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STRUCTURAL ANALYSIS OF COMPRESSORS OF TRACTION AND MULTIPLE UNIT ROLLING STOCK

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The article is devoted to a comprehensive analysis of the designs of compressors of traction and railcar rolling stock to identify their design features, principles of operation and determine areas for further improvement. Its purpose is a study aimed at systematizing existing design solutions of compressor equipment of railway transport and substantiating promising ways of modernization of pneumatic systems of modern rolling stock. The authors applied a systematic approach to studying the principles of operation of piston, screw, vane and trochoidal compressors, and conducted an analysis of technical documentation and a comparative assessment of their operational characteristics. It has been established that piston compressors remain the dominant types of compressor equipment used in traction and railcar rolling stock in Ukraine. From the consideration and analysis of the design of existing piston compressors, several of their shortcomings were identified, the main of which are: large mass-dimensional indicators, high energy consumption, significant vibration levels. The novelty of the conducted research is noted, which is characterized by the systematization of the advantages and disadvantages of various types of rotary compressors in relation to their potential application in railway transport. The analysis of the advantages of rotary compressors made it possible to substantiate the feasibility of their implementation to eliminate the above-mentioned disadvantages of piston compressors. The originality is highlighted by a comprehensive approach to the analysis of the problems of existing pneumatic systems and the justification of the directions of their modernization, considering modern technological achievements in the field of compressor construction. The prospects for the use of rotary compressors are noted and the need for further research in the direction of their adaptation to specific operating conditions in railway transport is identified. It is noted that the results of the study have significant practical value for railway transport specialists, as they create a theoretical basis for making informed decisions regarding the modernization of compressor equipment.

Keywords: *transportation, mechanics, railway transport, transport technologies, rolling stock, repair, operation, reliability, compressors.*

Statement of the problem

The current stage of development of railway transport in Ukraine requires constant improvement of its technical base. Its main components include traction (TRS) and multi-rail (MRRS) rolling stock, the key elements of which are compressors. It should be noted that their reliable and efficient operation directly affects the safety and productivity of railway transportation, and the wear of the existing compressor equipment fleet creates an urgent need for its modernization or replacement. At the same time, conducting a constructive analysis of compressors will allow identifying weaknesses in existing designs, and the results of research will become the basis for the development of more reliable and durable compressors (energy-efficient, low-noise, smaller in size and weight, high-quality, environmentally friendly, easy to maintain and repair). Therefore, the constructive analysis of compressors for traction and multi-rail rolling stock is an urgent and timely task, and its successful implementation will contribute to increasing the competitiveness of Ukrainian railways at the national and international levels.

Analysis of the latest achievements on the identified problem

In the work [1] factors affecting the traction energy consumption of electric trains were analyzed using data mining methods. A large dataset from real operations was collected. Key parameters influencing energy consumption – route, track profile, stop frequency – were identified. A prediction model for energy use was proposed. The results can be applied to optimize train schedules.

In the article [2] an integrated energy-efficient train operation approach based on the space-time speed network was presented. The model accounts for safety constraints, schedule adherence, and traction dynamics. Numerical experiments were conducted to validate the algorithm. The proposed approach enables energy savings of up to 12%. The methodology is recommended for integration into train control systems.

In the article [3] he technological development and trends of high-speed EMUs were investigated. The authors provided a historical overview of innovations in the field. Special attention was paid to aerodynamics, control systems, and safety. Key trends up to 2030 were forecasted. The importance of interdisciplinary engineering in EMU design was emphasized.

In the study [4] the optimization of the load-bearing structure of a hopper car for transporting hot agglomerate was substantiated. The finite element method was used to analyze the stress-strain state. A comparative analysis of conventional and modified designs was conducted. A reduction in structure weight without loss of strength was achieved. The results can be applied in serial production.

In the article [5] parameters of onboard capacitive energy storage systems for underground rolling stock were investigated. A theoretical model and experimental validation were proposed. Optimal characteristics for improving energy efficiency were determined. The analysis considered subway operation conditions. The results aim to reduce energy consumption and increase autonomy.

In the work [6] the dynamic loading on a semi-wagon fixed to a ferry deck using viscous coupling was analyzed. Modeling of the securing process and wave effects was performed. Critical stress modes were identified. Recommendations for improving securing safety were provided. The findings are important for maritime railway transportation.

In the article [7] a structural analysis of a freight wagon with composite walls was carried out. The stress-strain behavior under different loads was modeled. The authors demonstrated the feasibility of replacing steel parts with composites. Weight reduction was achieved without compromising strength. The use of composites is recommended for next-generation lightweight wagons.

In the study [8] the impact resistance of fiber-reinforced composite railway freight tanks was assessed. A series of impact experiments on composite materials was performed. Damage types under different impact speeds were analyzed. High energy absorption capacity of composites was confirmed. Such solutions are proposed for wagons carrying hazardous materials.

In the article [9] rational parameters for a capacitive energy storage system for underground transport were determined. A mathematical model for charge/discharge behavior was proposed. The influence of battery characteristics on system performance was analyzed. Simulation results were presented. The system is recommended for capturing braking energy.

In the work [10] vibratory stress and crack growth in a compressor blade under HCF loading were analyzed. Numerical analysis considered real operating conditions. Stress concentration zones and crack growth paths were identified. The results support fatigue life assessment. The study aims to improve the reliability of aerospace compressors.

In the article [11] performance analysis of a high-speed rotary compressor was conducted through experiments and mathematical modeling. A real-time measurement method was described. A model for efficiency and heat loss prediction was developed. The influence of rotation speed on performance was shown. The results are useful for optimizing industrial compressors.

In the study [12] durability of an open freight wagon body made of round pipes during ferry transportation was evaluated. A stress-based and fatigue analysis approach was used. Comparisons with traditional designs were made. Advantages of the tubular frame under vibration were shown. The study supports the design of ferry-resistant wagons.

In the work [13] a combination of operational modal analysis algorithms was used to identify modal parameters of a real centrifugal compressor. Multiple experimental methods were applied for model validation. Accurate values of natural frequencies and mode shapes were obtained. The combined approach improves resonance detection accuracy. The findings are valuable for rotating machinery diagnostics.

Purpose and task statement

The conducted analysis of literature sources revealed a noticeable shortage of in-depth studies devoted to the structural analysis of compressors of traction and multiple unit rolling stock. Existing works often consider issues of operation and maintenance, but do not delve sufficiently into the features of their internal structure and principles of operation. This creates a gap in understanding potential ways to optimize and improve these units. The lack of systematic structural analysis complicates the development of new, more efficient and reliable compressor units for railway transport. Thus, there is an urgent need to conduct targeted studies that will cover all aspects of the design of compressors of traction and multiple unit rolling stock, and their in-depth analysis will allow to identify reserves for increasing their productivity, reducing energy consumption and extending their service life.

Summary of the main material

Currently, the basis of air supply systems of modern TRS and MRRS in difficult operating conditions (significant vibrations and significant fluctuations in ambient temperature) are mainly piston compressors. The design features of these devices cause large mass-dimensional indicators and high energy consumption of the drive, while different operating conditions of compressors on diesel and electric locomotives lead to differences in their design. Thus, the design of the КТ6ЭЛ compressor does not have

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unloading devices in the suction valves of all three cylinders, which are necessary for switching the КТ6 and КТ7 compressors to idling. This is since the КТ6ЭЛ compressor does not switch to idling but stops.

Fig. 1 shows the design of the valve box of the first stage cylinder of the КТ6ЭЛ compressor. The valve box of the second stage cylinder has a similar structure. In an electric locomotive compressor, there is no need for a damper tank to eliminate fluctuations in the pressure gauge needle. This is since during 40…60 seconds of compressor operation (the approximate duration of one switching cycle), cold oil does not have time to fill the tank through the calibrated hole. With a longer switching duration, the low frequency of rotation of the crankshaft of the electric locomotive compressor and the oil pump shaft (440 rpm) do not give a noticeable pulsation of the oil pressure gauge needle, and the level of compressor vibration at such a shaft rotation frequency is insignificant.

To prevent the lubricant from freezing during winter operation, a tubular electric heater with a capacity of 200…260 W, operating at a voltage of 50 V, is placed in the crankcase of the electric locomotive compressor. Compressors КТ6 and КТ7 are not equipped with such a heater, since the required temperature in the engine compartment is provided by heat from the running diesel engine.

The КТ7 compressor is characterized by a left-hand direction of rotation of the crankshaft (when viewed from the drive mechanism side) in contrast to the right-hand rotation of the КТ6 compressor. This feature required modification of the fan design to maintain the specified direction of cooling air movement: from the fan units to the cylinder and further to the refrigeration unit.

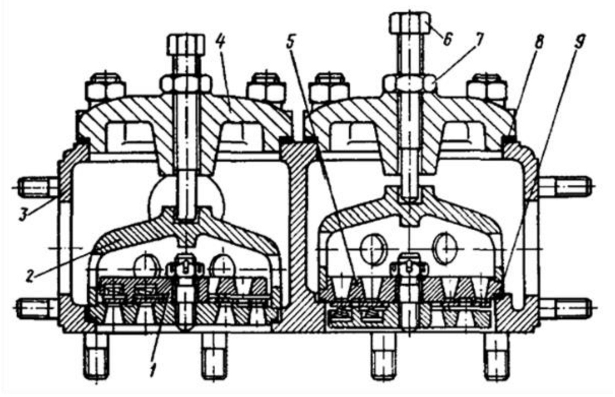

Fig. 1 – Valve box of the first stage cylinder of the КТ6ЭЛ compressor: 1 – discharge valve; 2 – valve stop; 3 – case; 4 – cover; 5 – intake valve; 6 – clincher; 7 – locknut; 8 – paronite gasket; 9 – copper gasket

The principle of operation of these compressors is considered using the example of the КТ6 compressor (Fig. 2).

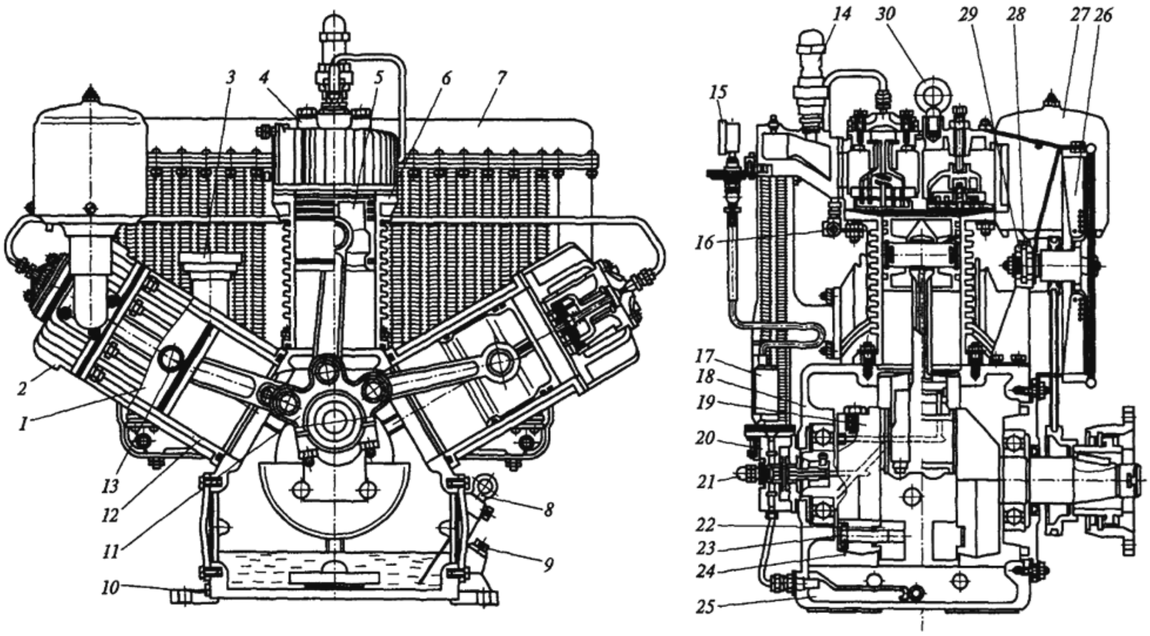

Fig. 2 – Compressor КТ6: 1 – low pressure cylinder (LPC) piston; 2 – valve box LPC (first degree); 3 – breathalyzer; 4 – high pressure cylinder (HPC) valve box (second degree); 5 – piston HPC; 6 – HPC; 7 – refrigerator; 8 – oil dipstick (probe); 9 – oil filler plug; 10 – oil drain plug; 11 – connecting rod assembly; 12 – LPC; 13 – piston pin; 14 – safety valve; 15 – oil pressure gauge; 16 – tee for connecting the pipeline from the pressure regulator; 17 – tank for dampening pulsations of the pressure gauge needles; 18 – housing (crankcase); 19 – crankshaft; 20 – oil pump; 21 – pressure reducing valve; 22 – additional balancer; 23 – additional balancer mounting screw; 24 – cotter pin; 25 – oil filter; 26 – fan; 27 – air filter that sucks; 28 – fan belt tension adjustment bolt; 29 – fan bracket; 30 – eye bolt

Structurally, it consists of a housing 18, two low-pressure cylinders 12 (LPC), which have a camber angle of 120 degrees, one high-pressure cylinder 6 (HPC), a radiator-type cooler 7 with a safety valve 14, a connecting rod assembly 11 and pistons 1 and 5 of the LPC and HPC, respectively. When the piston of the first stage 2 moves to the bottom dead center (BDC), the air is rarefied in the working cavity of the cylinder between the piston bottom and the valve box, which is sucked into this cavity from the atmosphere through the filter 27 and the intake valves.

During the movement of the piston to the top dead center (TDC), air is compressed, which through the discharge valve and side pipes enters the upper collector of the refrigerator 7. This collector has an internal partition dividing it into two sections (Fig. 3). From the first section, the air moves along the cooling tubes into the lower collector, and then rises along the second row of tubes to the second section of the upper collector, connected to the suction cavity of the second-stage valve box.

When the piston of the second stage 5 moves to bottom dead center, cooled air, previously compressed in the first stage cylinder, is sucked into the cylinder through the intake valves.

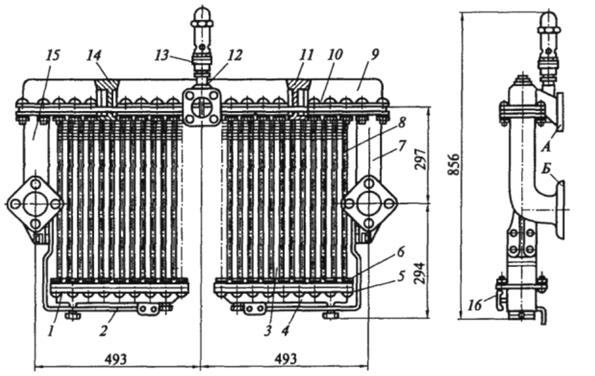

Fig. 3 – Radiator type compressor refrigerator КТ6, КТ7, КТ6Эл: 1,3 – radiator sections; 2,5 – connecting strips; 4 – bone bolt; 6,10,12 – flanges; 7,15 – branch pipes; 8 – copper tubes; 9 – upper collector; 11,14 – partitions; 13 – safety valve; 16 – drain cock; А,Б – flanges

When the piston of the second stage moves to TDC, additional compression of the air is carried out to a pressure slightly exceeding the pressure in the discharge line. When this pressure is reached, the discharge valve is activated, and the piston continues to supply compressed air to the storage tank. In parallel, different phases occur in the cylinders of the first stage: one sucks in atmospheric air, and the other performs initial compression with subsequent air direction to the cooler. The cylinder of the second stage provides the final air injection into the tank.

In the operating conditions of rolling stock, the KT6 compressor operates as follows: as soon as the air pressure in the tank reaches 0.85 MPa, the ЗРД pressure regulator (Fig. 4) opens the access of air from the tank to the cavity above the rubber diaphragm 5 (Fig. 5) of the unloading device of the valve boxes of the I and II stages. At the same time, the piston 3 will move to the BDC. At the same time, after the compression of the spring 7, the stop 6 will also drop down, which will press the small and large valve plates from the inlet valve seat with its fingers and the compressor will switch to idle operation. At the same time, the air in the refrigerator will be sucked in and compressed in the II stage cylinder, and in the I stage cylinder, air will be sucked in from the atmosphere and pushed back through the air filter. This process will be repeated until the minimum permissible pressure of 0.75 MPa is established in the tank, to which the regulator is adjusted. Then the pressure regulator will operate and connect the cavity above the rubber diaphragm 5 with the atmosphere, the spring 7 will lift the stop 6 up and after the valve plates are pressed against the seat, the compressor will switch to the working stroke.

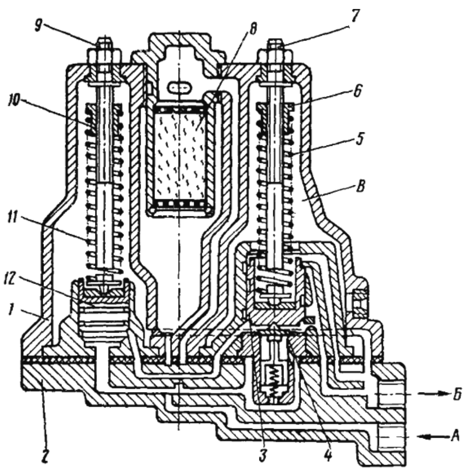

Fig. 4 – Pressure regulator ЗРД: 1 – case; 2 – cover; 3 – valve that includes; 4 – check valve; 5 – valve spring, including; 6,10 – nut; 7 – valve spring screw 3; 8 – filter; 9 – shut-off valve spring screw; 11 – shut-off valve spring; 12 – shut-off valve; А – air from main tanks; Б – to compressor unloading devices; В – valve cavity

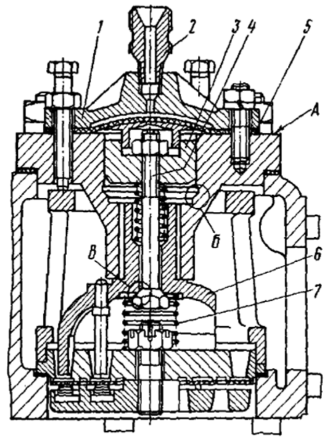

Fig. 5 – Unloading device for valve boxes of compressors KT6 and KT6: 1 – cover; 2 – fitting; 3 – piston; 4 – tie bolt; 5 – diaphragm; 6 – emphasis; 7 – spring

It is worth noting that modern traction and railcar rolling stock mainly uses piston compressors without compressed air-cooling systems. The cooling process takes place directly in the main tank, where condensation and sedimentation of the water-lubricant mixture occurs, which is periodically removed by drivers in manual mode. Insufficient purification of compressed air from moisture leads to undesirable phenomena in pneumatic systems: corrosion processes in air ducts and their icing during frosts. Such problems can cause serious failures of brake systems and pose a threat to the safe operation of railway transport.

In the context of the modernization of compressor equipment, a promising direction is the introduction of oil-free piston compressors. For example, in the industrial sector, such compressors have already been in operation for a long time. It is worth emphasizing that innovative oil-free compressors were created specifically for the railway industry by Knorr-Bremse.

As previously noted, piston compressors of modern traction and multi-rail rolling stock of Ukrzaliznytsia, with sufficient productivity and satisfactory operational reliability, are characterized by rather large mass-dimensional indicators and high levels of vibrations, which have a negative impact on people, as well as the reliability and durability of both the compressors themselves and the supporting elements of the rolling stock. Therefore, a rational direction for ensuring the required operational characteristics of air supply systems of modern rolling stock is to eliminate the indicated disadvantages of piston compressors by using rotary compressors (screw, single-rotor vane, trochoidal, etc.). The main advantages of rotary compressors include reduced vibration levels compared to piston compressors, reduced power consumption and mass-dimensional indicators.

For example, in screw compressors (Fig. 6), air compression is performed by a pair of interacting rotors with a certain number of spiral ribs.

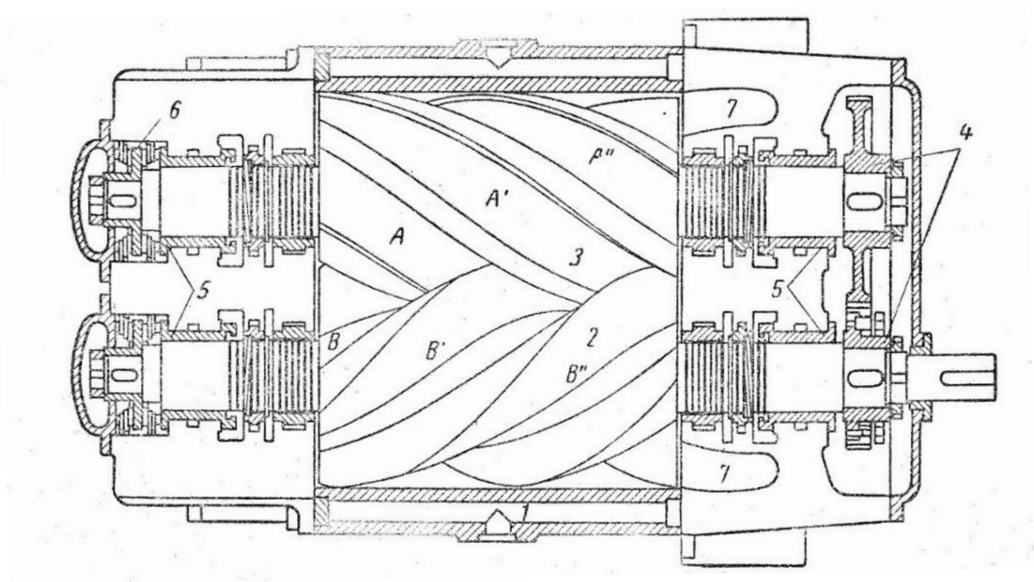

Fig. 6 – Twin-rotor screw compressor: 1 – case; 2 – driving rotor; 3 – driven rotor; 4 – gears; 5 – support bearings; 6 – thrust bearings; 7 – discharge window

The functional basis is to force the velocity of the compressed air medium in the inter-rotor cavity with its direction to the contact area of the screw ribs, where the minimum working chamber is formed. The outlet of the compressor unit is installed in this area. Prevention of leakage of compressed air during the compression process is realized through the maximum narrowing of the intervals between the planes of the ribs and the internal contours of the housing structure. The rotors are operated in the mode of mutual isolation and separation from the housing, which virtually eliminates mechanical wear of dynamic parts. The synchronization of rotational motion is provided by gears mounted on the rotor axes. In France, Germany, Switzerland, Belgium, Austria, and Italy, for example, screw compressors are considered the most promising for railway rolling stock. An example of such a compressor is the SL20-5 screw compressor from Knorr Bremse. It has a capacity of 0.7...2 m3/min at an air pressure of 10 bar and a rotor speed of 1000...3500 rpm. The disadvantages of screw compressors (in relation to the conditions of operation on rolling stock) are the need to ensure high rotor speed, high noise level due to pressure fluctuations during suction and discharge, significant complexity of manufacturing and repair technology, compressed air losses through leaks, and in compressors filled with oil, there are significant impurities in the compressed air.

As for the single-rotor vane compressor, a feature of its design (Fig. 7) is that a cylindrical rotor is eccentrically mounted in its fixed cylindrical housing, in the radial grooves of which blades with the possibility of sliding are installed. These blades divide the working volume into separate sealed chambers, and the injection occurs due to the change in their volumes. The advantages of these compressors include simplicity and reliability of the design (due to the absence of a valve assembly), uniformity of supply. Along with this, their main disadvantage is the sliding friction between the plates and the housing, which determines the release of a large amount of heat and intensive wear of the contacting surfaces, low efficiency, the cause of which is insufficient tightness of the working volumes.

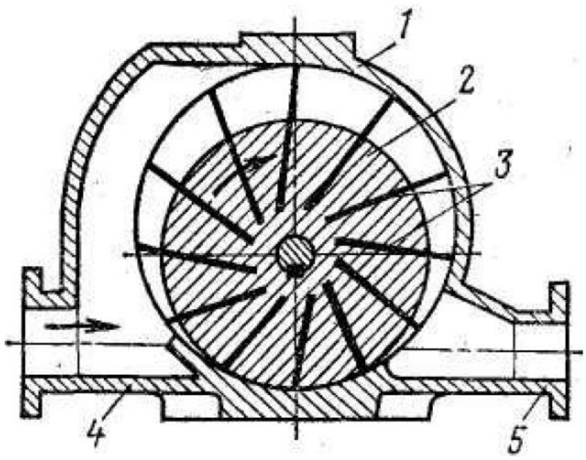

Fig. 7 – Structural scheme of the vane compressor: 1 – case; 2 – rotor; 3 – plates; 4 – suction pipe; 5 – discharge pipe

Trochoidal compressors (Fig. 8) have a fixed housing, inside which is located a rotor, which with its vertices is in contact with the inner trochoidal surface of the housing.

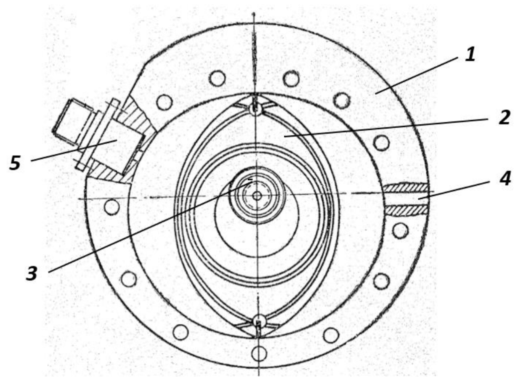

Fig. 8 – Schematic diagram of the trochoidal compressor: 1 – case; 2 – rotor; 3 – crankshaft; 4 – suction channel; 5 – discharge valve

The rotor performs a plane-parallel movement around the crankshaft and thus changes the volumes between the rotor and the housing, due to which the injection occurs. The main disadvantage of such compressors is the significant complexity of manufacturing the trochoidal surface, as well as high requirements for its wear resistance due to the too high speeds of relative movements of the sealing elements of the rotor relative to the surfaces of the housing. Due to the high accuracy and hardness of the trochoidal surface, the design is not repairable. In addition, to eliminate vibration, it is necessary to additionally install balancers or manufacture the compressor with several sections. The experience of manufacturing trochoidal compressors is associated with significant material and technological difficulties and has not yet been widely implemented.

Conclusions

The analysis conducted in the article revealed a significant variety of design solutions for compressors used on TRS and MRRS, due to the specifics of their application and requirements for performance and reliability. It was established that piston compressors remain the dominant type in many series of rolling stock due to their relative simplicity, maintainability and ability to provide high pressure. A trend towards the growth of the use of rotary compressors was identified, which, with structural balance, small weight and dimensions and lower power consumption for their drive, will provide the corresponding systems of traction and multi-rail rolling stock with compressed air with the necessary performance and pressure indicators. It should be noted that the results of the study have significant practical value for railway transport specialists, as they create a theoretical basis for making informed decisions on the modernization of compressor equipment.

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КОНСТРУКТИВНИЙ АНАЛІЗ КОМПРЕСОРІВ ТЯГОВОГО ТА МОТОРВАГОННОГО РУХОМОГО СКЛАДУ

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Стаття присвячена проведенню комплексного аналізу конструкцій компресорів тягового та моторвагонного рухомого складу для виявлення їх конструктивних особливостей, принципів функціонування та визначення напрямків подальшого вдосконалення. Її метою є дослідження, спрямоване на систематизацію існуючих конструктивних рішень компресорного обладнання залізничного транспорту та обґрунтування перспективних шляхів модернізації пневматичних систем сучасного рухомого складу. Авторами використано системний підхід до вивчення принципів роботи поршневих, гвинтових, лопатевих та трохоїдних компресорів, а також проведено аналіз технічної документації та порівняльну оцінку їх експлуатаційних характеристик. Встановлено, що поршневі компресори залишаються домінуючими типами компресорного обладнання, яке використовується на тяговому та моторвагонному рухомому складі України. З розгляду та аналізу конструкції існуючих поршневих компресорів було виявлено ряд їх недоліків, основними з яких є: великі масогабаритні показники, високе енергоспоживання, значні рівні вібрацій. Відзначено новизну проведеного дослідження, яка характеризується систематизацією переваг і недоліків різних типів роторних компресорів щодо їх потенційного застосування на залізничному транспорті. Проведений аналіз переваг роторних компресорів дозволив обґрунтувати доцільність їх впровадження для усунення вищенаведених недоліків поршневих компресорів. Оригінальним виділено комплексний підхід до

аналізу проблем існуючих пневматичних систем та обґрунтування напрямків їх модернізації з урахуванням сучасних технологічних досягнень у галузі компресоробудування. Зазначено перспективність застосування роторних компресорів та визначено необхідність подальших досліджень у напрямку їх адаптації до специфічних умов експлуатації на залізничному транспорті. Відмічено, що результати дослідження мають значну практичну цінність для фахівців залізничного транспорту, оскільки створюють теоретичну основу для прийняття обґрунтованих рішень щодо модернізації компресорного обладнання.
Ключові слова: *перевезення, механіка, залізничний транспорт, транспортні технології, рухомий склад, ремонт, експлуатація, надійність, компресори.*

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