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Design and Analysis of Composite Tank with End Domes

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Abstract: ***The work aims to establish an optimal design method of vacuum molded composite tank under internal pressure specifically for storage of LPG. In this geodesic path, equation was used to calculate the variable thickness of the dome portions, instead of constant thickness throughout the structures. The head shape is obtained by the numerical solution of the elliptical integral. The finite element analysis was performed to the identity of safest design cylindrical and dome portion of the structure. The stagnation of fiber matrix composite leads to the variable thickness dome. The experimental test of leak proof and the pressure test also carried out and the results also investigated.***

Keywords: Finite Element Analysis, Composite Tank, Dome Contour

1. INTRODUCTION

Modern composites, using continuous fibers in a resin matrix, are important candidate materials in the engineering of energy efficient structures. Composite structures can be used in civilian industries like liquid petroleum gas tank, fiber extinguisher, oxygen gas tank, etc. Among these commercial products, a common feature is that they must undergo a certain high working pressure with an appropriate safety factor and low maintenance costs. Composite structures are suitable for inclusion in engineered systems to satisfy such demands. For instance, many researchers have studied the manufacturing and designing aspects of laminated composite pressure vessels. Today, composite pressure vessels find widespread commercial application as automotive fuel tanks for compressed natural gas and hydrogen, cryogenic tanks for transportation of liquefied natural gas, parts of pneumatic compressors and elements of survival systems for firemen, drivers and mountain climbers.

The composite pressure vessel has a base radius and a polar opening radius. Such a dome is formed by winding resin coated high strength filaments onto an axisymmetric permanent lining or removable mandrel, then heat treating the resulting structure to produce a hard and resistance matrix. The filament patterns produced by the manufacturing methods consist of an even number of superimposed layers that spiral alternately so that clockwise-wound layer exists for each. The double symmetry of the resulting pattern is adopted herein, and the dome is generally treated as a thin-walled shell of revolution. The shell is subjected to uniform internal pressure and the conditions of thin walled structure and balanced symmetry winding pattern are adopted.

Liquefied petroleum gas (LPG) is a mixture of butane and propane gases stored under pressure usually in steel cylinders. LPG is heavier than air, non-toxic and odorless. A swelling agent is added to aid users to detect leaks. LPG is a safe, economical and convenient fuel as it has high calorific value (13.8 kWh/kg, which is equivalent to 13.8 units of electricity), provides instantaneous heat, is easy to ignite and clean-burning and is very portable. It is the most environment-friendly of the commonly used fossil fuels because it emits low levels of harmful combustion products. Approximately 280 million kilograms of LPG has consumed annually in South Africa. Typical uses of LPG include: cooking, space and water heating, refrigeration, lighting, brazing, soldering, and welding, in school/technical laboratories, domestic households, restaurants, hospitals, small businesses, and recreation/leisure

LPG appliances include stoves/ovens, grills/braais, heaters (portable and fixed), instantaneous water heaters, lamps (portable and fixed), refrigeration and welding plant, and Bunsen burners. Appliances are designed to operate both at an unregulated high pressure (e.g. CADAC (or similar) type of camping appliances) and at a lower pressure controlled by a regulator mounted on the gas storage cylinder. High-pressure and low-pressure appliances are not interchangeable. Most households use gas appliances with a small dedicated gas cylinder, rather than a reticulated system of gas piping and fixed storage cylinders. LPG storage cylinders are supplied in a range of standard sizes in two categories: camping/hobby type and household/industrial type. The larger (9-48 kg) cylinders are designed to operate at 7 bars and are tested at 22 bars.

2. ANALYTICAL METHOD

2.1 Geodesic Dome Contour

The geodesic profile is the elliptical curve connecting the two points taking the consideration of shortest distance. We need to define Geodesic profile between pole opening radius and cylindrical portion radius. Generally, friction is required to keep the path stationary. The fiber wound on the geodesic dome profile according to the claurit's principle does not slip and it directly follows the Geodesic path, this type of winding is called Geodesic winding, which does not require any friction to keep the fiber stationary. Geodesic dome profile is created by using Geodesic path equation

$$\bar{z} = -\sqrt{1-\bar{r}_0^{\,2}} \int_1^{\bar{r}} \frac{r^3 dr}{\sqrt{\bar{r}^2 - \bar{r}_0^{\,2} - \bar{r}^6 (1-\bar{r}_0^{\,2})}}$$

………………………….. (1)

z = Axial Coordinate r_0 = Polar Opening Radius

r = Radial Coordinate R = Radius of Cylindrical Portion

Where, $\bar{r}_0 = \frac{r_0}{R}$ $\bar{r} = \frac{r}{R}$ $\bar{z} = \frac{z}{R}$

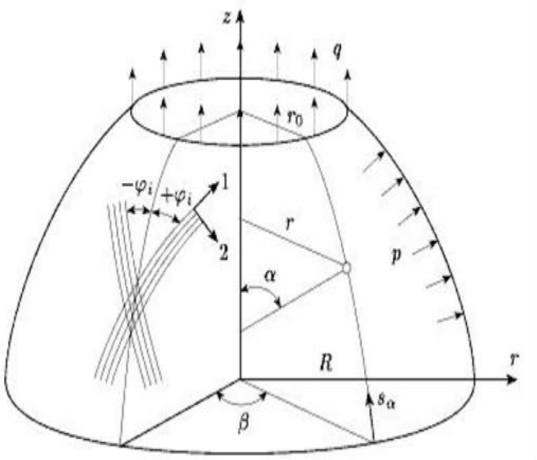

Figure 1. A shell of Revolution (Composite materials: Analysis, Manufacturing & Design by V V Vasiliev)

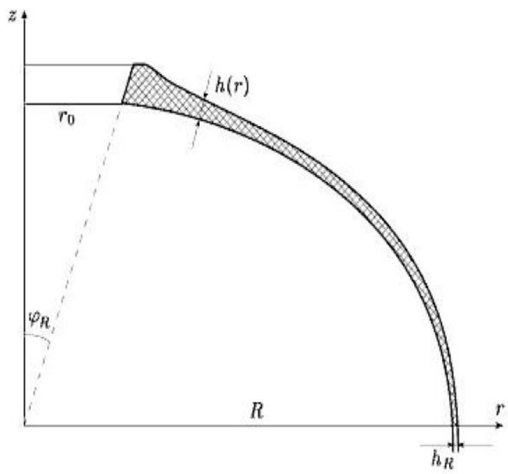

Figure 2. Geodesic dome profile (Mohammed Z Kabir)

Equator radius (R)
Radius of polar opening (r_0)
Winding angle (φ_R)
Thickness at equator (h_R)

The geodesic curve which is obtained from the above geodesic path equation has the point of inflection at which the radius of curvature reverses its direction as shown in the figure. At the distance of 1.225 times of the pole opening radius.

Table 1 coordinates of dome contour

z(mm)	r(mm)
0	69
6	64
11.87	60
17.47	55
22.71	50
27.5	45
31.78	40
35.53	35
38.74	30
41.44	25
43.67	20
45.41	15

3. GEOMETRICAL CONSIDERATION

A winding pattern includes many wraps with different wrap angles. The desirable winding pattern, as explained earlier to satisfy isotensoid condition, is calculated from Eq. (6). The determination of the overall geometry and elastic constant of a composite involves the calculation of the local wrap angle of each wrap and it's corresponding cross-sectional thickness. By assuming the wrap angle at the juncture of the cylinder and head shape, a0, and using Eq. (6), the local wrap angle corresponding to any point on the geodesic profile, (x, y), can be determined as

$$\text{Sin}\ \varphi = r_o / r \ \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where r_0 is the polar opening radius and

r is a radial distance from the longitudinal axis at each level to maximum value R.

The curve of the head shape has a point of infection at $x=1.22X_0$ and is not applicable for smaller X_0. Consequently, for region $X_0=1:22X_0$, the vicinity of the opening, additional reinforcement is required in the form of an insert to distribute the meridional load. In this study, for sake of simplicity, the head shape curve for this region is obtained as a tangent to the geodesic curve at $x = 1.22X_0$.

Table 2 Variable thickness of geodesic dome contour

z(mm)	r(mm)	Thickness (h) mm	Winding Angle (φ)
0	69	2.373	19.5
6	64	2.427	19.62
11.87	60	2.595	20
17.47	55	2.91	20.6
22.71	50	3.443	21.6
27.5	45	4.381	22.9
31.78	40	6.345	24.6
35.53	35	10.955	26.8
38.74	30	9.415	29.8
41.44	25	8.958	33.8
43.67	20	8.467	39.5
45.41	15	6.937	51.5

4. DESIGN METHODOLOGY AND CONSIDERATION

The composite LPG cylinders will comprise of three layers; the seamless polymer liner for gas containment to act as a gas barrier, the fiber structure to hold the burst pressure under extreme conditions and the fully integrated outer casing to help protect the valve/regulator and the pressure vessel from the surrounding environment. The different components for the chosen concept were assigned the following materials

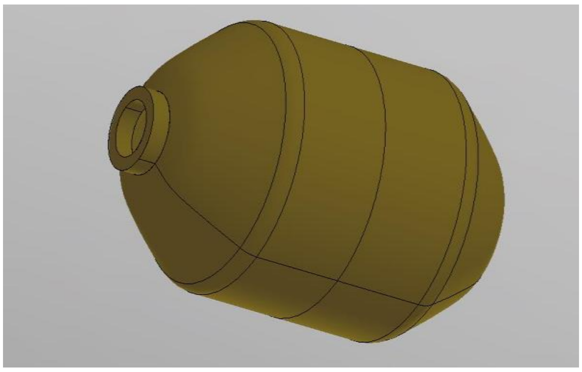

Figure 3 Model of LPG tank

Specifications of composite LPG Tank (2 KG Capacity)
Inside diameter = 138 mm
Diameter of polar boss = 15mm
Total Length = 152 mm
Cylindrical portion length = 110 mm

- Inner-layer/liner = Plastic; type HDPE-Blow Moldable Grade.
- Outer-Liner = E- Glass Fiber / Vinyl ester

Various components of the proposed design. The outer-layer will be wound around the inner layer as strands of filaments mixed with vinyl-ester resin. Vinyl-ester resin is ideally suited for being semi-transparent and having the ability to prevent UV rays.

The following manufacturing process is proposed for the different components:

- HDPE liner will be blow molded.
- Fiber glass layer vacuum molded and oven cured.

All LPG cylinders are portable gas containers and can be regarded as pressure vessels. In any pressure vessel, the contents can be regarded as subject to change in phase frequently or often (from liquid to gas or vice versa). LPG gas is heavier than air, and it can cause pockets of oxygen-depleted atmosphere in low-lying areas. However, it has been proven scientifically that LPG does not pose an ecological hazard, unless the gas/air mixture is ignited.

5. FINITE ELEMENT MODELING AND ANALYSIS

The properties of E-glass fiber and vinyl-ester resin used for the estimation of composite properties are given in Table

Table 3 Properties of E -Glass Fiber and

Properties	E-Glass continuous fiber	Cured Vinyl Ester
E (Elastic modulus)	72 GPa	3.4 Gpa
G (Shear modulus)	29.51 GPa	1.25 GPa
σ (Tensile strength)	345 MPa	338 MPa
ρ (Density)	2580 kg/cm3	1120 kg/cm3
V(volume fraction)	60%	40%

Vinyl Ester

The advantages of E-Glass Fiber include:

- Stiffness
- Less Weight

- Fatigue and Corrosion resistance
- Geometric flexibility
- Translucency

Yield Strength = 48.3 MPa of E-glass fiber. Based on Rule of Mixtures (RoM) concept.

Table 4 Properties of E-glass/vinyl ester composite

Properties	Values	Units
E1	44.56	GPa
E2	9.54	GPa
G12=G13	5.86	GPa
G23	5.99	GPa
Longitudinal-Transverse tensile strength σ12= σ13	158.4	MPa
Transverse Tensile strength	162.1	MPa

The entire CAD modeling and FEA simulation were carried out using the commercial FEA software ANSYS. The composite laminate of thickness = 2mm was modeled using 10 plies in the Composite Layup module of ANSYS keeping the orientation alternately at 45°/-45° for each layer. The Engineering Constants option was invoked for assignment of composite material properties. Burst Pressure is the designated pressure acting on the Inner Layer/Liner as per the design standards (EN12245:2002) for testing the prototypes of the composite LPG cylinder. The value assigned to the burst pressure = 22 bars and is applied as a uniform pressure load. 3-d linear shell elements (total number 780) were chosen for the FEA meshing.

Von-mises stress contour plot of the composite LPG cylinder after Static FEM analysis the analysis technique is utilized for cylindrical and dome portion of the composite tank individually.

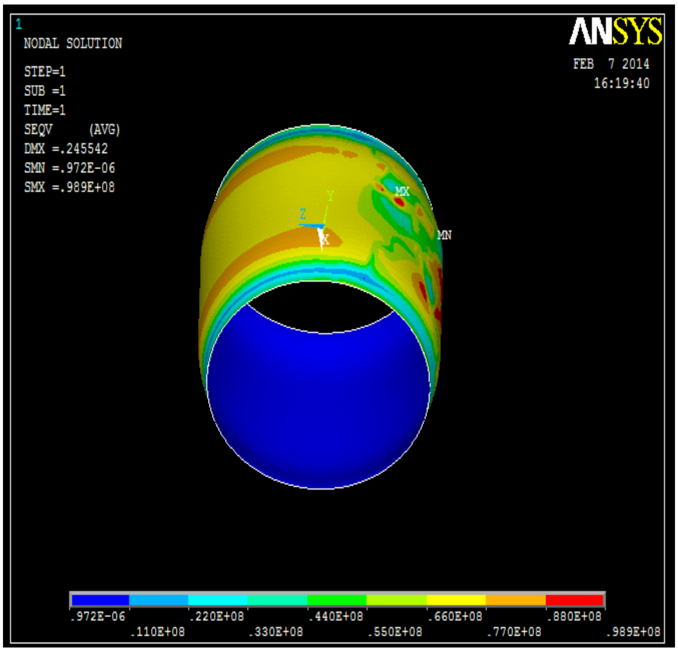

Figure 4 vonmises stress of cylindrical portion

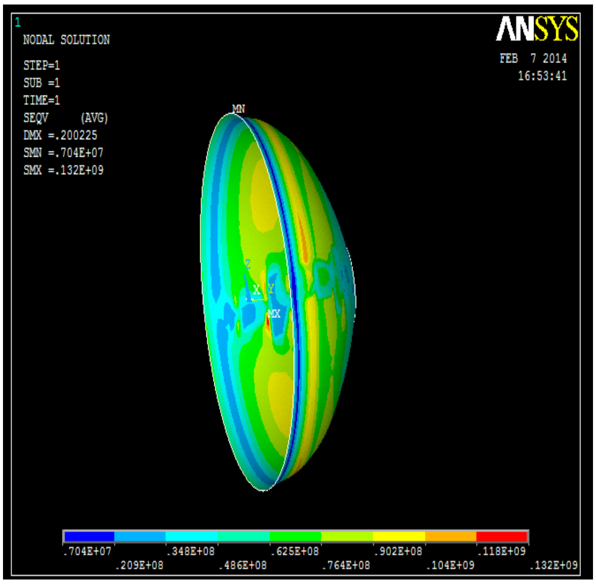

Figure 5 vonmises stress of dome portion

The results show no signs of immediate failure. The maximum operating LPG-cylinder pressure is Less than 13 bars and the testing was done at 30 bars in the present study. Hence, a factor of safety in the range of 2.15-9.1 was established. When product failure could result in serious injury or loss of life, exhaustive testing and higher safety factors have to be employed.

CONCLUSION

Three design concepts were generated and the best concept was finally selected for comprising of functionality, ergonomics, convenience, ease of manufacturing, cost etc. satisfying the customer and design needs. The FEA results showed that the material being used; HDPE Liner of 1.5 mm thickness and the wrapping composite layer of 2 mm thickness are suitable for the product to behave safely. The results show that the maximum burst pressure the chosen thicknesses could sustain is about 22 bar which is well above the subjected pressures. With the introduction of composite cylinders, dust and rain water will become a smaller concern. The FRP LPG cylinder is believed to be superior to the existing steel and aluminum cylinders in terms of weight, cost, ergonomics (semitransparent cylinder wall), safety, environmental compatibility and user friendliness. Further, studies on design analysis, optimization and fabrication of a test prototype are in progress.

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