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COMPARATIVE ANALYSIS OF MATHEMATICAL MODELS FOR THE SCREW UNIT IN SMALL CONTINUOUS-OPERATION PLASTERING MACHINES

ABSTRACT. *The development of modern construction necessitates improving mechanized mortar application methods. One of the key elements of small-sized continuous plastering units is the screw assembly, which ensures uniform supply and mortars transportation.*

Its effectiveness directly depends on the design parameters, physical and mechanical properties of the material and operating conditions. To analyze the operation of the screw assembly, various mathematical models are used to describe hydrodynamic processes, mechanical interactions between system components and mortar flows characteristics.

Important criteria for choosing mathematical models are forecasting accuracy, implementation complexity, and practical application. The article provides a detailed review of existing modeling approaches and identifies their features.

In the course of the study, a mathematical model's comparative analysis used to describe the screw operation assembly was carried out. Their advantages and disadvantages, as well as areas of application, are established.

It is shown that each of the models has its own applicability limits and forecasting accuracy depending on the type of working environment and unit design features. Recommendations for choosing the most effective mathematical model for predicting the screw assembly operation of small-sized plastering units are proposed.

The results obtained contribute to improving the efficiency of plastering units through a well-founded choice of mathematical models for analyzing their work processes. The defined evaluation criteria can be used to further improve theoretical approaches to calculating the characteristics of the screw assembly and its optimization.

Keywords*: screw assembly, small-sized plastering units, mathematical modeling, comparative analysis, mortars.*

1. Problem statement. Small-sized continuous plastering units are widely used in construction due to their ability to ensure uniform application of mortars. However, their efficiency largely depends on the screw unit operation, which performs the function of feeding and transporting the mixture. During operation, problems arise associated with wear of parts, changes in the physical and mechanical characteristics of mortars and work process instability [1].

The screw assembly operates in difficult conditions, accompanied by exposure to abrasive particles, significant loads and variable parameters of the building mixture. This necessitates taking into account a wide range of factors during the design and unit operation. In addition, the mixture physical and rheological properties may change during transportation, which affects the efficiency of the unit and leads to unpredictable deviations in the material supply.

The development and selection of an adequate mathematical model that allows you to describe the working processes of the screw assembly as accurately as possible is a difficult task. Existing mathematical models are divided into analytical, numerical and experimentally-statistical. Each of these approaches has both advantages and limitations[2]. Analytical models make it possible to establish general patterns of node functioning, but are often based on simplified assumptions about physical processes. Numerical methods provide high modeling accuracy, but require significant computational resources. Experimental-statistical approaches allow obtaining empirical data, but their application can be complicated due to experimental research complexity. Another important aspect is the development of a universal criterion for evaluating mathematical models' effectiveness. Modern research offers different approaches to assessing the performance of a screw assembly, but there is no single approach that would take into account all the necessary parameters: energy efficiency, wear resistance, supply stability, influence of mixture physical and mechanical characteristics, etc. This makes it difficult to choose the optimal model and its practical application.

In view of the above, a systematic comparative analysis of existing mathematical models describing the screw assembly operation in small-sized plastering units is needed. Such an analysis will allow not only to identify their strengths and weaknesses, but also to determine the most suitable approaches for specific operating conditions. It is also important to form recommendations for the use of different models depending on the technological requirements and parameters of the mortar.

2. Analysis of recent sources and publications. Different researchers propose different approaches to mathematical modeling of screw assembly's operation. Mathematical modeling is a key tool for optimizing mechanism operation, particularly screw assemblies in small-sized plastering units [3].

The screw assembly acts as the main element for transporting and feeding building mixtures, and the efficiency of its operation directly affects the productivity of the unit as a whole. Developing and improving mathematical models of these mechanisms is crucial for ensuring high reliability and cost-effectiveness in construction processes.

Traditionally, screw assembly mathematical models rely on the fundamentals of fluid and solid mechanics. One of the first modeling attempts used classical equations to describe fluid movement through a screw in pipelines, considering factors like fluid compressibility, friction, flow velocity changes, and mixture viscosity.

The authors of these developments believed that the most important parameters are the pitch of the screw turn, its diameter, as well as the size of the gap between the screw and the cylinder wall.

One example of such models was proposed by scientists in papers where the theory of mass and energy transfer was used to determine the speed of working medium movement through the propeller [4-6].

These models were based on the assumption that the solution was homogeneous and viscous, and took into account only the mechanical aspects of motion.

Given that plaster mortars are complex non-Newtonian fluids with different properties, including viscosity and ductility, there is a need to create more complex rheological models. y accounting for the nonlinear interaction between the screw and the mixture, researchers achieve more accurate modeling of real operating conditions.

One such model is the Bingham model, which is widely used to describe the flow of plastic fluids. It allows you to accurately simulate the processes of mixing and transporting thick mortars, such as plaster or cement mixture. According to this model, the fluid exhibits plasticity when a certain limit stress is reached, after which it can flow like a viscous liquid.

An important point in the use of rheological models is their ability to take into account the effect of temperature and humidity on the viscosity and fluidity of the solution, which significantly increases the accuracy of modeling. Such models make it possible to predict not only the efficiency of transporting solutions through screw assemblies, but also to optimize the design of the unit itself to reduce energy costs [7].

With the development of technology and the need to increase the performance of units, some researchers have proposed thermodynamic models that take into account the heat exchange between the working surfaces of the screw and the environment. Such models are especially important when the working mixture experiences intense heating due to friction or when the medium's temperature significantly affects the solution's properties. Taking into account such factors allows you to more accurately predict the behavior of the screw assembly in different temperature conditions.

In the works of recent years, the authors have developed models in which the equations of heat transfer and friction are integrated to analyze changes in the properties of the mixture during its movement through the screw. This allows not only to increase the accuracy of mathematical calculations, but also to ensure proper control over the quality of plaster application [8].

The modern development of numerical methods, such as the finite element method (FEM), opens up new opportunities for more detailed modeling of screw assembly's operation.

The difference between such models lies in the ability to accurately take into account complex geometries of screw elements, deformations of materials and local unevenness of stress distribution.

Modern research employs multi-physics models that integrate mechanical, thermodynamic, and rheological equations for more accurate simulations. Numerical methods enable the analysis of screw assemblies at various operational stages, particularly in detecting areas of increased wear or malfunction [9].

In addition, an important aspect is the use of technologies such as machine learning to optimize the parameters of screw assemblies. This allows processing large amounts of experimental data and identifying optimal solutions to improve the design and operation of the units.

3. Purpose of the work. The aim of this study is a comprehensive analysis of mathematical models describing the screw unit operation in small-sized continuous-action plastering machines. In particular, the comparison of different modeling approaches is envisaged, along with the assessment of their accuracy, efficiency, and computational complexity. Particular attention is given to identifying the key advantages and disadvantages of each method, as well as determining the optimal conditions for their application in engineering practice and scientific research

4. Research objectives. It is proposed to analyze existing mathematical models of the screw unit operation, define the main criteria for model comparison, perform a comparative analysis based on the defined criteria, determine the optimal conditions for applying different models, and provide recommendations for selecting the most effective mathematical model for predicting the screw unit operation.

5. Discussion of research results. Classical mathematical models for screw units are based on fluid mechanics and solid mechanics principles, using the laws of motion to describe the interaction between the screw and the fluid or mixture. The main task is to simulate the process of transporting liquid or viscous mixtures through the screw assembly, taking into account the design parameters and characteristics of the medium. Screw assemblies operate on a principle similar to that of screw pumps, where fluid moves through a conduit or cavity that has a spiral surface. In this case, the mathematical model of fluid motion can be described by an equation based on the balance of forces and energy.

Under real conditions, the working mixture transported through the screw has the properties of a viscous liquid. In this case, the Navier-Stokes equation can be applied to describe the flow of a viscous fluid in pipes or channels with complex geometry, in particular for helical assemblies. The general Navier-Stokes equation in unreduced form for a stationary flow is of the form

$$\rho\left(\frac{\partial v}{\partial t}+v\cdot\nabla v\right)=-\nabla p+\mu\nabla^{2}v+f \tag{1}$$

where - ρ- liquid density, kg/m^3; ν - flow velocity vector, m/s; p - fluid pressure, Pa; μ - dynamic viscosity; f- external forces.

Screw pumps are used to pump a wide range of liquids, such as water, petroleum products, and to move thick pastes, sludges, and mortars. After the fluid flow passes through the screw channel, the liquid is transported along the pump axis. For this type of equipment, an important characteristic is the volumetric flow of liquid, which determines the pumping efficiency.

The liquid flow through the screw pump depends on several key factors, the most important of which are the channel size, liquid viscosity, pressure difference between the pump's inlet and outlet, and channel length.

To determine the volumetric flow through a pump operating under such conditions, a special mathematical model can be used. One approach to the calculation is to apply a formula that describes the volumetric flow based on the pump's main parameters and the liquid's properties.

When studying the mathematical model of a screw pump with a rheological component, it can be built based on equations for flow velocity, liquid viscosity, and interaction with the pump mechanism. One of the main approaches is to use equations that describe the liquid flow through the screw channels of the pump. For rheological fluids, a generalized equation for flow velocity can be applied, accounting for viscosity and changes in the flow structure:

$$Q = \frac{2\pi \cdot R^3 \cdot \Delta p}{L \cdot (\mu + \mu_0)}. \tag{2}$$

where Q — volumetric fluid flow, m^3/s, R — pump channel radius, m, Δp — pressure difference between pump inlet and outlet, Pa, L — channel length, m, μ — dynamic viscosity of the liquid, Pa·s, μ_0 — the base viscosity of the fluid, which characterizes its behavior at low flow rates, Pa·s.

The channel radius is an important parameter in a screw pump, as it directly determines the amount of liquid that can be moved through the pump. With a larger channel radius, the amount of liquid transported per unit of time increases. At the same time, increasing the radius leads to changes in flow velocity and pressure, as it alters the flow geometry within the channel. This requires taking such changes into account in the rheological properties of the liquid for more accurate calculations.

The pressure difference between the pump's inlet and outlet is the main factor that drives the liquid through the screw channel. Increasing the pressure difference enhances the flow velocity, which is particularly important for pumps handling high-viscosity liquids or large volumes. However, this also increases energy consumption and can affect equipment durability, as higher pressure imposes additional loads on the pump's mechanical components.

Liquid viscosity is one of the key characteristics that determine the liquid's flow ability. For high-viscosity liquids (such as thick pastes, slurries, or construction mixtures), higher pressure must be generated to ensure flow through the pump. Since the viscosity of such liquids changes depending on the flow velocity, this must be considered in calculations using dynamic viscosity. As flow velocity changes, viscosity can increase or decrease, which can affect the pump's efficiency.

Base viscosity is a property of the liquid that determines its ability to flow under low flow velocity conditions.

Base viscosity is a value used as a constant to assess changes in the liquid's properties depending on fluctuations in its flow velocity. Liquids with high base viscosity generally create much greater resistance during movement, which in turn leads to reduced pump efficiency, especially at high flow velocities. This effect is crucial for understanding liquid dynamics under various operating conditions, as an increase in viscosity can lead to a significant rise in energy consumption and a decrease in system productivity.

The channel length is also an important factor in flow calculations. Increasing the channel length typically leads to a decrease in flow, as the liquid encounters more 'resistance' along its path. This can be particularly important when designing pumps with long channels, as reducing the channel length can improve pump efficiency.

The rheological properties of the liquid determine how it behaves when flowing through a screw pump. For some liquids, such as water, oils, or gases, viscosity can be considered constant.

However, for rheological fluids, such as slurries, cement mixtures, or pastes, viscosity changes depending on the flow velocity.

For rheological fluids, the previously mentioned Bingham model or other models describing viscosity changes depending on flow velocity are often used. In such cases, flow calculations through a screw pump may require additional correction factors to accurately reflect the impact of viscosity changes on pump efficiency.

$$\tau = \tau_0 + \eta \cdot \gamma \, , \tag{3}$$

where τ - shear stress, Pa; τ_0 - yield point, Pa; η - plastic viscosity, Pa·s; γ - shear Speed, 1/s.

Bingham's model is based on two main characteristics: fluidity and viscosity. It describes fluids that require a certain minimum force to start moving. Such a fluid will not flow if the applied force is less than a certain threshold, which is called the "yield threshold". This makes it possible to describe the rheological behavior of substances, such as clay or dirty liquids, which behave like solids until a certain threshold of strength is reached, and after overcoming it, behave like liquids.

When studying this model, it is especially important to take into account the design of screw pumps used to transport thick liquids containing large amounts of solid particles or pasty substances. Because these fluids are not ideal and viscous, their behavior when moving through the pump requires a specific modeling approach. Considering the complexity of their movement, the model must describe not only the change in viscosity, but also the interaction of the liquid with solid particles, which affects the pumping efficiency. Therefore, in order to accurately predict the operation of pumps under such conditions, it is necessary to take into account many factors that can affect work processes, including changes in viscosity depending on the flow rate, particle characteristics and other physical properties of the fluid.

Reducing pitch increases the number of turns per unit length of the screw, resulting in slower but more stable fluid movement. This is especially important when transporting thick and viscous materials, as the small step allows for a more uniform and consistent flow, reducing the risk of clogging the pump. Such a screw copes better with liquids containing solid particles or having high viscosity (Fig. 1).

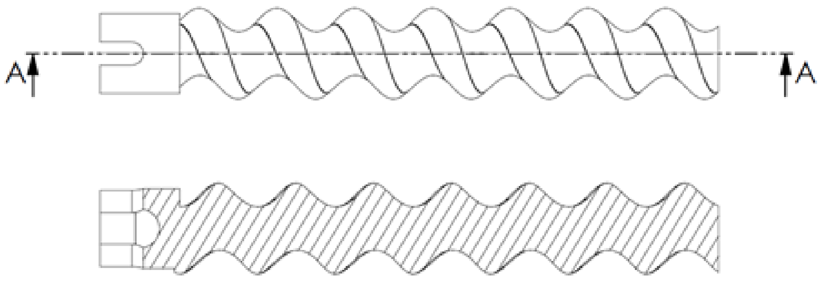

Figure 1. Screw with changed geometric dimensions and ridge pitch

Screw pumps work by creating mechanical energy that causes fluids to move, and Bingham's model allows you to accurately predict how much energy is needed to move such fluids through the system.

In addition, the yield threshold is important in determining under what conditions the fluid will begin to flow. This can be useful for determining the energy costs of pumping and optimizing pump designs for handling different types of liquids.

Considering the yield threshold, we can say that it can be used to describe the minimum force or stress that must be applied for the fluid to start flowing. If the force acting on the fluid is less than the yield threshold, the fluid behaves like a solid. This can be important for processes where it is necessary for the fluid to remain stable or stationary until a certain load is applied.

Plastic viscosity as an indicator determines the resistance of a fluid to deformation after it has begun to flow. High ductile viscosity indicates that the fluid strongly resists flow, even after the yield threshold has been overcome. For fluids with low viscosity, on the other hand, the movement will be easier and they are able to flow with less applied force.

Shear velocity tells us how quickly a fluid is deformed by the applied force. It is defined as the ratio of the change in velocity to distance. It is important for determining how fast a fluid will move through a pump or pipe under certain loading conditions.

When studying the flow through the helical channel, you can use a modified version of the Darcy-Weisbach equation, which takes into account the rheological properties of the fluid:

$$Q = \frac{2\pi \cdot R^3 \cdot \Delta p}{L}\left(\frac{1}{\mu + \mu_0}\right) \quad (4)$$

The Darcy-Weisbach equation has a number of assumptions and limitations. One of the main assumptions is that fluid flow occurs under conditions of a linear relationship between flow rate and pressure drop, which occurs only at low flow rates, when inertial effects can be ignored. For faster flows, where these effects become significant, more complex models such as the Navier-Stokes equation need to be used.

Another constraint is the assumption of the constancy of the porosity of the medium and the constant viscosity of the liquid. In real conditions, these parameters can change, which requires the use of more complex models.

In the general case, for a rheological model of a non-Newtonian fluid that does not have a yield threshold, the dependence of viscosity on the flow rate can be taken into account.

For a more accurate mathematical model of a screw pump that takes into account thermodynamic processes, it is necessary to consider factors such as heat loss, changes in pressure and temperature in the liquid, as well as the viscosity and change in state of the fluid as it moves.

The liquid pumped by the pump can be considered to be subject to changes in pressure and temperature when moving through the channel. As a result of the mechanical work performed by the pump, the temperature of the liquid may rise due to friction between the fluid and the walls of the channel.

Given the thermodynamic process, changes in temperature can be described by the equation:

$$Q = \Delta T \cdot C_p \cdot m, \quad (5)$$

where Q — the amount of heat absorbed or released by the liquid; ΔT — fluid temperature change; C_p — specific heat capacity of a liquid at constant pressure; m — mass of the pumped liquid.

Thermal processes can also affect the viscosity of the liquid. As the temperature increases, the viscosity of the fluid may decrease, which in turn will affect the flow rate and efficiency of the pump.

To describe the dependence of viscosity on temperature, the Arrhenius equation is used:

$$\mu(T) = \mu_0 \cdot e^{\frac{E_a}{RT}}, \quad (6)$$

where μ(T) — viscosity of a liquid at temperature; μ_0 — fluid viscosity at standard temperature; E_a — activation energy; R — universal gas constant; T — liquid temperature.

The general mathematical model of a screw pump, which takes into account thermodynamic and rheological factors, describes the process of pumping a liquid through a pump, taking into account its rheological properties, temperature changes and pressure drop. The model integrates equations for fluid flow, flow rate, and heat and energy losses.

The basis of the model is an equation that determines the flow rate of the fluid through the pump, taking into account the cross-sectional area and flow rate, which depends on the pressure drop and the fluid's flow threshold.

The viscosity of the fluid changes with the temperature, which is described by the Arrhenius equation, which makes it possible to adjust the flow depending on the operating conditions of the pump.

The rheological properties of the fluid are described through the Bingham model, which takes into account the yield threshold and plastic viscosity, which is important for more accurate flow modeling in fluids such as mortars.

In addition, the model takes into account energy losses and power consumed by the pump, which allows optimizing its efficiency and ensuring stable operation under conditions of variable temperatures and fluid composition.

This model is the basis for more accurate calculations and design of screw pumps for pumping various types of liquids, including viscoplastic materials widely used in construction. The general mathematical model in this case for screw pumps will be as follows:

$$Q = A \cdot \frac{\Delta P - \tau_0}{\mu_0 \cdot e^{\frac{E_a}{RT}}}, \quad (7)$$

where Q — fluid flow rate, m³/s; A — cross-sectional area of the pump channel, m²; ΔP — differential pressure, Pa; τ_0 — yield point, Pa; μ_0 — viscosity at standard temperature, Pa·s; E_a — activation energy, J/mol; R — universal gas constant, 8.314 J/mol K; T — liquid temperature, K.

Thus, the resulting model of the screw pump is a universal tool for predicting the efficiency of its operation under various fluid parameters, such as temperature, viscosity, yield threshold and pressure drop. This allows engineers to optimize the pump design and ensure stable and efficient pump operation under various conditions of pumping mortars and other viscoplastic materials.

The mathematical model can be applied to calculate pump parameters in various industries, including construction, chemical and oil industries, where it is important to take into account the rheological and thermodynamic properties of liquids.

6. Conclusion. In the course of the analysis of mathematical models of screw pumps and the development of a complete mathematical model that takes into account the thermodynamic and rheological properties of the liquid, important results were achieved to improve the theoretical foundations of the calculation and design of such pumping units. This allows you to more accurately predict the efficiency of screw pumps when pumping viscoplastic fluids, such as mortars or cement mixtures. Due to the inclusion of various factors such as viscosity, temperature, yield threshold, pressure drop and thermodynamic changes, the model allows for a more detailed assessment of the performance of pumps under real operating conditions.

The mathematical models of screw pumps considered in the work, including classical models and models that take into account the rheological properties of liquids, make it possible to understand the basic principles of calculating pumping units. Classical mathematical models based on the basic laws of fluid mechanics make it possible to determine the flow rate of fluid through the pump at a given pressure drop, but these models do not always take into account the influence of the rheological properties of liquids, which is important for the accuracy of calculations in cases where the fluid has nonlinear characteristics, as is the case with viscoplastic materials.

In research, particularly in the construction industry, various rheological models are often used to describe viscoplastic fluids, among which the Bingham model stands out. This model allows you to take into account the fluidity threshold, which is a critical parameter in pump calculations, since it determines at what value of the shear stress the fluid begins to move. However, standard models that do not take into account rheological properties have significant limitations, since they are not able to accurately model the behavior of fluids with nonlinear viscosity or viscoplasticity. As a result of the study, a new model was developed that allows taking into account both classical mechanical parameters (pressure drop, flow rate, cross-sectional area of the channel) and rheological properties of the fluid, which determine its viscosity and yield threshold.

The inclusion of rheological parameters such as yield threshold and temperature in this model greatly improves the accuracy of calculations, especially for viscoplastic fluids. The viscosity of the liquid in the model is described in terms of the Arrhenius equation, which takes into account changes in viscosity with changes in temperature. This is critical to providing more accurate forecasts of pump performance under variable temperature conditions, which is typical for many industrial processes where the temperature can vary depending on the environment or pumping conditions.

In addition, thermodynamic factors such as heat loss and power consumption by the pump are also introduced into the model.

One of the key aspects that greatly improves the accuracy of the model is taking into account the rheological properties of the fluid, such as the yield threshold and temperature. The rheological properties of liquids directly affect the shear rate and flow of fluid through the pump. Viscoplastic fluids require higher shear stress values to start moving, and this is taken into account by our model because of the yield threshold parameter. In addition, a change in temperature can significantly change the viscosity of the liquid, which is also taken into account in the model due to the temperature dependence of viscosity.

The developed model is a universal tool for the analysis and design of screw pumps, in particular for pumping viscoplastic fluids such as mortars. The model allows you to accurately assess how changes in fluid rheological properties, temperature, and pressure affect pump efficiency, allowing designers and engineers to optimize pump parameters for specific operating conditions. This is especially important in industries such as construction, chemicals, and oil production, where a wide range of variable parameters must be taken into account to achieve maximum efficiency.

References:

1. Baladynskyi, V. L., Livynskyi, O. M., Khmara, L. A., et al. (2001). Budivelna tekhnika: Pidruchnyk (Construction machinery: Textbook). Kyiv: Lybid.
2. Baladynskyi, V. L., Nazarenko, I. I., & Onyshchenko, O. H. (2002). Budivelna tekhnika: Pidruchnyk (Construction machinery: Textbook). Kyiv–Poltava: KNUCA – PoltNTU.
3. Onyshchenko, O. H., Drachenko, B. F., & Holovkin, O. V. (1998). Mekhanizatsiya ozdobliuvalnykh robit u budivnytstvi (Mechanization of finishing works in construction). Kyiv: Urozhai.
4. Holovkin, O. V., Nadobko, V. B., & Ust'yantsev, V. U. (1996). Universalna rozchynnoshchepetilna ustanovka (Universal mortar mixing unit). In Prohresyvni tekhnolohii ta mashyny vyrobnytstva budivelnykh materialiv, vyrobiv i konstruktsii: Vseukrainska konferentsiia: Tezy dopovidei (Progressive technologies and machines for the production of building materials, products, and structures: All-Ukrainian conference: Abstracts) (pp. 98–100). Poltava.
5. Kucherenko, L. V., Rabocha, T. V., & Strilets, Ya. O. (2013). Suchasni pidkhody do pidvyshchennia efektyvnosti nanesennia tonkosharovykh shtukaturnykh pokryttiv (Modern approaches to improving the efficiency of thin-layer plaster coating application). Naukovotekhnichnyi zbirnyk "Suchasni tekhnolohii, materialy i konstruktsii v budivnytstvi", 1(14), 47–50.
6. Korobko, B. O., Virchenko, V. V., & Shapoval, M. V. (2018). Feed solution in the pipeline with the compensators mortar pump of various design solutions pressure pulsations degree determination. International Journal of Engineering & Technology, 7(3.2), 195–202.
7. Ruhrberg, K., & Woishnis, W. (Eds.). (2016). Chemical resistance of engineering thermoplastics. Elsevier Inc., William Andrew.
8. Yan, D., Tang, Q., Kovacevic, A., et al. (2018). Rotor profile design and numerical analysis of 2-3 type multiphase twin-screw pumps. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 232(2), 186–202. https://doi.org/10.1177/0954408916667204.

9. Li, Z., Zhang, R., Gao, Y., et al. (2008). Profile analysis and simulation of twin-screw pump. China Petroleum Machinery, 36(3), 41–44. (In Chinese)
10. Ohbayashi, T., Sawada, T., Hamaguchi, M., & Miyamura, H. (2001). Study on the performance prediction of screw vacuum pump. Applied Surface Science, 169-170, 768–771. https://doi.org/10.1016/s0169-4332(00)00788-1.
11. Hu, B., Cao, F., Yang, X., Wang, X., & Xing, Z. (2014). Theoretical and experimental study on conveying behavior of a twin-screw multiphase pump. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 230(4), 304–315. https://doi.org/10.1177/0954408914549789.
12. Pfaller, D., Brümmer, A., & Kauder, K. (2011). Optimized rotor pitch distributions for screw spindle vacuum pumps. Vacuum, 85(12), 1152–1155. https://doi.org/10.1016/j.vacuum.2011.03.002.
13. Ohbayashi, T., Sawada, T., Hamaguchi, M., et al. (2001). Study on the performance prediction of screw vacuum pump. Applied Surface Science, 169–170, 768–771. https://doi.org/10.1016/S0169-4332(00)00788-1.
14. Wang, J., Cui, F., Wei, S., et al. (2017). Study on a novel screw rotor with variable cross-section profiles for twin-screw vacuum pumps. Vacuum, 145, 299–307. https://doi.org/10.1016/j.vacuum.2017.09.006.