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Design of low-pressure transportable steel tanks for storing hydrogen for an electric tractor

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Abstract: The presented contribution offers a theoretical analysis of the possibilities of implementing hydrogen technologies in agricultural machines and tractors. It discusses in more detail the structural designs and strength calculations of low-pressure transportable steel tanks for hydrogen storage for the ET 3000 electric tractor, in which the accumulators will be replaced by designed metal hydride tanks. The structural design of low-pressure tanks meets the requirements of the STN EN 13322-2 standard, which deals with the technical and structural design of transportable pressure tanks. The design and construction of tanks are key from the point of view of the real implementation of hydrogen technology in a fully functional small tractor for the purpose of its long-term testing.

1 Introduction

Due to the expanding share of hydrogen technologies, research and development of hydrogen storage equipment is also underway. The most widely used hydrogen storage system is based on the high-pressure principle, and from a safety point of view, this type of storage may not always be the most suitable. This type of storage is used, for example, by the New Holland NH2 tractor with a drive based on the principle of fuel cells with a total output of 78 kW, presented in 2009 at the SIMA agri-business show in Paris. Hydrogen weighing 2.4 kg is stored in a pressure tank in the front part of the vehicle and enables the machine to operate for a maximum of 2 hours. The H2 Dual Power model from the same manufacturer from 2020 has 11.5 kg of hydrogen stored in 5 tanks with a pressure of 350 bar located above the driver's cabin. The drive is provided by a modified 4.5 liter diesel engine with 2 operating modes, enabling the combustion of 100% diesel or 30 to 60% hydrogen-diesel mixture. A modified 4.8-liter diesel engine burning a lean mixture of hydrogen (1% H_2 and 99% air) using high-pressure hydrogen storage is also applied in the 2022 JCB Hydrogen tractor.

In the 80s of the 20th century, the first efforts to implement low-pressure hydrogen tanks based on metal hydride in a tractor were recorded. A tractor operated on a farm in Clarsburg, Ontario, Canada, used a modified dual duty gasoline engine. The hydrogen storage system consisted of 11 metal hydride tanks containing a total of 80 kg of metal hydride alloy, while the total maximum amount of stored hydrogen represented 1 kg.

With the gradual development of low-pressure storage of hydrogen in metal alloys, there is a need to design such gas tanks that meet the criteria defined in the currently valid regulations and standards. A characteristic feature of low-pressure hydrogen tanks containing metal hydrides is the need to cool the alloys during the process of hydrogen absorption into the metal alloy structure and to heat the alloys during hydrogen desorption. The article describes the design process of metal hydride hydrogen tanks according to current standards. Metal hydride tanks were designed for the electric mini tractor ET 3000, in which they will replace the accumulators, which are located in two dedicated spaces located under the driver's seat.

For the 1st reserved space, a steel tank was designed according to the valid standard STN EN 13322-2. For the second space, a system of tanks was designed so that they fill the reserved space as efficiently as possible. Designs of cylindrical tanks were made, which would be stored in the first horizontal variant and in the second vertical variant.

The volume of stored hydrogen was also calculated for individual tanks. The structural designs of the tanks were realized in the Solidworks program tool, and the ANSYS Workbench-Static Structural software was used for the strength analysis of the designed tanks [1-13].

2 Design of transport steel containers for an electric tractor

The transport steel tanks for hydrogen storage are designed for the electric small tractor ET 3000, the serial number of which is 3000-4B-002. In the next part of the work, transportable steel tanks for hydrogen storage are designed, which will replace accumulators in the electric mini tractor. The tanks contain Hydralloy C5 powder alloy and from the point of view of location, they are located in two reserved spaces, where the first reserved space has dimensions of 800x250x220 mm and the dimensions of the second reserved space are 530x240x265 mm.

3 Design of the MNTZV-194 tank for the first reserved space

The STN EN 13322-2 standard was used in the design of the tank for the first reserved space. The designed tank is double-shelled and consists of a primary tank, which contains a TiFe-based metal hydride alloy called Hydralloy C5, and a shell that is welded to the primary tank. Between the primary tank and the shell is a gap in which the cooling liquid flows and serves to cool the tank during the process of hydrogen absorption into the metal alloy structure.

3.1 Calculation of the thickness of the cylindrical wall of the primary tank

The thickness of the wall of the cylindrical part must not be less than the minimum calculated thickness of the wall of the cylindrical part *a*, while it is calculated according to the formula:

$$a = \frac{D}{2}\left(1 - \sqrt{\frac{10 \cdot F \cdot J \cdot Re_v - \sqrt{3} \cdot p_h}{10 \cdot F \cdot J \cdot Re_v}}\right) \qquad (1)$$

where: D - outer diameter of the reservoir (mm), F - design stress factor, J - stress reduction factor, Re_v - calculated yield strength (MPa), p_h - maximum test hydraulic pressure above atmospheric (bar).

A value of 194 mm was chosen for the outer diameter of the container *D*. According to the standard, the design stress factor is F = 0.77 and the stress reduction factor is 1 because there is a butt weld on the tank cap. The calculated yield strength based on the selected material, which is steel 1.4404/AISI 316L is set on a value of 425 MPa according to the standard. The maximum test hydraulic pressure above atmospheric p_h is determined according to the relationship:

$$P_h = p_p \cdot k \qquad (2)$$

where: p_p – working pressure and has a value of 30 bar, k – safety coefficient, determined according to the established standard with a value of 1.43.

By substituting into equation (2), it was found that the minimum p_h value is 42.9 bar. A higher value of 47 bar was chosen for the test hydraulic pressure above atmospheric. By substituting the values into equation (1), it was found that the minimum wall thickness is equal to 1 mm.

3.2 Determination of bottoms of designed tank

For closing the vessel, the standard prescribes 2 types of bottoms, namely torispherical and ellipsoidal. During the design, ellipsoidal bottoms were chosen, the shape of which must meet the conditions:

$$H \geq 0{,}19 \cdot D \qquad (3)$$

$$h \geq 4 \cdot b \qquad (4)$$

where: H – outer height of the arched part of the bottom (mm), h – height of the cylindrical part of the bottom (mm), b – calculated minimum thickness of the cylindrical bottom (mm).

Substituting into equation (3), the value of the outer height of the arched part of the bottom is obtained $H \geq$ 37.248 mm, a higher value of 60 mm was chosen for *H*.

Calculation of the minimum thickness of the cylinder bottom:

$$b = a \cdot C \qquad (5)$$

where: C is the shape factor of the arched bottoms, where according to the standard it takes the value of 0.775.

The calculated minimum thickness of the cylinder bottom b has a value of 0.775 mm. After substituting into equation (4), it was found that the minimum height of the cylindrical part is 3.1 mm. The value chosen is: h = 15 mm.

3.3 Minimum wall thickness of the primary reservoir

In addition to the above equations for calculating the minimum wall thickness of the cylindrical shell and the bottom, it must be valid that its value is not less than the value derived from the following relationship:

For $D \geq$ 150 mm applies:

$$a = b = \frac{D}{250} + 0{,}7 \qquad (6)$$

After substituting the values into equation (6), the value of the thickness of the cylindrical part and the bottoms of the tank is obtained as 1.476 mm. The standard further describes that the absolute minimum thickness of the tank wall for diameters greater than 150 mm is 1.5 mm. The

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selected value of the thickness of the cylindrical part of the primary tank is 4.5 mm and the selected thickness of the bottoms of the tank is 5.5 mm.

3.4 Design of the tank shell

The same procedure as for the primary tank, which is described above (see chapter 3.1), will be used for the design of the shell. Equation (1) is used for the calculation, in which only the diameter of the cylindrical part D, which has a value of 219 mm, and the test hydraulic pressure p_h, which has a value of 5 bar, are changed. The calculation determines the minimum thickness of the cylindrical wall of the case a = 0.144 mm. The minimum wall thickness of the tank shell is determined in the same way as for the primary tank using relation (6) and the chosen value of the thickness of the cylindrical part of the shell is 2 mm.

In Table 1 there is a recapitulation of all selected dimensions for the designed tank.

Table 1 Selected dimensions of the metal hydride reservoir

	a (mm)	*b* (mm)	*a₂* (mm)	*h* (mm)	*H* (mm)
Selected dimensions	4,5	5,5	2	15	60

The next step of the work is the creation of a simulation model for the strength calculation of the designed tank.

3.5 Strength analysis of the designed tank

The ANSYS Workbench – Static Structural software was used for the strength analysis of the metal hydride tank MNTZV-194. To calculate the strength analysis, it is necessary to set the boundary conditions. Inside the tank there is a metal hydride, in boundary conditions the function of hydrostatic pressure was used for the metal hydride. The density value was set to 7,000 kg·m^{-3}. There is water with a density of 1,000 kg·m^{-3} between the cylindrical part of the primary tank and the cylindrical part of the shell. The value of the maximum test hydraulic pressure on the inner walls of the primary vessel is defined as 4.7 MPa. Earth's gravity was set as another boundary condition. The last boundary condition was the bond setting. Cylindrical bonding was used on the surfaces between the elliptical bottoms and the cylindrical part of the shell.

3.6 Results of the strength analysis of the designed tank

From the strength analysis, it was found that the maximum stress according to the von Mises theory takes on values of around 110 MPa, which is significantly lower than the value of the yield strength of the selected material determined by the manufacturer, which is 210 MPa. The result of the tension is shown in Figure 1. The total deformation on the tank according to the simulation represents a value of 0.07 mm and is shown in Figure 2.

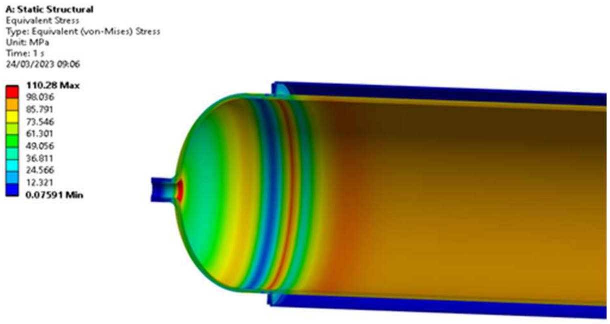

Figure 1 Field of reduced stress according to von Mises theory on the designed tank

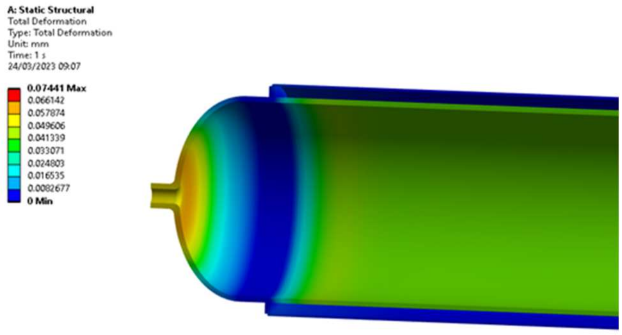

Figure 2 Formed deformations on the tank

Based on the strength analysis, it was found that the tank complies with the operating parameters.

3.7 Calculation of the amount of stored hydrogen in the designed tank

In order to determine the amount of hydrogen stored in the reservoir, it is necessary to determine the individual parameters of the selected metal hydride Hydralloy C5: The bulk density of Hydralloy C5 is ρ_{MH} = 3500 kg·m^{-3}, the hydrogen storage capacity α_{MH} = 1.5 was subtracted from the PCI curve, at working pressure 30 bar and absorption temperature 50 °C, storage volume V = 1.889·10^{-2} m^3 and hydrogen density ρ_{H2} = 0.0899 kg·m^{-3}.

The weight of the alloy m_{MH} is determined from the equation:

$$m_{MH} = \rho_{MH} \cdot V = 64{,}8\ kg \qquad (7)$$

The mass of stored hydrogen m_{H2} is calculated according to the formula:

$$m_{H2} = \frac{\alpha_{MH} \cdot m_{MH}}{100} = 0{,}972\ kg \qquad (8)$$

Subsequently, the volume of stored hydrogen V_{stored} was determined:

$$V_{stored} = \frac{m_{H2}}{\rho_{H2}} = 10{,}8\ m^3 \qquad (9)$$

4 Design of a storage system for the second reserved space

In this part, the design of the tank system for the 2nd reserved space of the electric small tractor ET 3000 with dimensions of 530x240x265 mm will be presented in more detail.

In this design, it was considered that the cylindrical tanks in the 2nd space of the ET 3000 electric tractor would occupy as much space as possible. Two variants were made, specifically in the first variant, the tanks would be stored horizontally, and in the second variant they would be stored vertically. Three models were made for each variant, in which all parameters remained the same, only the thickness of the wall was changed, and thus the inner diameter of the tank was reduced. In both the first and second variants, the wall thicknesses for the three models were as follows: 1.5 mm, 2 mm and 2.5 mm. The radii of the rounding on the neck are 1 mm on the outside and 0.5 mm on the inside. In the first variant, the tank diameter is 48 mm and the length is 480 mm. In the second variant, the diameter of the tank is 50 mm and the height is 170 mm. The structural design includes only the cylindrical part and the bottoms of the tanks, while one bottom has a hydrogen inlet.

During the design, it was considered that the tanks would be placed in a corrosion-resistant steel container, which would be placed in the 2nd space, and the entire space in the container would be filled with water, which would ensure full-surface cooling of the reservoirs. In the first length variant, 9 tanks would be placed in the corrosion-resistant steel container - 3 rows and 3 tanks are stored in each row. For the second vertical variant, three rows were considered and there would be 7 tanks in each row, so a total of 21 tanks. Both horizontal and vertical tanks variants were strength analyzed for different thicknesses like the tank in the previous chapter. The result of the strength analysis of the tank of one of the variants is shown in Figure 3 and Figure 4.

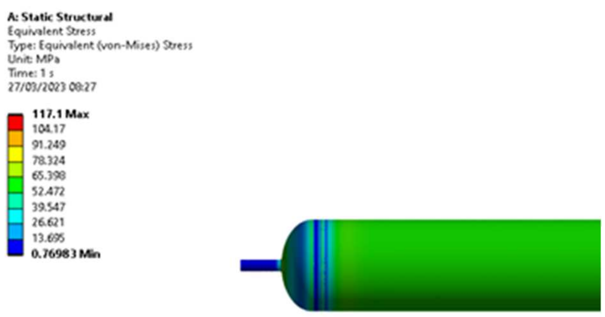

Figure 3 Field of reduced stress for 1st horizontal variant with 1.5 mm wall thickness

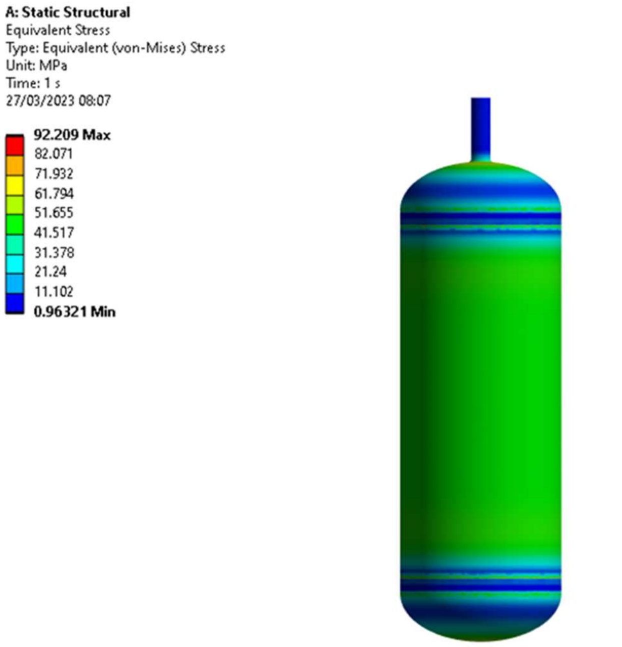

Figure 4 Field of reduced stress for 2nd variant in vertical with a wall thickness of 2 mm

The results of all tank strength analyzes are shown in Table 2 and Table 3.

Table 2 Results of the strength analysis of the designed tanks of the first horizontal variant

	1st horizontal variant		
Wall thickness (mm)	1.5	2	2.5
Maximum stress (MPa)	117.1	85.71	92.02
Maximum deformation (mm)	0.013	0.0096	0.0072
Volume of the tank (m^3)	$7.12\cdot10^{-4}$	$6.8\cdot10^{-4}$	$6.48\cdot10^{-4}$
Weight of the metalhydride (kg)	2.44	2.33	2.22
Weight of stored hydrogen (kg)	0.037	0.035	0.033
Volume of stored hydrogen for 1 tank (m^3)	0.4	0.38	0.36

Table 3 Results of the strength analysis of the design tanks of the second vertical variant

	2nd horizontal variant		
Wall thickness (mm)	1.5	2	2.5
Maximum stress (MPa)	138.64	92.21	107.42
Maximum deformation (mm)	0.042	0.011	0.0083
Volume of the tank (m^3)	$2.39{\cdot}10^{-4}$	$2.28{\cdot}10^{-4}$	$2.17{\cdot}10^{-4}$
Weight of the metalhydride (kg)	0.82	0.78	0.74
Weight of stored hydrogen (kg)	0.0123	0.0117	0.0111
Volume of stored hydrogen for 1 tank (m^3)	0.14	0.13	0.12

5 Discussion

The MNTZV-194 tank designed according to the STN EN 13322-2 standard for the first reserved space of a small tractor, based on strength calculations, meets the operational parameters and is suitable for use from the point of view of structural strength.

For the second reserved space, in terms of operating parameters, it is most suitable to use a tank with a wall thickness of 2 mm with length storage - 1st variant. This tank has the lowest tension according to the von Mises theory and the total deformations do not exceed the value of 0.01 mm. It is also more advantageous from an economic point of view, because if the 2nd vertical variant was chosen, then the proposal contains 21 tanks, while the height of 1 tank is only 180 mm. The total cost of production and assembly of a given design is greater. The last decisive criterion is the amount of stored hydrogen in the system, which was calculated on the basis of formulas (7) to (9), considering the same conditions as when calculating the stored hydrogen for MNTZV-194 (see chapter 3.7). When comparing tanks with the same wall thickness, more hydrogen is stored in the first variant. Of course, for the lowest wall thickness of 1.5 mm, the volume of stored hydrogen is the largest, but such a tank has a much higher stress.

6 Conclusion

In the paper, efficient hydrogen storage systems in a metal alloy structure were proposed for the ET3000 small tractor. The first part was the design of the metal hydride tank according to the valid standard STN EN 13322-2 and then the verification of its structural strength. Based on strength calculations, it was found that the tank meets the operating parameters. The next step in the design of this tank would be the investigation of the generated temperature fields and the subsequent design of an effective method of cooling. For example, a suitable passive heat transfer intensifier would be inserted into the tank, which serves to remove the generated heat from the core of the tank to the inner wall of the primary tank during the hydrogen absorption process.

In the second part, the main task was to design an effective system of cylindrical tanks that would fill the second reserved space of the small tractor with dimensions of 530x240x265mm as efficiently as possible, where storage of the horizontal and vertical were considered. On the basis of strength calculations and the amount of stored hydrogen, it was found that in this case it is most appropriate to use the tank of the first vertical variant with a wall thickness of 2 mm.

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