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SLOSHING EFFECTS ON THE LONGITUDINAL TANK TYPE C DUE TO MOTIONS OF THE LNG SHIP

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This paper described the sloshing simulation of the LNG (Liquid Natural Gas) tank due to the LNG ship's motion during operation at sea. The ship motions in irregular wave were obtained by 3D diffraction panel method in frequency domain. Coupled motions of surge, heave, and pitch due to the head sea of incoming wave were considered in the solving of longitudinal sloshing problem in certain range of wave frequency. The LNG sloshing on the Bilobe tank type was studied by using the Computational Fluid Dynamic technique with attention to obtain a maximum pressure that was occured on inner wall of the tank. Three cases of the LNG filling level including an empty (10%h), a half (50%h), and a full (90%h) conditions of tank height (h) were considered in order to investigate the free surface effect due to the LNG sloshing. The simulation results have shown that the maksimum pressure due to sloshing at inner wall have increased by 11.1%, 5.4%, and 11.5% while in the load conditions of full, a half, and an empty respectively. The maximum pressure that occurs did not exceed 6 percent based on the calculation of probability occurrence for all LNG filling level conditions.

Key words: sloshing, ship motion, LNG tank type c, computational fluid dynamic

INTRODUCTION

In general, an excessive ship motion could cause dissonance of passengers, increasing wave resistance, and occurrence of sloshing phenomena due to liquid-free LNG surface in the tank. Sloshing could be defined as the fluid movement inside a container due to free surfaces and external forces that cause a sudden load of fluid. The amount of liquid free LNG surface pressure could have a direct impact cause damage to the tank wall [1]. Another effect of sloshing was to increase the LNG temperature which affects the increasing pressure in the tank [2], and if the pressure tank exceeds the maximum limit of the design pressure, it could cause damage. The major problem in the study of sloshing was how to estimate the hydrodynamic pressure, force, and moment distribution of the LNG free sur-face against the inner wall of the tank [3].

Sloshing phenomenon was successfully evaluated by using Computational Fluid Dyna- mic (CFD) technique which was the Navier-Stokes equation solved using the implicit time scheme finite volume method (VOF) [4]. The VOF method was successfull applied to solve the sloshing problem of the rectangular tank [10]. The volume of fluid (VOF) method was also used to track the free surface of sloshing. The liquid sloshing behavior in 2-D rectangular tank was simulated consider to the multiple coupled external excitations imposed through the motions of the tank by using the dynamic mesh technique [11].

The effects of the inner tank sloshing play an important role in the motions of ship system. An experiment work was performed to study the phenomena of liquid sloshing in partially filled tank being mounted on a FLNG due to a regular wave [5]. The numerical study was also carried out with aim to observe on a physical phenomenon of the violent sloshing flow as well as the development of the proper mathematical models for practical use [5]. The FLNG motion performance due to sloshing effects was observed with the experimental and the numerical approach [6].

Commontly, the motions of a FLNG ship were solved by the solution of a linear potential theory under assumption of small amplitude ship and wave motions. The diffraction and radiation problems were carried out by the three-dimensional panel method [6]. Another work of the LNG ship motion in irregular wave were studied using the 3D diffraction theory as explained in [10].

In this paper, the CFD method was used to investigate the liquid sloshing behaviors in the Bilobe tank which was a type of Iso tank as described in [8]. The sloshing simulation was performed using the FLUENT software while the tank system was modelled by the GAMBIT software. The volume of fluid (VOF) method was adopted to solve the sloshing problems, and the external excitation was imposed to the tank motion with the dynamic mesh technique. Some other studies also might be found in research [10, 11].

The sloshing study was performed in the 2D-longitudinal Bilobe tank under the multiple coupled external excitations imposed at the same time with step procedures follow [7]. The variations of fluid volume inside the tank were considered including the conditions of ballast 10% of tank height (h), a half 50%h, and full 90%h. Maximum pressures in three different areas of the inner tank i.e after-wall, bottom-wall, and front wall might be identified to determine where sensitive area in the tank were due to static and dynamic pressure. The excitation of

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the LNG tank has followed the ship's motion response which were coupled surge, heave, and pitch motions in irregular waves within range of the 0.8 - 1.2rad/sec wave frequency.

METHODOLOGY

For ship's motion analysis, the definition of the coordinate system was described. The coordinate system XYZO had the origin O in the vessel center of mass, X-axis positive in the bow direction, the Y-axis toward port side direction and Z-axis toward up direction, see Figure 1. The ship motions were defined in this coordinate system including (1) surge, (2) sway and (3) heave motion were measured along the X-axis, Y-axis and Z-axis respec-tively; the ship motions of (4) roll, (5) pitch and (6) yaw were measured about X-axis, Y-axis and Z-axis respectively. Under the assumption of small-amplitude, the motions of ship in frequency domain could be solved by the linearized potential flow theory. Generally, the motion equation was given in Equation (1).

$$\left[M_{ij}+m_{ij}(\omega)\right]\frac{\partial^2\vec{\varphi}}{\partial t^2}+\left[b_{ij}(\omega)\right]\frac{\partial\vec{\varphi}}{\partial t}+\left[c_{ij}(\omega)\right]\vec{\varphi}=\vec{F}(t) \quad (1)$$

where M_{ij} and m_{ij} (ω) were mass and added mass matrices, b_{ij} (ω) was damping coefficient matrix, and c_{ij} (ω) was restoring coefficient matrix, F(t) was exciting force, i, j where 1, ... , 6 as ship motions considered, and ω was wave frequency.

The body motions , and force vectors , could be written as solutions of Equation (1) presented in Equation (2) and (3) respectively.

$$\vec{\varphi}=R_e\left(\varphi_{j,0}e^{i\omega t}\right) \quad (2)$$

$$\vec{F}(t)=R_e\left(F_{j,0}e^{i\omega t}\right) \quad (3)$$

Response of ship motions were evaluated using the Panel method follow [8]. The ship hull form was modelled to full scale as a fined mesh with panels representing the hull surface as depicted in Figure 1 with the main dimensions as shown in Table 1. The wetted surface of the LNG ship was discretized into number of panels about 7126. On the surface body, the hydrodynamic forces were obtained by imposing boundary conditions on the wetted surface of the LNG ship in the infinity depth water. The wave heading angle, μ, relative to the vessel direction was defined i.e head sea (1800) while the wave approach to the ship's bow.

In the computation process, the input data required were the main dimensions, the hull shape (lines plan), the centre of gravity, and the moment of inertia. And the outputs were given in the forms of the Response Amplitude Operator (RAO) for the six degrees of freedom (6-DOF) motions such as surge, sway, heave, roll, pitch, and yaw as function of encountering frequency. The data of wave was taken from the Agency of Meteorological, Climatology, and Geophysics of Indonesia including height, period, and direction of wave. Based on these data, the wave spectrum could be determined using the standard formula of JONSWAP [9].

Table 1: The main dimensions of the LNG ship

Item	Value	Unit
Length of hull, (L_{wl})	103.26	m
Breadth of hull (B)	16.8	m
Depth of hull (H)	5.05	m
Draft of hull (T)	3.4	m
Displacement (Δ)	5257.6	ton
Radius of gyration in X-axis	5.7	m
Radius of gyration in Y-axis	25.8	m
Radius of gyration in Z-axis	26.9	m
Centre of buoyancy from AP	50.6	m
Speed of ship (V_s)	11	knot

For the sloshing case of the longitudinal tank, the considered motions of the LNG ship were only surge, heave, and pitch as the most dominant motions. And the incoming wave was considered from a head direction of the ship's hull. Furthermore, response spectrum of the LNG ship motions in irregular waves, Sz (ωe), were calculated by multiplication of the RAO and the encountered wave spectrum, Sζ (ωe), as shown in Equation (4).

$$S_z(\omega_e) = S_\zeta(\omega_e)\ .\ RAO(\omega_e) \quad (4)$$

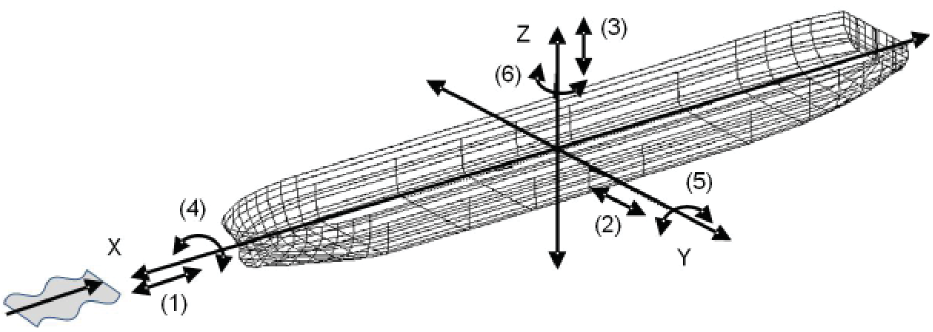


Figure 1: Co-ordinat system of ship motions

Where ω_e was encountered wave frequency.

The behavior of sloshing was represented by an incompressible viscous fluid flow with a free surface which was governed by the Navier-Stokes equation and the continuity equation as shown in Equation (5) and (6) respectively.

$$\frac{\partial y}{\partial x} + \nabla.(uu) = -\frac{1}{\rho}\nabla.\left[\frac{\mu}{\rho}\left(\nabla u + \nabla u^T\right)\right] + \rho g + F \quad (5)$$

$$\nabla.u = 0 \quad (6)$$

Where *u* was the velocity, *p* the pressure, *ρ* the density, *g* the acceleration of gravity, *F* a body force, and *μ* the viscosity of the mixture. In this work, the Reynolds number of fluid flow was above 3.5E5 so that flow was identified as turbulent.

The sloshing of the Bilobe tank were under imposed by the multiple-coupled external excitations simultaneously. And the velocity of excitations were represented in Equation (7).

$$\begin{cases} \dot{x} = \omega x_a \cos \omega t & \text{surge} \\ \dot{z} = \omega z_a \cos \omega t & \text{heave} \\ \dot{\theta} = \omega \theta_a \cos \omega t & \text{pitch} \end{cases} \quad (7)$$

There were three Iso tanks on the ship with each capacity of 1270 m^3, and one located on the middle of vessel was selected to be studied. The centre of gravity was assumed to be located at the same point as the center of ship. The tank design was specifically shown in the form of the 2-dimensional longitudinal tank in Figure 2, while the length 17.2 m, the height 6.9 m, the half breadth 6.65 m, and the longitudinal area about 73.84 m^2. The tank was equipped with the insulation thickness of 300 mm.

Numerically, the LNG Belobe tank was modelled using GAMBIT and the body was discretized into certain numbers of triangular mesh. The optimum numbers of mesh were determined after perform a grid independence study and it was known about 19756 panels. The panel size which was modelled evenly and equally throughout the fluid and the gas portions inside the tank.

Figure 3 described the simulation model of the LNG Bilobe tank in a half load condition. Two other variations of loads were considered the ballast and the full condition. The sloshing simulations were conducted using FLUENT which was the popular the CFD software particularly the approach of the Fluid Volume Method (VOF).

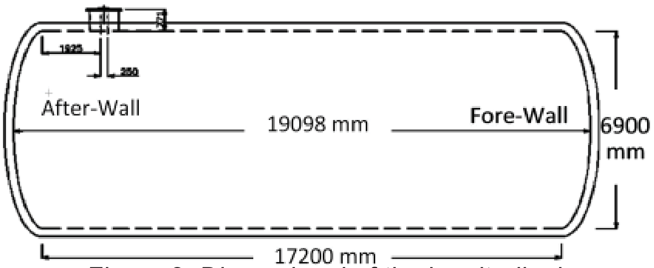


Figure 2: Dimensional of the longitudinal Bilobe tank type

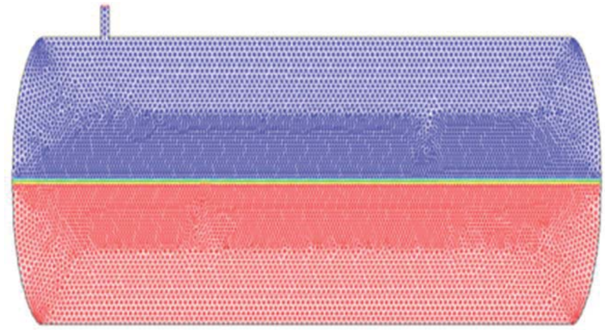


Figure 3: Modelling in a half-load condition

The set-up of simulation was described i.e the solver-based pressure solving model with set-up of implicit, unsteady, and non-iterative time advancement formula. The fluid flow was modelled in two phases with the volume of fluid (VOF) method. The parameters were the explicitly determined and the implicit body force formula was selected. The flow type was assumed turbulent with k-epsilon selected. The standard model was defined as standard wall function. This two-phase material was specified by its density value i.e. LNG and air. The operational conditions such as pressure of fluid, acceleration of gravity, temperature of fluid, and density were determined according to fluid characteristic. The fluid boundary condition of tank wall was specified with zero velocity condition. Meshing was modelled into the dynamic mesh using layering method and the dynamic mesh zone was set up on the rigid body of the tank wall.

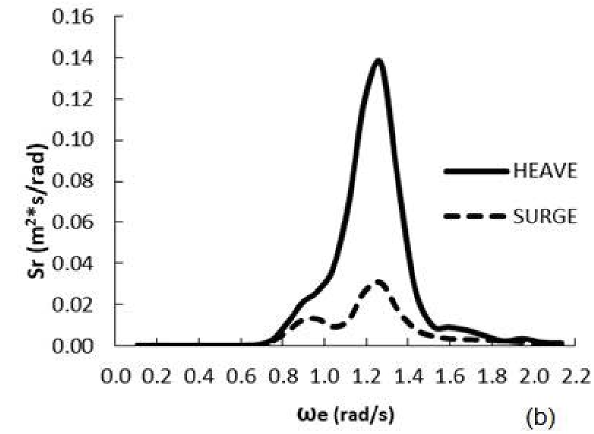
The user defined was determined by uploading the libudf (library user defined function) file into the UDF library, which was ship motions promotion code, and compiled it. The results of the simulation were presented in terms of the pressure value per unit of time step on the tank wall and the longitudinal bulkhead. The value of the maximum pressure and it located on the tank wall, the bottom, and the longitudinal bulkhead might be precisely predicted. Probability occurrence of the maximum pressure was predicted by the probability exceed method using the Weibull 3-parameter distribution with 95% confidence level.

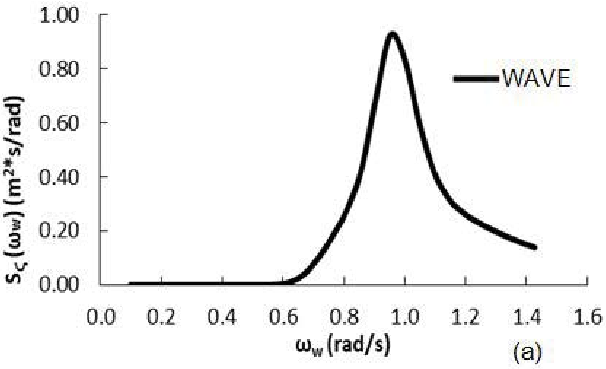
RESULTS AND DISCUSSIONS

Numerical results of the ship motion in regular waves were presented in terms of the RAO of surge, heave, and pitch motion. The translation motions of surge and heave were presented per unit wave amplitude, and the rotation motion of pitch was presented per unit degree amplitude. The surge, heave, and pitch were suitable motions to analyze liquid sloshing on the 2D-filling tank longitudinally. The wave heading angle, μ, relative to the vessel direction was defined that the head sea (180°) was the wave approach to the vessel's bow. The maximum response of motions had been taken, and for this reason the incoming wave come to the ship's bow or head sea (μ = 180°) was a suitable case for the purpose of sloshing analysis longitudinally.

Response motions of the coupled surge, heave, and pitch were obtained by multiplica-tion of the RAO and the encountered wave spectrum as formulated in Equation (4). Figure 4 illustrated the JONSWAP spectrum based on the environmental of the ship operation area, and the response spectrums of surge, heave, and pitch motions.

Furthermore, the response motions were converted into the LNG tank excitation for the total range of frequency throughout sloshing simulation. Figure 5 shown the simulation results of the static and dynamic pressure at the 10% loading condition taken from the back wall (after wall) area, bottom wall, and fore wall. The static pressure was the pressure while the fluid was not moving. Fluid would press against the tank wall equally in all directions. The dynamic pressure was defined as the pressure of a fluid that results from its motion.





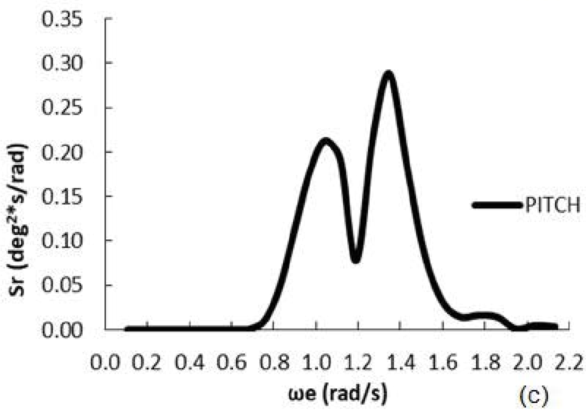


Figure 4: (a) Wave Spectrum, (b) Surge and Heave of responses spectrum, (c) Pitch of response spectrum

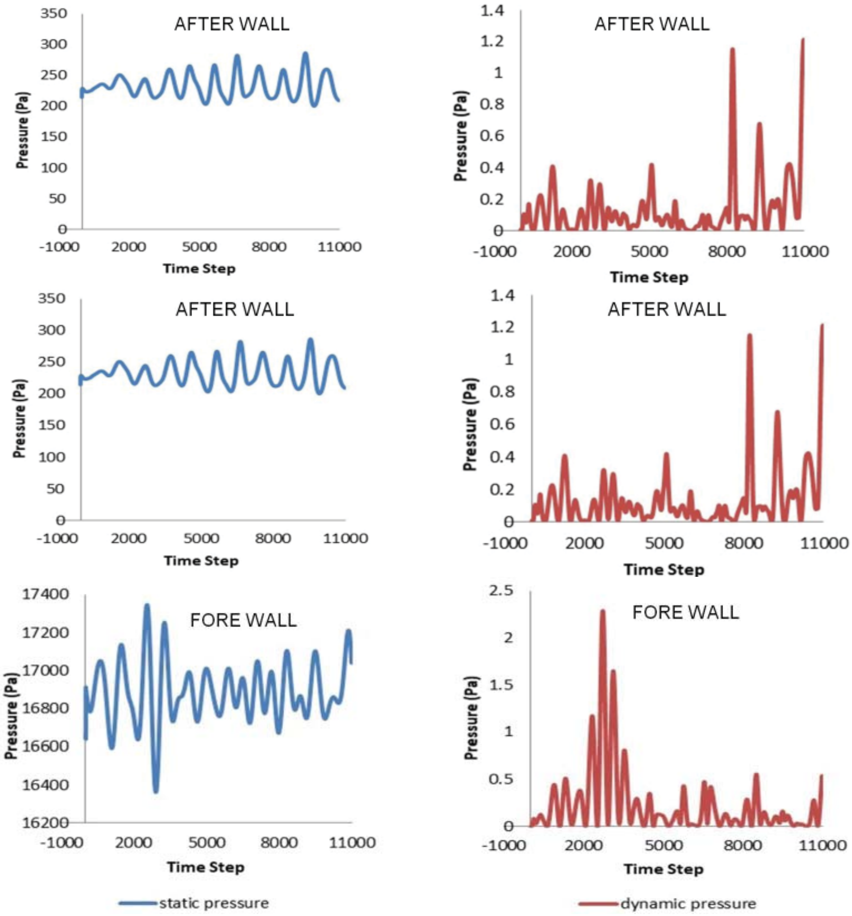


Figure 5: Static and dynamic pressure on wall tank for 10%h load condition

The static and dynamic pressure were recorded from the sloshing simulation carried out within 55 second for each time step of 0.005 second. The maximum static pressure on the area of back wall was found about 280.44 Pa occurred at the time of 54.84 second. The maximum dynamic pressure was about 1.21 Pa occurred on the back wall area at the time of 54.85 second. And the total number of time step was about 10970

The maximum pressure of the static and dynamic pressure on the area of bottom wall were about 3473.65 Pa and 9.21 Pa while it was occurred at the time step of 2532 and 2714 respectively. The maximum pressure on the fore wall were about 286.72 Pa of the static pressure and 2.29 Pa of the dynamic pressure and both were occurred at the time step of 9568 and 2714 respectively.

The effects of sloshing were predicted by getting the difference between the maximum and the initial pressure. The details as follow, the static pressure at the after wall increased up to 58.41 Pa, and the dynamic pressure to 1.21 Pa. The pressures on the after wall area had almost the same value with the pressure on the fore wall area at any time steps. All the cases of static and dynamic pressure which were pointed at the walls of fore, bottom, and after for variation filling level of 10%h, 50%h, and 90%h, were recapitulated in Table 2.

The probability exceed processes were conducted in order to figure out how many chances the maximum pressure occurred on the tank walls within sloshing simulations. The probability of exceeding used a Weibull 3-parameter distribution with a 95% confidence level. Figure 6a shows the probability plot of static pressure regarding the after wall in the filling condition of 10%, which was obtained by the Weibull 3-parameter such as the shape = 1.605, scale = 34.21, and thresh = 195.4. The three values were used further as an input to find the distribution density function as shown in Figure 6b. Figure 6 explained that the probability of occurrence of the maximum static pressure on the after wall while filling level of 10%h was about 1.39%.

Furthermore, with the same approach and procedures, the probability of the occurrence of maximum pressures for each filling levels could be calculated at certain location in the LNG tank. A brief summary of the results of calculations could be seen in Table 3.

Table 3 explained the probability exceed of maximum

Table 2: Recapitulation of the sloshing effect

Variations of Filling Condition	Effect of Sloshing					
	After-Wall		Bottom-Wall		Fore-Wall	
	Static (Pa)	Dynamic (Pa)	Static (Pa)	Dynamic (Pa)	Static (Pa)	Dynamic (Pa)
10% h	58.41	1.2	261.06	9.21	72.616	2.29
50% h	312.07	5.4	706.93	9.16	339.11	9.59
90% h	1935.41	15.5	2378.52	9.34	1860.46	20.76

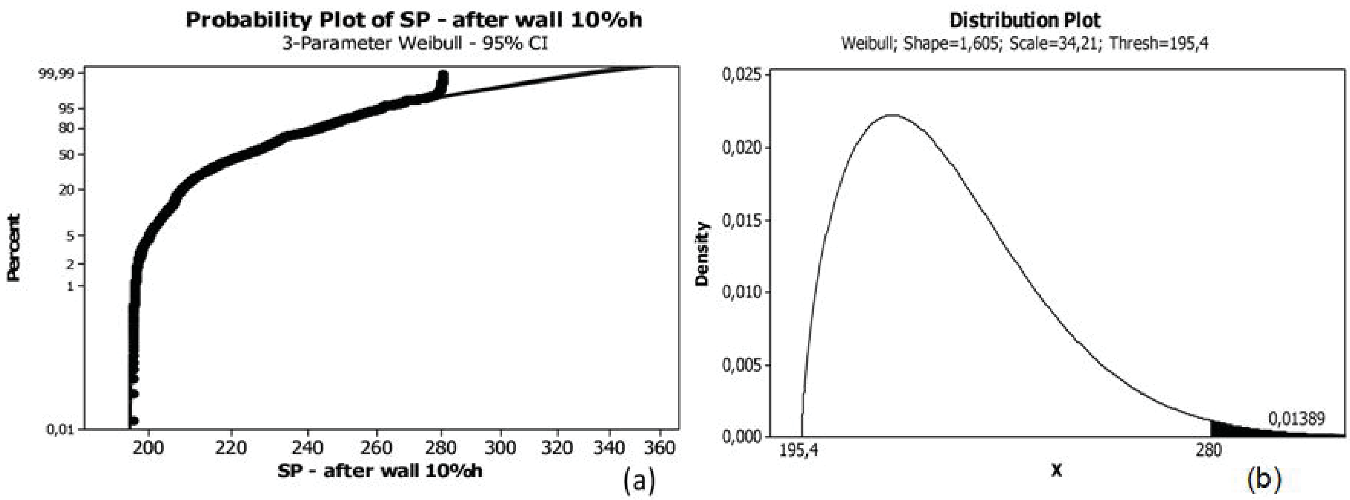


Figure 6: (a) probability exceed distribution of static pressure and (b) probability density function of the static pressure at after wall in 10%h filling condition

pressure on the tank wall due to sloshing. It was known that the highest probability about 5.78% that was occured in the bottom wall of the tank due to the dynamic fluid load under the filling condition of 90%h. The probability exceed of the maximum pressure was occurred on the front wall about 2.8% due to static loads under the condition of 90%h. The probability exceeds decreased to 2.75% and 0.93% which were under conditions of filling load 50%h and 10%h respectively. Overall, the probability exceed value in Table 3 did not exceed 6%.

CONCLUSIONS

The effect of sloshing on the LNG load tanks due to the coupled surge, heave, and pitch motions of the LNG ship at the sea were investigated. It had been simulated in the three conditions of LNG filling level including the conditions of ballast load (10%h), a half load (50%h), and full load (90%h). The results explained the maximum pressure were occurred on the wall areas of the Bilobe tanks at the filling load condition of ballast, a half, and full were about 4053,53 Pa, 26805,55 Pa, and 60113,11 Pa respectively. And the effect of sloshing due to fluid pressure distribution on the wall areas were totally about 404.80 Pa, 1382. 22 Pa, and 6219.94 Pa for the filling level conditions of ballast, a half-full, and full respectively. It could be concluded that the greater LNG load in the Bilobe tank could cause the greater effect of LNG sloshing. The results of the probability exceed explained the probability occurrance of the maximum pressure on each inner side of the LNG tank wall at all loading conditions were not more than 6%. This indicates that the opportunity for maximum pressure was relatively small or could be uncritical condition.

Table 3: Recapitulations of probability exceed of the maximum pressure

Variations of Filling Condition	Probability Exceed		
	After-Wall	Bottom-Wall	Fore-Wall
	Static Pressure		
10% h	1.39%	0.06%	0.93%
50% h	2.57%	0.20%	2.75%
90% h	1.03%	0.05%	2.80%
Dynamic Pressure			
10%h	0.21%	0.44%	0.20%
50%h	0.12%	0.33%	0.23%
90%h	2.15%	5.78%	0.53%

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