Nonlinear Finite Element Analysis of Pressurized LPG Toroidal Tank with Radial Flush Nozzle

Asnawi Lubis[1], Ahmad Suudi, dan Novri Tanti

Jurusan Teknik Mesin, Fakultas Teknik, Universitas Lampung
Jalan Professor Soemantri Brojonegoro No.1 Bandar Lampung, 35145
[1]Email: asnawi-lubis@unila.ac.id

Abstract

This paper reports a nonlinear finite element analysis of pressurized circular toroidal tank with radial flush cylindrical nozzle used for gas fuel tank of personal car. The analysis determines the position of radial cylindrical nozzle that gives the highest limit pressure. Toroidal tank having volume of 45 liters and radius ratio of 3 were used in this analysis. Cylindrical nozzle of 12.5 mm diameter and 10 mm height was attached in radial direction of toroidal cross section. The position of nozzle was checked for five points: extrados, 45^0 from extrados, crown, 45^0 from crown, and intrados. The maximum applied internal pressure was 1.5 times pressure to yield. Limits pressure were obtained via nonlinear finite element analysis using the well-known Newton-Raphson algorithm with large deformation. It was found that the best design for nozzle position, indicated by the highest limit pressure, is located at the extrados. For any circumstances, nozzle can be located between extrados and crown, but should not be located between crown and intrados. This result conforms to the membrane theory that the highest stress in toroidal shell under internal pressure occurs at intrados and nozzle shall not be located next to that location.

Keywords: pressurized toroidal tank, limit pressure, finite element analysis

Introduction

In order to reduce the subsidy of oil fuel, the goverment of Indonesia try to initiate conversion program from oil fuel (BBM) to gas fuel (BBG) for personal cars. For long term, this third option (first to limit the usage of oil fuel, second to increase the price of oil fuel) is very appropriate. However, the goverment of Indonesia needs to build infrastructures and technology before applying this option, particularly public access to gas fuel (SPBU) and conversion kit from oil fuel to gas fuel.

One of the components of combustion system that needs to be redesigned is fuel tank. Fuel tank for gas as a pressure vessel must be designed carefully against burst type failure. Perfect design need to be done to avoid explosion. From economic point of view, toroidal shape is the most appropriate shape for car's fuel tank. By classical mechanics, it can also easily be proof that toroidal tank can withstand internal pressure load much higher than an equivalent cylindrical, spherical, or conical shape. Here, toroidal tank is proposed for gas fuel tank of personal cars.

The study of static dan dynamic behaviour of toroidal shell had been carried out by many researchers. Free vibration analysisi of two toroidal shell had been carried out by Tzou dan Wang (2003) to control the vibration of toroidal shell structure and to enhance its accuracy and reliability. Jiang dan Redekop (2003) carried out analysis of static dan dynamic charecteristics of orthotropic toroidal shells of variable thickness and obtained solution based on the shell equations of Sanders-Budiansky. Experimental limit external pressure tests had been carried out on three toroidal tanks by Btachut (2003), two of the tanks were fabricated from mild steel by spinning two part of toroidal and welded at its intrados and extrados, while another one was fabricated by welding circumferentially four 90-degree elbows. Stress and strain analysis of LPG toroidal tanks had been carried out by Velickovic (2007) using finite element method. Kisioglu (2009) is one of few researcher who had carried out investigation on limit pressure of toroidal tank of LPG storage for vehicle in Turkey. Strength design of toroidal tank for LPG 3kg was reported by Lubis (2011) and Lubis, et al (2012). To the best of author's knowledge, it was not found in modern literature a comprehensive study of strength design of toroidal tanks for personal cars, particularly for using in Indonesia. This paper reports results of nonlinear finite element analysis of toroidal tank having radial flush nozzle to be used for personal cars in Indonesia.

Finite Element Modelling

Toroidal tank model used in this study was modeled based on volume of tank of 45 liters. Volume of a toroidal tank can be calculated using the following equation:

$$V = \pi r^2 . 2\pi R \qquad (1)$$

where, r is toroidal cross-section radius, and R is radius of curvature of toroidal. Equation (1) can be written in the following form:

$$V = 2\pi^2 r^3 \rho \qquad (2)$$

or,

$$r = \left(\frac{V}{6\pi^2}\right)^{1/3} \qquad (3)$$

For a toroidal tank having volume of 45 liter = 45 x 10^6 mm^3, the corresponding radius is:

$$r = \left(\frac{45x10^6}{6\pi^2}\right)^{1/3} = 91.3mm$$

or R = 273.8 mm.

Membrane theory of shell shows that the highest stress for a toroidal shell under internal pressure located at intrados and the lowest located at extrados. This fact guides engineers not to located a nozzle at intrados, and if possible, located at extrados

In this study, geometry modeling was done in toroidal coordinate. The torus was obtained by rotating a circle of radius r about a circle of radius R as shown in Figure 1. Handguard was not modeled with an assumption that this accessories would not affect the limit pressure.

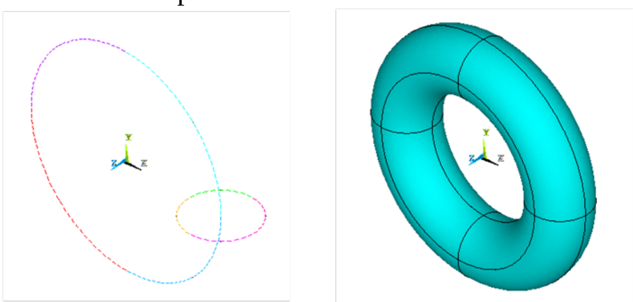

Fig.1 Geometry modeling of a torus

Material for the tank was the same as the material for PERTAMINA LPG 3kg tank, i.e., steel sheet produced by PT Krakatau Steel, having specification JIS G3116 SG-295, and thickness of 2.3 mm. Material for handguard dan footring was carbon steel with specification JIS G3101 SS42, thickness of 2.5 mm also produced by PT Krakatau Steel. Meanwhile, welding wire used for circumferential joint of the tank was imported from China with specification EM 12 K [Winarto dan Wahyuadi, 2008].

Material properties needed for finite element modeling are Young's modulus E, yield stress σ_Y, and Poisson's ratio ν, the values for those properties are 207 GPa, 295 MPa, dan 0.3 respectively [Winarto dan Wahyuadi, 2008]. In this analysis, it was assumed that the toroidal tank was fabricated by welding four 90^0 elbows circumferentialy. The welding joint was assumed to be perfect (joint efficiency equals to unity). Other assumption was uniform thickness of the tank.

Element type used was SHELL281 of the ANSYS element library. The element has eight nodes with six degrees of freedom for every node: displacement in the x, y, dan z direction, and rotation about the x, y, dan z axis. The element can be used for linier analysis, large rotation, and non-linier analysis with large strain. Typical finite elemen model include radial flush nozzle is shown in Fig.2.

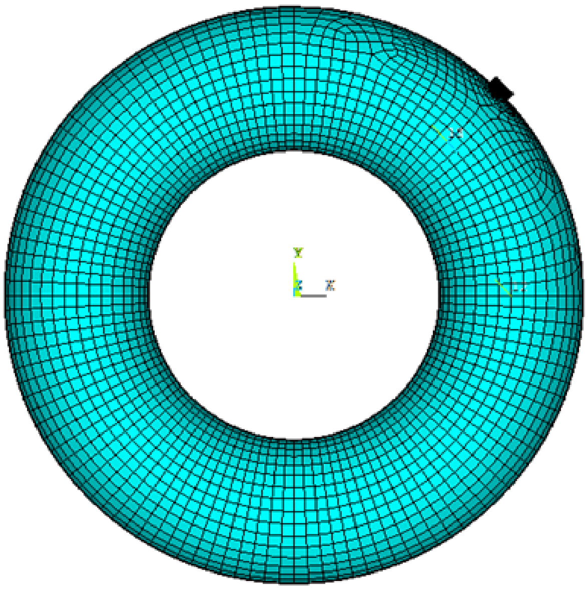

Fig.2 Typical FE model of a toroidal tank

For finite element model shown in Fig.2 subjected to internal pressure loading, boundary condition that needs to be applied was zero displacement for all nodes at a cross-section as shown in Fig.3. Internal pressure load (MPa) to be applied to find the limit pressure can be estimated by calculating the pressure to yield, σ_y (Lubis, et. al., 2012):

$$p_Y = \frac{2t.\sigma_Y}{r} \frac{\rho - 1}{2\rho - 1} \qquad (4)$$

Equation (4) is based on stress at intrados position where highest stress occurs. For cross-section radius r = 91.3 mm and material properties of the tank, JIS G3116 SG-295 (σ_Y = 295 MPa), pressure to yield for radius ratio ρ = 3, can be calculated as follows:

$$p_y = \frac{2t.\sigma_y}{2.5r} = \frac{(2)(2.3mm)(295MPa)}{2.5(91.3mm)} = 5.95MPa$$

Internal pressure of 5.95 MPa is the pressure needed for material to start plastic. Limit pressure would be somewhat higher than this value. For finite element analysis using ANSYS, the limit load can be obtained via nonlinear solution using the Newton-Raphson algorithm. The pressure load can be applied by steps to reach the yield, followed by ramp load after yield to reach limit pressure. Maximum internal pressure applied was 10 MPa. Boundary condition and loading is shown in Fig.3.

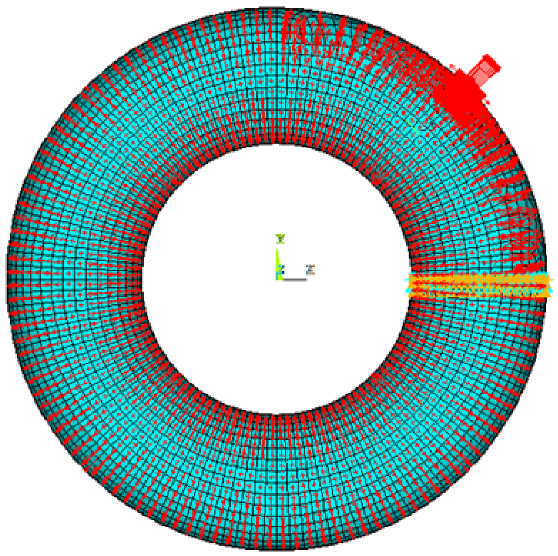

Fig.3 Boundary condition and internal pressure load

Results and Discussion

The results are given in form of graph. There are three graphs that can be plotted to describe the behaviour of the toroidal tank with nozzle as reported here: stress versus internal pressure (σ – *p*), internal pressure versus strain (*p* – ε), and stress versus strain (σ – ε). All graphs are given in nondiensional form.

Figure 4 shows the relation between internal pressure and resulting stress. The stress plotted was stress intensity at the inner (bottom) surface of the shell, the surface of a shell undergoing the highest stress for shell under internal pressure. The graph was plotted in nondimensional form by dividing the pressure load by the pressure to yield and dividing the resulting stress by the yield stress (295 MPa). Figure 4 shows that the relationship between applied pressure and resulting stress in a toroidal shell without nozzle is linear.. For toroidal with radial nozzle, stress at the tank is much higher that tank without nozle. When limit pressure is achieved, the maximum stress almost identical which shwos that plasticity has spread over the entire thickness of the shell.

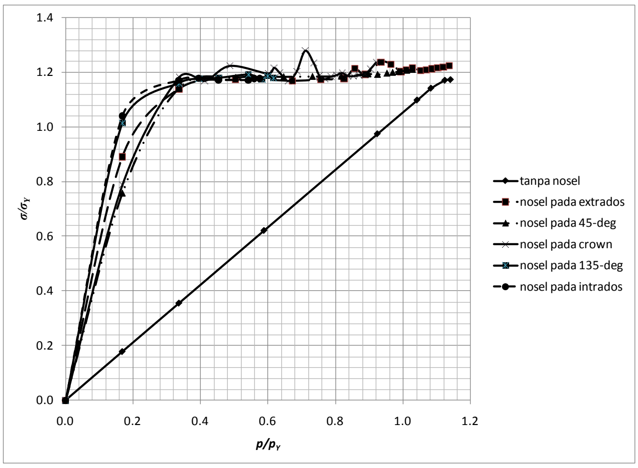

Figure.4 relationship between applied internal pressure and resulting stress.

Figure 5 shows the relationship between applied internal pressure and resulting strain. It can be seen that the maximum strain before failure is much higher for toroidal tank with nozzle compared to toroidal tank without nozzle. Figure 5 also shows that the highest limit pressure and resulting strain is obtained when the nozzle located at extrados position.

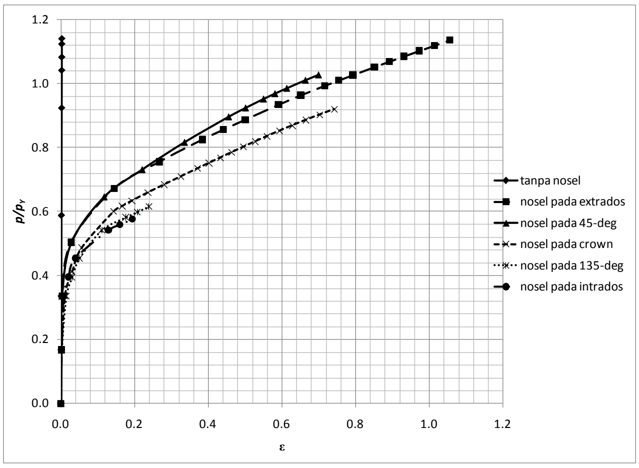

Figure.5 relationship between applied internal pressure and resulting strain.

Figure 6 shows the stress-strain curve for various nozzle position of nozzle. It can be seen that the structure considered here exhibits large strain behaviour. Overall, the highest strain was obtained when the nozzle located at the extrados. Figure 7(a) and 7(b) shows typical stress and strain distribution respectively when limit pressure achieved. It was plotted for stress intensity at the inner surface of the tank's wall.

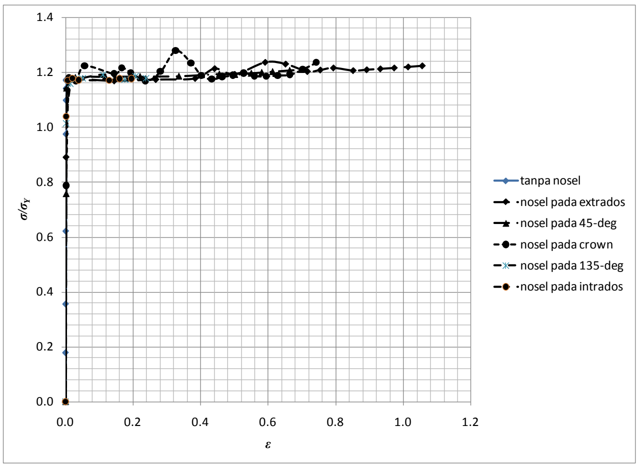

Fig.6 stress-strain cuve for a toroidal tank under internal pressure

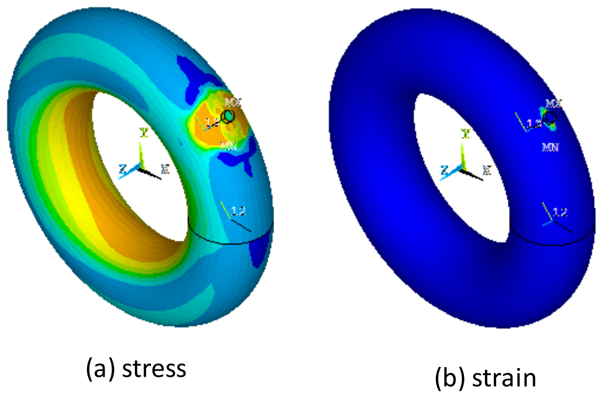

Fig.7 stress and strain distribution when limit internal pressure achieved

Conclusion

From this analysis, it was found that the best design for nozzle position in a circular toroidal tank, indicated by the highest limit pressure, is located at the extrados. For any circumstances, nozzle can be located between extrados and crown, but should not be located between crown and intrados. This result conforms to the membrane theory that the highest stress in toroidal shell under internal pressure occurs at intrados and nozzle shall not be located next to that location.

Acknowledgment

The authors would like to thank Faculty of Engineering the University of Lampung for partially fund this research in PNBP 2012.

Lists of symbols

E	Young's modulus (MPa)
p	Internal pressure (MPa)
r	Cross-section radius of the tank (mm)
R	Radius of curvature (mm)
t	Wall thickness (mm)
V	Volume of tank (mm^3)

Greek letters

ε	Normal strain (%)
ρ	Radius ratio = *R/r*
σ	Normal stress (MPa)
υ	Poisson's ratio

Subsripts

Y	Yield stress

References

ASME, ASME Boiler and Pressure Vessel Code, Section VIII Division 1 (2007).

Btachut, J., Collapse Tests on Externally Pressurized Toroids. ASME Journal of Pressure Vessel Technology, Vil. 125, No. 1, hal. 91 – 96 (2003).

Jiang, W., dan Redekop, D., Static and Vibration Analysis of Orthotropic Toroidal Shells of Variable Thickness by Differential Quadrature. Thin-Walled Structures, Vol.41 No.5, hal. 461 – 78 (2003)

Kisioglu, Y., Burst Tests and Volume Expansions of Vehicle Toroidal LPG Fuel Tanks. Turkish Journal of Engineering Environmental Science, Vol.33 hal. 117 – 125 (2009).

Lubis, A., Saragih, R.S., and Suudi, A., 2010, Studi limit tekanan pada tabung LPG 3kg dengan metode elemen hingga. Prosiding Seminar Nasional Tahunan Teknik Mesin (SNTTM) ke-9, 13 – 15 Oktober, Universitas Sriwijaya, Palembang (2010)

Lubis, A., Strength design of toroidal tank for LPG 3-kg. Proceeding SNTTM-10, Universitas Brawijaya, Malang, 2–3 November, ISBN: 978-602-19028-0-6, (2011)

Lubis, A., Oktazari, Z., and Tanti, N., Nonlinear Finite Element Analysis of Pressurized LPG Toroidal Tank with Non-Radial Nozzle. Prosiding Seminar Nasional Energi Terbarukan dan Produksi Bersih, Jurusan Teknik Mesin Universitas Lampung, Bandar Lampung, 20 – 21 Juni, (2012) Tzou, H.S., and Wang, D.W., Vibration Control of Toroidal Shells with Parallel and Diagonal Piezoelectric Actuators. ASME Journal of Pressure Vessel Technology, Vol. 125, No. 2, pp. 171 – 176 (2003)

Velickovic, V., Stress and Strain States in the Material of the Stressed Toroidal Container for Liquefied Petroleum Gas. Scientific Technical Review, Vol. LVII, No.3-4, pp. 94 – 105 (2007)

Winarto, and Wahyuadi, J.S., Pengkajian Karekteristik Bahan Baku (Raw Material) Lembaran Baja (Steel Plate) untuk Tabung Gas 3kg Produk Lokal dan Impor Secara Matalurgi. *BSN Indonesia* (2008)