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OPTIMIZATION OF THE SUPPORT OF A HORIZONTAL PRESSURE VESSEL

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Purpose: The purpose of this study is to explore the optimization of support structures for horizontal pressure vessels using simulation modeling. The research aims to reduce the mass of the support while ensuring structural integrity and identifying opportunities for future improvements in materials and design.

Design/methodology/approach: The research was conducted by creating a three-dimensional support model in SolidWorks, compliant with GOST standards. The stress–strain behavior and optimization of the support structure were analyzed using SolidWorks' Simulation module, which employs the finite element method (FEM). Non-uniform load distributions, such as sinusoidal and parabolic loads, were applied during the loading process to enhance the accuracy of the simulation without incorporating the vessel body itself.

Findings: The simulation results showed that optimizing the support structure led to a 15% reduction in its mass. Even though this also resulted in a 23% increase in equivalent stresses in critical areas, the support structure remains safe to operate, with a strength reserve factor under static loads exceeding 2.

Research limitations/implications: Further research should include simulations that account for the type and properties of connections between elements, particularly weld calculations. Additionally, future studies could explore the use of higher-grade steels than the tested 09G2C steel to achieve further mass reductions, provided the cost is justifiable.

Practical implications: This study is particularly relevant for the design of pressure vessel supports used in vehicles, trailers, and semi-trailers transporting liquids or liquefied hydrocarbon gases. Reducing the mass of support structures can increase payload capacity, offering significant commercial benefits in transportation efficiency.

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Social implications: A lighter, optimized support structure can contribute to more fuel-efficient transportation of liquid and gas materials, thereby reducing the environmental impact of logistics operations.

Originality/value: The originality of this study lies in the combined use of topological and parametric optimization techniques for modeling horizontal pressure vessel supports. The paper provides valuable insights into how simulation-based optimization can lead to significant mass reductions while maintaining structural safety. This research is particularly useful to engineers and designers working on pressure vessel supports for transportation applications.

Keywords: pressure vessel, tank, tank support, simulation modeling, topological optimization, parametric optimization.

1. Introduction

During the design of various products, the primary objective is to select design parameters that ensure high efficiency, which includes minimizing material consumption, achieving the necessary strength and rigidity, and reducing costs. This involves a cyclical iterative process where multiple product variants are considered, compared against selected efficiency criteria, and evaluated through calculations (Buchert et al., 2018; Zheng et al., 2020). Oftentimes, setting appropriate technological parameters also plays a vital role in achieving the desired quality while keeping the manufacturing costs relatively low (Bembenek et al., 2023).

Typically, in the development of complex products, only two or three design variants are considered owing to time constraints for performing detailed calculations. The most intensive calculations are those assessing the product's performance. For strength calculations, simplified models are often used. For instance, in the strength analysis of horizontal cylindrical pressure vessels, a beam mathematical model is commonly applied, which may not account for the actual geometry or all possible loading conditions (Zheng et al., 2020).

Based on practical experience, these simplified models can produce functional designs; however, enhancing their efficiency remains a critical task. The lack of precise and accessible methods for calculating the strength of horizontal vessels often leads to the use of inflated safety factors (Quin, Widera, 1996). Consequently, this results in increased material usage and higher costs (Wang et al., 2023). Therefore, there is a growing emphasis on optimizing design by applying refined strength calculation methods. This approach allows for a systematic study of product characteristics through both physical and numerical experiments, ultimately improving load-bearing capacity, service life, and overall efficiency (Javidrad, H.R., Javidrad, F., 2023).

The prompt and efficient analysis of the stress–strain state of product elements using advanced mathematical models that consider specific operating conditions, the reliable assessment of their load-bearing capacity, and the search for optimal design solutions are possible only through the effective use of modern computer programs (Krantovska et al., 2019; Selejdak et al., 2023).

Pressure vessels are designed to be airtight and are used for conducting physical, chemical, and thermal processes with hydrocarbon raw materials or other media. They are also used for storing and transporting compressed or liquefied gases or liquids (Mykhailiuk, 2023). These vessels are widely employed across various industries, including oil and gas, oil refining, chemical, energy, pulp and paper, cement, and food (Lyakh, Mykhailiuk, 2022; Mykhailiuk et al., 2024, 2022a).

Because of the unique design and the loads acting on pressure vessels, stress distribution within their elements is often uneven. For horizontal vessels, the stress–strain state of the support is particularly crucial for their operation (Błachut, Magnucki, 2008; Varga, 1991). Modern methods and tools enable the calculation and optimization of pressure vessel design elements, which enhances the reliability of the vessels, reduces their weight, and increases their operational safety (Chavda et al., 2022).

Pressure vessels, whether vertical or horizontal, are typically mounted on foundations, special structures, legs, or supports. The supports for horizontal vessels are usually made of steel and welded to the hull, or they may be designed to move relative to it. A typical support for a horizontal tank consists of a backing sheet and vertical ribs attached to its base. The support must cover at least 120° of the vessel's circumference (OST 26-2091-93, 1993). The dimensions and designs of supports for horizontal vessels are standardized and regulated (Widera et al., 1988).

In a work by Yang et al., simulation modeling of a vessel operating under pressure was carried out taking into account the effect of internal pressure (16.9 bar) and external load (wind). During the study, special attention was paid to the stress-deformed state of the support of the vessel. The structure of the support was also optimized in order to reduce its weight and cost (Yang et al., 1994).

In a later study, a horizontal pressure vessel was analyzed using the finite element method (FEM) in ANSYS. The optimal location of the vessel's supports was determined, and the impact of structural elements on the vessel's stress–strain state was assessed. Optimization of the vessel's wall thickness led to a reduction in mass (Adithya, Patnaik, 2013).

In another work, a pressure vessel was analyzed using finite element simulation in ABAQUS. The boundary conditions included the vessel's weight and internal pressure. The simulation yielded the stress–strain state under these loads, and the results were consistent with theoretical calculations, demonstrating the accuracy and reliability of the method (Zhang et al., 2014).

There was also another study, where the primary goal was to develop and analyze the stress–strain state of the tank and identify the parameters that have the greatest impact on its efficiency. Results obtained using PV-ELITE software were compared with analytical calculations, showing a 4.99% difference (Vivekanandan et al., 2019).

Research by Nayak and Singru examined the influence of stiffness ring placement on stress concentration in the transition zone between the hull of a horizontal vessel and the saddle. The analysis considered internal pressure, the vessel's own weight, and other loads (Nayak, Singru, 2021).

Finally, there was a study that involved simulation modeling of a 10 m^3 pressure vessel used for liquefied petroleum gas (LPG) storage, with the vessel comrising a cylindrical body, two elliptical ends, a hatch, and two supports. The study confirmed that the strength of the vessel structure under applied loads is sufficient. It also identified the highest stress concentrations near the hatch and the junction between the hull and elliptical ends, while the lowest stresses were observed in the saddle (Abdewi, Fahel Alboum, 2023). Lowest stresses were observed in the saddle (Abdewi, Fahel Alboum, 2023).

The foregoing studies have employed finite element simulation to analyze and optimize pressure vessel designs, also highlighting the importance of considering external loads, such as wind, to optimize the weight and cost of the vessel’s support structure. They help to identify critical stress points, ensure structural integrity, and optimize material usage.

2. Methods

Modern design tools enable not only the prediction of product deformation but also the optimization of design within specified mass and strength constraints. This capability is particularly crucial for pressure vessel designs. Various computer program modules implementing parametric and topological optimization methods are employed for this purpose (Mykhailiuk et al., 2022b).

Topological optimization is a method used to determine the most efficient material distribution within a structure to maximize or minimize an objective function (such as overall stiffness or natural frequency) while adhering to specific constraints (such as mass reduction). Unlike parametric optimization, where optimization parameters are explicitly defined, topological optimization focuses on the material distribution function across the product’s volume. This approach often results in models with the required strength and minimal weight, though they may be more challenging to manufacture with traditional methods.

The process of topological optimization involves setting boundary conditions, similar to static strength analysis. Additionally, optimization criteria, such as the best stiffness-to-mass ratio, must be specified. The result of topological optimization is a smoothed mesh of the optimized part.

For optimization, a three-dimensional model of the pressure vessel support was created (Fig. 1). The dimensions of the support are shown in Figure 2.

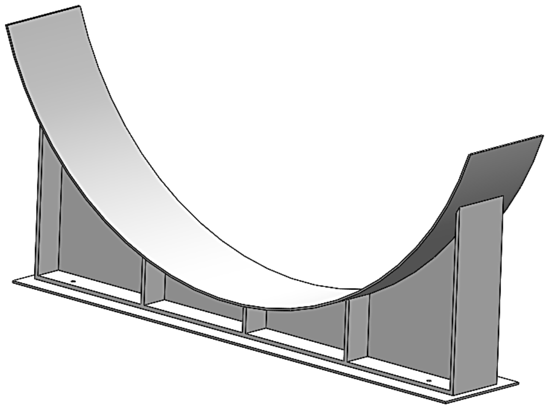
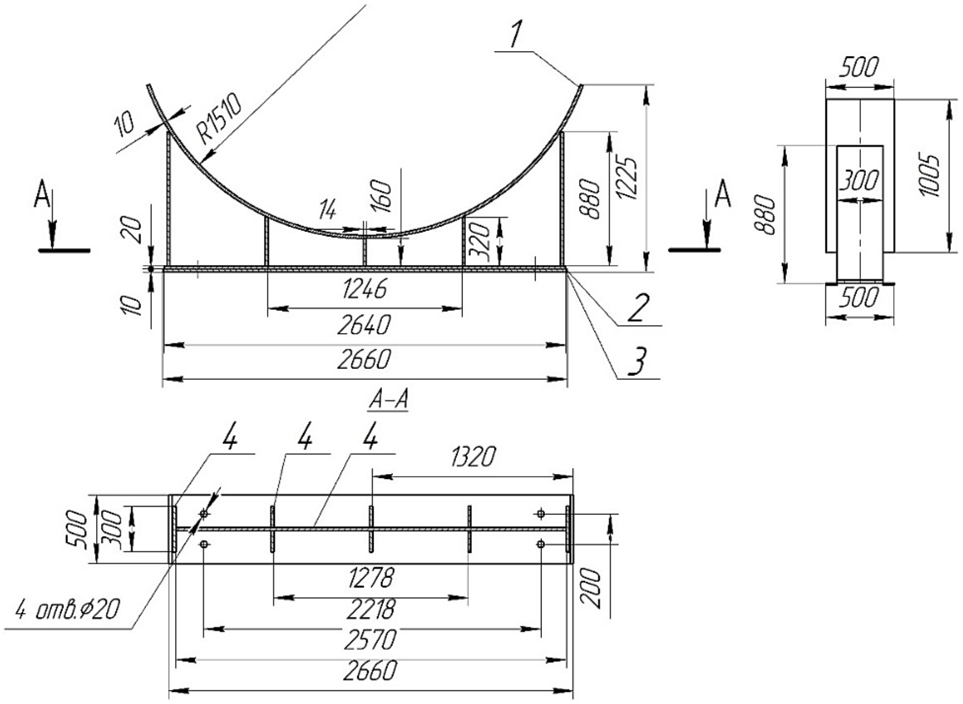


Figure 1. Three-dimensional model of the support.



1 – sheet of paper; 2 – support plate; 3 – supporting sheet; 4 – rib.

Figure 2. Geometric dimensions of the investigated support.

The boundary conditions for the study included the fixation of the lower sheet, allowing movement only in the horizontal direction, and the application of a resistance load from the vessel’s mass and its contents, totaling 568,195 N.

A key feature in applying the load to the support was the use of the SolidWorks tool “working load on a support”. This tool enables the creation of an accurate load distribution on the support without incorporating the existing three-dimensional model of the vessel hull during simulation. At the same time, the load from the vessel body causes an uneven distribution of contact pressure at the contact boundary (Fig. 3), namely, on the supporting sheet 1 of the support (Fig. 2). Additionally, various load distribution patterns, such as sinusoidal or parabolic, can be applied if necessary (Fig. 4).

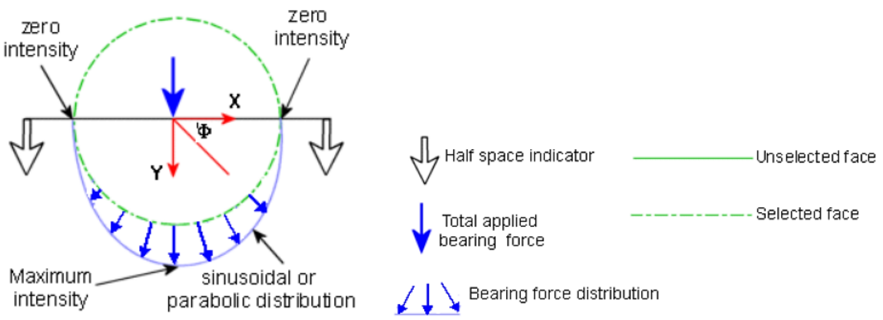
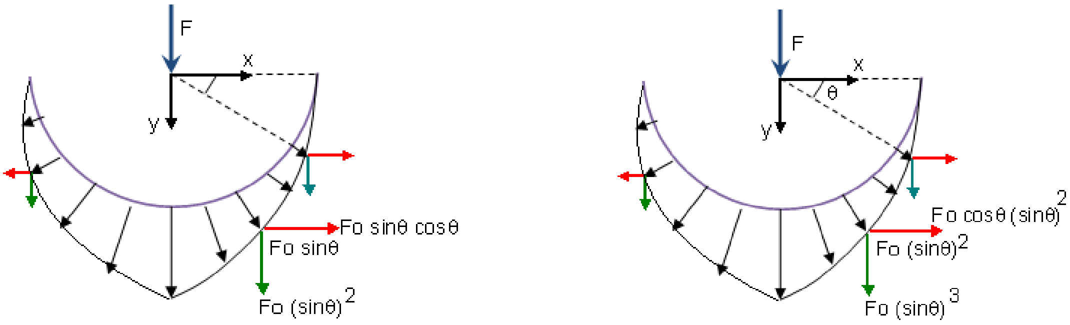


Figure 3. Load distribution on the support.

Fig. 4a shows the sinusoidal load distribution, and Fig. 4b – parabolic.



a) b)

Figure 4. Variations of load distribution on the support.

According to Fig. 4a, the program distributes the force F_0 from $\sin\Theta$ to each node along the circle of the selected edge or the cross-section of the selected faces. In Figure 4, the arrows show the load components *x* and *y*, respectively.

The magnitude of the force F_0 is determined from the equilibrium condition:

$$F = \sum_{i=1}^{n} (F_0)_i \sin^2 \Theta \tag{1}$$

where *n* is the number of nodes along the length.

For the parabolic distribution of the force $F_0(1 - x^2)$, which is transmitted to each node along the length of the circle, which reduces the components $F_0 \sin\Theta$.

The magnitude of the force F_0 is determined from the condition of balance of forces:

$$F = \sum_{i=1}^{n} (F_0)_i \sin^3 \Theta \tag{2}$$

Steel 09G2S with a yield strength of 325 MPa is used as the material for the support parts of the vessel.

3. Results

For the convenience of analyzing the results obtained by means of simulation modeling, the results of the topological optimization of the support of the separator are given first, and then its strain-deformed state before and after optimization.

The optimized shape of the vessel support is shown in Figure 5.

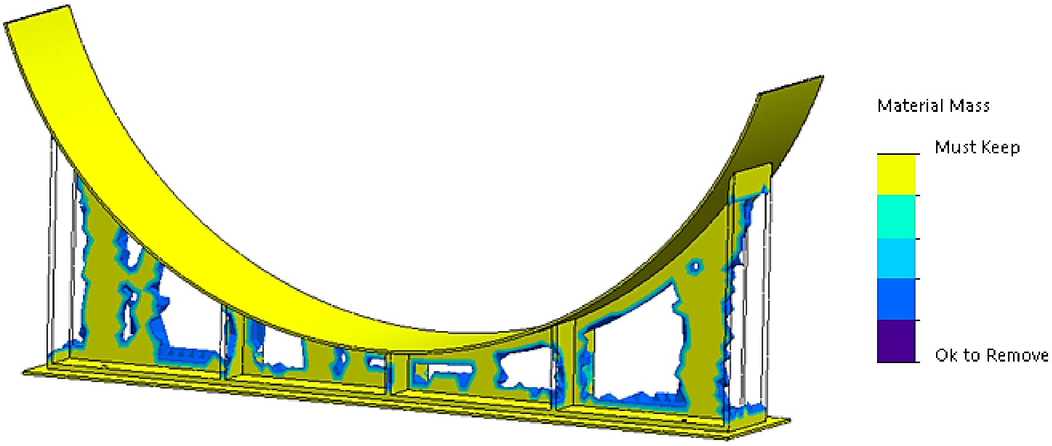


Figure 5. The shape of the vessel support obtained through topological optimization.

Figure 6 shows the design of the support taking into account the results of topological optimization.

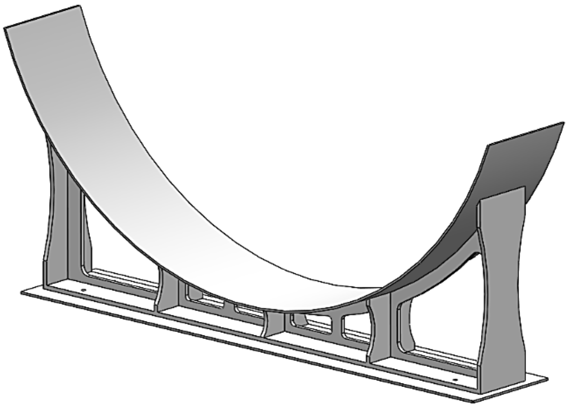
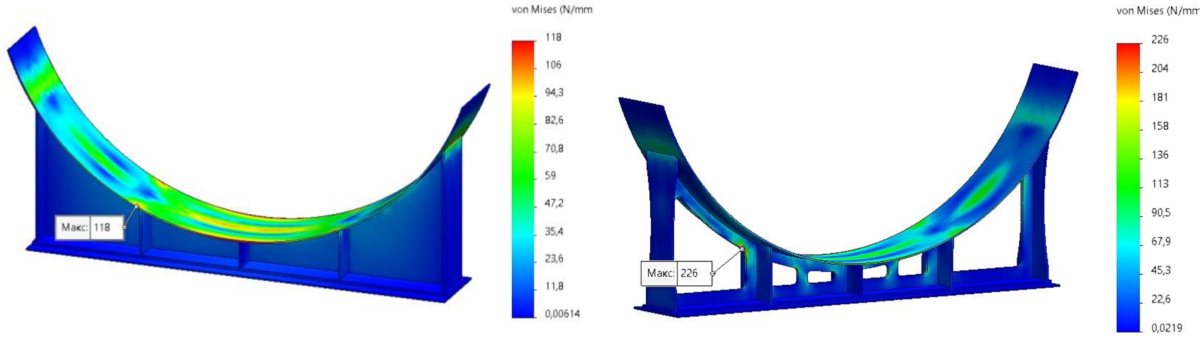


Figure 6. Optimized support design.

Using SolidWorks Simulation tools, the mass of the support was calculated before and after optimization. The mass of the non-optimized support was 595 kg, while the optimized support weighed 505 kg, resulting in a 15% reduction in mass.

The following is a comparison of the stress–strain state of the unoptimized and optimized supports under idenctical boundary conditions and using the same material properties (Fig. 7).



a) unoptimized b) optimized

Figure 7. Distribution of equivalent stresses in the resistance.

According to the results (Fig. 7), the maximum equivalent stresses in the non-optimized support are 118 MPa, concentrated in the backing sheet. In contrast, the optimized support exhibits maximum stresses of 226 MPa, located in the rib. Notably, reducing these maximum equivalent stresses in the optimized support can be achieved by increasing the rounding radius.

Based on the maximum equivalent stress values, the safety factor for the non-optimized support is 2.75, while the optimized support has a safety factor of 1.43.

Parametric optimization was applied with the rounding radius as the variable, initially set at $R = 100$ mm (Fig. 8) and aimed at stress minimization. It was found that increasing the radius from 100 mm to 300 mm reduced the maximum equivalent stress from 225 MPa (Fig. 7b) to 154 MPa (Fig. 9).

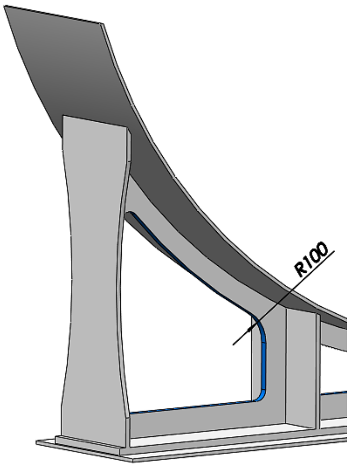


Figure 8. Variable parameter (rounding radius *R*)

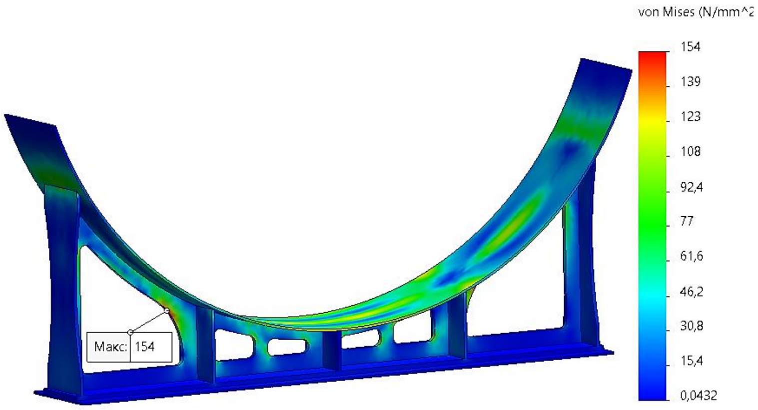


Figure 9. Distribution of equivalent stresses in the resistance

As a result, the safety factor increased from 1.43 to 2.1. This shows that utilizing modern tools in finite element analysis programs during the design process enables effective topological and parametric optimization of various products.

4. Discussion

Reducing the mass of support structures for pressure vessels is a critical issue, particularly for those mounted on car chassis, trailers, or semi-trailers used to transport liquefied hydrocarbon gases or liquids. Lowering the mass of the support structure increases the payload capacity, thereby enhancing the efficiency of the transport system. Achieving this reduction in mass can be accomplished by utilizing materials with higher performance characteristics than the studied steel 09G2C. However, it is essential to balance this approach with economic feasibility, as higher-grade materials may lead to increased costs. This necessitates a comprehensive analysis of both material properties and cost implications to ensure that the benefits of reduced weight do not come at an impractical expense.

5. Summary

Topological optimization of the vessel's support structure resulted in a 15% reduction in mass. However, this optimization led to an increase in maximum equivalent stresses from 118 MPa to 154 MPa. Despite the elevated stress levels, the support structure remains safe for operation because its strength reserve factor is still above 2, which is considered an acceptable safety margin for such applications.

This outcome underscores the delicate balance between reducing mass and managing stress distribution within structural components. While mass reduction is crucial for enhancing the efficiency and payload capacity of pressure vessels, it often introduces higher stress concentrations that must be carefully evaluated. The increased stresses observed in this case highlight the importance of thorough analysis and validation to ensure that the optimized design maintains its integrity and safety under operational conditions.

Therefore, while the mass reduction achieved through topological optimization is beneficial, continuous monitoring and potential further refinements may be necessary to ensure long-term reliability and performance.

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References

1. Abdewi, E., Fahel Alboum, N. (2023). Design and Static Structural Analysis of a Horizontal Pressure Vessel. *International Science and Technology Journal, 31*.
2. Adithya, M., Patnaik, M. (2013). Finite Element Analysis of Horizontal Reactor Pressure Vessel Supported on Saddles. *International Journal of Innovative Research in Science, Engineering and Technology, 2,* 3213-3220.
3. Bembenek, M., Dzienniak, D., Dzindziora, A., Sułowski, M., Ropyak, L. (2023). Investigation of the Impact of Face Milling Parameters on the Roughness of the Machined Surface for 1.4301 Steel. *Advances in Science and Technology. Research Journal, 17.*
4. Błachut, J., Magnucki, K. (2008). Strength, Stability, and Optimization of Pressure Vessels: Review of Selected Problems. *Applied Mechanics Reviews 61,* 060801. https://doi.org/10.1115/1.2978080
5. Buchert, T., Ko, N., Graf, R., Vollmer, T., Alkhayat, M., Brandenburg, E., Stark, R., Klocke, F., Leistner, P., Schleifenbaum, J. (2018). Increasing resource efficiency with an engineering decision support system for comparison of product design variants. *Journal of Cleaner Production, 210*. https://doi.org/10.1016/j.jclepro.2018.11.104
6. Chavda, B., Shukla, R., Tiwari, H., Pandey, A., Rehman, Y. (2022). Design of Pressure Vessel Using Computational Techniques. *International Journal for Research in Applied Science and Engineering Technology*. https://doi.org/10.22214/ijraset.2022.41116
7. Javidrad, H.R., Javidrad, F. (2023). Review of state-of-the-art research on the design and manufacturing of support structures for powder-bed fusion additive manufacturing. *Prog. Addit. Manuf., 8,* 1517-1542. https://doi.org/10.1007/s40964-023-00419-6
8. Krantovska, O., Petrov, M., Ksonshkevych, L., Orešković, M., Synii, S., Ismailova, N. (2019). Numerical simulation of the stress-strain state of complex-reinforced elements. *Tehnički glasnik*. https://doi.org/10.31803/TG-20190417112619
9. Lyakh, M.M., Mykhailiuk, V.V. (2022). Аналіз конструкції газорідинного сепаратора та дослідження його характеристик [Analysis of the structure of a gas-liquid separator and study of its characteristics]. *Scientific Bulletin of Ivano-Frankivsk National Technical University of Oil and Gas, 2,* 31-37. https://doi.org/10.31471/1993-9965-2022-2(53)-31-37
10. Mykhailiuk, V., Zasadzień, M., Liakh, M., Deineha, R., Mosora, Y., Faflei, O. (2024). Analysis of the possibility of modeling gas separators using computational fluid dynamics. *Management Systems in Production Engineering 32,* 80-86. https://doi.org/10.2478/mspe-2024-0009

11. Mykhailiuk, V.V. (2023). Дослідження кільцевого адсорбера [Study of a ring adsorber]. *Scientific Bulletin of Ivano-Frankivsk National Technical University of Oil and Gas, 2,* 40-46. https://doi.org/10.31471/1993-9965-2023-2(55)-40-46
12. Mykhailiuk, V.V., Faflei, O.Y., Melnyk, V.O., Zakhara, I.Y., Malyshev, A.R., Protsiuk, H.Y. (2022a). Моделювання газового вертикального сіткового сепаратора [Modeling of a gas vertical grid separator]. *Scientific Bulletin of Ivano-Frankivsk National Technical University of Oil and Gas, 1,* 91-100.
13. Mykhailiuk, V.V., Protsiuk, H.Y., Yurych, A.R., Yurych, L.R., Babets, M.V., Stetsiuk, R.B. (2022b). Автоматизоване розроблення градуювальної таблиці горизонтальних резервуарів [Automated development of the grading table of horizontal reservoirs]. *Scientific Bulletin of Ivano-Frankivsk National Technical University of Oil and Gas*, 47-53.
14. Nayak, A., Singru, P. (2021). Effect of Number of Stiffening Rings, Their Position and Cross Section on Stress Concentration Near Saddle Support in Horizontal Pressure Vessels. In: Y.V.D. Rao, C. Amarnath, S.P. Regalla, A. Javed, K.K. Singh (Eds.), *Advances in Industrial Machines and Mechanisms* (pp. 521-530). Singapore: Springer, https://doi.org/10.1007/978-981-16-1769-0_47
15. OST 26-2091-93 (1993). *Supports for Horizontal Process and Pressure Vessels*. Design.
16. Quin, S., Widera, G. (1996). Use of Stress-Strength Model in Determination of Safety Factor for Pressure Vessel Design. *Journal of Pressure Vessel Technology-transactions of The ASME, 118,* 27-32. https://doi.org/10.1115/1.2842158
17. Selejdak, J., Bobalo, T., Blikharskyy, Y., Dankevych, I. (2023). Mathematical modelling of stress-strain state of steel-concrete beams with combined reinforcement. *Production Engineering Archives, 29*, 108-115. https://doi.org/10.30657/pea.2023.29.13
18. Varga, L. (1991). The optimum support of horizontal pressure vessels made from reinforced plastic. *Composites, 22,* 227-238. https://doi.org/10.1016/0010-4361(91)90323-9
19. Vivekanandan, M., Venkatesh, R., Sathish, T., Dinesh, S., Ravichandran, M., Vijayan, V., 2019. Pressure Vessel Design using PV-ELITE Software with Manual Calculations and Validation by FEM. *Journal of Engineering Technology, 8,* 425-433.
20. Wang, L., Cai, W., He, Y., Peng, T., Xie, J., Hu, L., Li, L. (2023). Equipment-process-strategy integration for sustainable machining: a review. *Frontiers of Mechanical Engineering, 18,* 36. https://doi.org/10.1007/s11465-023-0752-4
21. Widera, G.E.O., Sang, Z.F., Natarajan, R. (1988). On the Design of Horizontal Pressure Vessels. *Journal of Pressure Vessel Technology, 110,* 393-401. https://doi.org/10.1115/1.3265621
22. Yang, L., Weinberger, C., Shah, Y.T. (1994). Finite element analysis on horizontal vessels with saddle supports. *Computers & Structures, 52,* 387-395. https://doi.org/10.1016/0045-7949(94)90224-0
23. Zhang, Y., Guo, H., Li, J., Yang, G., Ma, Y. (2014). *Simulation Research of a type of Pressure Vessel under Complex Loading. Part 1: Component Load of the Numerical*

Analysis. Proceedings of the 2012 2nd International Conference on Computer and Information Application. https://doi.org/10.2991/iccia.2012.165

24. Zheng, A., Bian, S., Chaudhry, E., Chang, J., Haron, H., You, L., Zhang, J. (2020). Minimizing Material Consumption of 3D Printing with Stress-Guided Optimization. In: V.V. Krzhizhanovskaya, G. Závodszky, M.H. Lees, J.J. Dongarra, P.M.A. Sloot, S. Brissos, J. Teixeira (Eds.), *Computational Science – ICCS 2020* (pp. 588-603). Cham: Springer International Publishing, https://doi.org/10.1007/978-3-030-50426-7_44