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SCROLL COMPRESSOR. ANALYSIS OF CALCULATION METHODS

The paper deals with some aspects of mathematical modeling of a scroll compressor. Various approaches to modeling the working processes of machines of the volumetric compression principle, their applied value and priority of use are presented. An analytical review of the methods for calculating the leakage of a compressed medium, applied to a scroll compressor, taking into account the classification of slots, is carried out. Conclusions are made about the need to clarify the assumptions and improve this technique by taking into account the fact of the mobility of the walls of the gap, depending on the share of the influence of various factors on the leakage of the compressed medium. And also about the influence of this fact on the accuracy of calculations and the optimal choice of the operating mode of the compressor. Examples are given in which taking this condition into account in the transformed systems of equations will improve the accuracy in applied calculations of the working processes of spiral machines, when designing new samples.

Key words: Scroll compressor, calculation method, mathematical modeling, mass flow rate of the working substance, regrinding of the compressed medium.

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Спираль компрессор. Есептеу әдістемесін талдау

Бүгінгі таңда экологиялық проблемаларға байланысты тоңазытқыш жабдықтары нарығындағы тез болып жатқан өзгерістер жағдайында жабдықтың жаңа түрлерін бейімдеу немесе құру мәселесі туындайды. Тоңазытқыш өнеркәсібінің көптеген салаларында сұранысқа ие тоңазытқыш компрессоры температура мен қысымның кең диапазонында жаңа салқындатқыштарды қолдануға мүмкіндік беретін сапалық өзгерістерді қажет етеді. Бұл жұмыста спираль компрессорды математикалық модельдеудің кейбір көріністері қарастырылған. Көлемдік сығу принципі машиналарының жұмыс процестерін модельдеудің әр түрлі тәсілдері, олардың қолданбалы маңызы мен пайдалану басымдылықтары келтірілген. Саңылаулардың жіктелуін ескере отырып спираль компрессорға қатысты сығылатын ортаның ағып кетуін есептеу әдістемесіне аналитикалық шолу жүргізілген. Сығылатын ортаның ағып кетуіне әр түрлі факторлардың әсер етуіне байланысты саңылау қабырғаларының қозғалу жағдайын ескерудің есебінен рұқсат етілген жағдайлар мен осы әдістемені жетілдіру қажеттілігі туралы тұжырымдар жасалды. Сондай-ақ осы жағдайдың есептеу дәлдігі мен компрессордың жұмыс режимін оңтайлы таңдауға әсері туралы тұжырым жасалды. Түрлендірілген теңдеулер жүйесінде осы шартты ескеру жаңа үлгілерді жобалау кезінде спираль машиналардың жұмыс процестерін қолданбалы өлшеу дәлдігін жоғарылатуға мүмкіндік беретін мысалдар келтірілген.

Түйін сөздер: спираль компрессор, есептеу әдістемесі, математикалық модельдеу, жұмыс затының массалық шығыны, сығылатын ортаның ағып кетуі.

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Спиральный компрессор. Анализ методик расчёта

Сегодня, в условиях стремительных изменений на рынке холодильного оборудования, связанных с экологическими проблемами, возникает проблема адаптации или создания новых типов оборудования. Спиральный холодильный компрессор, который так востребован во многих областях холодильной промышленности, также требует качественных изменений, позволяющих использовать новые хладагенты в широком диапазоне температур и давлений. В работе рассмотрены некоторые аспекты математического моделирования спирального компрессора. Представлены различные подходы к моделированию рабочих процессов машин объёмного принципа сжатия, их прикладное значение и приоритет использования. Проведён аналитический обзор методик расчёта протечек компримируемой среды, применительно к спиральному компрессору, с учётом классификации щелей. Сделаны выводы о необходимости уточнения допущений и совершенствования данной методики за счёт учёта факта подвижности стенок щели, в зависимости от доли влияния различных факторов на протечки компримируемой среды. А также о влиянии данного факта на точность расчётов и оптимальный выбор рабочего режима компрессора. Приведены примеры, в которых учёт данного условия в преобразованных системах уравнений позволит повысить точность в прикладных расчётах рабочих процессов спиральных машин, при проектировании новых образцов.

Ключевые слова: спиральный компрессор, методика расчёта, математическое моделирование, массовый расход рабочего вещества, протечки компримируемой среды.

Introduction

Today, in the stream of rapid changes in the refrigeration equipment market related to environmental issues, the problem of adaptation or creation of new types of equipment arises. The refrigeration scroll compressor, which is so in demand in many areas of the refrigeration industry, also requires qualitative changes that allow the use of new refrigerants in a wide range of temperatures and pressures. So, the determining factor in the choice of a refrigeration compressor for operation at various operating modes is the possibility of smooth regulation of performance with a change in the degree of pressure increase of the working fluid, while maintaining the maximum efficiency indicators [1-3].

For the design of such samples, the development of the most adequate compressor model is required. Why is the concept of approximation of description used in the practice of mathematical modeling, which is characterized by the assumptions and assumptions adopted in its preparation? The choice and consideration of the factors affecting the operation of the compressor requires a balanced approach and should be based on the task set by the researcher, since the limited application of the developed model will depend on this [4–6]. Solved problems of increasing the efficiency of compressors of the volumetric principle of operation, inevitably touch upon the issues of thermo- and gas dynamics of working processes [7, 8]. The scroll compressor belongs to the volumetric type of machines and has leaks of the working fluid due to the contactless coupling of the working bodies. Working fluid leaks are the dominant losses that have a significant impact on its characteristics. So, in a number of studies, attention is paid to the study of the feed rate, and the expressions obtained have an important applied nature [9]. However, statistics indicate a significant percentage of error in calculating the leakage of a compressible medium when using conventional techniques based on traditional approaches that allow the acceptance of the stationarity of the slot walls and do not take into account the loaded operating mode of the compressor. In this case, one has to ask about the possibility of full-scale use of classical models, or rather the calculation methods included in them, taking into account the accepted assumptions, for various operating modes of the compressor [10–12]. This fact undoubtedly requires an assessment of a sufficient degree of accuracy of calculations, and at the same time an analysis of the correspondence of the system of assumptions to the real processes of the scroll compressor operation. For this, special attention should be paid to the thermal and power factors in the loaded state of the compressor and the study of the influence of the mobility of the slot walls on the nature and dynamics of leaks, including these factors in the mathematical model. Having met this condition, we will be able to compare the accuracy of the calculations using various techniques, identifying the modes with the greatest discrepancy. Ultimately, expand the scope of the general model of scroll compressor workflows and improve its adequacy.

The methodology for calculating the working processes in the compressor should be built on the basis of an understanding of the real compression process, which can be described by a mathematical model, which is the basis for developing the methodology. In fact, the mathematical model reflects the sequential change in the states of the compressed medium and is, a set of relationships connecting the characteristics of the system states with the system parameters, initial information, initial and boundary conditions in the presence of restrictions imposed on the functioning of the system; moreover, this set forms a mathematical object that is in a certain correspondence with the real system and can replace this system, so that the study gives new information about the processes occurring in the real system, or about the entire real system as a whole [13]. When simulating the working processes of positive displacement compressors, such relationships are the basic equations of thermodynamics, converted into differential equations for changing the parameters of the working fluid in the process. The integrity of the mathematical model should be considered from the standpoint of the presence of its constituents, such as: parameters and characteristics of the state of the system; background information; initial and boundary conditions; equations that specify the set of relationships between the characteristics of the state of the system and the listed elements of the mathematical model; information obtained by means of a mathematical model, etc. [14–16].

Analysis of the methodology for calculating work processes, as a set of methods and techniques that give the final result, can be carried out, in addition to assessing the integrity of the mathematical model, also from the standpoint of assessing: simplicity and completeness of the description of the real process; the degree of closeness to the description of the real process; limited application and adequacy of the model. In positive displacement compressors in general and scroll compressors in particular, work processes are performed with a variable mass of the working fluid. This is due to the filling and emptying of the working cavities in the processes of suction and discharge, as well as to the overflow of the compressed substance between the working cavities through the gaps. There are various approaches to the mathematical description of work processes in scroll compressors. In practice, for calculating processes with variable mass, three types of differential equations can be distinguished that describe the change in pressure and temperature in the considered thermodynamic system.

The paper presents a mathematical model based on a complete energy balance, which determines the heat fluxes between the refrigerant being compressed and the compressor elements used [17]. The complete energy balance has been established, the control volume method is applied. The work [18] presents a method for calculating the working process of a refrigeration scroll compressor, based on the following equations:

$$\begin{cases} \dfrac{dm_{ref}}{dt} = \sum \dot{m}_{in} - \sum \dot{m}_{in} \\ q_{ref} + \sum h_{in} \cdot \dot{m}_{in} = \dfrac{d}{dt}\left(m_{ref} \cdot u_{ref}\right) + p\dfrac{dV}{dt} + \sum h_{out} \cdot \dot{m}_{out} \end{cases}, \tag{1}$$

The first of these equations is the mass balance equation in differential form, and the second is the energy conservation equation. The mass flow rate m is determined by passing the refrigerant through a diaphragm. To ensure efficient and reliable operation of the scroll compressor at high casing temperatures (relevant for SS compressors), it is necessary to provide certain openings during operation (i.e. after heating the machine) that cannot be predicted without a mathematical model of heat transfer from the main elements of the scroll compressor. In such cases, the mathematical model of the workflow is complemented by the mathematical model of heat transfer.

So, from the review of methods of thermodynamic analysis based on mathematical modeling of the working process of positive displacement compressors, it can be seen that the most promising, differentiated and adequate method for calculating a scroll compressor is the method of mathematical modeling of working processes, in the general case based on the equations of thermodynamics of a variable mass body and the equation of state for gas. Considering this conclusion, first of all, it should be understood that the integrity of the mathematical model of the working process of the scroll machine (in particular, the scroll compressor), in turn, will depend on the integrity of the mathematical model that sets the method for calculating the loss of the compressed medium.

Methods

Based on the nature of our study, we chose a comparative method for its conduct, which in this case has obvious validity. At the first stage of the study, topical issues are identified in the field of modeling a scroll compressor, as a special case of machines of the volumetric principle of action. And shows the fundamental components of the integrity of the mathematical model for this area of knowledge.

At the second stage, we identified the approaches to the mathematical description of work processes most used in foreign practice, studied the reasons for this choice and the composition of the systems of equations. Because of a generalized analysis, equations were identified based on the description of work processes with a variable mass of the working fluid [19–21].

Having revealed this fact, we proceeded to the third stage of our work, at which the approaches to determining the leakage of a compressible medium in the working area of compressors of the volumetric principle of action were studied in a similar way. At the same time, we paid attention to which of these methods are of a real practical nature, what is the difference in methods, what is the percentage of error in the calculations. Together with this, we considered the issue of the outflow of the working medium through the movable slot. Note the aspects of the operating mode of spiral machines, in which this fact acquires the ability and it should be taken into account in calculating the leakage of a compressible substance [22,23].

We classify the slots in the scroll compressor and provide analytical data on the quality and quantity of the working substance overflow during the compression process, i.e., at different orbital angles of the spiral position. At the last stage, we analyzed and generalized the revealed facts. We made conclusions and assumptions.

Results and discussions

To date, a lot of theoretical and experimental material has been accumulated to determine the flow rate of the working substance through the gaps of the working elements of rotary machines. At the same time, as already seen in relation to the scroll compressor, the greatest losses from gloves through the radial clearances, to a lesser extent through the tangential clearances, the clearances themselves change during the operation of the compressor from force and thermal deformations. Moreover, the deformation of the spiral from gas forces is incomparably less than the deformations caused by the heating of the spiral.

The total differential of the change in the mass of the compressed medium in the working cavity can be represented:

$$dm_i = dm_{i+1} - dm_{i-1}, \tag{2}$$

where dm_{i+1} – change in the mass of the compressible medium in the working cavity, associated with the overflow of the working fluid from the leading cavity; dm_{i-1} – change in the mass of the compressible medium in the working cavity, associated with the overflow of the working fluid from the considered cavity. The mass of the compressible substance flowing in or out of the working cavity through the slots between the working elements:

$$dm_i = \mu_i F_i W_i \rho_i d\tau, \tag{3}$$

where μ_i – the coefficient of the flow rate of the working fluid through the slot; F_i is the area of the passage section of the slot; W_i is the adiabatic outflow rate; ρ_i is the density of the working substance in the cavity from which the compressible medium flows out; $d\tau$ is the period of time during which the expiration occurs. No generalizing dependences on the choice of values of the flow coefficient W_i for different types of slots at different parameters before and after the slot have been obtained so far.

In the design practice of positive displacement compressors, an equation is most often used to determine the mass of the overflowing working substance, which may be of practical interest.

$$m = \sqrt{\frac{\rho \cdot P_i l^2 \cdot \delta^2 \left[\left(P_2/P_1\right)^2 - 1\right]}{ln\left(P_2/P_1\right)^2 + \xi + \lambda\Sigma}}, \tag{4}$$

где P_1, T_1, P_2, T_2 – параметры рабочего тела до и после щели; $\rho_1=P_1/RT_2$ – плотность рабочего тела; R – газовая постоянная; l и δ – длина и минимальная высота щели; ξ – коэффициент, учитывающий местные сопротивления на входе и выходе из щели; λ – коэффициент трения компримируемого потока в щели; Σ-коэффициент формы щели.

This formula takes into account the parameters of the working substance before and after the slot, the type of slot, the geometric dimensions of the slot, the length of the throttling path, the friction of the compressible flow, the losses at the inlet and outlet from a sudden narrowing or expansion. The calculations carried out by many researchers using this formula, in principle, have good quantitative agreement with the experimental data [24,25].

When carrying out calculations, the equation is written in the form:

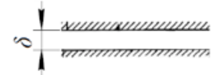
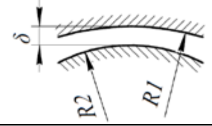
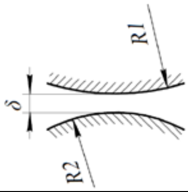
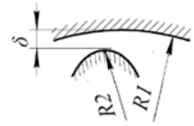
$$\overline{m} = K_p F \sqrt{\frac{1}{RT_2}\left(P_2^2 - P_1^2\right)}, \qquad (5)$$

where $K_p = \dfrac{1}{\sqrt{ln\left(P_2/P_1\right)^2 + \xi + \lambda\Sigma}}$ – is the dimensionless experimental flow rate.

$F = \delta \cdot h$ – cross-sectional area of the slot; h is the height of the spiral.

The coefficient K_p takes into account the decrease in consumption due to losses during the movement of the working fluid through the slot. With known shapes and sizes of the slot, physical properties and parameters of the working fluid before and after the slot, the determination of the flow rate through the slot is reduced to the determination of the flow rate coefficient K_p.

Table 1 – Type of slot in a scroll compressor

Slit name	Slit configuration
Along the line of contact of the end of the feather of the spiral with the platform of another spiral (type a)	
Along the line of contact of the surfaces of the feathers of the spirals (type b)	
Along the line of contact of the end sections of the spirals (type c)	
Along the line of contact of the end section and the surface of the feather of the spiral (type d)	

Analysis of the literature on determining the flow rate in rotary compressors, which are the closest in the type of slots (see Table 1) and the principle of operation to scroll compressors, showed that this issue is most fully summarized in work [26]. The resistance parameter is determined by the formula:

$$S = \frac{b \cdot C_R}{2 \cdot \delta \cdot \sqrt{R_e}}, \qquad (6)$$

where C_R is the coefficient of resistance, taking into account the roughness of the walls of the slot,

determined by the function $C_R = f(Re)$; b is the depth of the slot.

The determination of the flow rates, according to [27], is carried out by the approximation method, which complicates the use of this method in the numerical solution of the system of differential equations. The implementation of the considered methodological approach is carried out in a computational program and is possible only with obtaining the following analytical dependences: the C_R coefficient on the Reynolds number and the consumption coefficient Kp on the parameter S, which, as noted above, are presented in [27] in the form of graphical dependencies. For this purpose, these graphs can be approximated by the design equations presented below. It should be noted that to improve the accuracy of the calculation, the dependencies are divided into intervals.

So, the dependence of the C_R coefficient on the Re number is represented by the following equations:

$$R_e = 42.148 \div 300 \rightarrow C_R = -2.1632 \cdot ln(R_e) + 18.256;$$
$$R_e = 300 \div 500 \rightarrow C_R = 125.99 \cdot R_e^{-0.5437};$$
$$R_e = 500 \div 2000 \rightarrow C_R = 100.17 \cdot R_e^{-0.5119} + 0.015;$$
$$R_e = 2000 \div 2500 \rightarrow C_R = 0.0166 \cdot R_e^{-0.6338};$$
$$R_e = 2500 \div 10000 \rightarrow C_R = 0.4274 \cdot ln(R_e) - 0.8754;$$

The dependence of the flow rate K_p on the parameter S when using the specific critical flow rate of the compressible medium q_{KP} in the calculation of the Reynolds number is represented by the following equations:

$$S = 0 \div 5 \rightarrow K_p = -0.1078 \cdot ln(S) + 0.4985;$$
$$S = 5 \div 20 \rightarrow K_p = 0.4443 \cdot e^{-0.0625S};$$
$$S = 20 \div 50 \rightarrow K_p = 0.262 \cdot S - 0.2503 - 0.001;$$
$$S = 50 \div 100 \rightarrow K_p = 0.1037 - 0.00003 \cdot S;$$

The dependence of the flow rate K_p on the parameter S when using the specific second flow rate of the compressible medium q in the calculation of the Reynolds number is represented by the following equations:

$$S = 0 \div 0.144 \rightarrow K_p = -0.1032 \cdot ln(S) + 0.501;$$
$$S = 0.144 \div 2 \rightarrow K_p = 0.5418 \cdot S^{-0.119};$$
$$S = 2 \div 10 \rightarrow K_p = 0.6309 \cdot S^{-0.3114} - 0.002;$$
$$S = 10 \div 25 \rightarrow K_p = 0.9888 \cdot S^{-0.5177};$$
$$S = 25 \div 30 \rightarrow K_p = 0.6808 \cdot S^{-0.4007};$$
$$S = 30 \div 200 \rightarrow K_p = 0.2225 \cdot S^{-0.0735};$$

This approach, together with the developed calculation subroutine, can significantly reduce the time when calculating the working process of the scroll compressor and eliminate the possibility of mechanical errors when using graphic material. In a scroll vacuum pump, in contrast to a scroll compressor, the flow through the clearances due to pressure changes can vary from viscous through transient to molecular. Taking this into account, when studying foreign works [28,29] in this area, the proposed general equation, which is equally applicable for three different flow regimes, may be of interest. Here, the overflows through the slotted channel are found using the formula for a flat rectangular slot, in particular, from the Navier-Stokes formula for the viscous (laminar) regime:

$$Q_S = -\frac{h\delta_p^3}{12\eta} \cdot \rho \frac{dp}{dx} + \frac{h\delta_p^2}{2\eta} \cdot \rho\lambda \left(\frac{2}{\sigma_V} - 1 \right) \frac{dp}{dx}, \quad (7)$$

where $\lambda = \frac{kT}{\sqrt{2}\pi\sigma^2 p}$ – is the average free path of molecules.

To improve the accuracy, an expression with three coefficients was proposed, which is presented in the form:

$$Q_S = -\exp\left(\frac{-C_i \pi s}{1.488\lambda} \right) C_2 Q_m + \left[1 - \exp\left(\frac{-C_i \pi s}{1.488\lambda} \right) \right] \left(Q_V + C_3 Q_{ps} \right), \quad (8)$$

where empirical coefficients C_1 = 10, C_2 = 1,86, C_3 = 1,5, $Q_V = -\frac{h\delta_p^3}{12\eta} \cdot \rho \frac{dp}{dx}$ and $Q_{ps} = \frac{h\delta_p^2}{2\eta} \cdot \rho\lambda \left(\frac{2}{\sigma_V} - 1 \right) \frac{dp}{dx}$.

The disadvantages of this technique include the fact that the empirical coefficients C_1, C_2, C_3 were obtained for slits of specific sizes and geometry. The possibility of using these coefficients for slots with other spiral sizes and gaps was not considered. The presented methods also require solving differential equations for calculating conductivity.

The most interesting approach was proposed in [30–32], where a dependence was obtained for determining the mass flow rate of the working substance through the slot, taking into account the wall mobility. Mass flow is presented as

$$G = \frac{P_i F}{\sqrt{R_r T_i}} \bar{q}, \qquad (9)$$

where $\bar{q} = f(v, \tau)$ is the flow coefficient – a function determined by numerical methods, which depends on the ratio of the pressures at the ends of the slot and the slot parameter Ʋ, which is equal to

$$\vartheta = \frac{5 l \eta \sqrt{R_r T_i}}{\delta^2 P_i}, \qquad (10)$$

where l is the length of the channel in the direction of flow of the compressed medium.

Thus, formulas (9), (10) are applicable only for a flat rectangular slot. But in works [33, 34] it was proposed to use this technique for calculating the mass flow rate of a gas-oil mixture when flowing through channels of variable cross-section. For this, the equivalent channel length, determined from the condition of channel expansion to 4δ, is substituted into equation (10) instead of l. An obvious drawback of this technique is that the transition to an equivalent channel was carried out by processing experimental data for the flow of a gas-oil mixture, which can introduce a significant error in determining the mass flow rate of a pure working substance, especially when varying the dimensions of the channel.

The technique for determining the leakage of a compressed medium, as the flow of a viscous flow in slots with movable walls, was further developed in the works of Pronin V.A. [35,36]. Here, two mathematical models have been developed for calculating the flow rate of the compressed medium through the slots formed by the working bodies of a single-rotor screw compressor, taking into account the mobility of their walls. The following were used: the equation of continuity for the unsteady flow of a compressible medium, the equation of unsteady motion of a continuous medium and the equation of conservation of energy in a form that is valid for a real gas. When solving the problem, it was assumed that the height of the slots is small compared to their depth, and the flow of the medium is laminar (viscous). This approach gave good agreement with the experimental data obtained in a wide range of temperatures and pressures for R717. The validity of the data should be considered primarily for a single rotor screw compressor. It should be taken into account and taken into account the fact that in the region of low pressures the mobility of the walls affects the flow of the working substance much more strongly, this is described by the authors in [37], devoted to rotary vacuum pumps, including spiral type.

The use of widely known, in compressor technology, methods for calculating the mass flow rate of a working fluid in slotted channels, which were mentioned earlier, in a number of cases can lead to significant errors. The need to use graphical dependencies to determine the coefficients included in the equations and various formulas, depending on the type of slot, also create inconvenience in calculations. The graphs shown may not cover the required pressure ranges. With different combinations of radii R_1, R_2, types of slit and gap, the calculation of the conductivity gives an underestimation from 10% to 3 times in comparison with the experimental data. Moreover, the error grows with decreasing channel length. Analyzing the leaks through slots of various shapes of rotary compressors, we can assume an interesting formulation for calculating the flow rate of the working fluid through the slots using the dependence of the friction coefficient on the Reynolds number.

Conclusion

Thus, we can conclude that at present, in most of the works devoted to the study of scroll compressors, a technique is used to calculate the loss of a compressed medium with the assumption that the walls of the slot are stationary. However, studies in some works obtained using the model and its correlation with experimental data cast doubt on this assumption. Moreover, one should take into account the calculation error and the relative laboriousness of these methods.

Based on the nature of the movement of the working fluid and its interaction with the working organs of the scroll compressor during overflows, we can talk about the presence of both a passing movement, when the flow rate of the working substance increases, as well as a counter movement of the wall and working substance, when its consumption decreases. If, at the same time, we take into account the dynamics of the compressor operation, spiral deformations, which change the gap during operation, and a number of other factors, then the quantitative issue of leakages is far from unambiguous, being very promising for research.

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