Design of LPG Pressure Vessel-A case study of Aboabo Community in the southern part of Ghana, West-Africa

Godwill Agyare Peprah, Anthony Morgan and Jamel Aidoo

Abstract— The paper entails design of a pressure vessel to store liquefied petroleum gas (LPG). The design was based on a survey conducted in Aboabo community. Data obtained from the survey and Ghana Statistical Service were used in the design. In the design, fatigue life of the vessel, static loading and the environment were considered to ensure safe and clean environment. Leak before fracture criterion was employed in the design to guard against catastrophic failure in case of crack in the vessel. The bending moments and shear forces of the vessel were considered to determine the position of coalescence of the vessel components at 0.542m and 6.48m. Based on the shear stress value of 6.321 MPa, 1016 electrode was used for the colescence. The vessel can withstand 2.47 x10 ^{7} cycles of cyclic loading before failure occurs.

Index Terms— Liquidfied Petroleum Gas, Pressure Vessel, Design, Fatigue, Failure, Moment, electrode.

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1 Introduction

Increasing use of LPG both domestically and industrially in the country is really encouraging considering the high cost of petrol (fuel) and increasing electricity tariffs. However, the rural communities are limited in the use of LPG due to the unavailability of storage pressure vessels in such areas. The few ones available are in the cities and may have to travel long distance in search for gas. Owing to this, inhabitants in villages and small towns still resort to the use of charcoal that contribute to deforestation, release of carbon monoxide into the atmosphere and major cause of corrosion on their roofs when these gases react with water as well as numerous respiratory problems.

In addition the occurrences of explosions last year June, 2016 and early January this year, 2017 which claimed many Ghanaian life's and the causes unestablished has necessitated the need to design and manufacture pressure vessel which will incorporate safety measures such as leakage in case failure is to occur as a safety measure before fracture.

1.3 OBJECTIVES

- Design an LPG pressure vessel for LPG storage.
- To design against fatigue, static loading, and the environment.
- To incoorperate leak before fracture criterion in the design

1.4 SCOPE OF WORK

The design outline the basic procedures that entail the design of pressure vessels such as material selection, designing against fatigue and static loading, and environment.

As quality is hallmark, the right fabrication processes was employed to obtain the desired shape and the appropriate surface treatment and coating technology applied to design against the environment.

2. METHODOLOGY

Data was gathered to estimate the capacity of the vessel to be designed. The population of these two communities was obtained from the Kumasi Statistical Service.

Two design procedures were followed:

- A survey was done at Aboabo, a community in Kumasi with a population of about 4043 people and the information below were gathered;

I. Source of fuel: It was found that out of 5 people, 4 use charcoal and wood while the remaining person use gas. The community obtain the fuel (charcoal) from the Upper East region and wood from sawmill. This imply that out of 4043 people, for every 5 people investigated, 3234.4 use charcoal and wood whereas 808.6 use gas.

II. Impact of the fuel on the environment: About the impact of charcoal, wood and LPG on the environment, we found out that charcoal and wood produce heat which makes the surrounding hotter than normal. Also some of the wood for charcoals and from sawmill do not completely burn during charcoal production thus producing sooth and carbon dioxide which cause respiratory problems and global warming whereas LPG is hydrocarbon which is environmentally friendly. Aside all these risk, natural vegetation is being destroyed through deforestation in the Upper East region of the country where the charcoal is produced.

- Benefit of using gas verses charcoal: The 4 people on charcoal and wood expressed displeasure about the time it takes charcoal and wood to cook food which affect the daily activities such as work, education, etc. The use of charcoal deteriorate utensils by causing them to be black. The proximity of the source of gas along with a great number of people from other communities filling their cylinders from the same source which normally leads to gas shortage.

A case study done at Allied filling station, Kentenkrono, a suburb of Kumasi which consisted of a population of about 3222 people consumes 16000litre of LPG per week. The vessel had rotor gauge and thermometer connected to it. These instruments gave readings of the environmental temperature and the corresponding pressure that keeps the LPG liquid (vapor pressure). The maximum environmental temperature the thermometer usually record is 40^{o}C and a corresponding vapor pressure of 3 bar (307KPa)

The case study enabled us to estimate the capacity of the vessel and the pressure (vapor pressure) that acted on the

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LPG to keep it liquid at the maximum environmental temperature of 40°C.

3. Equations

$\sigma_a = ½ (\sigma_{max} - \sigma_{min})$

σ_{max} –maximum stress on the vessel when 80% loaded. σ_{min} – minimum stress on the vessel when it is left with 5% of gas after offloading

$S_O = AN^b$

N-Fatigue life of the material

For medium carbon steel,

A-fatigue strength coefficient (1006MPa)

b- Fatigue strength exponent (-0.0809) (Wikipedia)

$\sigma L = Pr/2t$, $\sigma h = Pr/t$: σh, σL (hoop and longitudinal stresses),

r= radius and t=thickness (Asby, 2005)

EI d^2x/dy^2=M=Bending moment

EI dx/dy=V=Shear force

Ely=deflection

$\sigma = MC/I$, $C=1/2t$, $I = \pi/64[d_o^4 - d_i^4]$ (Agyemang, 2008)

$KIC = \sigma Y\sqrt{\pi a}$, $P=F/A$

3.1 CALCULATING CAPACITY AND PRESSURE

From our case study at Kentinkrono and survey at Aboabo No.2, Aboabo will consume 20076.97L of LPG. This volume occupies only 80% of the total capacity. Pressure vessels are designed having about 20% of the total capacity for expansion (Wikipedia). If 80% of the vessel capacity is 20076.97L, then 100% is equivalent to 25096.21L. With reference to data gathered at Kentinkrono; at maximum temperature of 40°C. 307kPa acts on 16000L of LPG, then 385kPa will act on 20276.97L of LPG. Total capacity (vol.) of designed pressure vessel = 25.096m³. Total vol. of designed pressure vessel = vol. of cylinder + 2 (semi-elliptical ends)

$V_T = a_iL + 2(\pi 2/3abc)$, $a= D/2$, $b= D/2$, $c=D/4$

$V_T = \pi D_i^2/4 + \pi D^3/12$ (Wikipedia, 2006)

L= 6m D= 2m, $25.096= A_i(6) + \pi 2^3/12$, A_i of cylinder = 3.833m²

DIAGRAM OF PRESSURE VESSEL

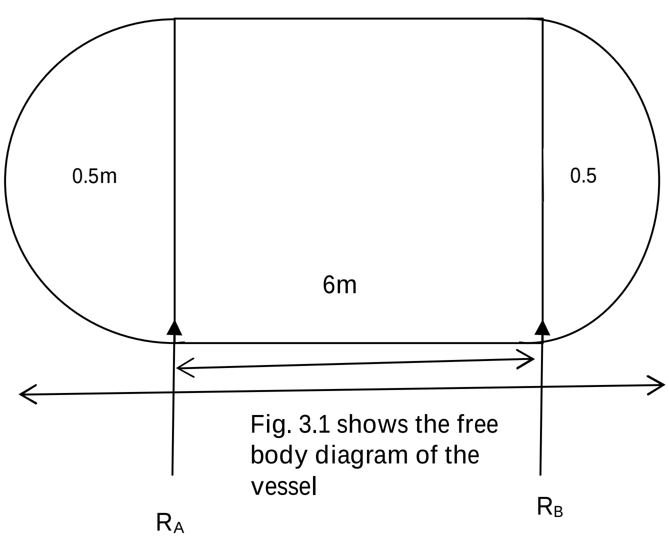

Fig. 3.1 shows the free body diagram of the vessel

$P_{80\%} = F/A$

$F_{80\%} = P.A$

P = 385kPa

$A = \pi r^2 + 2(1.084d^2) = \pi(1)^2 + 2(1.084 \times 2^2)$, A = 11.81m², F =385kPa x 11.81m²

F = 4546.85 kN = 4.5MN

For thin walled pressure vessels, r/t> 10 (Roylance, 2001)

i.e.1/0.005, 200 > 10. Hence the vessel is thin-walled

As the pressure (385kPa) compresses the LPG to keep it in a liquid state, two stresses (hoop and longitudinal) acts on the material.

$\sigma_{h80\%} = Pr/t = 385x1/0.005 = 77$Mpa, $\sigma_{L80\%} = Pr/2t = 385x1/2x0.005$

= 38.5 MpaWhen the vessel is offloaded (5% of LPG in the vessel)

If 80% = 20076.97L

5% = 1254.81L ≈ 1.25m³

If 385kPa acts on 20076.97L, then 24.06kPa acts on 1254.81L

Calculating the hoop and longitudinal stresses from the 5% LPG;

$\sigma_{h5\%} = Pr/t = 24.06kPax1/0.005 = 4.8MPa$

$\sigma_{L5\%} = Pr/2t = 24.06kPax1/2x0.005 = 2.4$ MPa

The equivalent 5% load, $F_{5\%} = P_{5\%}\ A_i$

= 24.06kPa $[\pi(1)^2 + 2(1.089.2^2)]$

= 24.06kPa x 12.81 m²

=284.14kN

3.1.2 DESIGNING AGAINST STATIC LOAD

Using the maximum shearing stress criterion, when the LPG is static in the vessel, for no yielding to occur, the yield shearing stress of the material must be greater than the maximum shearing stress of the LPG on the material.

Loading the vessel exerts two principal stresses (σ_1 and σ_2) on the material as depicted in the fig.

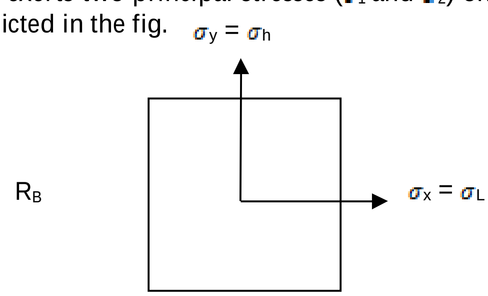

Fig. 3.2a

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$\sigma_{max} = \sigma_1 = \sigma_{ave} + R$

$\sigma_{min} = \sigma_2 = \sigma_{ave} - R$
$R = \sqrt{(\sigma_x - \sigma_y)^2/2 + \tau xy^2}$ but $\tau xy^2 = 0$

$R = \sqrt{(\sigma x - \sigma y)^2/2}$

The principal stresses σ_1 and σ_2 on the material at 80% loading;

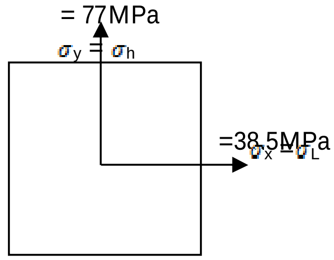

Fig 3.2b

$\sigma_{ave} = (\sigma_x + \sigma_y)/2 = 77+38.5/2 = 57.75$ MPa
$R = {}^2 = \sqrt{(\sigma x - \sigma y)^2/2} = \sqrt{(38.5-77)^2/2} = 19.25$MPa

$\sigma_{max} = \sigma_1 = 57.75 + 19.25 = 77$MPa
$\sigma_{min} = \sigma_2 = 57.75 - 19.25 = 38.5$MPa
Since the two principal stresses are positive, $\tau_{max} = 1/2\tau_{max} = 1/2 \times 77$ MPa $= 38.5$MPa
Offloading the vessel to 5% of the capacity, principal stresses

exerted on the material as in figure

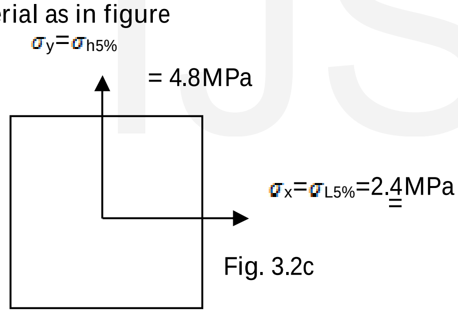

Fig. 3.2c

$\sigma_{ave} = (\sigma_x + \sigma_y)/2 = 2.4+4.8/2$, $R = \sqrt{(\sigma x - \sigma y)^2/2} = \sqrt{(2.4-4.8)^2/2} = 1.2$MPa

$\sigma_{max} = \sigma_1 = 3.6 + 1.2 = 4.8$Mpa, $\sigma_{min} = \sigma_2 = 3.6 - 1.2 = 2.4$MPa
Since the two principal stresses are positive, $\tau_{max} = 1/2\sigma_{max} = 1/2 \times 4.8 = 2.4$MPa but τ_{max} of the 80% volume is greater than the 5%, we will use that of the 80%
From the maximum shear stress criterion;
If $\tau_{max} < \tau_y$ no yielding occurs, $\tau_{max} > \tau_y$ yielding occurs
Factor of Safety (N) $= \tau_y/\tau_{max}$ (Agyemang, 2008)
Pressure vessels have a factor of safety of 3 (Wikipedia).
The table below shows some materials and their ultimate yield strength, yield shear stress and F.S from calculation.

The table below shows some materials and their ultimate yield strength, yield shear stress and F.S from calculation.

Material	Ultimate Yield strength, σ_u(MPa)	Yield shear strength $\tau y = \sigma_u/2$	Factor of safety (τ_y / τ_{max})
Low carbon alloyed steel	344.82 MPa	172.41 MPa	$4.4 \approx 4$
Medium carbon alloyed steel	440MPa	220MPa	$5.7 \approx 6$

Table 3.1 shows the yield strength and factor of safety for some materials

From above table, the factor of safety for low carbon alloyed steel is $4.4 \approx 4$. In other to cut down cost (overdesign) this material will be used in our design.

3.1. DETERMINATION OF THE POSITION OF THE WELD

From fig 3.1 the position of the weld has not been indicated. The weld is placed at a point when the bending moment (point of inflexion) is zero. (Bowes, 1984)
The thickness of the vessel is uniform throughout so we assume that the load in it is uniformly distributed.

The fig below shows the free body diagram of the vessel and the content (80 LPG) as well as the reactions from the support

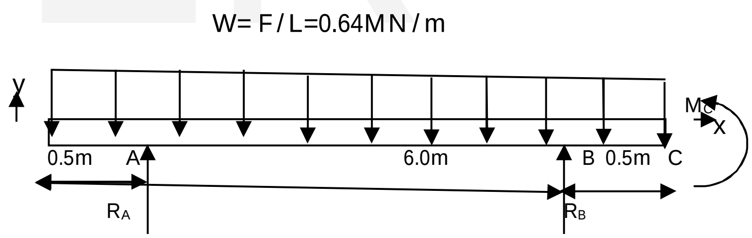

Fig. 3.3 shows free body diagram of vessel and content

$\Sigma M \quad R_A + R_B = W$

$+M_B = 0$

$-R_A(6) + 3F/L.\ L = 0$, $R_A = F/2$ $\quad R_B = F/2$

Using singularity function; the general equation is obtained by

taking moment about C;

$+ \quad M_C = 0$

$EId^2y/dx^2 - R_A\langle x - 0.5\rangle - R_B\langle x - 6.5\rangle + wx.\ x/2 = 0$
$EId^2y/dx^2 = M_C = R_A\langle x - 0.5\rangle + R_B\langle x - 6.5\rangle - wx^2/2$
From the bending moment diagram, the point of inflection lies between 0.5 and 6.5

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$0 = F/2 \langle x-0.5\rangle - wx^2/2;$ $F_{80\%} = 4.5\text{Mpa}$
$0 = 4.5/2\,(x - 0.5) - 0.64x^2/2$
$0 = 2.25x - 1.125 - 0.32x^2$
$X_1 = 0.542\text{m}$ $X_2 = 6.480\text{m}$

The shear forces(V_1 and V_2) at these point in other to select the right electrode for the weld is obtain by integrating the bending moment equation and plugging in $X_1 = 0.542$m $X_2 = 6.480$m

$$EIdy/dx = F/4\langle x-0.5\rangle + F/4\langle x-6.5\rangle - wx^3/6 + C_1$$

The constant is obtained by integrating the shear force to get the deflection and setting in the boundary condition.

$$EIy = F/4\langle x-0.5\rangle + F/4\langle x-6.5\rangle - wx^3/6 + C_1x + C_2$$

Boundary condition: At $x=0$ $y=0$ $C_2=103.03M$
$x=L=7m$ $y=0$ $C_1=-29.18M$

Hence the shear force equation is;

$$EIdy/dx = V = F/4\langle x-0.5\rangle + F/4\langle x-6.5\rangle - wx^3/6 - 29.18$$

At $X_1 = 0.542$m $V_1 = 24.23$MN and $X_2 = 6.480$m $V_2=24.19$MN

This means the electrode to be used must have strength greater than these shear stresses. The shape of the pressure vessel is symmetrical hence the maximum bending moment occurs at the mid span. From equation, at $X_1 = 3.5$m $EId^2y/dx^2 = 2.8125$MNm. The table below shows the distances X along the vessel and their corresponding moment M for the bending moment graph.

The shearing force and bending moment graph for maximum loading

80% Capacity

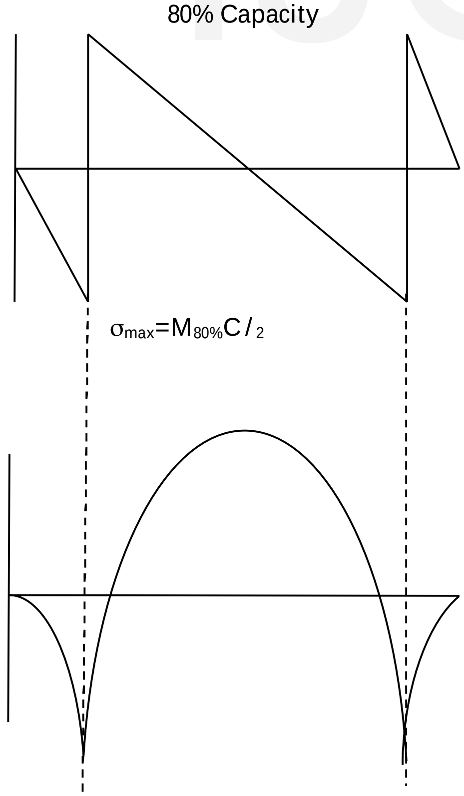

Fig. 3.4

At minimum loading (offloaded remaining 5%), following the same procedure for (80 loading) the free body diagram of the vessel, content and support are shown below;

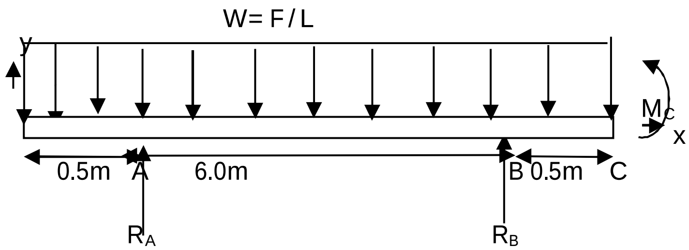

Fig. 3.5 shows the bending moment diagram at minum loading

ΣM $R_A + R_B = W$
$M_B = 0$
$-R_A(6) + 3F/L.\,L = 0,$ $R_A = F/2$ $R_B = F/2$

Using singularity function; the general equation is obtained by taking moment about E;

$+\ M_E = 0$

$$EId^2y/dx^2 = M_E = R_A\langle x-0.5\rangle + R_B\langle x-6.5\rangle - wx^2/2$$

Minimum bending moment for the minimum loading will occur at x=3.5m because of the symmetrical nature of the vessel, hence;

$EId^2y/dx^2 = M = 177.5$kN.m

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The table below shows the distances X along the vessel and their corresponding moment M for the bending moment graph.

Distance (X)	**Bending moment (M)**
0	0
0.5	-0.08
0.542	0
3.5	2.8125
6.48	0
6.5	-0.08
7	0

Table 3.3 shows the bending moment and the corresponding distances at which they occur.

The shearing force and bending moment graph for minimum loading

5% Capacity

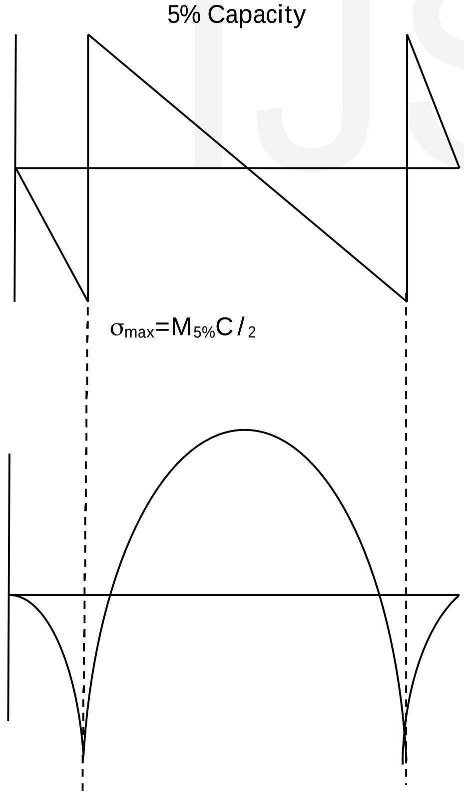

Fig. 3.6

3.1.4 DESIGNING AGAINST FATIGUE

From Fig. 3.4 and Fig. 3.6, the maximum and minimum stresses resulting from the maximum and minimum bending moment are;

$\sigma_{max80\%}=M_{max80\%}C/I$

$c=1/2t=1/2\,(0.005) = 0.0025m$

$I=\pi/64\,[d_o^4 - d_i^4]$

$d_o = d_i + t = 2 + 0.005 = 2.005m$

$d_i = 2m$

$I= \pi/64\,[(2.005)^4 - (2)^4]$

$I = 7.88 \times 10^{-3}m^4$

$M_{max} = 2.812MN.m$

$\sigma_{max80\%}= 2.812x0.005/(7.88x10^8) = 1.78MPa$

The minimum stress at 5 that will bring about a bending moment of 117.5kNm is;

$\sigma_{min5\%}=M_{min5\%}C/I$

$c= 0.005$ $M_{min} = 117.5kNm$

$\sigma_{min5\%}= 177.8x0.005/(7.88x10^8) = 112.62kPa$

From Goodman equation;

$Sa= So\,(1-S_m/S_y)$ (Bowes, 1984)

$S_o= (1-S_m/S_y)^{-1} S_a$

$Sa=(\sigma max80\%- \sigma min5\%)/2=(1.78M-112.62k)/2=833.69KN/m^2$

$S_m=(\sigma max80\%+\sigma min5\%)/2=(1.78M+112.62k)/2=946.31KN/m^2$

$Sy=260Mpa$

$S_o=(1-S_m/S_y)^{-1}S_a=(1-946.31k/440M)833.69K=0.835MN/m^2$

This gives the stress amplitude of LPG on the material. To avoid unexpected failure the life of the material N must be calculated. From the formula below;

$S_o=AN^b$,

The fig below shows the maximum and minimum stresses, the mean and stress amplitude of the LPG on the materials.

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4. LEAK BEFORE BREAK CRITERION

In case of any crack, the vessel should first and foremost leak before the occurrence of a catastrophic failure. This will happen if the ac≥ t Using the basic fracture mechanics equation;

$$K=\sigma_Y\sqrt{\pi a}$$

$$KIC=\sigma_{yY/N}\sqrt{\pi a}$$

$$ac=N^2/Y2\pi(KIC/\sigma y)^2$$ (Callister, 2007)

$$ac=9/1\pi(0.431)=1.2$$

From the above calculation, ac≥ t. This implies that if there is any crack the vessel will leak before the material fractures.

4.1 FABRICATION OF LPG PRESSURE VESSEL

Fabrication processes are the various deformation and joining processes that the slab (raw material) will be subjected to under pressure in other to achieve the desired shape. In obtaining the shape of our design, the types of fabrication process that were be employed are extrusion, forging, and welding.

The metal piece is cold extruded to obtain the cylindrical part of the vessel. This is because extrusion aligns the fibers in one direction and enhances the strength properties. The work material is compressed between two dies with an impression of the semi elliptical ends to obtain the shape, the required diameter, and thickness; Flashes produced are trimmed off by machining.

Cleaned open ends of the cylindrical and two semielliptical parts obtained are coalesced by Shielded Metal Arc Welding (SMAW). This welding method is portable and cost effective, versatile and can be used in all directions. It is also compatible with our base metal i.e. steel (Gloover, 2007). A 1016 electrode is used since its tensile strength of 10000psi surpasses the shear stress value of 6.321MPa (at the point where the bending moment is zero).

4.1.1 SURFACE TREATMENT

After the final shape of the pressure vessel is obtained by the deformation and joining processes, prior to painting, the surface is inspected for millscale, rust, sharp edges, laminations, burr marks and welding flux, forming or machine oils, chemical contamination or mortar splashes on them, all of which must be removed. Abrasive blasting cleaning is used because of its efficiency in removing millscale, provides a surface finish suitable for painting.

4.1.2 COATING

The LPG storage vessel is protected from the environment at Aboabo No 2 by coating. From the case study the maximum temperature recorded at Allied filling station (Kentenkrono) is 40°C. From this information the vessel is protected from water, harmful gases and ultra violet light by coating. Three types of coating is applied: Primer coating, an intermediate coating and a finish coating.

The inner part is coated with vitreous silica compound known as porcelain enamel lining (glass coating) for protecting the vessel walls against corrosive action of the LPG and possibly dissolved minerals. The thickness of the glass coating is in the order of 25μm (10mils) which serves as the primary coating against corrosion. The glass coating protects the steel due to its high corrosion resistance. (Perez, 2004)

5 DISCUSSION

5.1 INSPECTION

The vessel should be examined using nondestructive test techniques such as ultrasonic testing. Using this ultrasonic method, very short ultrasonic pulse-waves will be launched into the vessel to detect internal flaws and the thickness. From this test, point of stress concentration will be easily detected and hence corrosion avoided. This test should be performed every six months.

Visual inspection is also a very relevant inspection that should be done at all times primarily before and after daily operations to detect any surface change that occurred during operational and non-operational hours

The coating also weakens with time and as such, recoating should be done two month prior to the deterioration of the existing coating.

5.2 SAFETY MEASURES

In order to prevent any explosion or accidents from occurring, these measures should be put in place

- Since pressure is directly proportional to temperature, any degree rise with temperature significantly increases the pressure in the vessel. As a result of that, a rotogage should be connected to the vessel to record the pressure that acts on the LPG to keep it liquid and a thermometer to record its corresponding environmental temperature change.
- Pipes should be connected around the vessel to cool down the vessel when temperature (high) change is observed.
- The principle of fracture mechanics was used in our design to ensure that if any crack occurs, it will propagate through the thickness of the material causing leakage before a buildup of dangerous pressure leading to any catastrophic failure.
- The main power connecting all electrical appliances should not be switched off since switching it on and off can ignite a spark which can cause fire outbreak.
- Any activity that can cause fire outbreak such as smoking, leaving car ignition “on” or lighting a match stick should be prohibited.
- In order to avoid any unanticipated failure, a design factor of 3 was added to our design.

5.3 ASSUMPTIONS

Several assumptions were made during the calculations and they are;

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- The population of Aboabo No.2 was taken from the 2000 population census.
- The thickness of the vessel is the same throughout the walls and hence the load the LPG exerted on the vessel is uniformly distributed.
- There was no inlet and outlet made in our design.

6. Conclusion

Based on the case study and survey performed, information gathered aided in the design of a 25.096m^3 capacity pressure vessel. The vessel though designed for the Aboabo community, can be used in all parts of the country especially the rural areas where storage vessels are scarce.

From our calculations, the designed vessel during its lifespan can withstand static loading of 77MPa at maximum stress and 2.47 x10^7 cycles of cyclic loading before failure occurs.

Right material selection and adequate coating will help in protecting the vessel against the environment.

RECOMMENDATION

We recommend that the design project should be employed by manufacturing companies to start produce storage vessels to cater for the increasing demand of LPG.

The government should invest in industries that have the desire to use these designs in pressure vessel production.

Lastly, in subsequent projects, inlets and outlets should be factored into the design.

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