A STUDY OF NON-TRADITIONAL GEOMETRIES AND ALTERNATIVE ALLOYS FOR NGV STORAGE GAS TANKS

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Abstract: *The present paper presents a study on non-conventional geometries and alternative alloys for Natural Gas Vehicle storage tanks. The tanks have been designed to store compressed natural gas and adsorbed natural gas, according to Brazilian standards (NBR) for pressure vessels. Different tank geometries are studied using CAD models and then analyzed by finite element tools to verify the model efficiency. Finally, a comparison of the different designs is carried out, based on hydraulical capacity, volume of Natural Gas storage, weight and material.*

Keywords: *NGV Storage, CAD, FEM.*

1. Introduction

In the decades there has been an increasing worldwide consumption of natural gas. Environmental concern and economical reasons have been the main advantages of using natural gas as motor vehicles fuel.

Currently, there are three different types of storage of GNV: liquid natural gas (LNG), compressed natural gas (CNG) and adsorbed natural gas (ANG) (Holroyd et al., 1999).

The LNG type is stored and maintained at cryogenic temperatures (~ -161ºC) and atmospheric pressure. This process presents a reduction of about 600 times the original volume (Holroyd et al., 1999), however the relatively high costs for liquefaction of the gas is justified only in operations that require a larger autonomy in comparison to the CNG as, for example, in trains, buses and trucks.

The CNG is the most used stored type for vehicular applications at pressures between 15 and 25 MPa (Holroyd et al., 1999). One of the main problems of GNC use is the high weight of the storage tank due to the high pressure capability required. Because of this additional load, the vehicle looses power and its suspension system becomes overloaded. Another difficulty is the biggest tank size which reduces significantly the space available in the vehicle trunk. These aspects have encouraged engineers to investigate non-traditional shaped storage gas vessels. The challenge is to develop new tanks by considering the possibility of applying new materials as well as new geometries.

The ANG appears as an alternative to the CNG, where solid microporous are placed in the reservoir increasing the storage density and allowing operations at lower pressures (3.5 to 4,0 MPa) (Holroyd et al., 1999). Consequently, the stresses in the tank walls are reduced. Another parameter for comparison between CNG and ANG is the relation between the volume of natural gas and the tank volume capacity (V/V), which are approximately 220 V/V and 150 V/V (Cook & Horne, 1997), respectively. Thus the use of non-conventional geometries appear as an advantageous solution, increasing the internal space available in the vehicle trunk and allowing higher stiffness combined with lower weight.

2. Methodology

The non-conventional geometry parameters of the new tanks were calculated through a mathematical study of the internal pressure and the results were compared for a definition of the best parameters. Then, a simulation of the behavior of the new geometries was carried out using a commercially available Finite Element Method (FEM) software package (ALGOR), to verify the efficiency of the reservoirs under the gas pressure load.

3. Formulation

Since mathematical models for the studied tanks with non-conventional geometries were not found in the literature, as a first approximation, a mathematical study of the stresses developed was carried out for a better understanding of the strength behavior of high pressure gas reservoirs. The tank geometries were considered as simple geometries (circular, elliptical and cylindrical).

3.1. Spherical vessel

Considering a theoretically perfect geometry for fluid storage, under an applied pressure p, a spherical pressure vessel of internal radius r, and wall thickness t presents, for a symmetry reason, identical stresses on all faces of the infinitesimal element (Fig. 1 a). Thus, the stresses can be obtained from the free body diagram of a section cut by a referential plane passing through the center of the pressure vase (Fig. 1 b) The stress in the sphere is obtained through the analysis of the free body diagram (Higdon et al., 1985).

$$\sigma_{sphere} = \frac{pr}{2t} \tag{1}$$

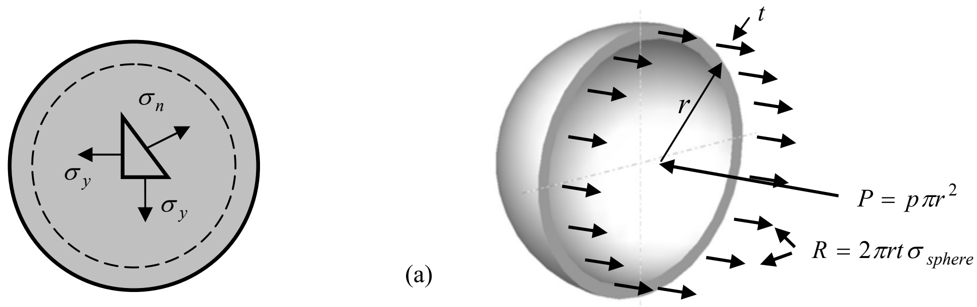

Figure 1. Spherical geometry (a) Infinitesimal element diagram (b) Free body diagram.

3.2. Cylindrical vessel

In order to analyze the load distribution for the cylindrical vessel with an internal radius r and a wall thickness t, under internal pressure p, it was necessary to establish the direction of the principal stresses in the infinitesimal element (Fig. 2 a), σ_1 and σ_2, in the radial and longitudinal direction, respectively (Higdon et al., 1985). The infinitesimal element stresses are obtained by analysis of the free body diagram (Fig 2 b):

$$\sigma_1 = \frac{pr}{t}; \qquad \sigma_2 = \frac{pr}{2t} \tag{2), (3}$$

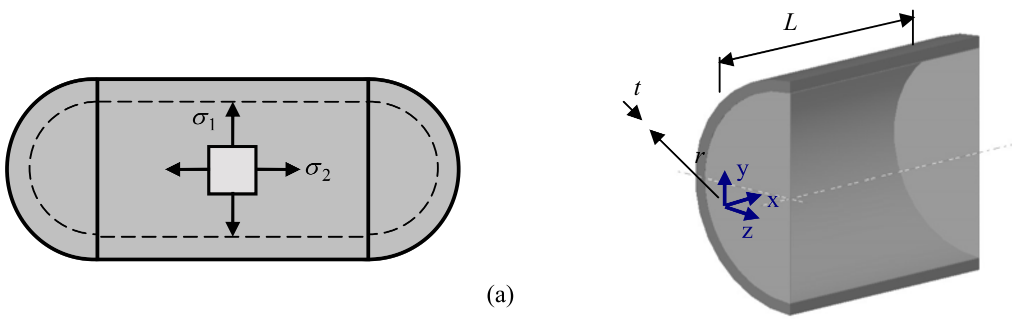

Figure 2. Cylindrical vessel (a) Infinitesimal element diagram (b) Free body diagram

NBR 12790 ABNT standards (1995) establishes that the minimum wall thickness (t_{min}) for steel cylinders without weld for maximum stress was determined using the equations (4) and (5):

$$t_{\min} = \frac{D}{2}\left(1-\sqrt{\frac{\sigma_{\min}-1{,}3H}{\sigma_{\min}+0{,}4H}}\right), \ \sigma_{\min} = \frac{H\left(1{,}3D^2+0{,}4d^2\right)}{D^2-d^2} \tag{4), (5}$$

where

σ_{min} : Maximum wall stress [MPa] was calculated using the equation (5)
d : Internal diameter [mm]
t_{min} : Minimum wall thickness [mm]
D : External diameter [mm]
H : Hydrostatic test pressure [MPa]

3.3. Elliptical vessel

Considering an elliptical pressure vessel with semi axes *a* and *b* and wall thickness *t*, the infinitesimal element stresses (Fig. 3 a), σ_1 e σ_2, were determined by the analysis of the free body diagram shown in (Fig. 3 b):

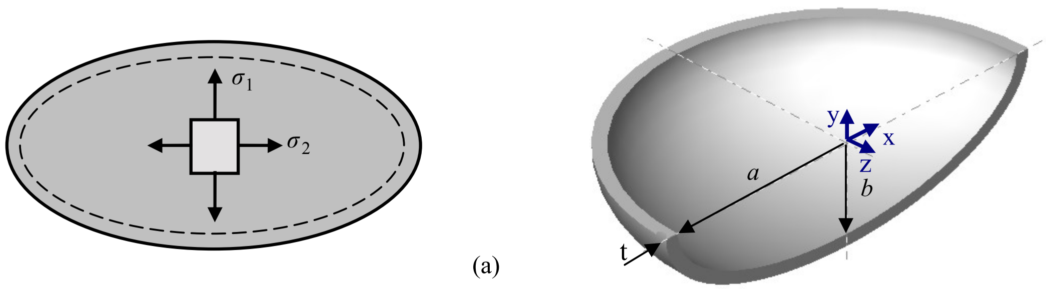

Figure 3. Elliptical gallery vessel, a) Infinitesimal element diagram (b) Free body diagram.

$$\sigma_1 = \frac{pr}{2t}, \qquad \sigma_2 = \frac{p(a*b)}{\left(2\sqrt{\frac{a^2+b^2}{2}}\right)t} \tag{6), (7}$$

3.4. Elliptical galleries vessel

Considering an elliptical gallery pressure vessel with semi axes *a* and *b*, length *L*, and wall thickness *t*, the infinitesimal element stresses (Fig. 4), σ_1 e σ_2, were determined by the analysis of the free body diagram shown in (Fig. 4):

$$\sigma_{1a} = \frac{pa}{t}; \qquad \sigma_{1b} = \frac{pb}{t}; \qquad \sigma_2 = \frac{p(a*b)}{\left(2\sqrt{\frac{a^2+b^2}{2}}\right)t} \tag{8), (9), (10}$$

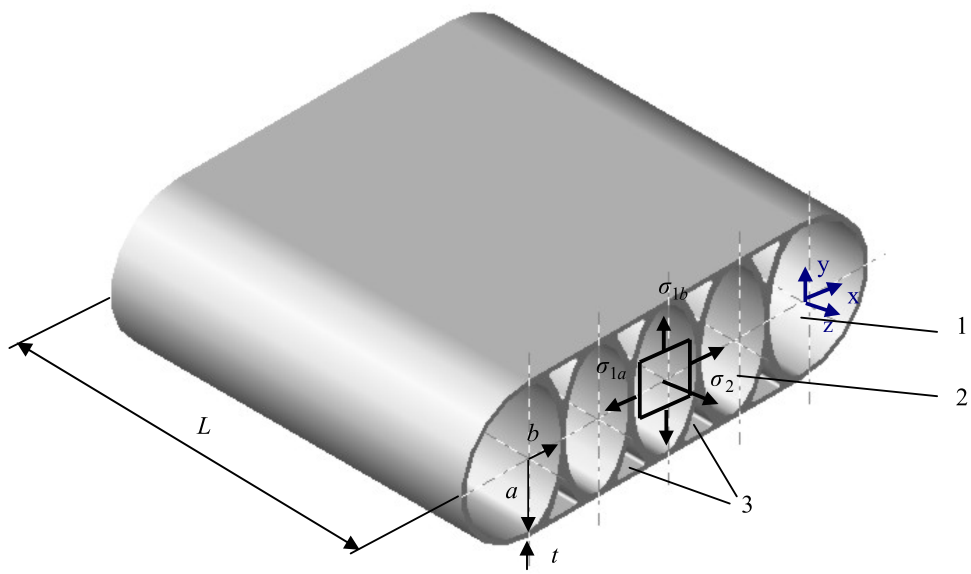

Figure 4. Infinitesimal element diagram and free body diagram of elliptical galleries vessel.

3.5. Toroidal Geometry

Considering a toroidal pressure vessel with external radius *R*, internal radius *r*, and wall thickness *t*, the infinitesimal element stresses (Fig. 5 a), σ_1 e σ_2, were determined by analyzing the free body diagram shown in (Fig. 5 b):

$$\sigma_1 = \frac{pr}{t}; \qquad \sigma_2 = \frac{pr}{2t} \qquad (11), (12)$$

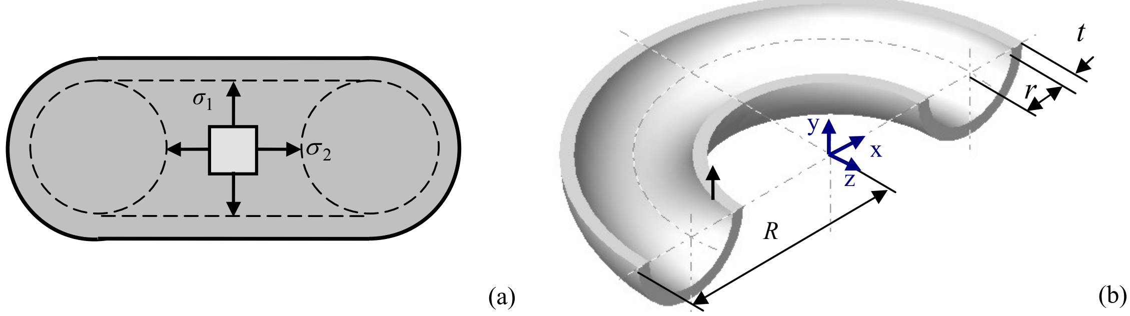

Figure 5. Toroidal vessel (a), Infinitesimal element diagram (b), Free body diagram.

4. Analysis parameters

Materials: Two different types of materials were used in this work: steel AISI 4130, actually used in commercial cylinders CILBRAS, and the aluminum alloy AA-7075-T6.

Internal pressure: The internal pressure was determined using the NBR 12790 ABNT standards (1995). The NBR 12790 ABNT standards (1995) established that the internal pressure should be 3/2 (or 150%). Thus the internal pressure for CNG was 30 MPa and for ANG was 6 MPa.

Wall thickness: The tank wall thickness has been calculated based on the 12790 ABNT standards (1995) as a function of the internal pressures imposed by the gas. NBR 12790 ABNT standards (1995) establishes that the minimum thickness in the dome must be twice the minimum wall thickness calculated; it also establishes that for cylinders with internal pressure lower that 6.2 MPa, the minimum wall thickness must be 2.5 mm for any cylinder with diameter higher that 1.30 mm. Because of the lack of standards for calculation of the minimum wall thickness of the non-conventional geometry pressure vessel studied in this work (elliptical, elliptical galleries and toroidal), the minimum wall thickness for all the pressure vessels was established in 2,5 mm, and the thickness for the dome was considered twice the minimum wall thickness.

Maximum stress: For steel cylinder without welding the NBR 12790 ABNT standards (1995) establishes that the wall thickness must be such that the stresses do not exceed 520 MPa or lower that 5/6 of the material strength.

For aluminum cylinders without welding we take 5/6 established in the NBR 12790 ABNT standards (1995) because this material is not standardized, thus the maximum stress wall for Al 7075-T6 alloy was 419 MPa.

In the case of tanks with welding, the intensification factor established in the ASME code Volume II was used, that corresponds to 0.67 of maximum stress wall without welding. Thus the maximum stress wall in the tanks with welding was 347 MPa for steel AISI 4130 and 279 MPa for aluminum 7075-T6.

5. Results and discussion

Based on the theory discussed in this work, the parameters studied for a modular tank (Fig. 6 a) and three non-conventional geometry vessels the following aspects were calculated: elliptical geometry (Fig. 6 b), elliptical galleries (Fig. 6 c), and toroidal (Fig. 7 e).

The modular tank and the elliptical galleries tank concept arose from the necessity to increase the available space in the motor vehicle trunk (Fig. 7 a), by reducing the height of the types of vessels in comparison with commercially available cylindrical shaped. The main drawback was the fact that these vessels obstruct the access to the spare tire located in the trunk (Figs. 7 b, c). The elliptical and toroidal formats are possible to be installed in the spare tire compartment (Figs. 7 d, e). The motor vehicle model taken as reference for this study was a Fiat Palio EX automobile. The tank is designed to occupy most of the entire spare tire compartment. Consequently, it is necessary to position the spare tire somewhere else in the vehicle. A possible solution is to make some adaptation in order to place the tire on the back door (Fig. 7 f). However, it is of the utmost importance to be aware that this adaptation does not interfere with the back lights and license plates. This solution can also be applied in the case of the elliptical gallery tank.

Two toriodal tanks were analyzed, one with 100 mm of internal radius, considered a small toroidal tank, and the other one with 125 mm of internal radius regarded as a large toriodal tank.

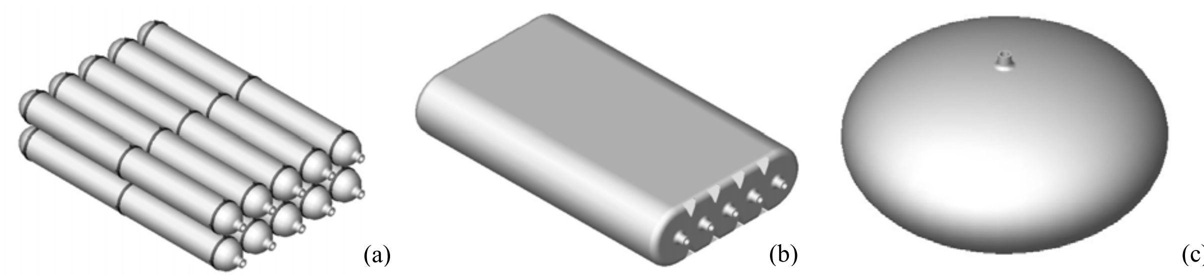

Figure 6. Pressure tanks (a) Modular (b) Elliptical galleries (c) Elliptical

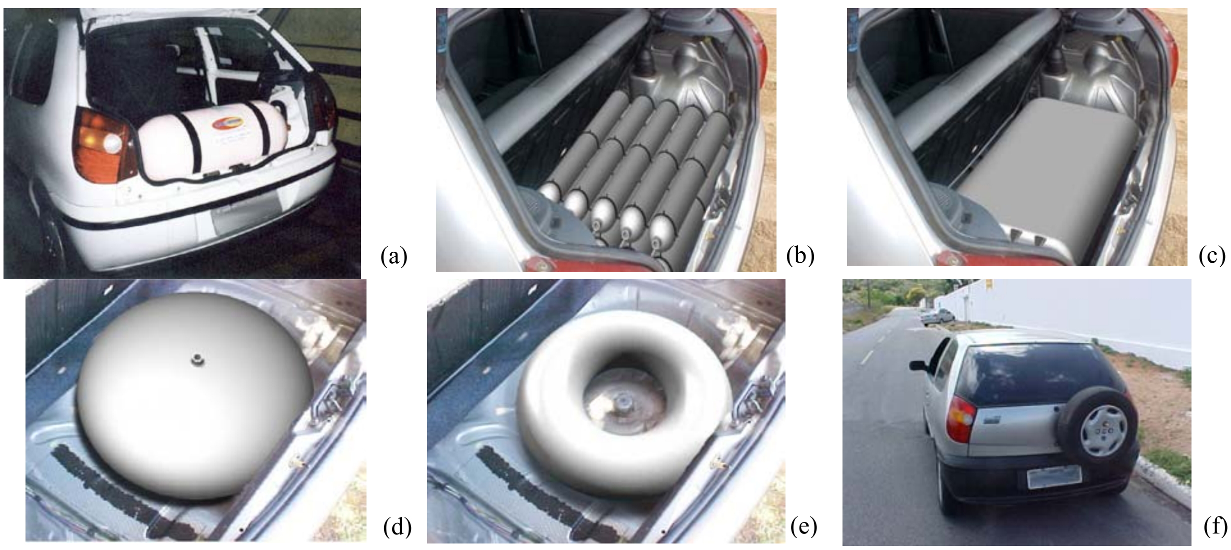

Figure 7. Fiat Palio EX (a) Trunk occupied by a commercially available cylinder (b) Modular prototype positioned in the spare tire compartment (c) Elliptical galleries positioned in spare tire compartment. (d) Elliptical prototype positioned in spare tire compartment (e) Toroidal prototype positioned in spare tire compartment (f) Spare tire repositioning at the back door.

The tank parameters for CNG and GNA in steel 4130 and Al 7075-T are presented in Tables 1 to 4, and are compared with commercially available cylinder parameters in steel AISI 4130 and Al 7075-T6.

Table 1. Tanks parameters with CNG compared with a commercial cylinder with CNG, made of steel AISI 4130.

Properties	**Commercial cylinder**	**Modular tank (10 units)**	**Elliptical galleries tank**	**Elliptical tank**	**Toroidal tank**	
Hydraulic capacity (m^3)	0,068	0,068	0,072	0,072	0,044	0,044
V/V relation	220	220	220	220	220	220
Natural Gas volume (m^3)	15,0	15,0	15,9	15,8	9,8	13,6
Material	AISI 4130	AISI 4130	AISI 4130	AISI 4130	AISI 4130	AISI 4130
Maximum stress (σ_{mp}) (MPa)	520	520	374	347	347	347
Density (kg/m^3)	7800	7800	7800	7800	7800	7800
Length (mm)	350	500	500	650	650	650
Height (mm)	350	200	180	325	200	250
Width (mm)	920	900	900	650	650	650
Internal pressure (MPa)	30	30	30	30	30	30
Wall thickness (mm)	9,0	2,5	9,5 – 7,2	26,0	13,8 – 6,9	17,2 – 8,6
Dome thickness (mm)	18,0	5	19,0	-	-	-
Weight (kg)	77,9	59,0	212,4	199,2	60,9	93,9

Table 1 shows that the gas storage capacity in the modular tank is the same of the commercial cylinder and the weight decreases to 75%. In the elliptical galleries and elliptical tanks the gas storage capacity increase in small percentage in relation to the commercial cylinder, in contraposition the weight increase to approximately 270% and 255%, respectively. In the case of the small toroidal tank the storage capacity decreases in approximately 65% in comparison to the commercial cylinder but the weight decreases in less than 78%. In the case of the large toroidal tank the storage capacity decreases in approximately 90% in comparison to the commercial cylinder, but the weight increases up to 120%.

Table 2. Tanks parameters with CNG compared with a commercial cylinder with CNG made of aluminum 7075-T6.

Properties	Commercial cylinder	Modular tank (10 units)	Elliptical galleries tank	Elliptical tank	Toroidal tank	
Hydraulic capacity (m^3)	0,068	0,068	0,072	0,072	0,044	0,061
V/V relation	220	220	220	220	220	220
Natural Gas volume (m^3)	15,0	15,0	15,9	15,8	9,8	13,6
Material	Al 7075-T6	Al 7075-T6	Al 7075-T6	Al 7075-T6	Al 7075-T6	Al 7075-T6
Maximum stress (σ_{mp}) (MPa)	419	419	279	279	279	279
Density (kg/m^3)	2810	2810	2810	2810	2810	2810
Length (mm)	350	500	500	650	650	650
Height (mm)	350	200	180	325	200	250
Width (mm)	920	900	900	650	650	650
Internal pressure (MPa)	30	30	30	30	30	30
Wall thickness (mm)	11	2,9	12,0 – 9,5	39,0	17,2 – 8,6	22,8 – 9,6
Dome thickness (mm)	22	5,8	24,0	-	-	-
Weight (kg)	36,5	24,0	92,6	107,8	27,3	40,4

Table 2 shows that the weight in the modular tank decreases to 65%. In the elliptical galleries and elliptical tanks the weight increases to approximately 250% and 293%, respectively. In the case of the small toroidal tank the weight decreases in less than 75%. In the case of the large toroidal tank the weight increases to approximately 110%. Also the weight of all tanks decrease in comparison with the steel tanks showed in the Table 1.

Table 3. Tanks parameters with ANG compared with a commercial cylinder with ANG made in steel AISI 4130.

Properties	Commercial cylinder	Modular tank (10 units)	Elliptical galleries tank	Elliptical tank	Toroidal tank	
Hydraulic capacity (m^3)	0,068	0,068	0,072	0,072	0,044	0,061
V/V relation	150	150	150	150	150	150
Natural Gas volume (m^3)	10,2	10,0	10,8	10,8	6,6	9,3
Material	Aço 4130	Aço 4130	Aço 4130	Aço 4130	Aço 4130	Aço 4130
Maximum stress (σ_{mp}) (MPa)	520	520	374	347	347	900
Density (kg/m^3)	7800	7800	7800	7800	7800	7800
Length (mm)	350	500	500	650	650	650
Height (mm)	350	200	180	325	200	250
Width (mm)	920	900	900	650	650	650
Internal pressure (MPa)	6	6	6	40	6	6
Wall thickness (mm)	2,5	2,5	3,5 – 2,6	4,3 – 3,3	2,5	2,7 – 2,5
Dome thickness (mm)	5,0	5,0	7,0	-	-	-
Tank weight	22,3	59,0	86,2	26,8	17,7	22,6
Adsorbent weight	27,8	27,9	29,6	29,5	18,2	25,3
Total weight (kg)	50,3	86,6	115,9	56,2	35,9	47,9

Table 3 shows that the gas storage capacity in the modular tank is the same of the commercial cylinder and the weight increases to approximately 172.6%. In the elliptical galleries and elliptical tanks the gas storage capacity increases in small percentage in relation to the commercial cylinder, on the other hand the weight increases to approximately 230% and 112%, respectively. In the case of the small toroidal tank the storage capacity decreases in approximately 65% in comparison to the commercial cylinder but the weight decreases in less than 71%. In the case of the large toroidal tank the storage capacity decreases in approximately 90% in comparison to that of the commercial cylinder, but the weight decreases in less than 95%. Also the tank storage capacity decreases in comparison with the tanks showed in the Tables 1 and 2.

Table 4. Tanks parameters with ANG compared with a commercial cylinder with ANG made of aluminum 7075-T6.

Properties	**Commercial cylinder**	**Modular tank (10 units)**	**Elliptical galleries tank**	**Elliptical tank**	**Toroidal tank**	
Hydraulic capacity (m^3)	0,068	0,068	0,072	0,072	0,044	0,061
V/V relation	150	150	150	150	150	150
Natural Gas volume (m^3)	10,2	10,0	10,8	10,8	6,6	9,3
Material	Al 7075-T6	Al 7075-T6	Al 7075-T6	Al 7075-T6	Al 7075-T6	Al 7075-T6
Maximum stress (σ_{mp}) (MPa)	419	419	279	279	279	241
Density (kg/m^3)	2810	2810	2810	2810	2810	2700
Length (mm)	350	500	500	650	650	650
Height (mm)	350	200	180	325	200	250
Width (mm)	920	900	900	650	650	650
Internal pressure (MPa)	6	6	6	40	6	6
Wall thickness (mm)	2,8	2,5	3,4 – 2,7	5,3 – 4,0	2,5	3,6 – 2,5
Dome thickness (mm)	5,6	5,0	7,0	-	-	-
Tank weight	8,7	20,1	29,8	11,7	6,3	9,1
Adsorbent weight	27,8	27,9	29,6	29,5	18,2	25,3
Total weight (kg)	36,2	48,1	59,4	41,9	24,5	33,4

Table 4 shows that the weight in the modular tank increases to approximately 132%. In the elliptical galleries and elliptical tanks the weight increases to approximately 164% and 115%, respectively. In the case of the small toroidal tank the weight decreases in less than 68%. In the case of the large toroidal tank the weight decreases in less than 92%.

The structural analyses for the geometries considered were performed using the commercially available FEM software (Algor) (Figs. 8, 9).

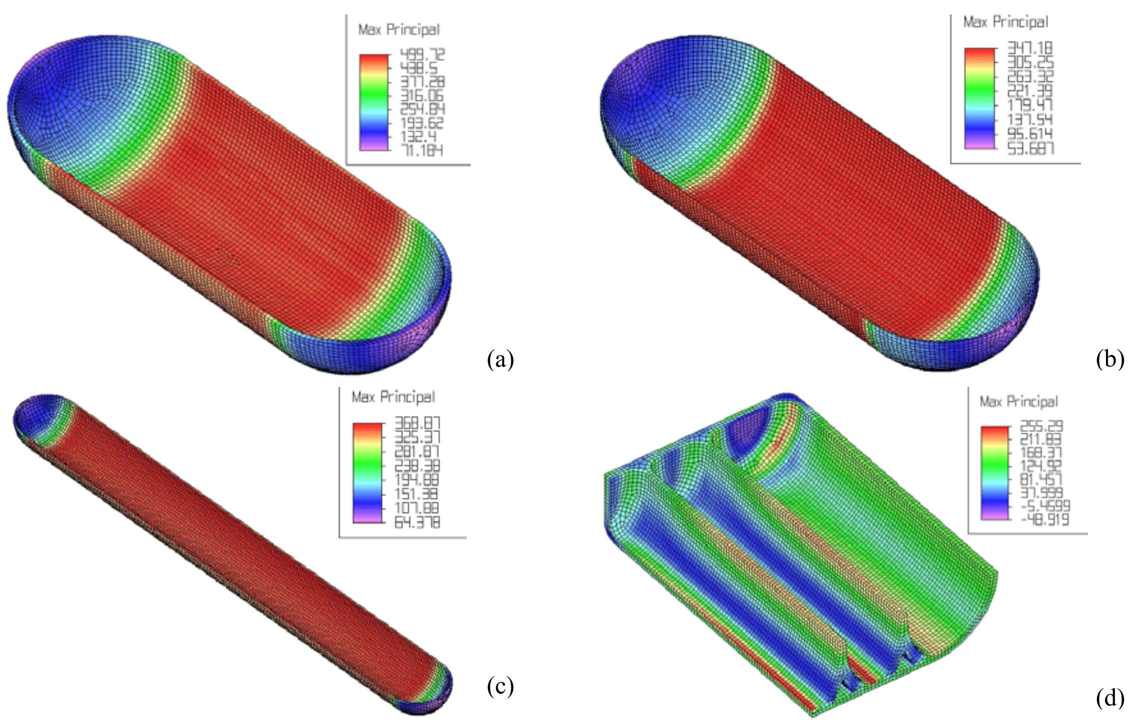

Figure 8. Tank stress distribution in MPa (a) Commercial cylinder in steel AISI 4130 with CNG (b) Commercial cylinder in Al 7075-T6 with ANG (c) Modular tank in Al 7075-T6 with CNG . (d) Elliptical galleries tank in Al 7075-T6 with CNG

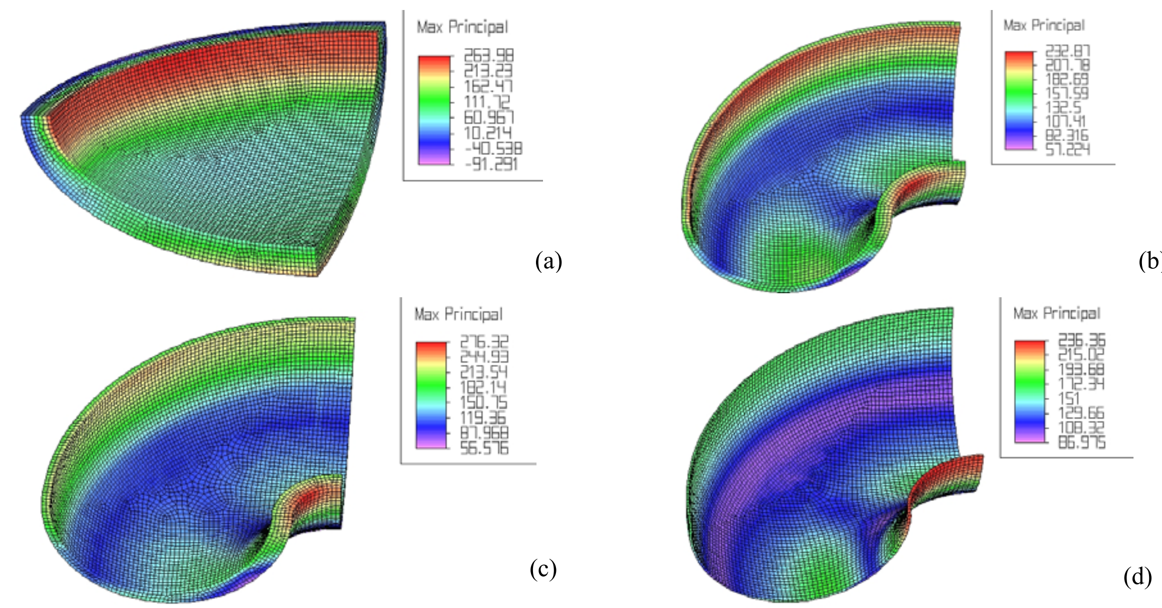

Figure 9. Tank stress distribution in MPa in Al 7075-T6: (a) Elliptical tank with GNC (b) Toroidal tank with CNG (c) Toroidal tank with CNG. (d) Toroidal tank with ANG.

6. Conclusions

The results presented in this work showed that the use of non-conventional geometries and alternative alloys for NGV vessels is viable. For CNG and ANG tanks in aluminum 7075-T6 presented low weight in comparison with the tanks in steel AISI 4130.

For the CNG fuel the modular and the toroidal tanks appear as a good solution. The larger toroidal tank concept presented the best results. With this geometry, although the storage volume had been reduced by 90%, a 50% reduction in the weigh decreases the load on the vehicle and there is also a gain in the available space in the trunk.

For the ANG modular, the elliptical and the toroidal tanks appear as a good solution. The elliptical tank and the larger toroidal tank concepts presented the best results. If weigh is the driving parameter, the toroidal geometry was more advantageous with a reduction of 10% in comparison with the cylindrical form.

It is recommend and also necessary, to develop further studies in this subject, using the set of tests established in the NBR 12790 ABNT standards (1995) because these tests provide qualitative data to verify the results reported in this work.

In general, the investigation showed a good performance for all the non-conventional geometries studied. Nevertheless, more studies are necessary to allow the application of lighter materials in the manufacture of these tanks and to increase the volume capacity of the vessels to be used as gas storage fuel systems for natural gas vehicles.

7. Acknowledgements

This research was supported by FINEP, Petrobrás and CTGás, Brasil.

8. References

ASME Code, Volume II, Appendix 2.

Cook, T. L., Horne, B. H., 1997, “Low pressure adsorbed natural gas vehicle demonstration”, 2oth Word Gas Conference, Copenhagen, Denmark.

Higdon, A., Ohlsen, E.H., Stiles, W.B., Weese, J.A., Riley, W.F., 1985, “Mechanics of Materials”, New York: John Wiley & Sons.

Holroyd, N. J. H., Ellis, M. B. D., Carrigan, J., Gorr, J. P., Davis, W. F., Davis, J. W., 1999, “Customized gas storage fuel systems for natural gas vehicles”, Society for Advanced of material and Process Engineering, Inc. Ohio USA.

NBR 12790 ABNT, 1995, "Cilindro de aço especificado sem costura, para armazenamento e transporte de gases a alta pressão”. Associação Brasileira de Normas Técnicas.

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