Optimal Design of a CNG Storage Tank with a Combined Form Consisting of a Torus and a Sphere

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Abstract: *This paper presents the optimum sizing of a storage tank composed of a torus and a sphere, made of steel, intended for compressed natural gas (CNG) storage from the automotive industry. A design strategy was proposed to determine based on the finite element method, the optimum thicknesses of the torus and spherical coverings, with the correction of their thickness taking into account: the temperature variation, the corrosion action during the operation, the tolerances of execution of the sheet laminate, and the technological process used to manufacture the elements. Numerical simulations were carried out to determine the optimum form and sizing of the storage tank based on an objective optimization function to minimize the storage tank mass. For size dimensioning, the exploatation temperature was computed in function of the maximum effort Von Misses and the corresponding resulting linear deformation. The 3-D (three-dimensional) model (modelled using the AutoCAD Autodesk 2017 software), was imported for numerical analyses to SolidWorks 2017 software). The results of analyzed cases can improve the technical performances of these particular types of CNG storage tanks to meet the customers' requirements.*

Keywords: *Automotive industry, compressed natural gas (CNG) storage tank, industrial engineering design, optimization methods, pressure vessel*

1. Introduction

In the last decades, the convergence of business models, technological developments and researches in the field of the fuel tank industry have revealed a fluent and coherent approach regarding the advanced design tools for the creation of new products with high performances and high quality [1-6].

The results of these researches are multifaceted. Not only is the demand for fuel storage tanks increasing, but the options available (such as the intended application, space constraints, weight, and cost price), safety and reliability considerations have become more sophisticated [7-11].

The dynamics of the storage tank markets has evolved in an upward direction both in the field of execution technology and in the strategy of qualitative innovation based on 3-D design, interdisciplinary and complex research in border areas that offers a competitive advantage [12-17].

In designing the fuel storage tanks, the researchers proposed and investigated through theoretical and experimental analyzes, models with different geometries (executed from various materials, with storage capacities and competitive prices to meet the customers' requirements [18-22].

Modeling prototypes of the fuel storage tanks used in the automotive industry with computer aided design (CAD) software and advanced design concepts allows avoiding the use of testing equipment and expensive tests performed with products under real conditions [23-27].

For the design, analysis and evaluation of storage tanks there are various software packages with virtual computer aided engineering (CAE) tools on the market, which offer users quick and precise projects for new tanks and evaluation of existing tanks in various environmental conditions, in accordance with the relevant guidelines and regulations outlined by the national/international standards [28-32]. Also, there are various valid implementations of mathematical methods in more efficient algorithms and programs [33-37] to find the optimized solution according the criterion of optimality to satisfy the general structural design [38-42] and certification rules [43, 44].

In our research, the optimum sizing of a fuel storage tank composed of a torus and a sphere, made of steel, intended for compressed natural gas (CNG) storage from the automotive industry was performed in accordance to the general structural design.

2. Design methodology

2.1 Basic geometry of the parametric 3-D model

Let's consider the parametric 3-D model of a CNG storage tank composed by a torus and a sphere as shown in fig. 1. By adopting the torus as a support element of the sphere, the aim is to achieve a constructive variant that can lead to the elimination of the sphere support system.

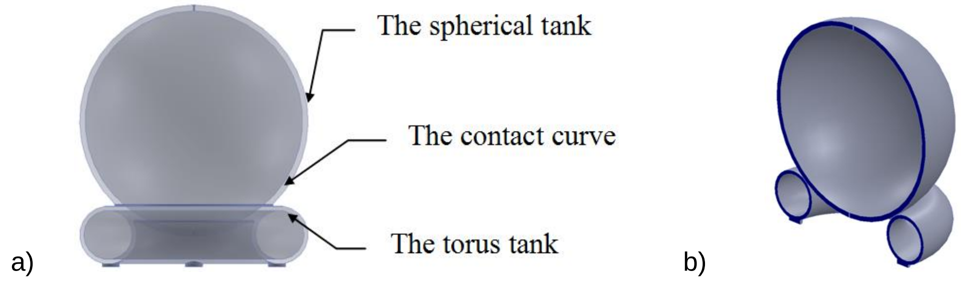

Fig. 1. The graphical representation of the parametric 3-D solid model: a) section; b) axonometric view

In this case, an intermediate bracelet type element (fig. 2a) was used, which supports the torus inside, and on the outside on the contoured surface of the sphere (fig. 2b and fig. 2c). In this way it was intended that the action of the forces generated by the sphere to discharge / towards the sole of the support element through its body without transmitting their action on the torus coverings.

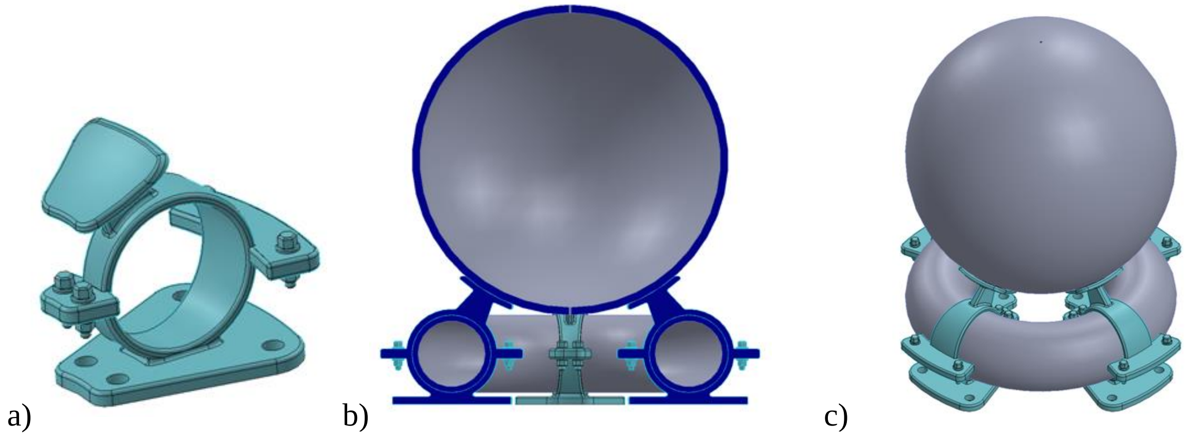

Fig. 2. The graphical representation of: a) the intermediate bracelet type element; b) section of 3-D solid model; c) axonometric view of 3-D solid model

In design, the aim was to determine the diameter of the sphere and the torus: the diameter of the cross-section and the diameter of the guiding curve of the cross-section needed to generate it.
Let's consider the dimensions B x H imposed in the cross-section of the storage tank and the depth dimension L1 (fig. 3).

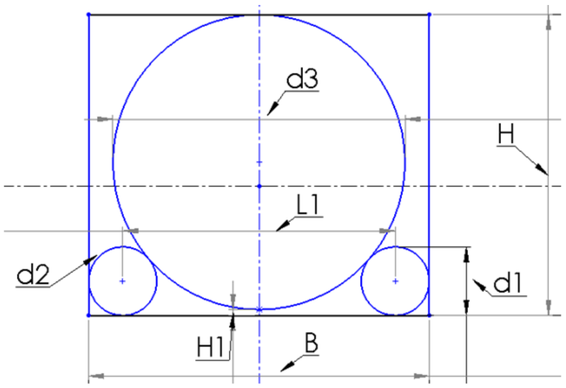

Fig. 3. The graphical representation of the dimensions B x H imposed in the cross-section of the storage tank and the depth dimension L1

The following parameters were applied as input parameters to the 3-D parametric model (fig. 3): a) H1 > 0; b) d1 = d2; c) B = H = L = 3000 mm.
The sizes d1, L1 and d3 will be determined considering a maximum total volume of storage tank (composed by a torus and a sphere). As a result of the variation of diameter d1 (which took into account the solution of construction of the support element) which decreased the radius of the cross-sectional storage section by Δd1 = 50 mm, the following dimensions were determined (shown in table 1).

Table 1: The constructive dimensions of the storage tank

d1 [m]	H1 [m]	L1 [m]	d3 [m]	V1 [m³]	V3 [m³]	VT [m³]	V [m³]	p_{vol} [%]	A1 [m²]	A3 [m²]	A_total [m²]
0.450	0.043	2.450	2.915	1.223	12.963	15.408	27.0	57.06	10.870	26.681	48.422
0.500	0.103	2.400	2.794	1.479	11.416	14.374	27.0	53.23	11.832	24.514	48.177
0.550	0.163	2.350	2.673	1.752	9.999	13.504	27.0	50.01	12.744	22.442	47.929
0.600	0.223	2.300	2.553	2.041	8.708	12.790	27.0	47.3	13.606	20.466	47.678
0.650	0.284	2.250	2.432	2.343	7.528	12.214	27.0	45.23	14.420	18.572	47.411
0.700	0.344	2.200	2.311	2.657	6.461	11.776	27.0	43.6	15.184	16.774	47.141
0.750	0.405	2.150	2.191	2.981	5.501	11.463	27.0	42.45	15.899	15.067	46.864
0.800	0.465	2.100	2.070	3.313	4.642	11.267	27.0	41.73	16.564	13.455	46.583
0.850	0.526	2.050	1.950	3.651	3.880	11.182	27.0	41.41	17.180	11.940	46.301
0.900	0.586	2.000	1.829	3.993	3.199	11.186	27.0	41.42	17.747	10.498	45.993
0.950	0.646	1.950	1.708	4.338	2.608	11.283	27.0	41.79	18.265	9.160	45.690
1.000	0.707	1.900	1.587	4.683	2.092	11.458	27.0	42.43	18.733	7.908	45.375
1.050	0.767	1.850	1.466	5.027	1.649	11.704	27.0	43.34	19.152	6.748	45.053
1.100	0.827	1.800	1.346	5.369	1.276	12.013	27.0	44.49	19.522	5.687	44.731
1.150	0.888	1.750	1.225	5.705	0.962	12.371	27.0	45.82	19.842	4.712	44.397
1.200	0.948	1.700	1.105	6.034	0.706	12.774	27.0	47.31	20.114	3.834	44.061
1.250	1.010	1.650	0.984	6.355	0.499	13.208	27.0	48.91	20.335	3.040	43.711
1.300	1.070	1.600	0.862	6.665	0.335	13.665	27.0	50.61	20.508	2.333	43.349
1.350	1.130	1.550	0.742	6.963	0.214	14.140	27.0	52.37	20.631	1.729	42.991
1.400	1.190	1.500	0.622	7.247	0.126	14.620	27.0	54.14	20.705	1.215	42.625

The graphs of H1 = f(d1), L1 = f(d1), d3 = f(d1), taking into account the results from Table 1, are graphically shown in fig. 4 and fig. 5.

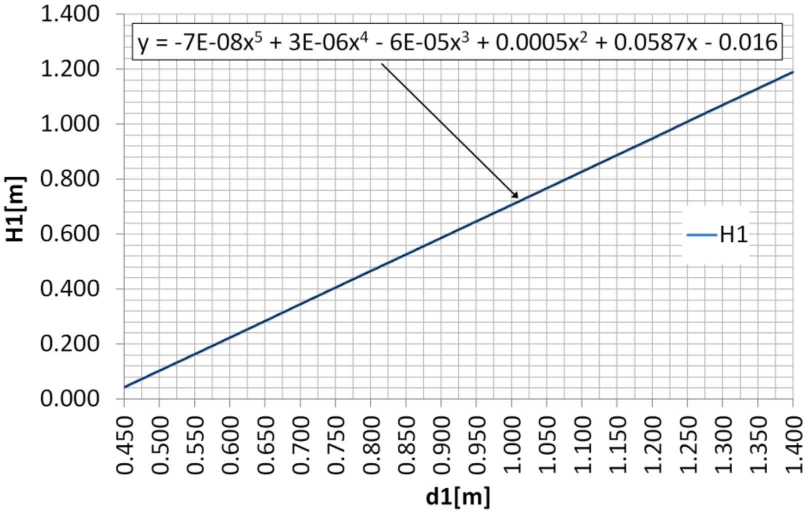

Fig. 4. The graph: H1 = f(d1)

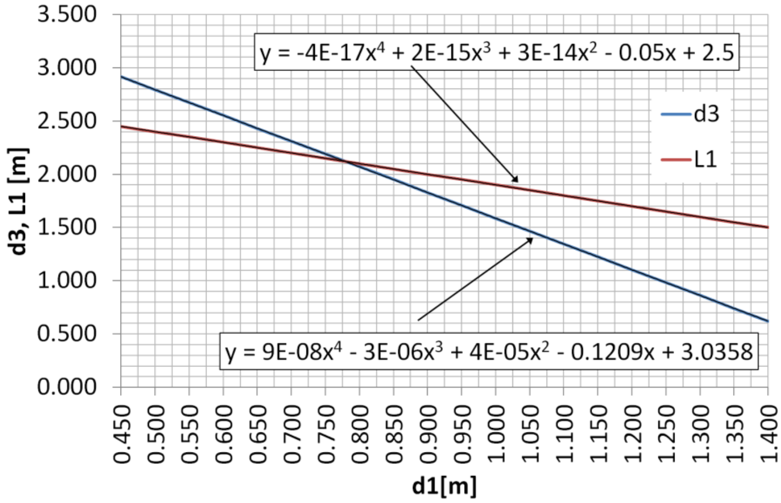

Fig. 5. The graphs: L1 = f(d1), d3 = f(d1)

The graphs of the variation of the volume of the torus V1 = f(d1), volume of the sphere V3 = f(d1), and the total volume of the tank VT = f(d1), are graphically shown in fig. 6. In fig. 7 the dependences of the torus area A1 = f(d1), the sphere A3 = f(d1), and the total area A_T = f(d1) are represented.

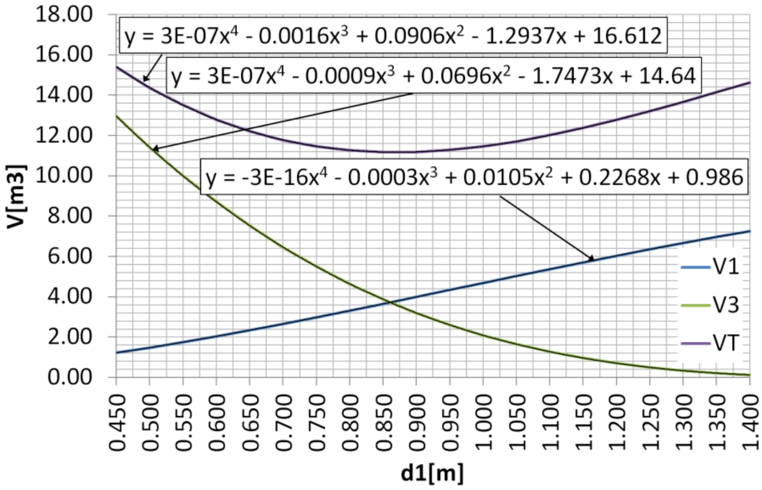

Fig. 6. The graphs: V1 = f(d1), V3 = f(d1), VT = f(d1)

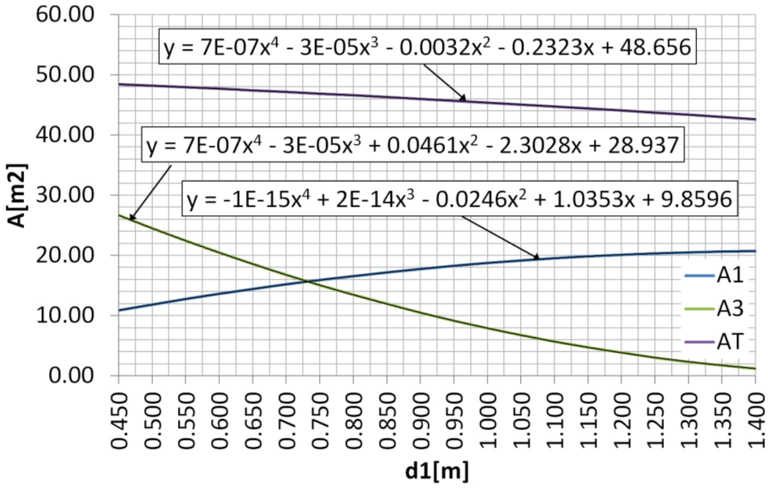

Fig. 7. The graphs: A1 = f(d1), A3 = f(d1), AT = f(d1)

In fig. 8 the dependence of the size of the percentage occupied by the volume of the tank (pv) from the maximum volume B x L x H are graphically shown.

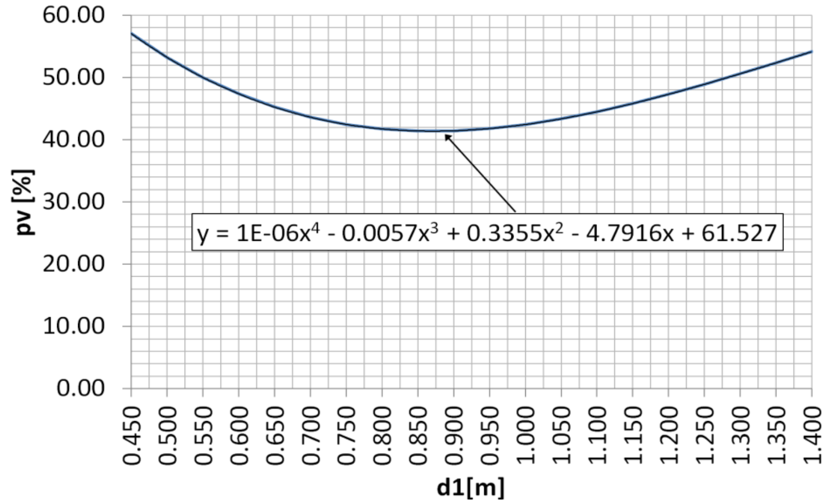

Fig. 8. The graph: pv = f(d1)

The optimal constructive dimensions of the storage tank are given in table 2.

Table 2: The optimal constructive dimensions of the storage tank

d1 [m]	H1 [m]	L1 [m]	d3 [m]	V1 [m³]	V3 [m³]	VT [m³]	V [m³]	p_{vol} [%]	A1 [m²]	A3 [m²]	A_total [m²]
0.450	0.043	2.450	2.915	1.223	12.963	15.408	27.0	57.06	10.870	26.681	48.422

2.2 Numerical analysis of the parametric 3-D model

Based on the physical model, the modeling was done in the AutoCAD Autodesk 2017 software [45] and the numerical analysis was performed with SolidWorks 2017 software [46] with the Static, Thermal and Design Study modules. The design data used were:

- the tank material is AISI 4340 steel; the intermediate bracelet type element is AISI 1045 steel;
- the maximum hydraulic test pressure: p_{max} = 300 bar;
- the working temperature between the limits: T = -30 ^{0}C up to T = 60 ^{0}C;
- the period of the tank exploitation: n_a = 20 years;
- the corrosion rate of the material: v_c = 0.06 mm/years.
- the fuel stored in the tank is CNG with a density of ρ = 20.5 kg / m^3.

In fig. 9 the parametric 3-D model of a CNG storage tank composed by a torus and a sphere with eight intermediate bracelets is graphically shown.

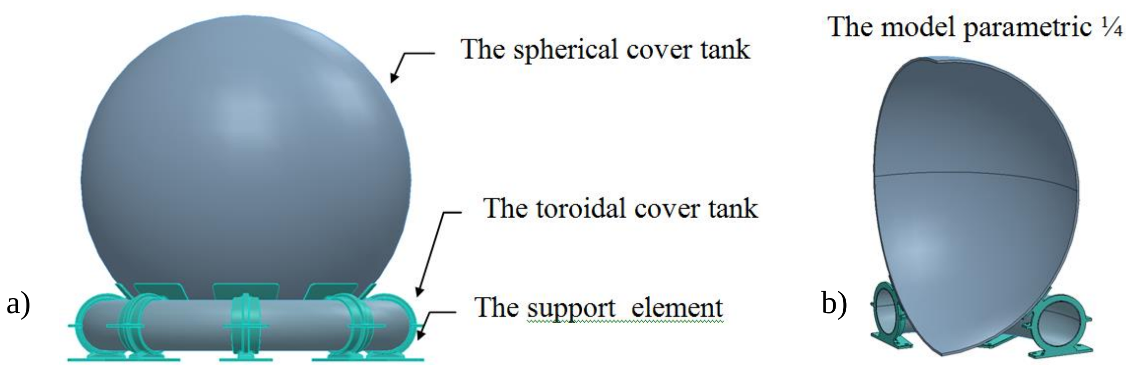

Fig. 9. The graphical representation of the parametric 3-D model of a CNG storage tank composed by a torus and a sphere with eight intermediate bracelets

The storage tank design takes into account the variation of the working temperature, the correction of the thickness of the cover material, the evolution of the corrosion process, the tolerance of the execution of the cover sheet, the thinning of the sheet thickness, and the exploitation period.
The parameterized model used in calculus is a section of ¼ from the initial cover (fig. 10a) and the corresponding surfaces to which the constraints and restrictions are applied are shown in fig. 10b.

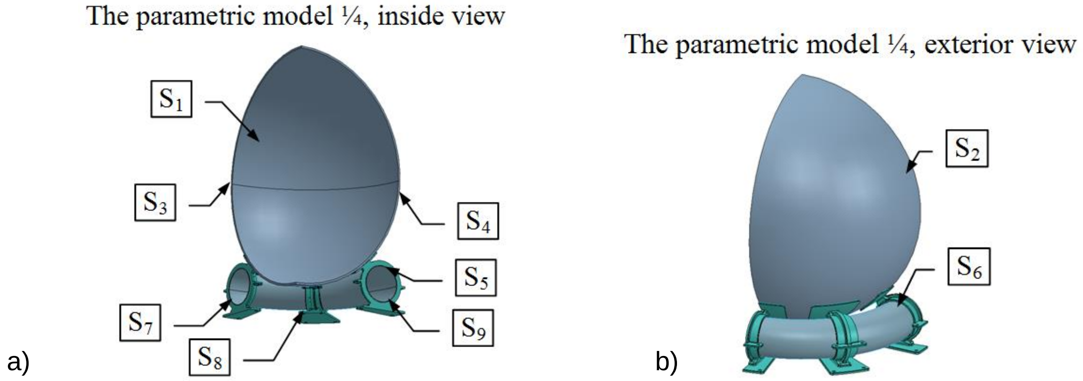

Fig. 10. The graphical representation of the parametric 3-D model ¼: a) inside view; b) exterior view

The following parameters were applied as input parameters to the parametric model (fig. 10):
- the maximum pressure p_{max} = 30 N/mm^2 on the inner surfaces S_1 and S_5;
- the temperature between the limits: T = -30 ^{0}C to T = 60 ^{0}C on the surfaces S_2 and S_6;
- the action of the weight force of the fuel F = 6953 N on the surface S_1, and F = 656 N on the surface S_5;
- the action of the force of weight of the metallic structure of the storage tank;
- the surface symmetry on S_3 and S_4;
- the fixing conditions on the surfaces: S_7, S_8 and S_9;
- an objective function of optimization to minimize the storage tank mass.

The applied optimization function is intended to achieve a minimum mass. The variable of optimization is the thickness of the cover *s* [mm].
The applied restrictions of constraints are:
a) for the cover material, the value of Von Mises effort $\sigma_{rez} \le \sigma_a$ = 710 N/mm^2 (σ_a - the admissible value of the traction stress of the cover material).
a) for the support element, the value of Von Mises effort $\sigma_{rez} \le \sigma_a$ = 530 N/mm^2 (σ_a - the admissible value of the traction stress of the support element).
After the optimization procedure, the obtained values are given in table 3.

Table 3: The optimal constructive dimensions of the cover of the torus and the sphere of the tank

The type of constructive element	s	T	σ	u_{rez}
	[mm]	[^{0}C]	[N/mm^2]	[mm]
Sphere	32.5	-30	709.35	4.93
Torus	6.2	-30	707.45	3.17

Distributions of the state of stress and of the linear deformation are shown in figures 11 and 12.
The optimized thicknesses of the covers (torus and sphere) were corrected taking into account: the corrosion phenomenon, the tolerance of negative execution of the sheet laminate and the thinning of the sheet in the embossing process. The formula for calculating the thickness is the following:

$$s_{real} = s_{opt} + \Delta s_c + \Delta s_T + \Delta s_{am} = s_{opt} + v_c \cdot n_a + abs(A_i) + 0.1 \cdot s \qquad (1)$$

where: s_{opt}, the optimal thickness; Δs_c, the loss of thickness by corrosion; Δs_T, the addition of thickness due to the tolerance of the laminate sheet; v_c, the corrosion velocity of the lateral cover, v_c = 0.06 mm/year; n_a, the number of years of exploitation; A_i, the lower tolerance of the laminate sheet; s = 9 mm.

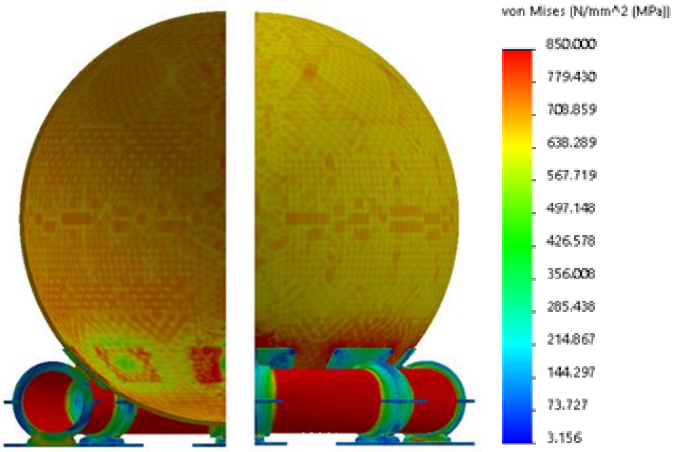

Fig. 11. The graph of Von Mises stress of lateral cover

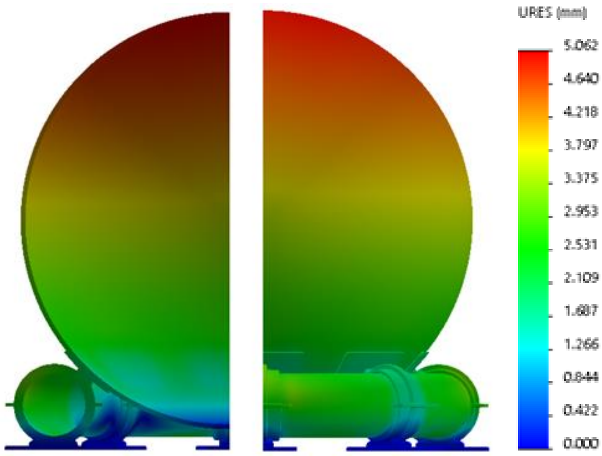

Fig. 12. The graph of linear deformation of lateral cover

The minimum value of the sheet thickness for the torus cover is determined as:

$$s_{real\ min} = 6.2 + 0.06 \cdot 20 + abs(-0.6) + 0.1 \cdot 9 = 8.9 \text{ mm} \quad (2)$$

A laminate sheet of AISI 4340 steel with a thickness of $s = 9^{0}_{-0.6}$ mm is chosen for analysis.
The minimum value of the sheet thickness for the sphere cover is determined as:

$$s_{real\ min} = 32.5 + 0.06 \cdot 20 + abs(-0.8) + 0.1 \cdot 32.5 = 37.75 \text{ mm} \quad (3)$$

A laminate sheet of AISI 4340 steel with a thickness of $s = 40^{+1.4}_{-0.8}$ mm is chosen for analysis.
After the end of the number of years of exploitation when n_a = 20 years, the toroidal envelope will have the thickness of s = 6.5 mm and the spherical one of s = 34 mm.
In this case for the real constructive solution after the exploitation periods are shown in fig. 13 and fig. 14, the Von Mises stress state and the resulting linear deformation state. Also their numerical values are shown in table 4.

Table 4: The real constructive dimensions of the cover of the torus and the sphere of the storage tank

The type of constructive element	s [mm]	T [^{0}C]	σ [N/mm^2]	u_{rez} [mm]
Sphere	34	-30	676.1	3.138
Torus	6.5	-30	684.3	2.94

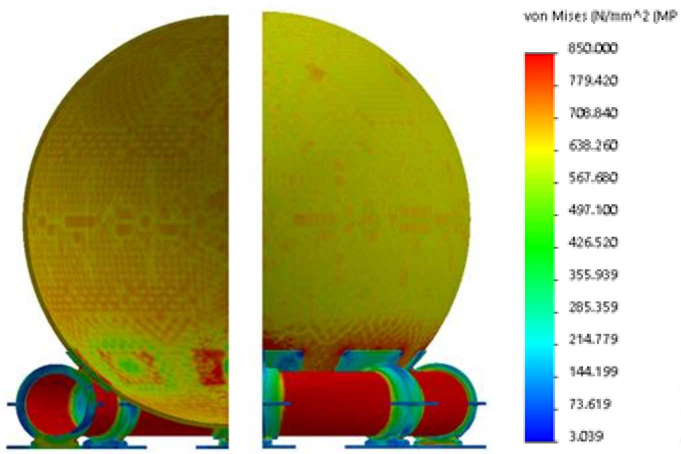

Fig. 13. The graph of real Von Mises stress of covers

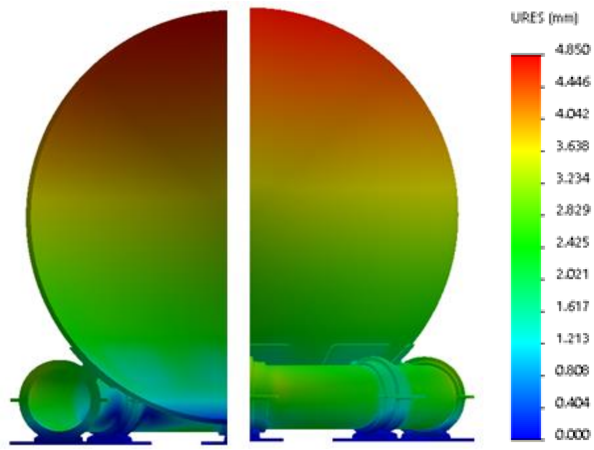

Fig. 14. The graph of real linear deformation of covers

The actual volume of storage of the tank, from the beginning of the exploitation period, is given in table 5.

Table 5: The volume constructive dimensions of the storage tank

d1	H1	L1	d3	V1	V3	VT	V	p_{vol}
[m]	[m]	[m]	[m]	[m^3]	[m^3]	[m^3]	[m^3]	[%]
0.450	0.043	2.450	2.915	1.223	12.963	15.408	27.0	57.06
0.432	0.043	2.450	2.958	1.127	11.924	14.178	27	52.51

The parameters ΔV1, ΔV3, ΔVT, and Δp_{vol}, calculated in relation to the initial dimensions, are shown in table 6.

Table 6: The ΔV1, ΔV3, ΔVT, and Δp_{vol}, calculated in relation to the initial dimensions

ΔV1	ΔV3	ΔVT	Δp_{vol}
[%]	[%]	[%]	[%]
7.84	8.01	7.98	7.98

3. Discussion

Following the numerical analyses and the resulting graphs for the parametric 3-D model structure through the method of finite elements it has been found that:
- the optimal design of the storage CNG tanks composed (such as a torus and a sphere) is efficient using the finite element method, on parameterized 3-D models for complex constructive variants;
- the use of the storage tanks with different storage spaces can obtain a percentage of occupancy of the maximum space. In our case the maximum initial value being p_v = 57.06%, having a minimum of p_v = 41.41% around to d1 = 0.850 m (fig. 8);
- the evolution of dimension H1 is strictly increasing (fig. 4), and for dimensions L1 and d3, these ones decrease to the value at d1 = 0.790 m (fig. 5);
- the total volume has a minimum value for d1 = 0.850 m (fig. 6 and table 1), and the total area has a decreasing evolution of the volume with the increase of d1;
- the calculation method used for optimization shows that the maximum stress state appears at the minimum negative temperature (table 3), for the minimal resulting linear deformation (fig. 11 and fig. 12);
- the dimensional correction of the actual constructive dimensions for the covers (table 5), determine the state of stress and of the linear deformation below the value admitted at the end of the exploitation period (table 4, fig.13 and fig.14);
- also the recalculation of the volume of the storage tank resulted by decreasing the calculated thickness of the covers from the initial volume of the tank shows that the volume reduction is with 7.98% (table 6).

4. Conclusions

The proposed method is efficient in the design phase of a storage tank composed of a torus and a sphere, made of steel, for compressed natural gas (CNG) fuel storage used in the automotive industry.

Conflict of Interest: The authors declare that they have no conflict of interest.

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