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THE EVALUATION OF THE INFLUENCE OF GEOMETRIC PARAMETERS ON THE LOAD-BEARING CAPACITY OF STEEL TANKS MADE OF HIGH-STRENGTH STEELS

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Abstract. Steel vertical above-ground tanks are widely used in the chemical, oil, and gas industries as vessels for storing liquid products and gases.

From the standpoint of vertical tank design, it can be noted that during operation, the cylindrical wall can be in two diametrically opposite design situations: in the filled state, all courses of the cylindrical wall are in a state of tension from the product pressure and the action of internal overpressure, while in the empty state – all courses are compressed in both the meridional and circumferential directions by corresponding loads. When designing steel tanks, the thickness of the cylindrical wall courses is determined primarily from the condition of ensuring strength, after which it is refined taking into account the stability requirements of the structure. This constitutes the essence of the problems associated with the effective use of high-strength steels for vertical tanks: the use of high-strength steels allows for reducing the thickness of the cylindrical wall courses, but this possible reduction is limited by stability conditions. An effective solution to this problem can be achieved by varying the geometric parameters of the tank, which, under the same external loads, will allow regulating the level of internal stresses and critical loads of the tank.

The paper investigates the influence of the cylindrical wall thickness and the geometric parameters of tanks of various capacities on the stress-strain state and critical stability parameters. It has been established that the determination of the minimum allowable wall thickness according to the stability conditions is more stringent than

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accord-ing to the strength conditions. At the same time, ensuring the strength of the lower courses of the cylindrical wall for medium and large capacity tanks is possible only through the use of high-strength steels. However, the efficiency of their use is limited by the stability requirements.

Keywords: steel tanks; cylindrical shell; strength; stability.

PROBLEM STATEMENT

Steel vertical above-ground tanks are widely used in various sectors of the economy. They have become most widespread in the chemical, oil, and gas industries as vessels for storing liquid products and gases. The main load-bearing element of this structure's tanks is the cylindrical wall, which is an axisymmetric cylindrical shell. It is formed from separate courses connected to each other by butt or lap welds. The thickness of the courses generally varies along the height of the wall: from the minimum in the upper part to the maximum in the lower part. For small-volume tanks, the use of courses of constant thickness is allowed.

During operation, the primary load for vertical tanks is the internal hydrostatic pressure of the stored product. Under the action of this load, the courses of the cylindrical wall work in tension and therefore must possess appropriate strength properties. In cases where the tank is not filled with product, the determining loads become those that cause compressive forces in the cylindrical wall. Such loads can act in both longitudinal and circumferential directions. Longitudinal loads include the self-weight of the wall courses, roof structures, and equipment installed on it, as well as the weight of snow and the action of vacuum. Circumferential compressive forces arise mainly due to wind load and vacuum. The presence of compressive stresses necessitates checking and ensuring the stability of the tank's cylindrical wall.

Thus, from the perspective of calculating vertical tanks, it can be noted that during operation, the cylindrical wall can be in two diametrically opposed design situations. In the filled state, all courses of the cylindrical wall are in a state of tension from the product pressure and internal overpressure, and in the empty state, all courses are compressed in both meridional and circumferential directions by corresponding loads. Therefore, during the design of steel vertical tanks, the thickness of the cylindrical wall courses is determined primarily from the condition of ensuring strength, after which it is refined taking into account the requirements for the structure's stability.

The above circumstance constitutes the core of the problems associated with the effective application of high-strength steels: the use of high-strength steel allows for a reduction in the thickness of the cylindrical wall courses, but this possible reduction is limited by stability conditions. According to the authors, an effective solution to this problem can be found by varying the geometric parameters of the tank, which, under the same external loads, allow changing the magnitude of internal stresses and critical stability parameters. Thus, the paper analyzes the main trends in the influence of geometric parameters of tanks on their strength and stability. This will significantly simplify the determination of the most effective structural solutions for tanks of the considered type.

ANALYSIS OF PREVIOUS RESEARCH

The issue of strength and stability of steel vertical tanks is considered within the framework of the theory of thin-walled shells and is one of the classic, yet complex areas of solid mechanics [1]. Modern research focuses on refining the stress-strain state of cylindrical shells, taking into account actual operating conditions, geometric nonlinearity, and initial geometric shape imperfections.

As is known, during the operation of tanks, one of the main loads on the cylindrical wall is the hydrostatic pressure from the stored product [2–4]. The performance of a thin-walled cylindrical shell under hydrostatic pressure is considered in [3]. The author, using classical approaches of shell theory, showed that the stress distribution in the tank wall varies linearly along its height in accordance with the law of hydrostatic pressure variation:

$$p = \rho \cdot g \cdot H \,, \qquad (1)$$

where ρ - is the density of the stored liquid;

H - is the height of the cylindrical tank wall.

The stress state of the tank wall predominantly has a membrane character with a dominance of circumferential stresses, which significantly exceed meridional ones.

The features of the stress-strain state of vertical cylindrical tanks under wind pressure are considered in [5]. The static analysis of shells showed that membrane circumferential stresses prevail. The stress distribution corresponds to the nature of the applied wind pressure. It was found that the wind loading is safe for the strength. The process of deformation of cylindrical shells under wind is generally stable. However, the nature of deformation, namely wave deflections along the perimeter of the shell, and especially in the zone of active wind pressure, can significantly affect the shell stability.

In [6], the influence of boundary conditions and edge forces is considered. Within the framework of such a stress state, the load-bearing capacity of the structure is determined mainly by the strength of the material, which theoretically justifies the feasibility of using high-strength steels.

At the same time, the actual performance of tanks is significantly complicated by the presence of local structural inhomogeneities [7–10]. In particular, welded joints are sources of stress concentration, which can lead to local exceeding of nominal stress values and initiate damage. Papers [7, 8] propose analytical dependencies for estimating stress concentration factors in thin-walled structures, including cylindrical tanks. Study [9] emphasizes the important role of assembly joints and initial geometric imperfections as factors causing local shell buckling. In the work [10] it is noted that the imperfection in the form of a vertical concave line of the assembly weld is the most common type of defect in steel tanks. Such imperfections significantly reduce the prebuckling, buckling and postbuckling parameters of tanks under uniform external pressure. It is shown that for the design of steel tanks under uniform external pressure, 65% of the classical buckling load should be used.

In the work [11], classical and modern approaches to the analysis of the buckling of steel thin-walled cylindrical shells are systematized. A wide range of problems is covered, namely, the buckling of shells under the action of axial compression, internal pressure and wind load. The author emphasizes that these loads often act simultaneously, and their combined effect significantly complicates the prediction of critical shell states. The influence of manufacturing defects on the operation of shells is also considered. It was found that the shell slenderness parameter *r/t* is a key factor, which is determining shell stability. As the ratio *r/t* increases, critical stresses decrease sharply, sensitivity to imperfections increases, and shell behavior becomes highly nonlinear.

The current stage of research is characterized by the widespread use of numerical modeling, particularly the finite element method (FEM) [12 – 16]. It allows taking into account geometric and material nonlinearity, initial imperfections, and complex loading schemes [17 – 19]. Considerable attention is paid to the problem of the stability of thin-walled shells [20–24].

In the work [20] it is stated that, in addition to the cylindrical shell slenderness *r/t*, the flexibility parameter *H/r* is of great importance for the operation of the shells, as it affects whether the shell buckling shape will be local or global. It is noted that for thin-walled cylindrical shells, the determining limit state is the loss of stability, which significantly depends on the geometric parameters of the shell and existing initial imperfections in them. This circumstance is especially characteristic of shells with large *r/t*. The obtained conclusions are supported by the classical theory of stability of thin-walled shells [25] and confirmed by modern FEM studies [12, 21–24].

A generalizing analysis of the problem of buckling of vertical steel tanks is presented in [23], where it is shown that such structures should be considered as thin-walled shells with high sensitivity to buckling. It is established that the determining factors are the nature of the load (wind, vacuum, foundation settlement, temperature effects), geometric parameters, and initial imperfections. It is emphasized that the failure of tanks in most cases occurs due to buckling, rather than reaching the yield strength of the material.

In addition to a large number of research papers, it is necessary to note the design standards EN 1993-1-6 "Eurocode 3: Shell structures" [26], which is valid in the EU countries and is the basic design standards for the design of shells in Europe. In EN 1993-1-6 "Eurocode 3: Shell structures" [26], similarly to the above-mentioned works, it is stated that in most cases, the failure of thin-walled cylindrical shells occurs due to buckling earlier than the stresses are reaching the yield strength of the steel. In addition, high-strength steels generally have less ductility than ordinary-strength steels, and due to the smaller shell thickness, the effect of local geometric shape defects is amplified.

Thus, summarizing the analysis of the provided sources, it should be noted that a key factor in ensuring the efficiency of steel vertical tanks is not only the strength of the material but primarily the stability of the vertical steel tanks as thin-walled shells. The use of high-strength steels allows for reducing the shell thickness, and consequently, reducing material consumption, but this leads to an increased risk of structural buckling. An effective solution to this problem can be achieved by changing the geometric parameters of the tank, which, under the same external loads, will allow regulating the level of internal stresses and critical loads of the tank. In this regard, the task of establishing the patterns of the influence of the geometric parameters of tanks on their stress-strain state and critical buckling parameters becomes particularly relevant.

MAIN RESEARCH

In this work, all calculations were performed using the following load values [27, 28]:

- dead load from the roof's self-weight 78 kg/m^2;
- overpressure in the gas space of the tank $P = 2.0$ kPa;
- vacuum $P_{vac} = 0.2$ kPa;
- density of the liquid $\rho = 1.0$ t/m^3;
- wind pressure $w_0 = 0.5$ kPa;
- snow load $S_0 = 1.5$ kPa.

Calculations were performed for the cylindrical wall of vertical steel tanks, the geometric parameters of which are specified in Table 1. The corresponding geometric dimensions of the considered tanks are recommended by DSTU B V.2.6-183:2011 [29].

Table 1. Geometric parameters of steel vertical tanks according to DSTU B V.2.6-183:2011 [29]
Табл. 1. Геометричні параметри сталевих вертикальних резервуарів за ДСТУ Б В.2.6-183:2011 [29].

Volume of tank V, m^3	Wall height H, m	Wall radius r, m
1000	12,0	5,2
5000	15,0	10,5
10 000	18,0	14,25

If meridional stresses are not taken into account, then, according to design standards [28, 30], the strength calculation of cylindrical shells, which are in a membrane stress state, is performed taking into account circumferential tensile stresses from the oil product pressure and overpressure in the gas space of the tank using the formula:

$$\frac{\gamma_n \cdot \left(\rho \cdot g \cdot H \cdot \gamma_{fm1} + P_{ef} \cdot \gamma_{fm2}\right) \cdot r}{t} \le \frac{\gamma_c \cdot R_{yn}}{\gamma_m} \quad (2)$$

where R_{yn} is the characteristic value of steel resistance (yield strength);

γ_n, γ_c, γ_m are coefficients, which depend, respectively, on the class of overall reliability of the structure, structural working conditions, and material reliability.

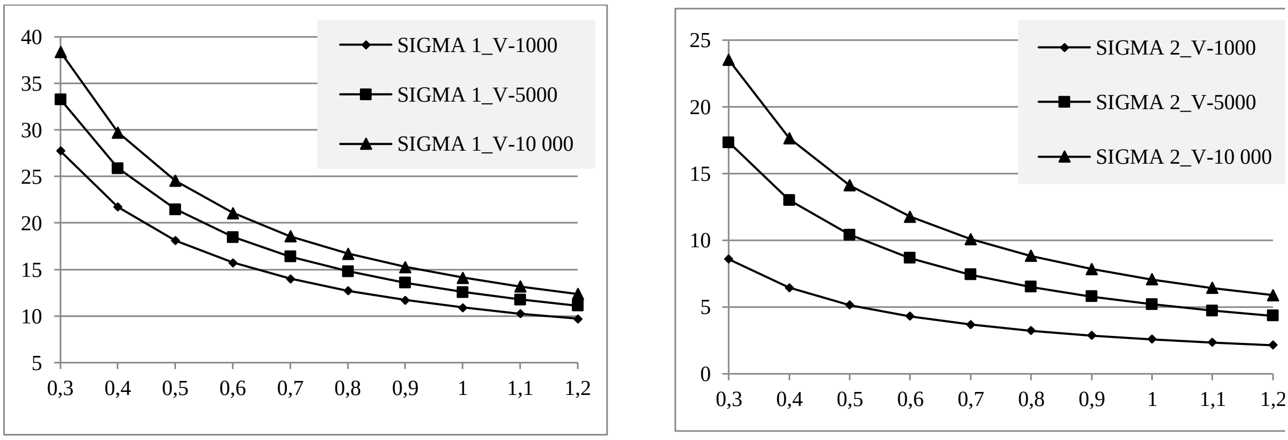
Condition (2) shows that for the same load-bearing capacity of a cylindrical shell, the relationship between its thickness *t* and the characteristic steel resistance R_{yn} has an inversely proportional dependence. That is, with an increase in steel resistance, for example, by 1.5 times, the permissible minimum shell wall thickness can also be reduced by 1.5 times to ensure the same load-bearing capacity.

An additional effect here may manifest due to the fact that as the thickness increases, the characteristic resistance value of the steel decreases, while transitioning to a stronger steel in this thickness range does not lead to a decrease in characteristic resistance. However, firstly, this is only a situational occurrence, and secondly, such an additional effect does not exceed 2–4%.

Another reason for a slight deviation from proportionality is that changing the thickness is accompanied by a change in the self-weight of the wall and the corresponding load from it. This concerns only meridional stresses, and if strength condition (2) is adopted taking into account loads in the meridional direction, the proportionality between the thickness value and the load-bearing capacity of the wall is violated. But even here, such a deviation will be insignificant, within 3–5%.

A significantly more complex relationship exists under the conditions of stability of a cylindrical shell [28, 30]. This is explained by the complex dependencies of the ratios σ_1 / σ_{cr1} and σ_2 / σ_{cr2} on the thickness of the cylindrical shell wall. The characteristic dependencies of stability indices on the cylindrical wall thickness are shown in Fig. 1–6.

The dependence of meridional stresses σ_1 and circumferential stresses σ_2 on the cylindrical wall thickness *t* is shown in Fig. 1.



a *b*

Fig. 1 Dependence of stresses, kg/cm^2, on the cylindrical wall thickness *t*, cm:
a – meridional stresses σ_1; *b* – circumferentional stresses σ_2.

Рис. 1 Залежність напружень, кг/см^2, від товщини циліндричної стінки *t*, см:
а – меридіональних напружень σ_1; *б* – кільцевих напружень σ_2

The graphs in Fig. 1 show that meridional stresses σ_1 decrease with an increase in thickness, but not as intensively as circumferential stresses σ_2, which can be explained by the influence of the wall's self-weight on the value of stresses σ_1. However, the overall dependence of stresses on thickness remains very close to inversely proportional. Circumferential stresses in the radial direction σ_2 also decrease with an increase in thickness, and a strictly inversely proportional relationship is realized here, see the graphs in Fig. 1, b.

The dependence of critical stresses σ_{cr1} and σ_{cr2} is shown by the graphs in Fig. 2, 3.

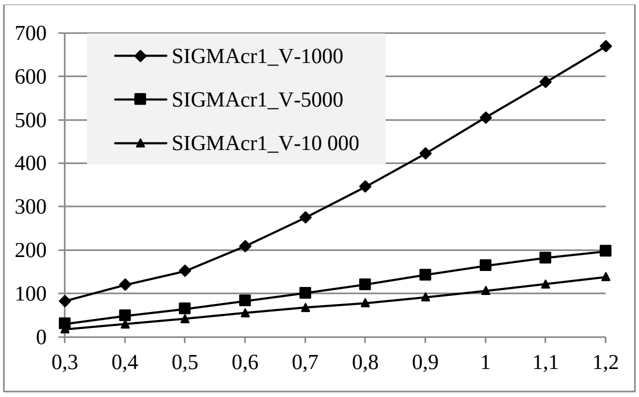


Fig. 2 Dependence of meridional critical stresses σ_{cr1}, kg/cm^2, on the cylindrical wall thickness *t*, cm

Рис. 2 Залежність меридіональних критичних напружень σ_{cr1}, кг/см^2, від товщини циліндричної стінки *t*, см

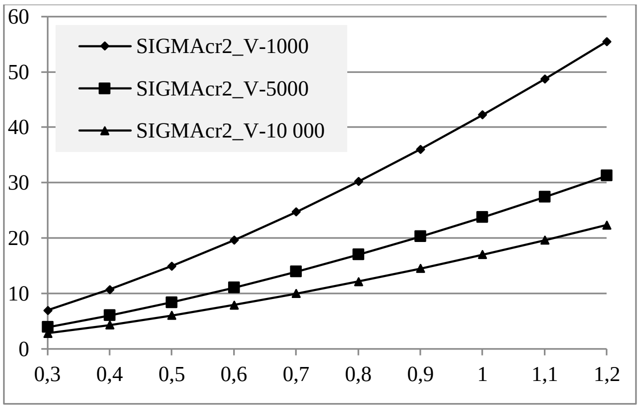


Fig. 3 Dependence of circumferentional meridional critical stresses σ_{cr2}, kg/cm^2, on the cylindrical wall thickness *t*, cm

Рис. 3 Залежність кільцевих критичних напружень σ_{cr2}, кг/см^2, від товщини циліндричної стінки *t*, см

Here too, an inversely proportional relationship takes place, but while stresses from the external load decrease with an increase in thickness, the critical stress values of the shell increase.

This result corresponds to the provisions of the theory of shells [1, 20, 25].

It is important to emphasize that the obtained relationship is nonlinear. A reduction in shell thickness is accompanied by a relatively greater decrease in the magnitude of the critical load. For example, from the graph of the variation of the critical meridional stresses σ_{cr1} for a tank with a capacity of 1000 m^3, see Fig. 2, it follows that when the thickness *t* is reduced from 1.2 cm to 0.3 cm, i.e., by 4 times, the critical stresses σ_{cr1} decrease from 700 kg/cm^2 to 100 kg/cm^2, i.e., by 7 times. It should be noted that such a reduction in wall thickness can occur when the high-strength steel is used for oil tanks.

A similar pattern occurs for the dependence of the critical circumferential stresses σ_{cr2} on the cylindrical wall thickness *t*. This very circumstance constitutes the main problem for the effective use of high-strength steels in oil tanks.

Fig. 4, 5 show the dependencies of the cylindrical wall stability indices in the meridional and circumferential directions:

$$S_1 = \frac{\sigma_1}{\sigma_{cr1}}; \tag{3}$$

$$S_2 = \frac{\sigma_2}{\sigma_{cr2}}; \tag{4}$$

$$S = S_1 + S_2; \tag{5}$$

where S_1, S_2 are the cylindrical wall stability indices in the meridional and circumferential directions, respectively; *S* is the overall stability index of the cylindrical wall.

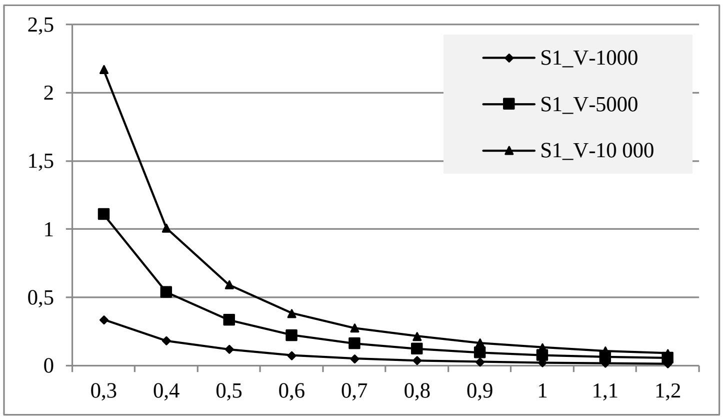


Fig. 4 Dependence of the cylindrical wall stability index in the meridional direction $S_1 = \sigma_1 / \sigma_{cr1}$ on the wall thickness *t*, cm.

Рис. 4 Залежність показника стійкості циліндричної стінки у меридіональному напрямку $S_1 = \sigma_1 / \sigma_{cr1}$ від товщини стінки *t*, см

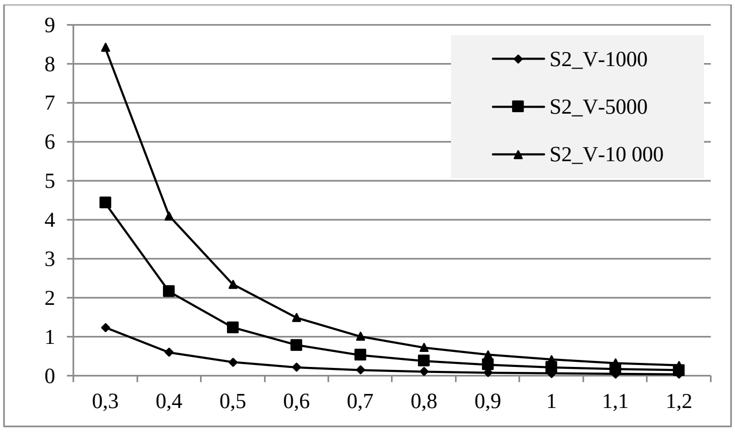


Fig. 5 Dependence of the cylindrical wall stability index in the circumferential direction $S_2 = \sigma_2 / \sigma_{cr2}$ on the cylindrical wall thickness *t*, cm.

Рис. 5 Залежність показника стійкості циліндричної стінки у кільцевому напрямку $S_2 = \sigma_2 / \sigma_{cr2}$ від товщини стінки *t*, см

The dependence of the cylindrical wall overall stability index *S* on the wall thickness *t* is shown in Fig. 6.

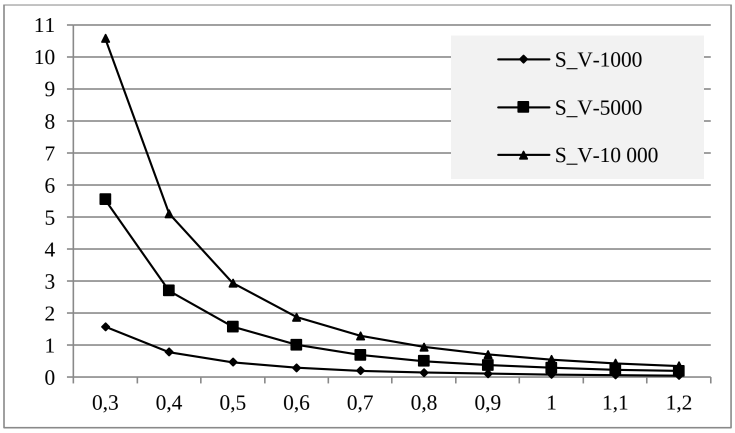


Fig. 6 Dependence of the cylindrical wall stability index $S = S_1 + S_2$ on the wall thickness *t*, cm.

Рис. 6 Залежність показника стійкості циліндричної стінки $S = S_1 + S_2$ від товщини стінки *t*, см

From the graphs, it follows that the general shape of the dependencies of the relative stability indices on the wall thickness *t* has approximately the same pattern. But for larger-capacity tanks, the intensity of changes in the relative stability indices turns out to be greater, meaning that for tanks of larger capacity, the stability of the cylindrical wall becomes more sensitive to thickness changes.

If we consider that in all cases the stability criterion is the condition [28, 30]:

$$S_i \le 1{,}0; \qquad (6)$$

then it turns out that for the considered tanks, this requirement for the minimum allowable thickness is realized according to different indicators at different thickness values.

It is important to note that the determination of the minimum allowable thickness by the stability index S_2, and therefore by *S*, is performed using the average thickness value of all courses of the cylindrical wall [28, 30].

This means that the thicknesses permitted by the index *S* are the minimum thicknesses that all courses of the cylindrical wall can have under the general stability condition (6). So, if for tanks with a capacity of 1000 m^3 the minimum thickness according to the *S* criterion is 3.7 mm, this means that the criterion *S*: $S \le 1{,}0$. In other words, the general stability condition will be fulfilled, and it will be fulfilled even when all courses of the cylindrical wall have a thickness of at least 4.0 mm.

The minimum permissible thickness values that a cylindrical tank wall can have according to various stability criteria are given in Table 2.

Table 2. Minimum permissible values of the tank cylindrical wall thickness for different stability indices and the corresponding stresses σ_2^* from the pressure of the stored liquid

Табл 2. Мінімально допустимі значення товщини циліндричної стінки резервуарів за різними показниками стійкості та відповідні напруження σ_2^* від тиску рідини, що зберігається

Tank capacity, m^3	Stability indicators			Stresses, MPa		
	S_1	S_2	S	σ_2^*	R_{ef}	R_{ef}^*
	Minimum permissible thickness values, mm					
1000	3,0	4,0	4,0	124,8	168	168 (C255)
5000	4,0	6,0	7,0	225,0	168	253 (C390)
10 000	5,0	8,0	9,0	285,0	168	286 (C440)

Analysis of the above data shows that with the values of the course thickness, which are determined by the stability condition, the strength condition for the lower courses of the cylindrical wall can be met only with the use of high-strength steel.

The corresponding information is also presented in Table 2.

Table 2 also presents the stresses σ_2^*, which arise in the lower courses of the cylindrical wall of the considered tanks from the pressure of the stored liquid. In the calculations, water was adopted as the stored liquid, as proposed by the design standards [28, 29]. Table 2 provides the design values of stresses R_{ef}, which are permitted by design standards [30] for ordinary strength steel of class C255, and R_{ef}^* for the steel that must be respectively adopted to satisfy the strength condition.The magnitude of stresses R_{ef}^* was calculated using the formula:

$$R_{ef}^* = \frac{\gamma_n \cdot \gamma_c}{\gamma_m} \cdot R_{yn}. \qquad (7)$$

The data in Table 2 show that when using ordinary strength steel C255, the strength condition is satisfied only for a tank with a capacity of 1000 m^3. In a tank with a capacity of 5000 m^3, the satisfying of the strength condition requires the use of high-strength steel of class C390 in the lower courses of the cylindrical wall, and in a 10 000 m^3 tank, high-strength steel of class C440 is required for this.

CONCLUSIONS AND PROSPECTS FOR FURTHER RESEARCH

As a result of the analysis is performed in this work, the following conclusions can be drawn:

- the thickness of the cylindrical wall is one of the main parameters that determines the strength and stability of steel vertical cylindrical tanks;
- an increase in thickness is unambiguously accompanied by an increase in the load-bearing capacity of the cylindrical wall;
- the obtained thickness of the cylindrical wall courses, at which the general stability condition for oil tanks is ensured, can guarantee the fulfillment of the strength condition only if high-strength steel is used for the lower wall courses of the tanks.

Further research can be directed towards establishing the interdependencies of the features of external loads and geometric parameters, including geometric imperfections, on the stability of the cylindrical wall of large-capacity tanks. The next research should aim to develop a comprehensive approach of “material + geo-metry”. This approach should be used when the assessing of the oil tanks stability is executed. The results of this research may be used for developing of applied recommendations for determining the minimum permissible wall thickness and the use of high-strength steel for vertical cylindrical tanks.

ETHICAL DECLARATIONS

The authors have no relevant financial or non-financial interests to report.

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ОЦІНКА ВПЛИВУ ГЕОМЕТРИЧНИХ ПАРАМЕТРІВ НА НЕСУЧУ ЗДАТНІСТЬ СТАЛЕВИХ РЕЗЕРВУАРІВ, ВИГОТОВЛЕНИХ ІЗ ВИСОКОМІЦНИХ СТАЛЕЙ

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Анотація. Сталеві вертикальні наземні резервуари широко застосовуються в хімічній, нафтовій та газовій промисловості як ємності для зберігання рідких продуктів і газів.

З точки зору розрахунку вертикальних резервуарів, можна зазначити, що під час експлуатації циліндрична стінка може перебувати у двох діаметрально протилежних розрахункових ситуаціях: у заповненому стані всі шари циліндричної стінки знаходяться в стані розтягнення від тиску продукту та дії внутрішнього надлишкового тиску, тоді як у порожньому стані – всі шари стискаються як у меридіональному, так і в окружному напрямках відповідними навантаженнями. При проектуванні сталевих резервуарів товщина поясів циліндричної стінки визначається, перш за все, з умови забезпечення міцності, після чого уточнюється з урахуванням вимог стійкості конструкції. Це становить суть проблем, пов'язаних з ефективним використанням високоміцних сталей для вертикальних резервуарів: застосування високоміцних сталей дозволяє зменшити товщину поясів циліндричної стінки, але це можливе зменшення обмежене умовами стійкості. Ефективного вирішення цієї проблеми можна досягти шляхом варіювання геометричних параметрів резервуара, що за одних і тих же зовнішніх навантажень дасть змогу регулювати рівень внутрішніх напружень і критичних навантажень резервуара.

У статті досліджується вплив товщини циліндричної стінки та геометричних параметрів резервуарів різної місткості на напружено-деформований стан і критичні параметри стійкості. Встановлено, що визначення мінімально допустимої товщини стінки за умовами стійкості є більш жорстким, ніж за умовами міцності. При цьому забезпечення міцності нижніх поясів циліндричної стінки для резервуарів середньої та великої місткості можливе лише за рахунок застосування сталей високої міцності. Водночас ефективність їх використання обмежується вимогами стійкості.

Ключові слова: сталеві резервуари; циліндрична оболонка; міцність; стійкість.

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