highest viscosity compared to latex and water. This makes the CPO has the highest fluid resistant to flow. As a result, the difference in average pressure for all filling volume is the smallest compared to CPO and latex. Other than that, because of its high viscosity, CPO has the lowest maximum pressure of 11.70 kPa compared to water and latex. On average, the reference filling volume of CPO is the highest with 6.65 kPa and the lowest is filling volume of 2 % with 4.60 kPa. Furthermore, the contour of CPO pressure distribution shows no significant changes in sloshing effect although at different angle of roll motion. Since CPO has high viscosity, the changes in filling volume hardly effect the sloshing of fluid inside the flexitank. This can be proved by the low changes in pressure about 30.76% although there is only extra 420 L. Since water have lower viscosity than CPO, it is acceptable that CPO will gives lower changes in pressure distribution contour than water. Besides, high viscosity also reduces the inertia caused by the roll motion as the molecule could resist more in fluid flow.

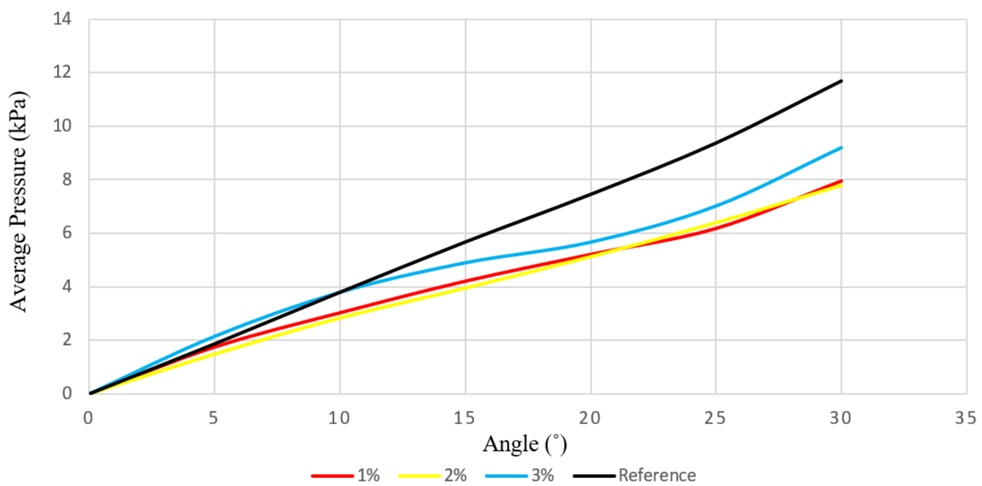


Fig. 7 *Average pressure of CPO.*

Based on the Figure 8 below, the pressure distribution of latex to flexitank increases as the angle of roll motion increases. This increase in pressure is the result of the momentum created by the roll motion as radial velocity increases. Figure 8 also represents all the graph for the filling volume of latex inside the flexitank. The reference filling volume of latex has the highest pressure produced then followed by the 3% filling volume. On average, the pressure of reference filling volume is the highest with 7.08 kPa while the lowest is filling volume of 1% with 4.78 kPa. Latex has lower viscosity compared to CPO but higher than water. This means that the molecule inside the latex is easier to move than CPO causing fluid resistance to flow is lower than CPO. Furthermore, this is also the factor that causing pressure graphs for latex is more dispersed than CPO. The maximum average pressure for latex is 12.40 kPa.

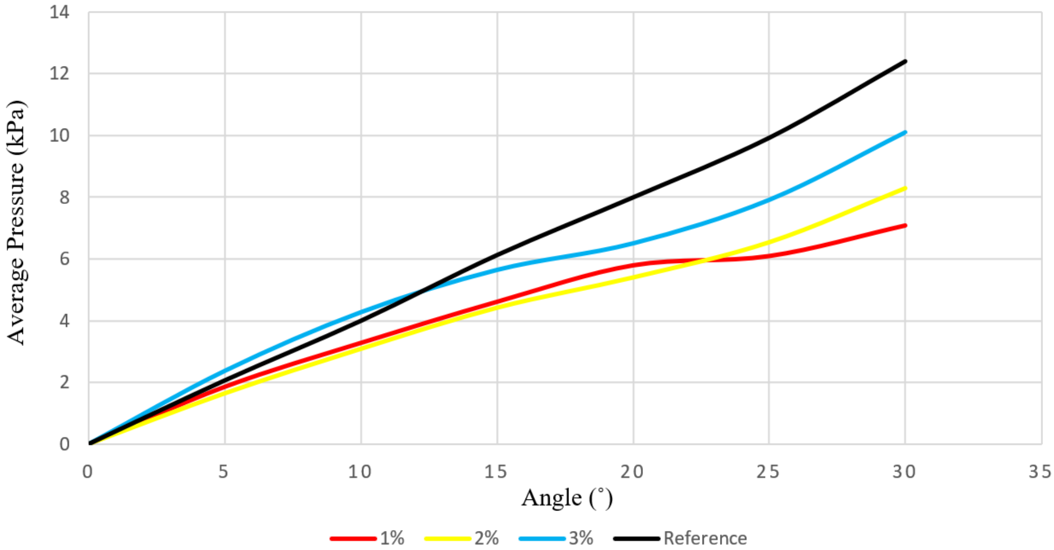


Fig. 8 *Average pressure of latex.*

In summary, as the viscosity increase the maximum average pressure will decrease. Besides, for all types of filling fluid, the reference filling volume has the highest average pressure. On the other hand, the lowest average pressure is 2% of filling volume for both water and CPO but 1% for latex. From the discussion, the highest maximum average pressure for water is 14.90 kPa, followed by latex 12.40 kPa and CPO with 11.70 kPa. LLDPE plastic packaging can withstand about 100 kPa to 200 kPa. This means that even though all the filling fluid density reach maximum average pressure, the flexitank would not be damaged.

3.2.3 Effect of Sloshing Force on Different Fully Volume of Flexitank

In hydrodynamic, sloshing force refers to the dynamic force acted on the tank subjected by the fluid motion. Sloshing force is directly proportional to pressure. If the pressure is increasing the sloshing force will also increases. Figure 8 below represents the average force of water inside the flexitank. As the roll motion angle increase, the average force of water inside flexitank also increase. This is because as the roll motion angle increase, more momentum is build resulting more force to be produced. The same principle also applied to CPO and latex.

Based on Figure 8, the reference filling volume has the maximum average force of 2.64 N which is the highest compared to CPO and latex. On average, 2% filling volume has the lowest average force of 0.98 N and reference filling volume is the highest with 1.54 N. Since force is directly proportional to pressure, viscosity will affect the force exerted by the fluid. Water has lowest viscosity than CPO and latex. So, water has the lowest resistant to fluid flow resulting in higher force produced.

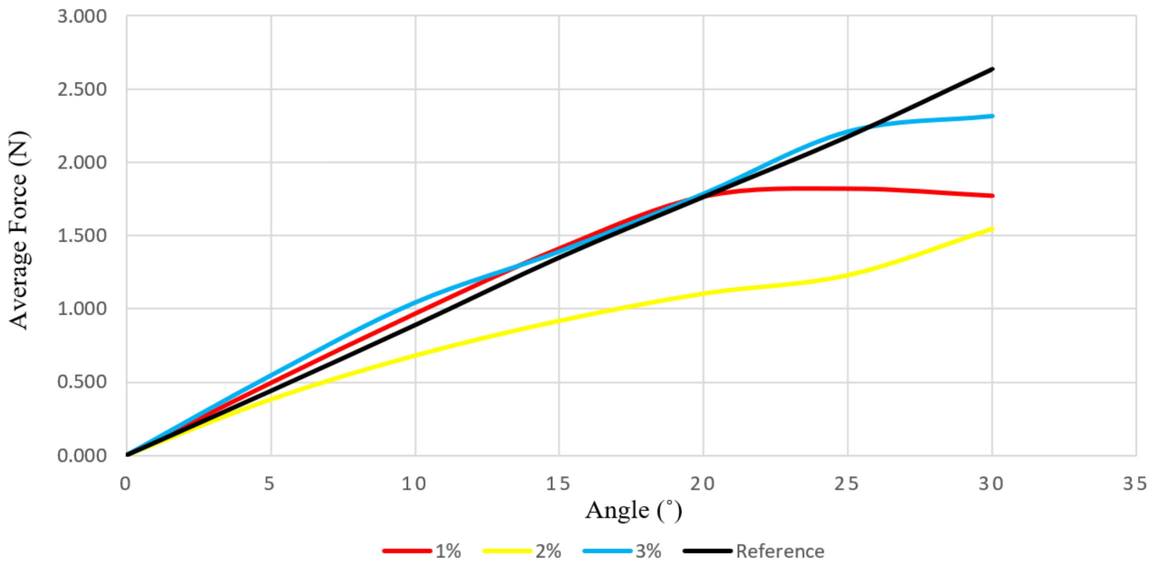


Fig. 9 *Sloshing force of water.*

Next, Figure 9 below represents the average force of CPO inside the flexitank. In contrast with Figure 9, the reference filling volume has the maximum average force of 2.64 N which is the lowest. This is because CPO has the highest viscosity. On average, 2% filling volume has the lowest average force of 0.82 N and reference filling volume is the highest with 1.18 N. Since of its high viscosity, CPO has the highest resistant to fluid flow resulting in lower force produced. However, CPO is a non-Newtonian fluid. This means that CPO's viscosity will change depending on the stress. This characteristic can alter the CPO to become either more solid or more liquid depending on the stress applied.

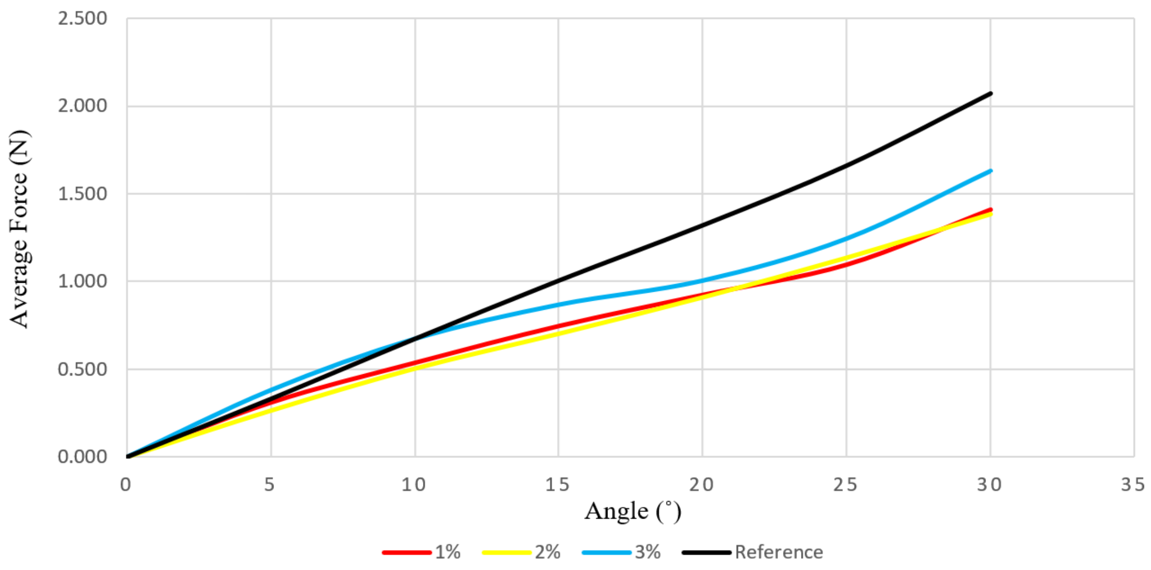


Fig. 9 *Sloshing force of CPO.*

Figure 10 below represents the average force of latex inside the flexitank. On average, 1% filling volume has the lowest average force of 0.85 N and reference filling volume is the highest with 1.25 N. Since of its viscosity is in the middle, latex has the medium resistant to fluid flow. As a result, latex produce force which is lower than water but higher than CPO. Latex is also a non-Newtonian fluid like CPO.

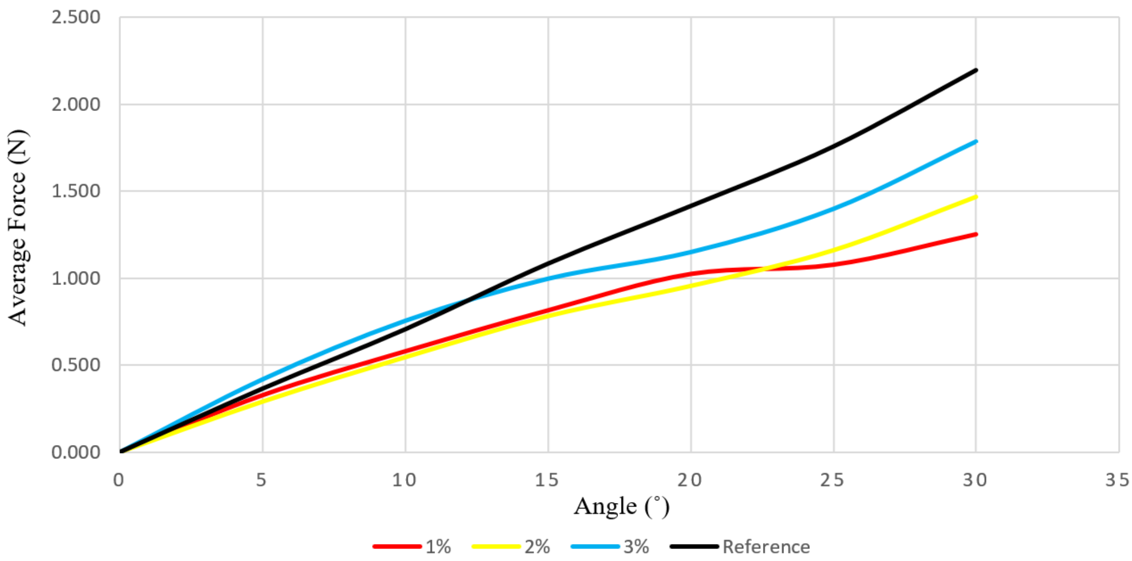


Fig. 10 Sloshing force of latex.

According to the discussion, average sloshing force exerted by the different filling fluid density to the flexitank is directly proportional to the average pressure. As we can see, both pattern for average sloshing force and average pressure is the same. It also concludes that; the lowest average sloshing force is 2% of filling volume for both water and CPO but 1% for latex. However, since both CPO and latex are non-Newtonian fluid, further understanding is needed to reduce the possibilities of damaging the flexitank.

3.2.4 Wall Shear Stress on Flexitank

Wall shear stress in hydrodynamic terms means force per unit area exerted by a fluid which is parallel to solid boundary. The friction between the fluid and container surface is measured which influence fluid movement near the solid boundary. Wall shear stress is affected by the viscosity, velocity and density of the fluid [66]. Higher velocity and lower viscosity will give greater wall shear stress. Since friction also affect the wall shear stress, the surface roughness between the flexitank and filling fluid density will also be considered.

Figure 11 below represents the wall shear stress of water inside the flexitank. Water has the highest density and lowest viscosity compared to CPO and latex. So, the maximum wall shear stress produced will be the lowest. This is because lower viscosity will reduce the fluid motion between the fluid and flexitank surface. Based on the Figure 11, the maximum wall shear stress for water is 9.57 Pa. In average, the reference filling volume has the highest wall shear stress of 5.96 Pa and the lowest wall shear stress is 5.22 Pa for 1% filling volume.

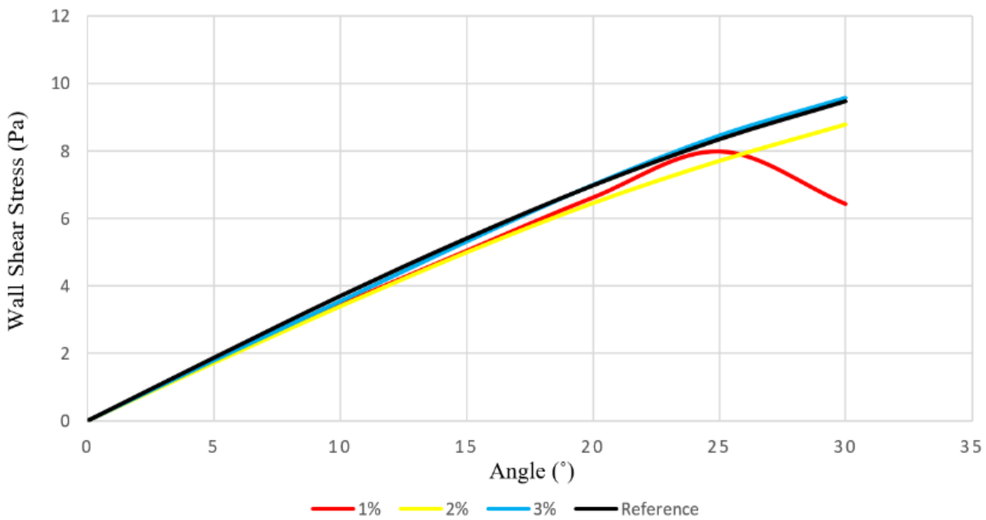


Fig. 11 *Wall shear stress of water.*

Figure 12 below represents the wall shear stress of CPO inside the flexitank. Unlike water, CPO has the lowest density and highest viscosity compared to water and latex. So, the maximum wall shear stress produced will be the highest. This is due to high viscosity that cause increase in fluid resistance between fluid layers and at the same time causing greater internal friction between the fluid. As a result, internal friction between the fluid and flexitank surface also increase. Based on the Figure 12, the maximum wall shear stress for CPO is 35.70 Pa. In average, the reference filling volume has the highest wall shear stress of 17.80 Pa and the lowest wall shear stress is 13.41 Pa for 1% filling volume.

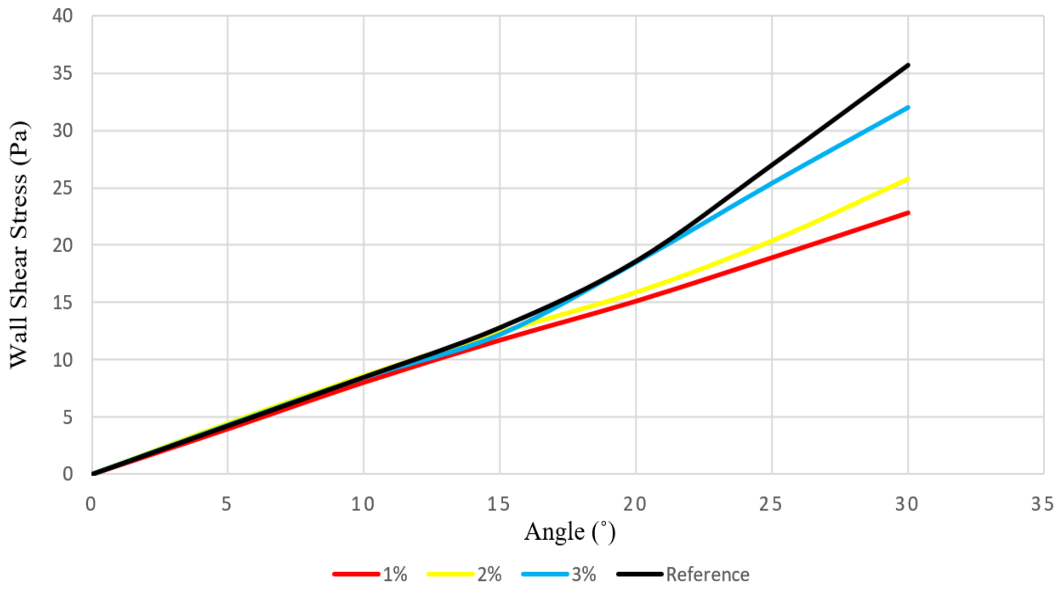


Fig. 12 *Wall shear stress of CPO.*

Figure 13 below represents the wall shear stress of latex inside the flexitank. Latex has the higher density but lower viscosity than CPO. On the opposite, latex has the lower density but higher viscosity than water. So, the maximum wall shear stress produced will be either highest or lowest. When compared to CPO, latex has lower internal friction between fluid layers resulting lower fluid resistance. Based on the Figure 13, the maximum wall shear stress for latex is 23.20 Pa. In average, the reference filling volume has the highest wall shear stress of 11.76 Pa and the lowest wall shear stress is 9.05 Pa for 1% filling volume.

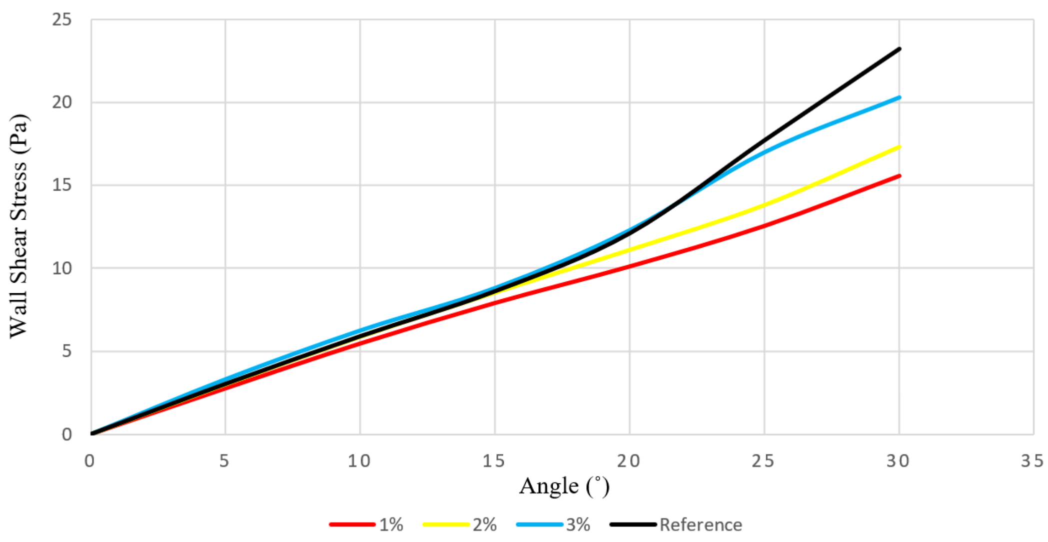


Figure 1

Fig. 13 *Wall shear stress of latex.*

In summary, as the viscosity increase, and density decrease the wall shear stress will increase. Besides, for all types of filling fluid, the reference filling volume has the highest wall shear stress. On the other hand, the lowest wall shear stress is 1% for all types of filling fluid density. The wall shear stress for CPO is 35.70 Pa, followed by latex 23.20 Pa and water with 9.57 Pa. It is important to understand and acknowledge the characteristics of each filling fluid density. This is crucial as it helps to prevents from the flexitank to withstand high wall shear stress if was not handled properly and without proper application. If high wall shear stress occurred, the flexitank could break and the filling fluid inside could leak out.

3.3 Selection Suitable Filling Volume of Flexitank

This topic will be discussed about the selection of suitable filling volumes of water CPO and latex inside the flexitank. By referring from the Figure 5 to Figure 13, the most suitable filling volume for water and CPO is 2% while latex is 1%. This is because 2% filling volume for water and CPO gives the lowest average pressure of 5.53 kPa and 4.60 kPa respectively. Latex on the other side with 1% filling volume gives lowest average pressure of 4.78 kPa.

4. Conclusion

In conclusion, the roll ship motion does give significant change in the hydrodynamic behaviour of different filling volume and filling fluid density. As the angular velocity increases or as the angle of ship roll motion increases, the average pressure and average force increases while wall shear stress decreases.

It is found that when the flexitank is filled with extra 1%, 2% and 3% from its reference volume, the average pressure, average force and wall shear stress said to be lower than the reference. In terms of average pressure and average force, it is found that viscosity can affect the results obtained. The higher the viscosity, the lower the average pressure and average force obtained. On the other hand, in terms of wall shear stress result, it is the opposite. The higher the viscosity, the lower the wall shear stress obtained.

Lastly, the suitable filling volume for each filling fluid density can be selected according to the results of average pressure, average force and wall shear stress. For water and CPO, the suitable filling volume is 2% while for latex is 1%.

5. Recommendations

Below is the list of recommendations for future research:

1. Improving the material or creating new materials is recommended.
2. Generating better and optimal design in increasing the durability of flexitank.
3. Since this study focuses on only roll ship motion, it is also recommended that future works should investigate other ship motion such as yawing and pitching.
4. Include the interaction of CFD-FSI subjected to ship motion or better a prototype. This could potentially give a bigger picture of the ship transportation of flexitank environment.
5. With the help of newer and faster technology software, it is also recommended that future work should use more detailed and accurate CFD simulations.

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