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RESEARCH OF STRESS-STRAIN STATE OF TANK OF SMALL-SIZE SELF-PROPELLED SPRAYER

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Abstract. *For the developed design of a small-sized self-propelled sprayer, it is proposed to use a tank from which the working fluid is displaced under pressure in the power system of the spraying devices. For the safe operation of such a shell, a method of determining its stress-strain state has been developed. The main analytical dependences are based on the principles of the momentless theory of shells. The results of the calculations are the determined numerical values of stresses in the cylindrical part of the shell and its bottoms. Similar results were obtained when simulating the operation of such a tank using the SolidWorks2019 application program. A comparative analysis of the obtained numerical values of the studied quantities was performed. Recommendations have been made regarding the method of securing the tank to the sprayer frame.*

Key words: *self-propelled sprayer, tank, shell, stress-strain state, momentless theory of shells, stresses, spraying devices, sprayer rod.*

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1. INTRODUCTION

Technologies for the production of plant products involve the performance of many agrotechnical operations. Practically in each of them there is an operation of plant protection or feeding with liquid fertilizers, where sprayers are used [1–5]. The issue is well resolved in agricultural holdings, which have the entire complex of machines, including boom sprayers. A worse situation is observed in small farms or auxiliary farms, where the level of resource provision is low. Spraying areas and plants with knapsack sprayers does not allow achieving the maximum effect, and the mounted mini-sprayers available on the market require an energy source for aggregation, etc. Therefore, the development of a small-sized self-propelled boom sprayer with an adjustable track width and a boom stabilization system solves the problem to some extent [6–11].

During the development of such a machine, there was a problem with the development of an effective power supply system for spraying devices [12, 13]. The adopted decision is implemented when using a pneumohydraulic system: a compressor, a tank with a working fluid operating under pressure, regulating equipment, a pressure line.

Therefore, our local research consists in substantiating the parameters of the sprayer tank, which will work from pressure, when displacing the working fluid to power the spraying devices. As a result, we get a vessel of certain geometric dimensions, which works under pressure and is loaded with hydrostatic pressure of the working fluid, taking into account the dynamics of the movement of the sprayer through field irregularities. Let's divide the load into components and in this study we will consider only the effect on the stress-strain state (SSS) of the internal pressure shell, since it will be a determining factor [6]. Of particular interest are the zones of stress concentration in the places of transition from the cylindrical part of the tank to the bottoms and the shape of the bottoms themselves.

The calculation of the shells under different loads follows from the general theory of plates, the main hypotheses of which were developed by Robert Kirchhoff. Later, they were transformed into a general theory of shells by August Lev. Various researchers consider partial cases of this theory, which take into account the features of the load, the geometry of the shells, the properties of its material, etc. [6, 14–16]. This led to the emergence of a number of special theories of shells, which are oriented towards a certain specificity. Therefore, at the stage of calculation, it is worth choosing the right theory, which would not be overburdened by the complexity of mathematical dependencies, which in the end are reduced or turned into zero.

If we consider shells that work under pressure, then axisymmetric deformation is maintained here as for shells of rotation [14, 15], and their momentless load is well described by the momentless theory of shells [15], which gives good results for practical calculations and is simple to implement.

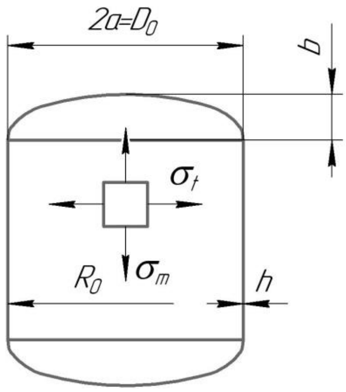
Studies of local structural elements of shells or the specifics of their load are also of practical interest [14]. These are factors that can be decisive for the strength and stability of the shell as a whole.

The objective of the paper is to develop a methodology for calculating VAT and substantiate the parameters of the sprayer tank, provide recommendations for fixing and safe operation of the formed pressure vessel in the power system of the spraying devices of the agricultural sprayer.

2. OUTLINE OF THE MAIN MATERIAL

As mentioned above, the load of the sprayer tank will be only in the form of internal pressure, which displaces the working fluid. This is a partial case of the working mode of the sprayer, when the tank has a minimum amount of working drug or is empty, and the air pressure created by the compressor completely pushes out all the residues.

The general appearance of the developed small-sized self-propelled sprayer is presented in Fig. 1 a. We will schematically show the design of the sprayer tank and indicate its main dimensions, Fig. 1 b.



a b

Figure 1. General appearance of a small-sized sprayer – a; tank diagram – b

The use of dependencies for VAT estimation is always accompanied by certain assumptions regarding the choice of theory, according to which this procedure can be implemented. It would be most appropriate to make such an estimate based on the momentless theory of shells, but first it is necessary to establish the limits of its use.

Scientist Biederman V. L. in his book «Mechanics of thin-walled structures. Statics» indicates that the application of the momentless theory of shells has limits of application. This is due to the fact that the load along the meridian should change significantly more slowly than the edge effect; the radius of curvature of the meridian of the formed bottoms of the shell should not have a relatively large value (the type of bottoms is close to or flat), because under such conditions, a transverse force will act on these elements, which for the momentless theory is assumed to be zero. Then, according to the second condition, no displacements can be found.

Analyzing the proposed design of the sprayer tank (Fig. 1 b), we see that it is a cylindrical shell with semi-elliptical bottoms. The first and second conditions for using the momentless theory are fulfilled: load (internal pressure is constant in each exact shell); the law of change of the meridian forms semi-elliptical bottoms.

Now let's conditionally divide such a shell into two structural parts – the cylindrical shell and the bottom. Let's estimate the VAT of each of them.

If the body is divide by a conventional cutting plane perpendicular to the longitudinal axis of symmetry, then its equilibrium will be in case when we apply the internal force factors, which we will determine by compiling the equilibrium equations.

The shell is in a flat stress state (Fig. 1 b), since its thickness h compared to the radius of the center line R_0 is much smaller and we do not consider the distribution of stresses in the wall σ_3, we consider that $\sigma_3 = 0$, and $\sigma_1 = \sigma_t$ are stresses in the circular direction and $\sigma_2 = \sigma_m$ in the meridional direction.

Then, in order to balance the cut off part, let's make the equation of balance in the meridional direction

$$2\sigma_m \pi R_0 h = P, \quad (1)$$

if P – the force that stretches the shell in the axial direction, regardless of the shape of the bottom,

$$P = \pi R_0^2 p, \quad (2)$$

if p – internal excess pressure, Pa.

Then, the expression for the meridional stress is deduced

$$\sigma_m = \frac{pR_0}{2h}, \quad (3)$$

To find the circular stress in the cylindrical part of the shell, we use Laplace's formula [14]

$$\frac{\sigma_t}{\rho_t} + \frac{\sigma_m}{\rho_m} = \frac{p}{h} \quad (4)$$

here $\rho_t = R_0$, $\rho_m = \infty$.

Then, the expression for the circular stress in the cylindrical part of the shell is determined

$$\sigma_t = \frac{pR_0}{h}. \quad (5)$$

For the plane stress state of the shell, it is advisable to use the fourth theory of strength to find the equivalent stresses in the considered sections [14]

$$\sigma_{IV} = \sqrt{\sigma_m^2 + \sigma_t^2 - \sigma_m \sigma_t} \le [\sigma], \quad (6)$$

if $[\sigma]$ – allowable stress for the shell material, Pa.

We will perform a practical calculation for the cylindrical part of the sprayer tank in order to estimate the maximum allowable pressure when operating it in the power system of spraying devices. The design of the tank proposed for use has the following parameters: the radius of the body $R_0 = 0.225$ m, the thickness of the wall $h = 0.001$ m, the maximum working pressure (defined as the operating parameter of spraying devices) – 0.6 MPa; tank material – stainless steel AISI 304 ($\sigma_T = 310$ MPa).

The result of the calculation is:

- meridional stress by expression (3)

$$\sigma_m = 67.5 \text{ MPa};$$

- circular tension (5)

$$\sigma_t = 135 \text{ MPa};$$

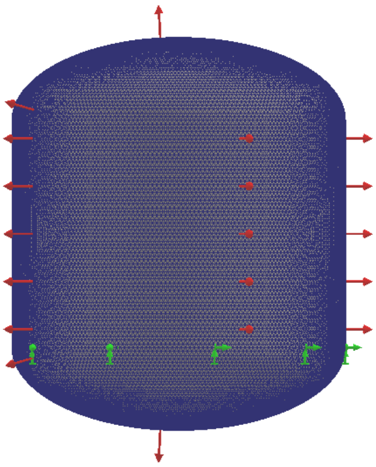
- equivalent stress (6)

$$\sigma_{IV} = 116.9 \text{ MPa}.$$

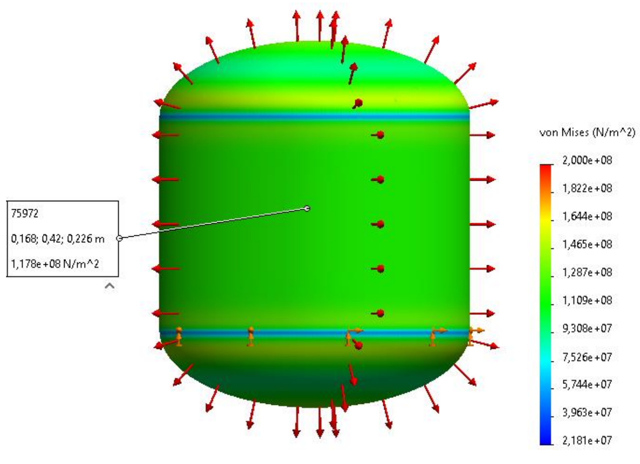
The maximum allowable internal pressure when calculating the cylindrical body will be $[p] = 1.07$ MPa at the allowable stress $[\sigma] = 206.7$ MPa, taking into account the safety factor $n = 1.5$.

A modern machine builder should have both a theoretical calculator for designing structures and be able to increase his productivity by using applied 3-D modeling programs.

At the same time, it should be understood that the result obtained by one method is exposed to a serious risk of error or gross inaccuracy. Therefore, to obtain reasonable results regarding the VAT of the sprayer tank, we will use the SolidWorks2019 application program with the Simulation module (Fig. 2).



a



b

Figure 2. Shell model – a; result of simulation of equivalent stresses – b

The difference between the obtained values of the equivalent stresses in the cylindrical part of the shell theoretically (116.9 MPa) and in automated mode using the SolidWorks2019 application program (117.8 MPa) is, which confirms the high accuracy of both methods of obtaining results.

Let's proceed to the calculation of the bottom of the shell – the tank of the sprayer, which works under the influence of internal pressure.

To estimate the VAT of a given element of the shell, it is first necessary to describe its geometry. As it was mentioned, such bottoms are semi-elliptical, for which the ratio between the values of the semi-axes a and b of the ellipsoid must be established. According to the physical structure of the bottom of the tank (Fig. 1) we have: $a = \frac{1}{2}D_0$, $b = \frac{1}{4}D_0$.

Then, for a body of rotation of the second order – a semi-elliptical bottom, the radii of curvature can be described by dependencies (7) and (8):

$$R_1 = \frac{D_0}{\sqrt{\left(1+\left(\frac{a^2}{b^2}-1\right)\sin^2\theta\right)^3}}; \qquad (7)$$

$$R_2 = \frac{D_0}{\sqrt{\left(1+\left(\frac{a^2}{b^2}-1\right)\sin^2\theta\right)}}, \qquad (8)$$

if θ – the angle formed by the normal to the middle surface of the bottom and the axis of symmetry of the bottom.

The radii R_1 and R_2 describing the geometry of the bottom lie in the range of angle change θ: $-\frac{\pi}{2} \le \theta \le \frac{\pi}{2}$.

Then the stress in the bottom in the meridional direction will be

$$\sigma_{md} = \frac{1}{2h}\frac{pD_0}{\sqrt{\left(1+\left(\frac{a^2}{b^2}-1\right)\sin^2\theta\right)}}; \qquad (9)$$

circular tension in the bottom –

$$\sigma_{td} = \frac{1}{2h}pD_0\frac{1-\left(\frac{a^2}{b^2}-1\right)\sin^2\theta}{\sqrt{\left(1+\left(\frac{a^2}{b^2}-1\right)\sin^2\theta\right)}}. \qquad (10)$$

The equivalent stresses arising in the bottoms will be found by a similar dependence to expression (6).

Based on the results of the analytical calculation, the maximum equivalent stresses in the bottoms are observed in the vicinity of their connection to the cylindrical part of the tank ($\theta = \pm\frac{\pi}{2}$) – 178.6 MPa. This is caused by the effect of compression of the cylindrical part from the action of internal pressure on the bottom. The circular compressive stresses in this section are – -135 MPa, meridional – 67.5 MPa. In the central part of the bottom, all stresses are significant – 135 MPa.

The graphic interpretation of the obtained calculation results is shown in Fig. 3. Here, the solid line shows the equivalent stresses, the dash-dotted ones show the circular ones, and the dotted line shows the meridional ones.

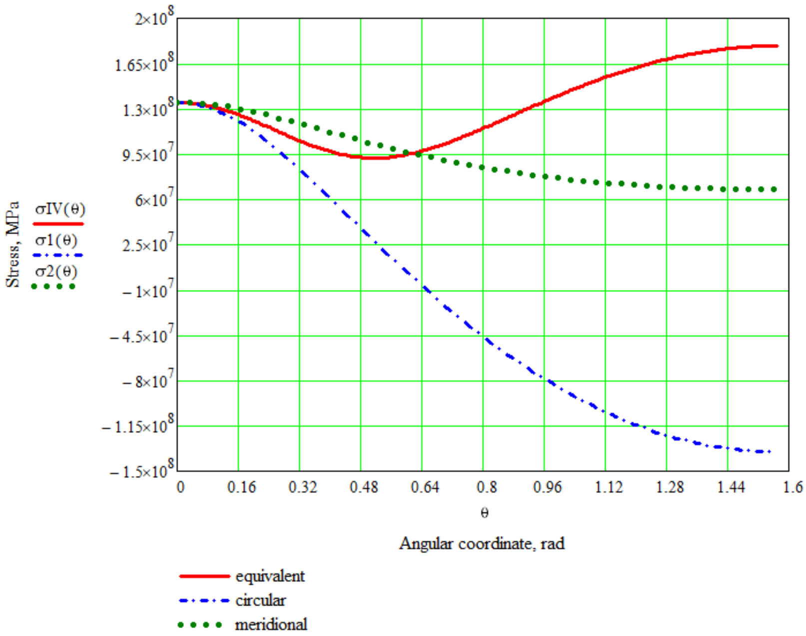
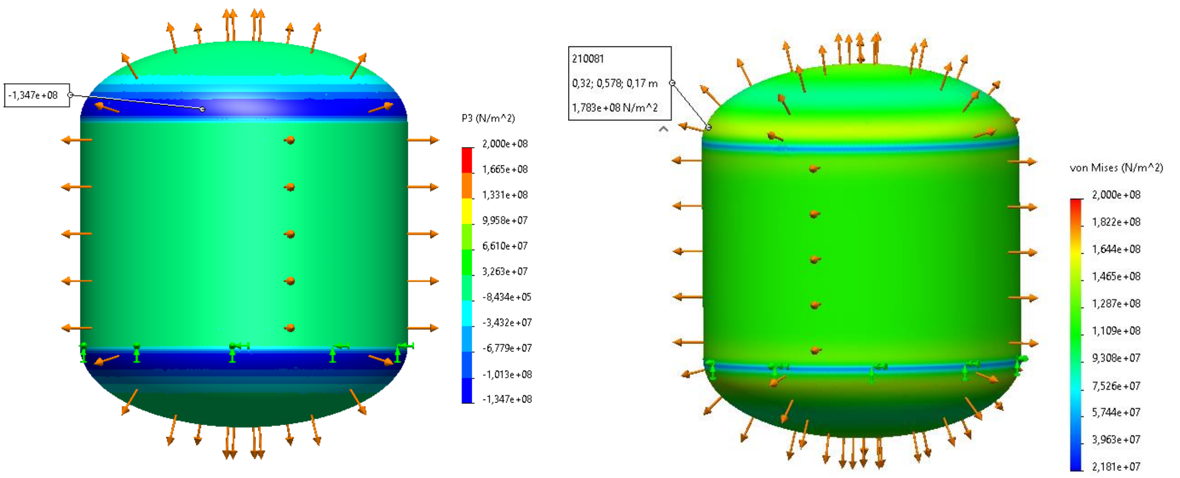


Figure 3. Stress distribution in the bottoms of the tank

The obtained analytical results with similar results found when using the specialized software SolidWorks2019 SolidWorks2019 are compared (Fig. 4).

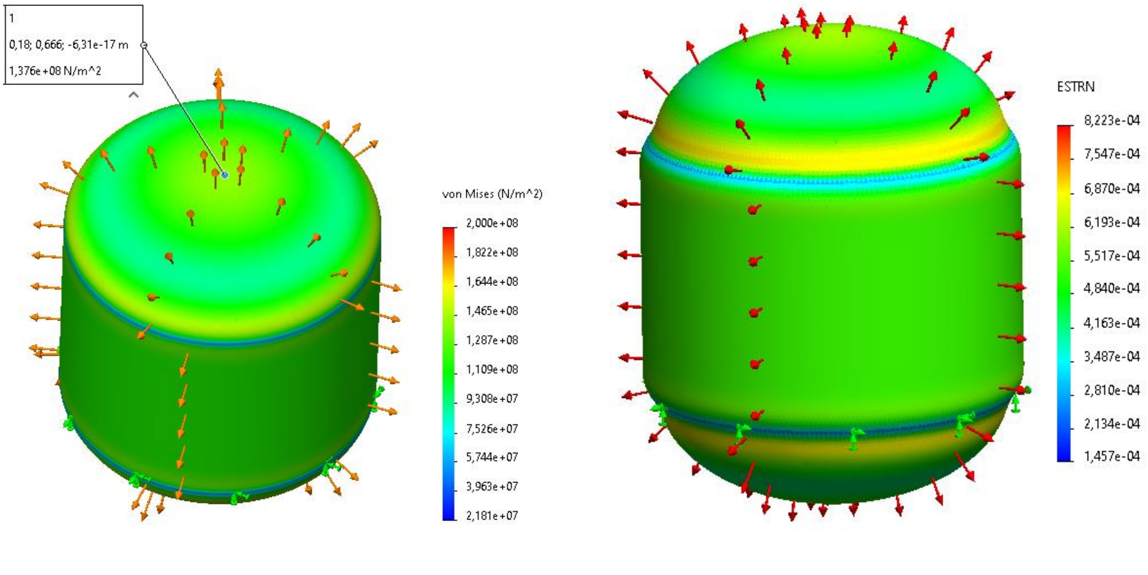


a b

Figure 4. Distribution of circular – a and equivalent – b stresses in the bottom

The greatest interest here is the circular stresses (Fig. 4a), which occur at the points where the bottoms join the cylindrical part of the tank, because they change their sign, become compressive and can cause a loss of shell stability. The values of stresses in this intersection are -134.7 MPa, which differ by 0.22% from similar stresses found theoretically.

The results of the found equivalent stresses (Fig. 5a) in the center of the bottom – 137.6 MPa and equivalent deformations of the shell (Fig. 5b) on a scale of 1:50 are presented.



a b

Figure 5. Distribution of equivalent stresses in the center of the bottom – a; equivalent shell deformations – b

3. CONCLUSIONS

For a small-sized self-propelled boom sprayer, it is proposed to make the power supply system of the pressure line pneumatic-hydraulic, where the working fluid is displaced from the tank under the action of excess pressure, which is injected into its cavity by a compressor.

When studying the stress-deformed state of the tank as a shell, which works under the action of internal pressure, the momentless theory of shells was applied, for which the limits of its application were established. Therefore, the expressions of the stresses arising in the cylindrical part of the shell are deduced; the change of the radii of curvature is defined that describe the bottoms; and the expressions of the meridional and circular stresses are written down. According to the theoretical calculation of the VAT of the shell under the action of the maximum internal working pressure of 0.6 MPa and taking into account the edge effects, the conclusions are drawn:

meridional stresses $\sigma_m = 67.5$ MPa arise in the cylindrical part of the shell; circular - $\sigma_t = 135$ MPa; equivalent – $\sigma_{IV} = 116.9$ MPa; the maximum permissible internal pressure for a cylindrical sleeve will be $[p] = 1.07$ MPa; for bottoms, the equivalent stress in the vicinity of their connection to the cylindrical part of the tank ($\theta = \pm\frac{\pi}{2}$) is 178.6 MPa; circular compressive stresses (an edge effect is manifested) in this section are -135 MPa, meridional stresses – 67.5 MPa; in the central part of the bottoms, all stresses have a value of 135 MPa; the maximum permissible internal pressure on the bottoms should not exceed 0.7 MPa.

The values of the theoretical calculations well coincide with the results obtained when simulating the operation of such a tank using the SolidWorks2019 application program; their discrepancy does not exceed 1%.

Thus, for safe operation of the sprayer tank, the working internal pressure should not exceed 0.7 MPa (without considering the hydrostatic pressure from the action of the liquid and the method of fastening). To increase the value of the permissible internal pressure to the value according to the strength criterion of the cylindrical part around the connection of the bottoms, it is necessary to strengthen it with spacer rings or other structural elements that make it impossible to lose the stability of the shell.

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УДК 631.348

ДОСЛІДЖЕННЯ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ БАКА МАЛОГАБАРИТНОГО САМОХІДНОГО ОБПРИСКУВАЧА

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Резюме. *Виділяючи проблему низького ресурсного забезпечення невеликих виробників сільськогосподарської продукції, зокрема ефективними машинами для хімічного захисту рослин, розроблено малогабаритний самохідний штанговий обприскувач. Особливістю цієї конструкції є те, що* *він має регульовану ширину колії, маятникову систему стабілізації штанги і для живлення розпилюючих пристроїв використано пневмогідравлічну систему. У зв'язку з тим виникло завдання дослідити напружено-деформований стан такого бака, який працює як посудина під тиском. Із попередніх досліджень випливає, що найбільшу питому частку навантаження складає якраз дія внутрішнього надлишкового тиску. Локальна проблема, яка розвивається у роботі, полягає у розробленні методики розрахунку НДС такої оболонки для встановлення максимального робочого тиску за умови безпечного її експлуатування. За основу взято безмоментну теорію оболонок, для якої встановлені межі застосування та на її основі описано залежності колових та меридіональних напружень, що виникають у циліндричній частині оболонки та в її півеліптичних днищах. При дослідженні виявлено краєвий ефект в околі приєднання днищ до циліндричної частини, що супроводжується стискуючими коловими напруженнями, які можуть спричинити втрату стійкості оболонки. Аналогічні результати отримано при моделюванні роботи такого бака з використанням прикладної програми SolidWorks2019. Виконано порівняльний аналіз отриманих числових значень досліджуваних величин, відносна похибка не перевищує 1%. Встановлено, що для безпечного експлуатування бака обприскувача, робочий внутрішній тиск не повинен перевищувати 0,7 MPa і це без врахування гідростатичного тиску від дії рідини та способу закріплення. Для підвищення значення допустимого внутрішнього тиску до значення за критерієм міцності циліндричної частини околи приєднання днищ потрібно підсилити розпірними кільцями чи іншими конструктивними елементами, що унеможливлюють втрату стійкості оболонки.*

Ключові слова: *самохідний обприскувач, бак, оболонка, напружено-деформований стан, безмоментна теорія оболонок, напруження, розпилюючі пристрої, штанга обприскувача.*

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