The Influence of Corrosion and Pressure Variation on the Minimum Safety Factor of a 3D Hexagonal Toroid with Regular Hexagonal Cross-Section Used in Manufacturing of LPG Storage Tanks

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Abstract: *This research was aimed to explore the minimum safety factor (SF) values of a three-dimensional (3D) hexagonal toroid with regular hexagonal cross-section used in manufacturing of LPG storage tanks from the automotive industry. Numerical simulations had been carried out to assess the influence of the corrosion and pressure variation on the minimum safety factor values. A polynomial interpolation was applied to provide a comparison between the surfaces or curves for which the SF has the minimum values. The development of the parametric 3D model (done in the AutoCAD Autodesk 2017 software, which was imported for analysis to SolidWorks 2017 software) on the actual conditions of the structure provides the decision-maker with the information necessary for making high-consequence decisions. The results of this study offer a fundamental understanding of the corrosion behavior of LPG storage tanks in exploitation environments.*

Keywords: *3D hexagonal toroidal LPG fuel tank, automotive industry, industrial engineering design, optimization methods, safety factor*

1. Introduction

Corrosion is a natural process defined as gradual degradation of metal caused by a chemical or electrochemical reaction with its environment. Many structural alloys corrode merely from exposure to moisture in air, but the process can be strongly affected by exposure to certain substances. Corrosion-related damage is accelerated by factors including the storage fuel tank's interaction with interconnected components and corrosive environmental conditions [1].
Corrosion protection of fuel storage tanks is a very important task which combines modern corrosion control methods with state-of-the-art technology to prevent storage fuel tanks from deteriorating. Common corrosion protection strategies include corrosion-resistant materials, application of coatings and/or linings as a barrier to the environment, and use of inhibiting chemicals in stored substances to control corrosion of the fuel storage tank interior.
Many researches have focused on technologies and innovation design strategies to create new models for the competitive market of fuel storage tanks [2-7].
Fuel storage tanks have complex shapes, mechanical and chemical resistance, range in size and complexity achieved through the combination of great design and manufacturing flexibility [8-15].
The modern engineering design of storage fuel tanks offers the perfect balance between safety, weight and cost to satisfy the demands of the competitive automotive market [16-19]. In order to meet these challenges, modern computer aided engineering (CAE) methods must be consistently applied throughout the manufacturing process.
3D CAD modelling of prototypes of storage fuel tanks used in automotive industry in an early phase of the design process with modern simulation tools is an indispensable requirement, as the design and optimization of subsystems is possible only within the complete product system [20-32].
In addition, to avoid expensive tests working with advanced materials and technology, various softwares with virtual computer aided engineering tools are challenged to quickly validate new models (In a hierarchical approach, the system, subsystems, components) while managing costs and protecting valuable test articles, which performs calculations in accordance with accepted national or international standards [33-41].

Factor of Safety (FoS), also known as Safety Factor (SF), in the technical literature can be computed using simplified approaches or more sophisticated methods with advanced numerical procedures. The factor of safety is often specified in a design code or standard [42-44].
In this research, starting from the aforementioned insights, a theoretical study was launched with the objective of researching the influence of the corrosion and pressure variation on the minimum safety factor values of a three-dimensional (3D) hexagonal toroid with regular hexagonal cross-section used in manufacturing of LPG storage tanks.
The performance analyses of investigated cases have a more dominant role in the understanding of the corrosion behavior of LPG storage tanks in exploitation environments.

2. Design methodology

In this research, it is used a 3D hexagonal toroid with regular hexagonal cross-section analyzed in our previous studies [14, 43].

2.1 Basic geometry of the parametric 3D model

The representative parametric 3D model generated by revolving of a closed generating curve C_G (a hexagon with rounded corners) along a closed guiding curve C_D (a hexagon with rounded corners) was used in this study, as shown in figure 1 [14].

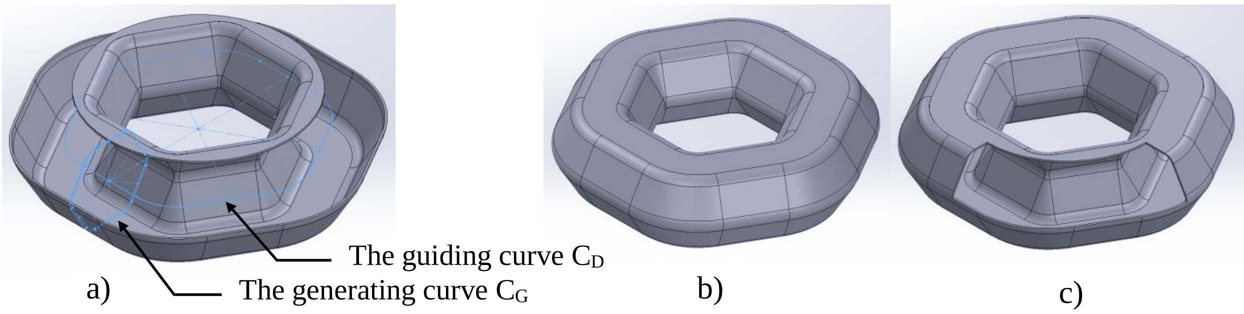


Fig. 1. The axonometric representation of the representative parametric 3D solid model

The following parameters were applied as input parameters to the 3D parametric model (figure 1): a) a closed generating curve C_G (a hexagon with a side value L = 175 mm, with rounded corners, radius R = 50 mm), and b) the guiding curve C_D (a hexagon with a side value L = 430 mm, with rounded corners, radius R = 180 mm).

2.2 Numerical analysis of the parametric 3D model

Based on the physical model, the modeling was done in the AutoCAD Autodesk 2017 software [39] and the numerical analysis was performed with SolidWorks 2017 software [40] with the Static, Thermal and Design Study modules. The design data used were:

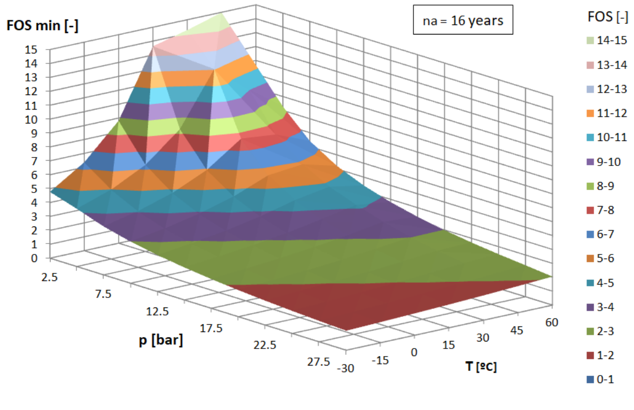
- the tank material is AISI 4340 steel;
- the maximum hydraulic test pressure: p_{max} = 30 bar;
- the working temperature between the limits: T = -30 ^{0}C up to T = 60 ^{0}C;
- supporting surfaces located on the inferior side;
- the duration of the tank exploitation: n_a = 16 years;
- the corrosion rate of the material: v_c = 0.07 mm/years.

The safety factor (SF) of the parametric 3D model was computed as a result of the pressure variation within the permissible design limits (p_{max} = 0 up to 30 bar) and the maximum corrosion.
Numerical calculations were performed for: mesh standard type, solid mesh with quality high, automatic transition, Jacobian in 16 points, element size 10 mm, tolerance 1 mm, number of nodes 130215, number of elements 68415, maximum aspect ratio 26.30, number of degrees freedom 346152.
It can be seen that due to the geometry of the cover material, the boundary conditions, or the intensity of application or distribution of different loads occurring during exploitation, the safety factor has different values on the surface of the envelope, with values ranging from 1.399 to 14.974.

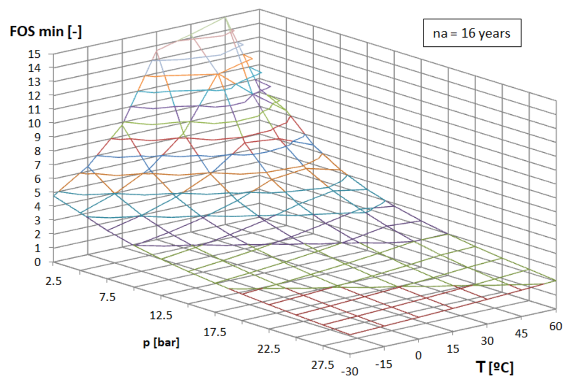
Table 1: The minimum safety factor

SF_{min} [-]	T = -30 ºC	T = -15 ºC	T = 0 ºC	T = 15 ºC	T = 30 ºC	T = 45 ºC	T = 60 ºC
p [bar]	-30	-15	0	15	30	45	60
2.5	4.769	6.360	8.807	13.625	14.26	14.974	9.264
5.0	4.15	4.986	6.233	8.268	12.05	10.053	8.281
7.5	3.477	4.04	4.813	5.928	7.646	7.400	6.404
10.0	2.989	3.393	3.917	4.619	5.598	5.853	5.216
12.5	2.619	2.922	3.301	3.784	4.416	4.839	4.398
15.0	2.330	2.566	2.852	3.204	3.645	4.125	3.801
17.5	2.098	2.287	2.510	2.778	3.104	3.505	3.346
20.0	1.908	2.062	2.241	2.452	2.702	3.003	2.988
22.5	1.749	1.877	2.024	2.195	2.393	2.626	2.700
25.0	1.615	1.723	1.846	1.986	2.147	2.333	2.462
27.5	1.499	1.592	1.696	1.814	1.947	2.099	2.262
30.0	1.399	1.480	1.569	1.669	1.781	1.908	2.051

The graphs of 3D surfaces (by type surf and fire) corresponding to the variation of minimum SF for SF_{min} (n_a = ct, p, T) taking into account the results from Table 1, are graphically shown in fig. 2.



a)



b)

Fig. 2. The 3D graphs SF_{min} (n_a = ct, p, T): a) surf type; b) fire type

The graphs of the isothermal coefficient variation curves, SF_{min} (n_a= ct, p, T = ct), are graphically shown in fig. 3.

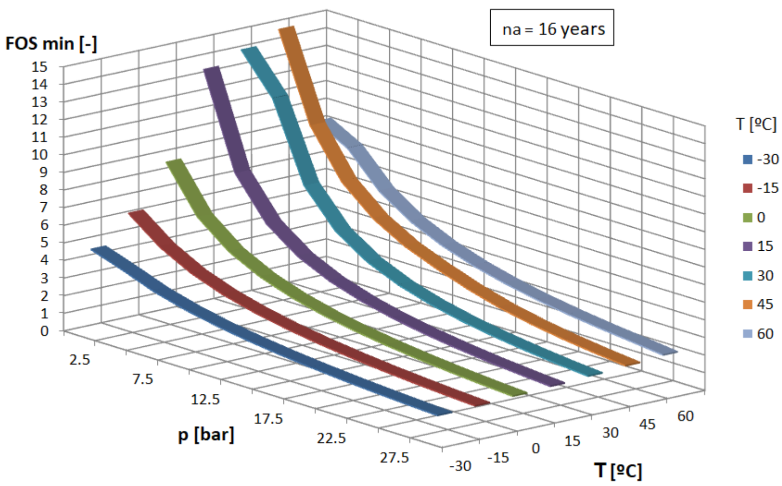
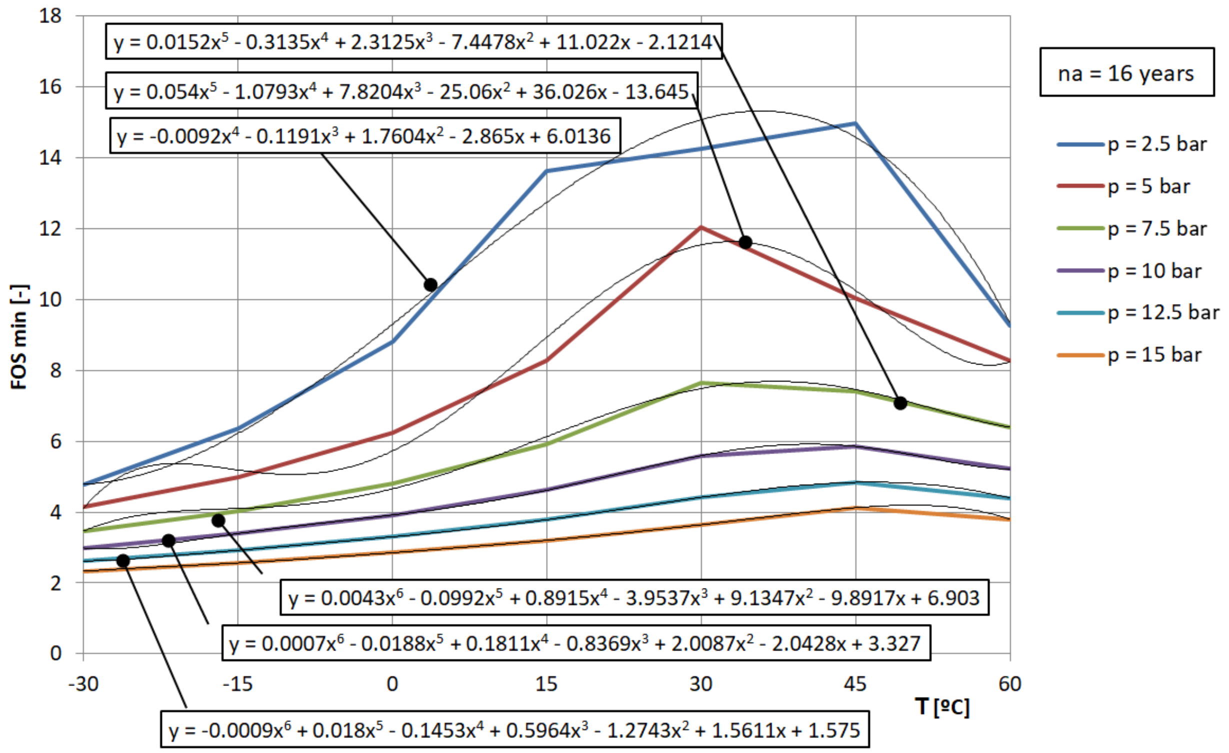
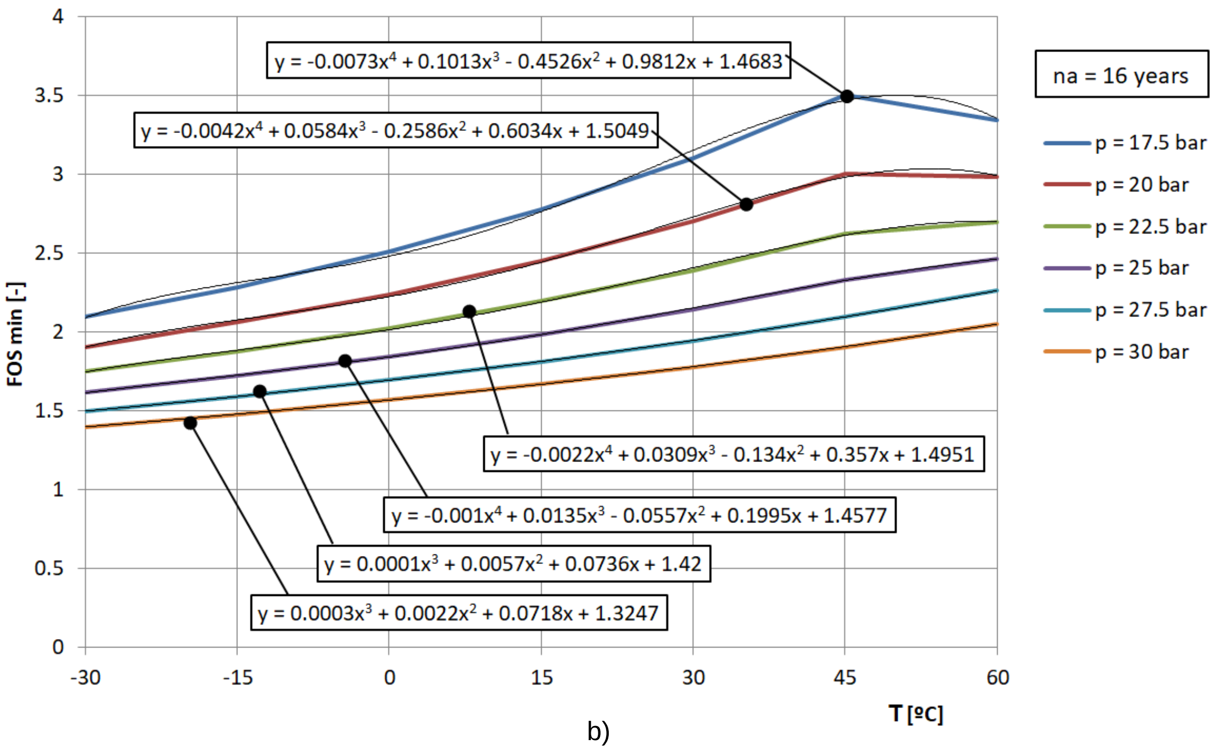


Fig. 3. The 3D graphs of the isothermal coefficient variation curves, SF_{min} (n_a= ct, p, T = ct)

The graphs and laws of the variance of resulting SF_{min} (n_a = ct, p, T), calculated through a polynomial interpolation using Microsoft Excel 2017 are shown in figs. 4 and 5.



a)



b)

Fig. 4. The 2D graphs and laws of the variance of resulting SF_{min} (n_a, p = ct, T)

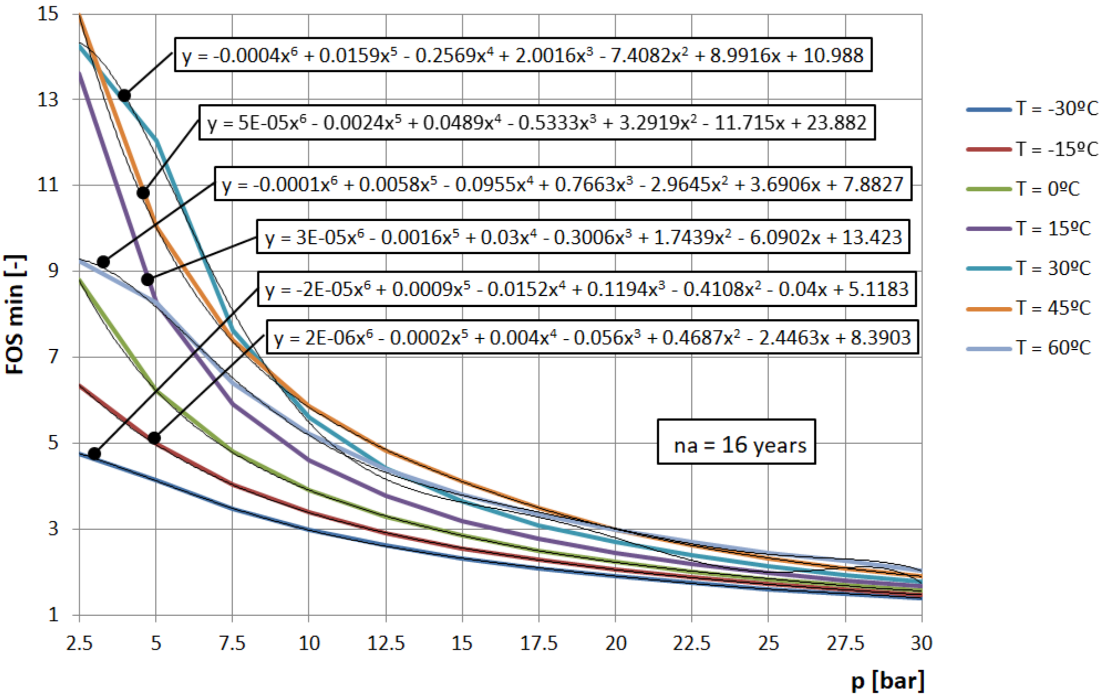


Fig. 5. The 2D graphs and laws of the variance of resulting SF_{min} (n_a, p, T = ct)

A direct determination of SF_{min} (n_a = ct, p, T) is shown in fig. 6.

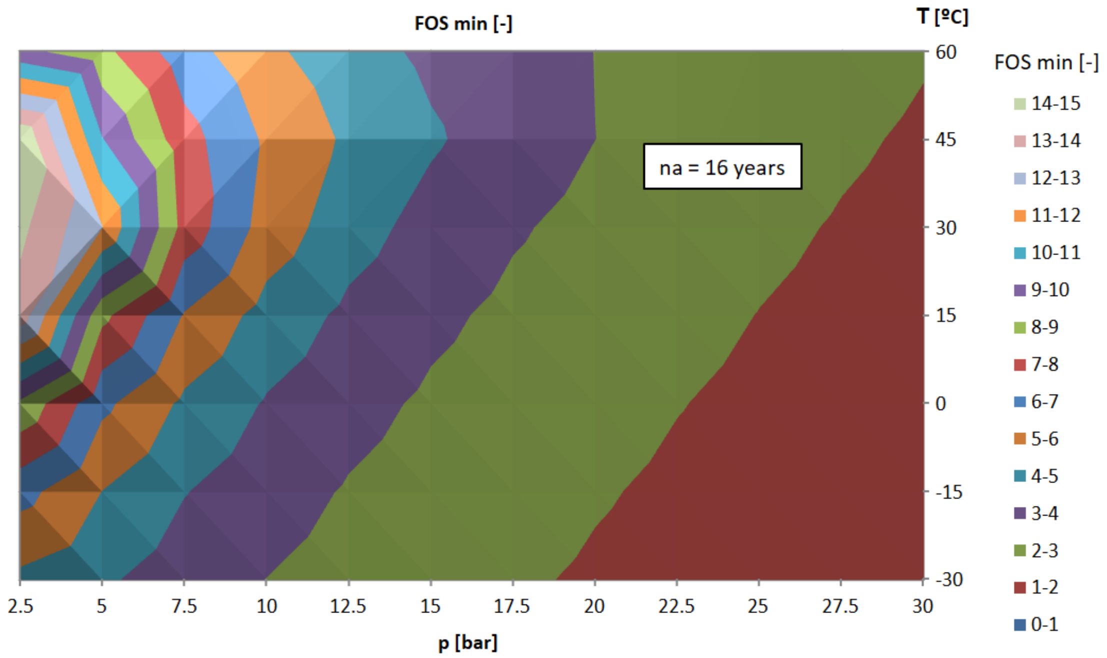


Fig. 6. The 2D graph of SF_{min} (n_a= ct, p, T)

3. Discussion

Following the SF analysis and the resulting graphs it has been found that:
- the graphical and analytical results of the mathematical dependencies determined by the laws of variation, allow for the determination of minimum SF considering the simultaneous influence of the corrosion and pressure;
- the obtained laws of variation highlight a major influence of pressure and temperature on the minimum SF. On the other hand, the minimum SF values decrease at lower temperatures (fig. 4) and increase at lower pressures (fig. 5).

4. Conclusions

Simulation results show that proposed method offer a major advantage and can lead to better applicability in the computational effort design of a 3D hexagonal toroid with regular hexagonal cross-section used in manufacturing of LPG storage tanks from the automotive industry.

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

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