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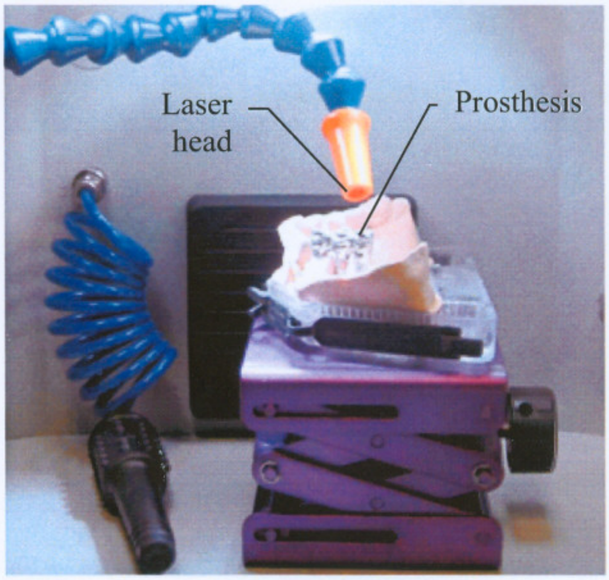

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CONTENTS

SolidWorks USED FOR THE PROCESS OF OPTIMIZATION OF SUPPORTING STRUCTURE OF A PRESSURE VESSEL

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Abstract: *According to the new regulations of the European Community (Directive 97/23/EC, design and manufacture of the pressure vessels (PV) shall be in accordance with legal and technical regulations stating the application of harmonized standards to be optional for a manufacturer of the equipment. Increased responsibility of the manufacturers gives more freedom in selection of the methods, design, calculation and optimization in order to provide safety. In this paper, using an liquid CO_2-containing vessel as an example, a survey of the process of optimization of a supporting structure has been presented. For parametric design, construction and calculation the SolidWorks programme has been used, taking into consideration the regulations and standards in effect, and in accordance with new and general approach to pressure equipment (Pressure Equipment Directive – PED) relating to structural integrity, i.e. fundamental requirements in terms of safety, calculation, design and testing of strength.*

Keywords: SolidWorks, DIRECTIVE, PRESSURE VESSEL, OPTIMIZATION, METHOD OF FINITE ELEMENTS

1. Introduction

Basic requirements determining the design, calculation and manufacture, i.e. the process of optimization, of supporting structures for the liquid CO_2-vessels are given in the Directive 97/23/EC and "Regulations of technical standards for mobile enclosed vessels for compressed, liquid and pressure-dissolved gases". The same is valid for the technical requirements of the SRPS M.E2.516/89 standard, material fundamentals contained in technical description and the capabilities and technological equipment of the manufacturers.

To determine relevant safety constraints for all possible failures, in the process of optimization one should use relevant safety factors and known, all-inclusive methods of calculation. Permissible stresses for pressure vessels shall be limited according to operating conditions. To eliminate the decrease of strength occurring in the process of manufacture, safety factors should be applied –operating conditions, stress, model of calculation, material properties and behaviour.

The above-specified requirements for the process of optimization can be met by applying one of the following methods, or by combining them as appropriate for the given case:

- the application of empirical formulae,
- the application of analytical procedures,
- the application of fracture mechanics.

For each of these methods, there is a large number of commercial computer programmes enabling either direct or indirect quickest optimization of a supporting structure of any pressure vessel with minimum possible error, on condition that the user knows well the facts related to the pressure vessels. One of these programmes is the SolidWorks programme.

Relevant calculations should be used in order to establish real strength of the pressure vessel. In doing so, one should know that calculation pressure must not be lower than the maximum permissible pressure, taking into consideration both highest static and dynamic fluid pressure.

2. The Contents of the Directive 97/23/EC Related to the Vessel

Directive 97/23/EC was introduced into legislation of the Republic of Serbia by enacting the Regulations on Technical Requirements for Pressure Equipment /1/. These regulations contain the regulations that shall be met in design, manufacture and estimation of harmonization of pressure equipment and its assemblies for the highest permissible pressure exceeding 0.5 bar.

In order to define how to apply the Directive to individual assemblies of the pressure equipment, the manufacturer should classify the equipment into one of four categories for estimation of harmonization, i.e. category I through IV. Category I relates to the smallest, and category IV to the highest danger of pressure /1,2,3/.

The equipment with parameters below category I is the subject of the existing engineering practice (EP), so that it is not subjected to an estimation of harmonization.

In order to determine the category into which an assembly of the pressure equipment should be classified, the manufacturer should identify the following:

- type of equipment;
- state of the fluid contained in the equipment – **gas or liquid**;
- group of fluids contained in the equipment – **group 1 or group 2**.

Group 1 includes the fluids that are designated as explosive, extremely inflammable, highly inflammable, inflammable (with maximum permissible temperature above flash point), highly toxic, toxic and oxidizing according to EC Directive for classification of dangerous substances.

Group 2 includes all other fluids, including both water/vapour.

Depending on the above-specified classifications, one of nine diagrams in Annex II of the Directive /2/ defines applicable estimations of harmonization (EP, I, II, III or IV). In each of the diagrams (1-9) of the Annex, the dependence of **maximum permissible pressure (PS)** and **volume in litres V (L)** has been presented. These diagrams are divided in five regions, each of them relating to various categories of the equipment (EP, I, II, III or IV).Boundary lines in each of the diagrams represent the upper limit of maximum permissible pressure and volume for each category. For classification of the pressure vessels, the diagrams 1-4 of the Annex II are used.

In this Directive, it is an imperative that all pressure equipment and assemblies to which it is applied should be safe at the moment of sale and start-up. Basic requirements of safety and certifying procedure are not to be applied to the equipment subject to engineering practice (EP) in effect.

Directive 97/23/EC relies on harmonized standards and additional harmonized standards. The harmonized standards concretize technical requirements and determine test methods. By applying the harmonized standards, minimum safety requirements imposed by the Directive shall be met. The harmonized standards for non-heated pressure vessels are given by the standards EN 13445, part 1-6.

These cite a wide range of additional harmonized standards defining the requirements related to the individual elements and details of the test methods. They are classified as follows:

- Standards in the field of non-destructive testing – NDT (the principles of NDT methods and NDT of welded joints),
- Standards defining welding and related processes,
- Standards for the materials,
- Standards for the products (pipelines, forgings...),
- Standards for thread fittings.

3. Technical Characteristics of the Vessels for Liquid CO_2

The vessels for liquid CO2 /4/ belong to the group of horizontal-type mobile pressure vessels for accommodation and transport of liquid CO_2. Technical characteristics of the vessels are as follows:

Highest permissible operating pressure:	20 bar
Calculating pressure, SRPS M.E2.250:	20 bar
Test pressure:	26 bara
Testing material:	Water
Temperature of testing material:	Environment temperature
Maximum and minimum wall temperature:	$-30^{\pm 3}$ °C
Operating medium:	Non-toxic, non-inflammable, non-explosive
Volume:	21 m^3
Empty-vessel mass:	4400 kg
Highest loading mass:	20440 kg.

Dimensions of the vessel are given in Fig. 1. Taking into consideration both general and location factors, the vessel belongs to the class II (SRPS M.E2.151) of pressure vessels.

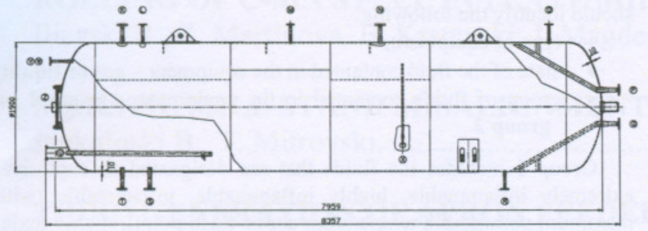

Fig. 1 The Vessel for Liquid CO_2, volume 21 m^3

In design, unification of sheets and fittings are preferred, while joining of the structural elements is conducted using the process of arc welding as regulated by the technology of welding.

The vessel should be installed on a railless vehicle, onto already prepared supports, loaded using steel cables hanged on the hooks of the vessel and a crane of adequate carrying capacity, and finally provided with proper equipment. Having been placed on the vehicle, there is a little probability that it will be transferred onto another vehicle during its life.

4. Loadings for Calculation

As a starting point for determination of relevant loadings, the norms regulating design, calculation and construction of mobile pressure vessels for liquid CO_2 are used, as defined by the SRPS M.E2.516/89 standard. In these norms, for calculation of strength and stability of the pressure vessels for liquid CO_2 (LCD), the following has been taken into consideration depending on vessel application and class:

1. Static loading induced by internal pressure;
2. Dynamic and impact loading, including rapid pressure variations;
3. Loading induced by static pressure of operating material;
4. Loading induced by individual vessel mass and operating, i.e. test material;
5. Loading induced by connection of the pipelines, operating equipment and isolation;
6. Loading induced by wind (in case of outdoor installation of the vessel);
7. Loading induced by seismic impacts;
8. Strain induced by temperature fields in the material;
9. Local strains at the points of connection or support;
10. Loading induced by lifting of an empty vessel using the cables on the hooks on the vessel at an angle of 45°.

4.1. Loading Analysis

During its operating life, this vessel is exposed to all above quoted loadings, but prevailing loadings are those specified under items 1, 3, 4 and 9, as well as the loading of an empty vessel at the moment when the vessel is lifted using the cables in the hooks, in order to place it onto conveyor or points of support.

Other types of loading, occurring rarely and with little effect on strength and stability of the vessels, will not be taken into consideration in calculations.

4.2. Adopted Loading for Calculation

In case of loading under item 1, static loading induced by internal pressure, test pressure of 26 bar = 0.26 kN/cm^2 has been adopted.

In case of loading under item 3, loading induced by static pressure of operating material, continuously distributed mass of maximum loading within the whole vessel of 20,440 kg ≈ 204.40 kN has been adopted.

In case of loading under item 4, loading induced by the vessel individual mass and mass of operating, i.e. test material, with simultaneous pressure effect, continuously distributed vessel mass and mass of maximum loading within the whole vessel of 4,400+20,440 = 24840 kg ≈ 248.40 kN and 26 bar = 0.26 kN/cm^2 has been adopted.

Strains induced by loading in case under item 9, local strains at the points of connection i.e. support, are partially taken into consideration. For this purpose, a special concept of □tructur of the vessel was used, showing that there is a possibility of extension of any of the existing fittings in order to determine more accurately the stress distribution in the vicinity of the fittings and thus to establish the effect of stress concentration on the whole structure.

In case of loading under item 10, induced by lifting of an empty vessel using the cables on the hooks on the vessel at an angle of 45°, loading induced by an action of individual vessel mass of 4,400 kg ≈ 44.0 kN has been adopted.

4.3. Permissible Strains and Stresses

Highest permissible strains are defined by the requirement from the SRPS M.E2.200/78 standard, p.8.1, stating that applied loadings shall not contain permanent strains, and these are determined by the material of manufacture of the vessel.

As a material for manufacture of the vessel for liquid CO^2, fine-grained steel TStE355 has been chosen, the mechanical properties of which have been given in Table 1.

Table 1: Mechanical Properties of the Material TStE355

Elastic Modulus	E [kN/cm^2]	20000
Poisson's Coefficient	PCv [ ]	0.3
Yield Limit	R_{eH} [kN/cm^2]	41.4-43.6
Tensile Strength	R_m [kN/cm^2]	57.4-58.2
Elongation	Lo=5d [%]	28-30
Toughness ISO - V [J]	-20 °C	176-200
	-50 °C	50-53

To keep all within the elasticity limits after termination of loading, minimum level of safety for both strains and stresses of v = 1.1 has been adopted. Thus

$$\sigma_{doz} = R_{eH} / \nu = 41.4 / 1.1 = 37.6 \text{ kN/cm}^2$$

$$l_{doz} = \sigma_{doz}\, l / E = 37.6\ 835.7 / 20000 = 1.57 \text{ cm}$$

Considering given requirements related to loading of the vessel structure, the following calculation has been conducted using the method of finite elements (FEM) in the COSMO/ Works model of the SolidWorks programme.

5. Modelling of the Pressure Vessel

SolidWorks belongs to the programmes for modelling of solid bodies. It makes it possible to transform basic, 2D drawing into model of a solid body using simple, but highly efficient tools for modelling /5/.

An illustrative example of modelling of a pressure vessel using SolidWorks programme is given in Fig. 2.

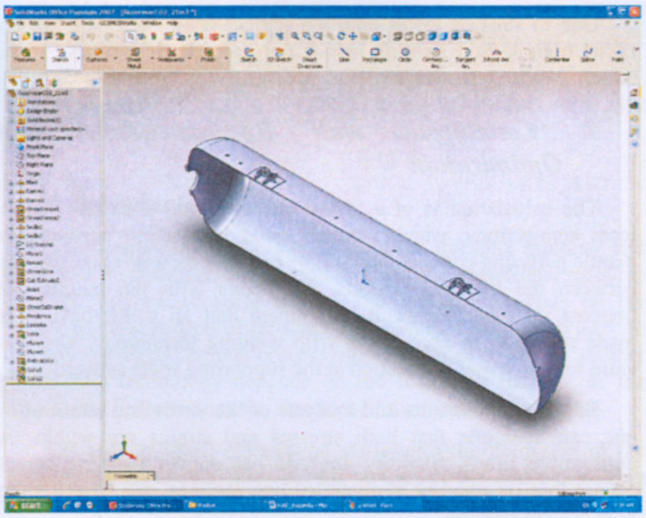

***Fig. 2** Model of the Pressure Vessel in SolidWorks Programme*

SolidWorks is a parametric tool for modelling of the solid bodies, based on the elements. It combines three-dimensional parametric elements with two-dimensional tools, and covers all the phases – from design through manufacture of a model to calculation using the method of finite elements, as well.

The adopted mechanical model (Fig. 3 through 6) has 104,397 nodes and 52,563 plate-type elements. Global coordinate system of the model (Fig. 3) is adopted so that:

- coordinate starting point "0" is in the central axis of the vessel, in the middle of its length;
- "0x" axis spreads vertically toward central axis of the vessel, in the direction opposite to the X fitting;
- "0y" axis spreads vertically toward central axis of the vessel, in the direction of the K fitting, and
- "0z" axis coincides with central axis of the vessel, forming trihedron with the first two axes.

Static calculation of a structure is based on the SRPS M.E2.516/89 standard defining the loadings that must be taken into consideration in calculation of the vessel strength and stability.

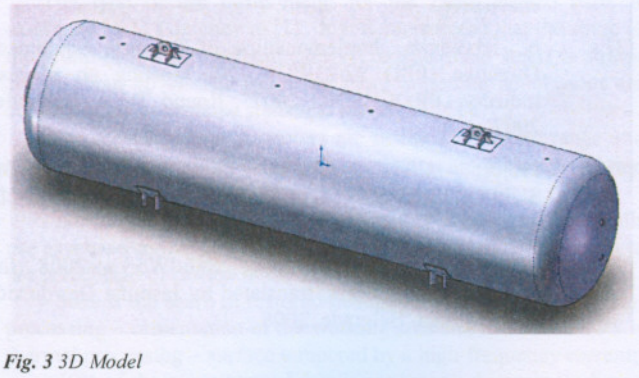

***Fig. 3** 3D Model*

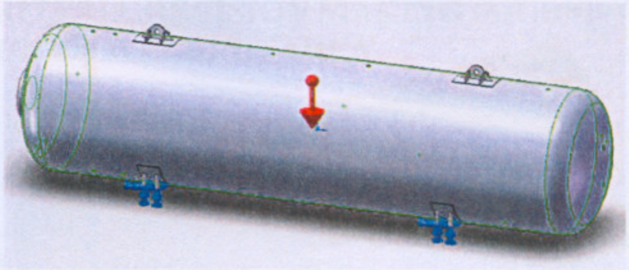

***Fig. 4** Loadings: Individual Mass + Fluid Mass + Test Pressure*

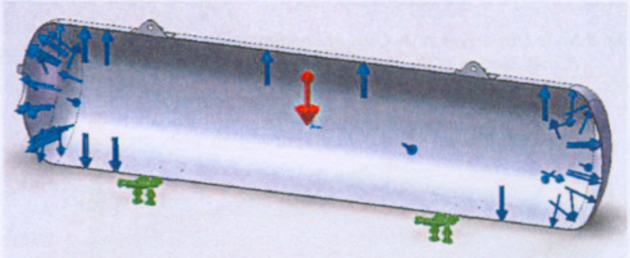

***Fig. 5** Cross Section of the Vessel and Presentation of Limit Conditions*

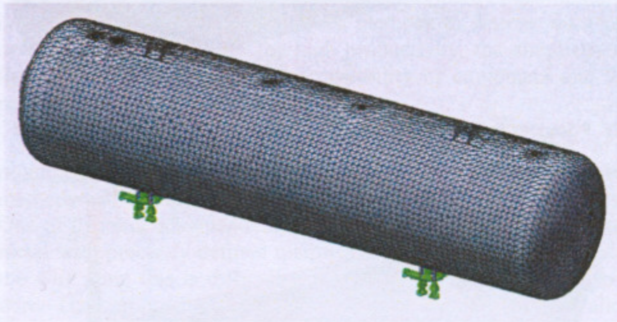

***Fig. 6** Adopted Mechanical Model of the Vessel with Finite Element Mesh*

Dynamic loadings have been taken into consideration in case of static loading, so that dynamic calculation of the structure has not been conducted separately.

6. The Results of the Calculation

For the plate-type elements, the highest equivalent stress for given section have been calculated using proper programme modules of the COSMOS/Works programme.

The strains (displacement of the node points) for characteristic and the most critical case of loading under item 4 are presented in Figs 7 and 8, and stress presentation of the vessel mantle in Figs 9 and 10.

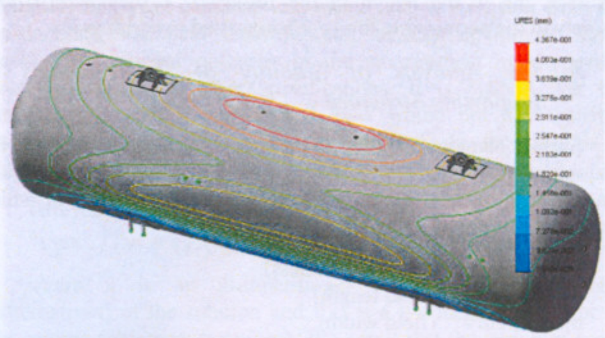

***Fig. 7** Node Displacement in Case of Loading under Item 4, Whole Vessel*

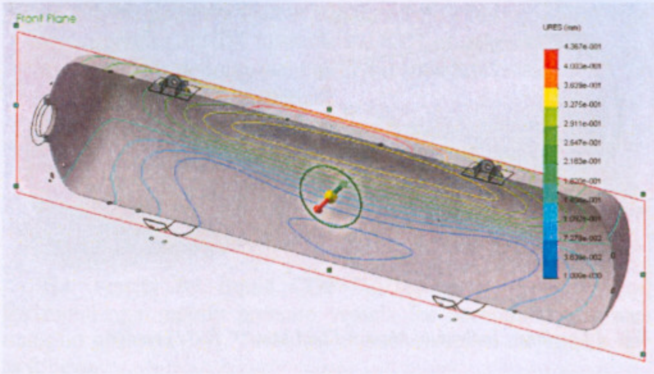

Fig. 8 Node Displacement in Case of Loading under Item 4 (Cross Section of the Vessel)

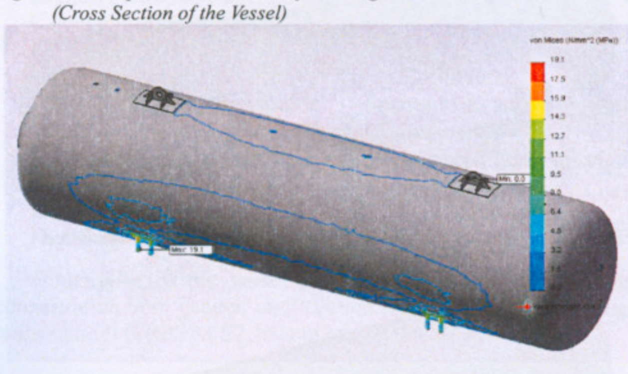

Fig. 9 Stresses in Elements in Case of Loading under Item 4, Whole Vessel

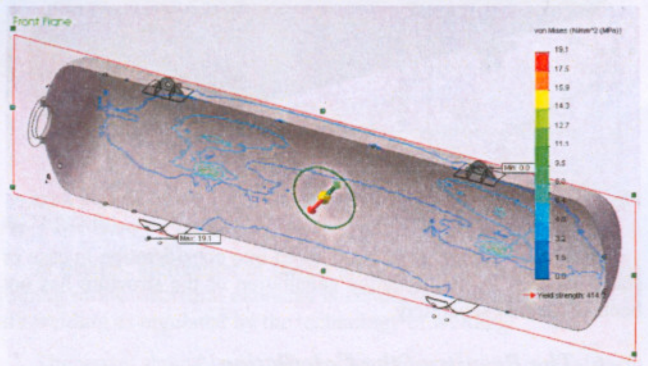

Fig. 10 Stresses in Elements in Case of Loading under Item 4, (Cross-Section of the Vessel)

In case of loading under item 4, highest displacement occurs in the part of the mantle between the vessel hooks and in the front and back dances in the region of the fittings U,Y,Z and P,Q, and the values are within the permissible ones.

The stresses in the plate elements are below permissible stresses, but in the region of the fittings U,Y they approximate largely to the permissible limit for anticipated material grade.

6.1.The Analysis of Stability of the Elements of Supporting Structure

Surface elements exposed to pressure and shear should meet the requirements of stability. Stability of the mantle should be checked on the mantle "belt" between the hooks, the dimensions of which are as follows:

h=1.0 cm - (mantle thickness),
a= 430.0 cm - (field length),
b= 33.5 cm - (field width)

Critical stresses are obtained according to the expressions:

$$\sigma_{kr} = K_{\sigma} \cdot E \cdot \left(\frac{h}{b}\right)^2 \text{ i } \tau_{kr} = K_{\tau} \cdot E \cdot \left(\frac{h}{b}\right)^2$$

For ratio b/a = 33.5/430.0 = 0.078, coefficients of contour conditions for the case of "jammed" field edges of the mantle are $K\sigma = 3.8$ and $K\tau = 8$, so that critical stresses are:

$$\sigma_{kr} = 3.8 \cdot 21000 \cdot \left(\frac{1.0}{33.5}\right)^2 = 71.11 \cdot kN/cm^2 \text{ i}$$

$$\tau_{kr} = 8 \cdot 21000 \cdot \left(\frac{1.0}{33.5}\right)^2 = 149.70 kN/cm^2$$

Due to stresses lower than the critical ones, these stresses are rather high so that stability loss is not possible in the parts of the mantle exposed to pressure/shear stresses.

7. Conclusion with Recommendation for Optimization

The calculation is of a global character and does not include local connections, which assumes good connection between the mantle parts and connection with the bottoms, as well as connection between the fittings, supports and hooks with the mantle and bottoms. In other words, it is assumed that all welds have been made properly, in accordance with welding technology, which is valid for the vessel connection at the supporting spots as well.

Based on the results and analysis of the stress and strain rates, one can conclude that both stresses and strains are within the permissible limits. Stability analysis has shown that the mantle cannot lose its stability in given loading regimes, due to extremely high critical stresses.

The calculation has shown that the material selected for manufacture of the vessels and fittings, TStE355, has satisfactory mechanical properties from the point of view of the loadings analyzed.

The stresses in the plate elements are considerably below the permissible stresses, except for the region of the U,Y fittings where they approximate permissible limits for anticipated material grade; thus, if one needs higher stability reserve, it is necessary to reinforce the vessel in this zone.

For more accurate stress distribution and concentration in the vicinity of the fittings, supports and hooks, it is necessary to make a more reliable model, and give more accurate instructions for possible reinforcement of the vessel in these zones, which will be based on such model.

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