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Design, Fabrication and Testing of Composite Overwrapped Pressure Vessel for CNG Storage

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***Abstract*—The compressed natural gas (CNG) cylinder pressure vessel becomes more important in natural gas vehicles (NGV) fuel driving system due to increase in demand for CNG. CNG pressure vessel suitable for gas operated vehicles can be made of fully metal, hoop wrapped with metal liner, fully wrapped with metal liner or fully composite. The fully metal pressure vessels are cheap but it will not prevent catastrophic failures and weight is also more. These limitations can be reduced by using composite pressure vessel. This paper discusses the design and fabrication of pressure vessel manufactured by carbon fiber reinforced epoxy based composite material with thin metallic liner. This study revealed that composite overwrapped pressure vessel (COPV) can be operated at higher pressures as compared to metallic storage cylinders.**

Keyword- Composite overwrapped pressure vessel; Netting analysis; Metallic liner; CNG storage.

I. INTRODUCTION

The amount of gasoline is limited on earth and moreover, gasoline using vehicles pollute the air and are becoming a serious problem throughout the world. Along with solar or electric powered vehicles, natural gas vehicles are one of the pollution-free vehicles being developed [1]. Storage cylinders for compressed natural gas used in vehicles are pressure vessels that have been traditionally produced using isotropic materials, such as steel and aluminum. Nevertheless, polymer composites have recently been introduced for that purpose [2]. A compressed natural gas pressure vessel made of carbon/epoxy composite with polyethylene liner weighs about 60% less than one made of aluminum. For passenger vehicles, composite CNG pressure vessels provide much safer burst behavior as compared to that of metallic CNG [1]. CNG storage manufactured with the only carbon fiber/epoxy leads to leakages due to the porosity of the composite. To overcome this drawback, the carbon filaments are coated on a metal liner. The liners may be metallic or plastic. Generally the liner used for load sharing purpose is metallic (typically aluminium 6061-T6, an Al-Mg-Si alloy). The liner also acts as a mandrel during filament winding. This storage media conception is regarded as a hybrid structure [3], where the liner provides the sealing and the corrosion resistance, while rolling up is charged to resist to the high internal pressure. This approach can provide several advantages: it ensures a perfect participation between the liner and the composite hull, it uses the overall resistance of the fiber in tension, and it allows reaching weight saving up to 50% in comparison with all metal vessels [3–5].

This paper presents the design of composite overwrapped pressure vessel (COPV) by using netting analysis & manufacturing. In this experimental work filament winding technique was employed for the fabrication of pressure vessel.

II. EXPERIMENTAL DETAILS

A. *Design and Fabrication*

The composite overwrapped pressure vessel (COPV) is configured to be made up of aluminium metal liner, a composite overwrap and aluminium polar boss at both openings.

The Table1 gives different materials used in the present work for the fabrication of COPV and manufacturing methods used for different parts of the composite casing.

Table1: Materials & Manufacturing techniques used in the fabrication of COPV

Component	Material	Method of Manufacturing
Polar boss	Al-6061	Machining
Liner	Al-6061	Spin forming
Composite overwrap	Carbon fiber & Epoxy resin	Filament winding
Liner to composite bonding	Lapox A16 / K-5	Cured

The mean effective operating pressure used in the present work is 50 bar, and the design pressure as 100 bar.

B. *Aluminum Liner*

The liner in pressure vessel is a low load bearing part and serves as a container to carry the gas and provides a definite shape to apply the filament overwrap. The shape of thin metallic liner is selected as cylindrical. A spinning method was applied to fabricate the dome of the liner. After spinning Gas tungsten arc welding (GTAW) technique was applied to the metallic liner for the assembly. The thickness of 1.5 mm was decided due to welding constraints in GTAW welding to weld the two domes to form cylindrical liner. The polar boss areas of liner are made typically thick to support the port fixture. The polar bosses are made with aluminum.

C. *Composite overwrap pressure vessel*

COPV structure based on thin shell theory has been found to agree well with large regions of the membrane portion of COPV structures. Therefore the use of thin shell theory was done for characterizing of bi-material COPV. The COPV structures exhibit a non-uniform distribution of stresses and deformation owing to a number of factors. These include the liner geometry its interaction with the overwrap winding pattern, the relative stiffness of the liner to the overwrap and the presence of incompatible curvature changes. The diameter of cylinder is taken as 159 mm, total length of the cylinder is 480 mm, with a capacity of 8.6 lit. The Fig1 shows the dimensions of the cylinder.

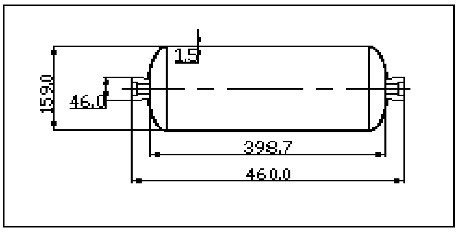

Fig.1 Pressure Vessel geometry

Load equilibrium in the COPV requires that the total applied pressure will be equal to the sum of the pressure carried by the individual components i.e.; liner and composite overwrap

$$P = P_L + P_c$$

Load carried by liner is given by

$$P_L = \sigma * 2 * t_L * _{weld}/d,$$

$$P_L = 23\text{bar}$$

$$P_c = 100-23 = 77\text{bar}$$

D. *Netting analysis*

For the calculation of thickness of shell netting analysis is used for preliminary design. For convenience and speed, this analysis ignores the structural contribution of the resin by essentially treating all composite materials as if they were a net of fibers. In other words, tensile forces are carried only along the length of the filaments. The helical wind angle and the thickness of the filament-wound layer changes continuously as measured from the tangent line to the turnaround point of the filament. Bending, bearing, and compressive stresses are not considered. This simplifying assumption is valid only if the casing wall stresses are dominated by internal pressure. The detail of netting analysis is shown inFig2.

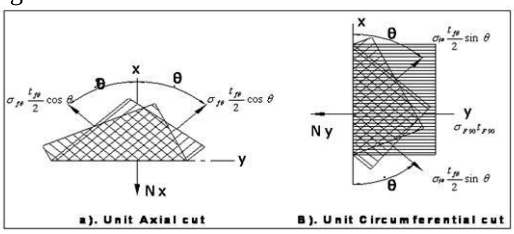

Fig. 2 Netting analysis

Simple cylinder-dome casing wall configuration consisting of single angle helical and hoop layers can be readily specified with the following closed form equations:

Geodesic winding is followed in the end dome portion between the pole opening and the point inflection at either end. The angles of winding at various points in these portions of the end domes are obtained by using the well-known Clairut theorem, rsinα = ro where, r is radius at the point, α is angle of winding, ro is radius at the pole opening and

$$\alpha \quad = \sin\text{-}1(19/79.5) = 13.8°$$

Certain technological constraints have to be considered while estimating the thickness requirements helical ply thickness is a function of both design as well as processing parameters such as local angle of winding, local cross sectional radius, volume fraction, number of spools, filament cross sectional area, etc. Helical thickness per ply for a given angle of winding and cross sectional radius can be experimentally estimated as: $r \times t_{hel} \times \cos\alpha$ = constant

All of the above technological constraints are considered and required total helical thickness at various stations for the 'design loads' with the 'material allowables' are calculated. The details of thickness are as follows::

$$t_{hel} = pr/(2\sigma f\cos 2\alpha) = 0.4\text{mm}$$

$$t_{hoop} = pr(2-\tan 2\alpha)/(2\sigma_f) = 0.6\text{mm}$$

Total thickness = $t_{hel} + t_{hoop}$ =1mm

Where,

t_{hel} : Required total helical thickness,
t_{hoop} : Required total hoop thickness,
p : Design burst pressure =100bar
r : Cross sectional radius of the cylinder
σ_f : Longitudinal tensile strength of filament wound composite
α : Angle of winding at corresponding station

The following ply sequence and each ply thickness are derived and finalized.

E .*Manufacturing of COPV*

The port openings and attachments are subjected to the full pressure load and external acceleration loads. Thus, high ultimate strength and high cycle fatigue characteristics are desirable qualities here. These experience random vibrations also. Al-6061 was chosen for making the Polar boss which will be machined out of Al-6061 forgings. The machined polar boss are shown below in Fig3.

Fig.3 Polar boss

The liner is divided into two half's with each end having polar bosses. Each piece is fabricated from rolled sheet by spin forming over the spin forming fixture. The liner halves and polar boss are assembled using GTAW welding technique. All welds are fully radiograph inspected and critical penetrate inspected. The assembled liner is then fully annealed and hydraulic leak tested at 2 bar prior to wrapping with composite. The finished metallic liner is shown below in Fig 4.

Fig. 4 Finished Metallic liner

The composite overwrap is obtained by wet winding over the mandrel. The liner itself serves as mandrel for this structure. Prior to filament winding, a layer of film adhesive is applied to the liner's surface, adhesive is prepared by dissolving hardener K-5 to heated Araldite A-16 (100°C) at the ratio of 100 parts A-16 : 27 parts K-5 by weight.

The filament winding along with doily lay-up is carried out on mandrel is shown below in Fig5.

Fig. 5 Filament winding over liner

III.RESULTS & DISCUSSIONS

The COPV was successfully fabricated by using filament winding technique. It has been calculated that 1mm was chosen as composite layer thickness by using netting analysis. The manufactured vessel was tested by pressurizing it internally with water. When the test specimen is applied with internal hydrostatic pressure, the pressure vessel will expand and elongate. Burst test involves a specimen that can be permitted to expand in both the circumferential and longitudinal directions. Circumferential and longitudinal strain gauges are bonded to the specimen with in centre of the test section. Pressure is applied by a hydrostatic test machine equipped with a device to record continuously.

It is observed that the actual burst had occurred at 106 bar. When there was sudden drop of pressure it was observed that the rupture had occurred between 106-108 bar. This indicates that there is a progressive failure of the material which results in ply by ply failure. Hence catastrophic failure is prevented in the composite cylinder unlike that of cylinder which is made of conventional steel. The actual failure occurred at dome junction due to hoop stress, at which failure strain is observed as 16500 micro-strains.

IV.CONCLUSIONS

A composite overwrapped pressure vessel has been designed and manufactured to meet the purpose of making a CNG storage vessel with high strength and low weight compared to existing metallic tanks. The design is cost effective also. The netting analysis is used for design has been verified for the application of COPV designing. The composite CNG cylinder designed and fabricated under the scope of this investigation is capable of withstanding the stipulated Mean effective operating pressure of 50bar.The design stresses are within safe limits. The carbon fiber composite CNG cylinder is suitable for storage of CNG.

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