Information Technology in the Modeling of Dry Gas Seal for Centrifugal Compressors

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Abstract. The developed specialized software package for computer modeling of dry gas seals for the rotors of centrifugal compressors is presented. This software package implements the mathematical model that describes improved methodology for seals modeling and solving under steady-state compressor operating conditions. It allows to make a model of working gap between the seal rings, which changes under the influence of gas pressure and temperature. This improved computer modeling can provide the reliable operation of dry gas seals. The developed software package has been tested on real constructions of dry gas seals with different types of groves. The results of test solutions were compared with available in literature and experimental studies.

Keywords: Computer Simulation, Engineering Software, Compressor Gas Seals

1 Introduction

The issues of computer modeling and information technology are very relevant in the study of engineering objects. Increasingly, they are the basis of a computer experiment, which in most cases can be used to replace the implementation of expensive real experimental studies during finishing work and in the process of servicing working structures. Computer technology capabilities allow for rather accurate modeling and numerical research of engineering structures, using existing technical software systems for general engineering solutions. Particular difficulty in this case is the need to solve problems from different areas of physics within the solution of general technical problem [1].

Another way is to create specialized software products using different programming languages and environments. This allows to use more accurate mathematical models for analysis, taking into account processes and phenomena of different physical nature. The use of such information technology for modeling improves quality of design work when creating prototypes and industrial designs [2].

The need to create a specialized software package also arose for the modeling of dry gas seals for the rotors of centrifugal compressors, designed to maintain gas pressure in main gas pipelines [3]. Such compressor are shown in Figure 1.

This type of seals is shown in Figure 2. It has been widely applied in view of a number of advantages. The main ones are: the possibility of operation at high rotation speeds for compressor rotor; the absence of an expensive oil supply system; minimal gas leakage during operation [4, 5].

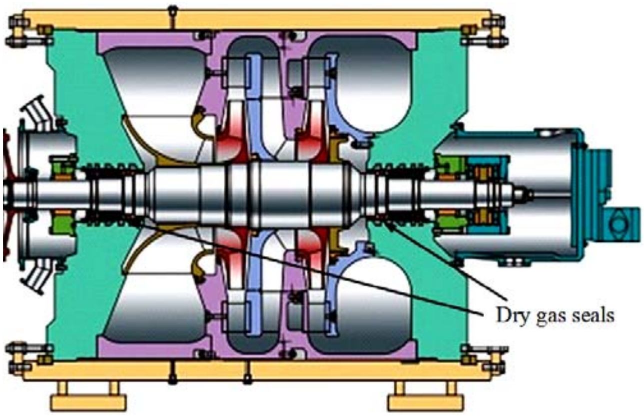

Fig. 1. Centrifugal compressor

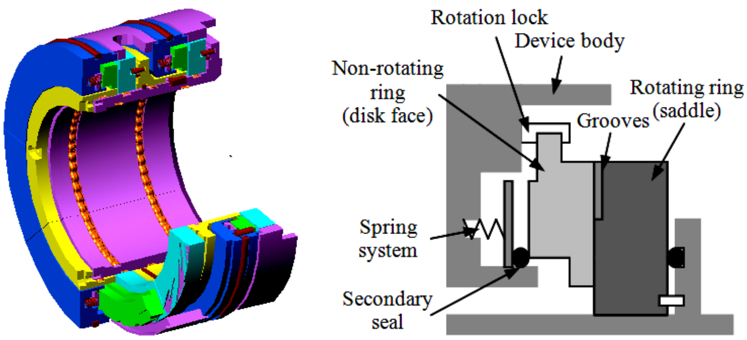

Fig. 2. Dry gas seals

Dry gas seals can work stably and reliably with various gases and under various operation conditions only in the case of it very accurate modeling and solving. An improved methodology of gas seals analysis under steady-state operation conditions should include solving of gasdynamics, heat transfer and thermoelasticity problems [5].

The seals system is one of the most critical centrifugal compressor systems. That is why the presence of improved methodology for gas seals modeling and software product that implements this methodology makes a huge contribution to the reliable operation of the system as a whole.

This paper is devoted to the issues of using information technology for computer modeling of processes that take place during the operation of dry gas seals and the creation of specialized software package for modeling and solving.

2 Formal problem statement

The aim of this work is to present the developed specialized software package for computer modeling and solving of dry gas seals for the rotors of centrifugal compressors. This software package implements the mathematical model that describes improved methodology for seals modeling under steady-state compressor operating conditions.

3 Literature review

An analysis of the existing researches, dedicated to the modeling of gas face seals, has shown the relevance of this problem. Despite the large number of publications on this topic, many issues of modeling and solving remain open.

The main operation condition of dry gas seals is the existence of the necessary gap between the seal rings with a thickness of 3-4 μm (micrometer) in steady state operations, supported by the gas pressure (Fig. 2). The necessary gas pressure between the rings in working condition is created and maintained due to the special type of microgrooves on the rotating seal ring, with a depth of 6-7 μm.

The type of grooves is selected, taking into account the operation features of seals. More often spiral grooves are used. Considering such small gaps between the sealing rings and the shallow depth of the grooves, much attention is paid to computer modeling and solving of gas seals.

Nowadays, the existing universal engineering software packages based on the finite element method are widely used for modeling and solving of dry gas seals. So, in studies [6, 7, 8, 9, 10], well-known general technical software packages are used to analyze the gas pressure between the rings. These works are devoted to the selection of the optimal type of microgrooves for direct and reverse seal operation, by calculating the gas pressure in the gas layer between the rings. The influence of the surface treatment of the rings on the working pressure of the gas in the gap is studied [11].

Existing software packages are also used for modeling and visualization of calculation results.

However, it is necessary to take into account the temperature distribution in the seal rings and the appearance of temperature strains in rings.

Taking into account these strains is necessary in view of small gap between the rings. Temperature strains can lead to redistribution of gas pressure between the seals rings and incorrect seals operation. The literature review on solving of heat-transfer and thermoelasticity tasks for dry gas seals showed the existence of a few number of papers devoted to this problem [12, 13, 14].

So, in studies [12, 14], the temperature distribution in the rings is taken into account. The appearance of temperature strains is taken into account in [13]. These problems are solved by using of general technical software packages. Either an alternative to this are developed programs, which are based on simplified engineering solution methods. The above tasks are solved separately, because of their rather difficult simultaneous analysis.

Existing software packages allow to create accurate model research object, visualize the results of the solution. However, the existing general technical software systems are designed to solve a wide class of problems and they, of course, cannot fully take into account the aspects of a highly specialized task in solving a specific problem for a particular object. The presence of a specialized program allows more accurately and adequately simulate processes, and take into account the relationship between phenomena of different physical nature.

Therefore, the creation of specialized software package for computer modeling and solving of dry gas seals is a relevant problem today.

4 Specialized software package GasDin

In this paper, the developed specialized software package GasDin is presented that implements an improved methodology of modeling of dry gas seals for the rotors of centrifugal compressors. This methodology is based on iterative solution of related gasdynamic, heat transfer and thermoelasticity tasks.

4.1 Theoretical basis

The two-dimensional distribution of gas pressure in the gap between the seal rings is described by the nonlinear gas lubrication equation. After some conversions, taking into account the temperature changes, this equation has the form [15]:

$$\frac{\partial}{\partial x}\left[\frac{1}{\mu T_{av}}\left(h^3\frac{\partial p}{\partial x}-12\mu h\omega\sqrt{pz}\right)\right]+\frac{\partial}{\partial z}\left[\frac{1}{\mu T_{av}}\left(h^3\frac{\partial p}{\partial z}+12\mu h\omega\sqrt{p}\,x\right)\right]=0\,, \qquad (1)$$

where μ – dynamic coefficient of viscosity for gas; $T_{av}=T_{av}(x,z)$ – an average integral function of changing the gas temperature over the gap thickness (along the y coordinate); h – the thickness of the gas layer; $p=P^2$ – is the square of the gas pressure; ω – the angular velocity of rotating ring.

The temperature distribution in the gas film between the rings is described by the heat equation, taking into account the heat generation in the gas layer due to viscosity and convective heat transfer [15]:

$$\frac{\partial}{\partial x}\left[k_T\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[k_T\frac{\partial T}{\partial y}\right]+\frac{\partial}{\partial z}\left[k_T\frac{\partial T}{\partial z}\right]+\mu\left[\left(\frac{\partial v_x}{\partial y}\right)^2+\left(\frac{\partial v_z}{\partial y}\right)^2\right]-\frac{PC_v}{RT}\left(v_x\frac{\partial T}{\partial x}+v_z\frac{\partial T}{\partial z}\right)=0\,, \qquad (2)$$

where k_T – thermal conductivity of the gas film; $T=T(x,y,z)$ – gas temperature; v_x and v_z – gas velocity components along the gap; C_v – specific gas heat intensity ratio at a constant volume; R – universal gas constant.

The boundary conditions for equations (1), (2) are the set values of temperature and pressure at the inlet and outlet of the seal.

The temperature distribution in working rings is:

$$\nabla(k_{T_{1,2}}\nabla T)=0\,, \quad (3)$$

where k_{T1} and k_{T2} – thermal conductivities of rotating and axially movable seal rings.

4.2 Computer modeling methodology

An algorithm based on the use of the Bubnov-Galerkin method in combination with the finite element method has been developed to solve the gasdynamic task for dry gas seals. The finite element method in variational formulation is used for solving the heat transfer and thermoelasticity tasks. Because of non-linearity of formulated tasks, an iterative algorithm of their simultaneous solution has been developed.

The conversion of cumbersome analytical expressions for resolving system of non-linear equations, which formed the basis of the GasDin software package, were made using package of computer mathematics. These expressions were automatically translated into the codes of C++ programming language. Thus, it was possible to avoid numerous mistakes. Analytical expressions were also used in testing to compare the results of calculations.

This software package has been developed by use of C++ programming language.

The main window of the developed software package is shown in Figure 3.

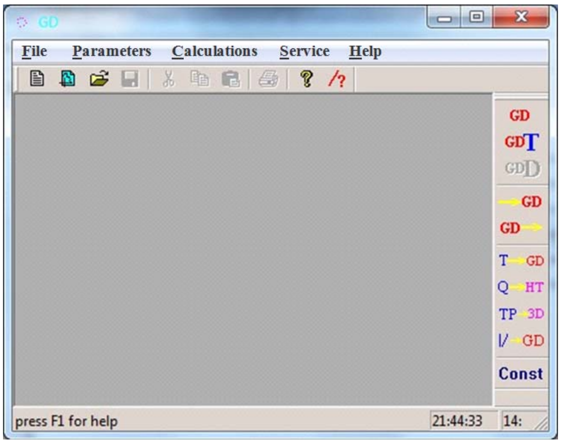

Fig. 3. The main window of the software package GasDin

The main requirement for the service part of the software package was the creation of an on-screen menu with corresponding "buttons", allowing to manage standard set of work with files and program modules, various forms of data input and output, visualization of results of calculations.

4.3 Structure and implementation of the software package GasDin based on the use of integrated technologies

Block scheme of software package GasDin is presented on Figure 4.

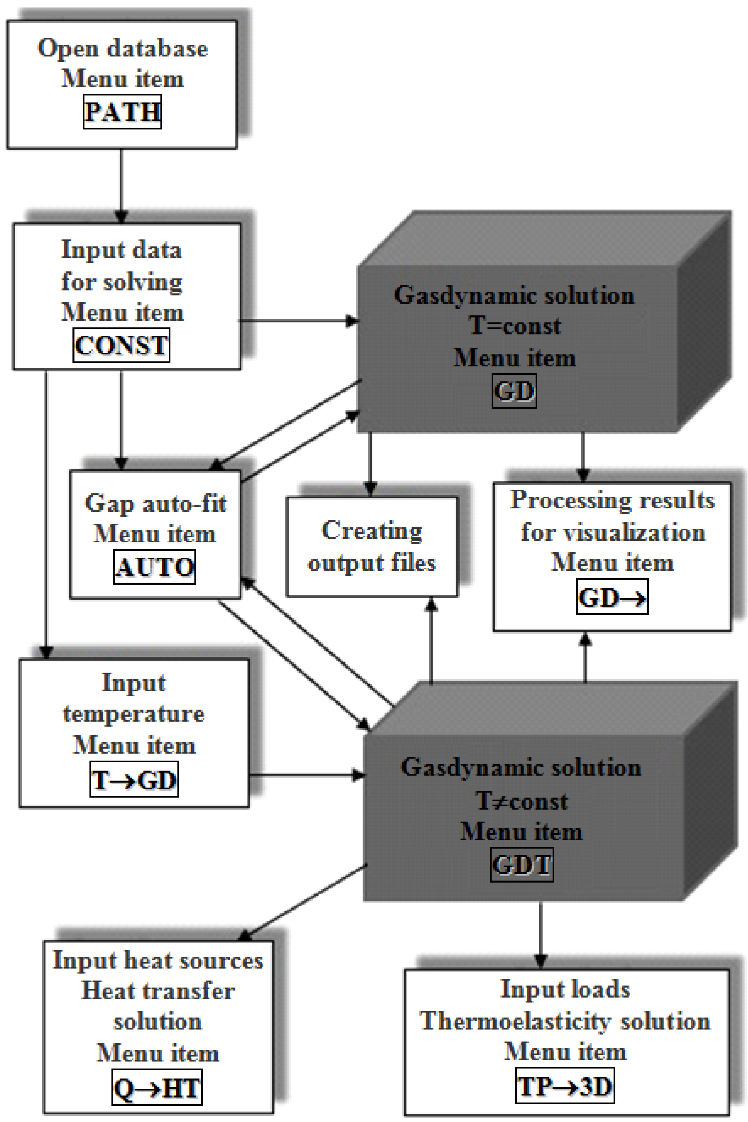

Fig. 4. Block scheme of software package GasDin

It should be noted that the solution of heat transfer and thermoelasticity tasks, the visualization of the obtained pressure fields and gas velocities in the gap is carried out using universal finite element software package. Data exchange between the software packages during iterative process is carried out by specially designed programs.

The developed software package allows solving for databases located in any directory. The initial data for the gasdynamic solution are: the gas pressure at the inlet and outlet of the seal P_2 and P_0, the external and internal radius of the flow region r_2 and r_0, the working gap δ, the depth of the grooves, the specific gas heat intensity ratio at a constant volume C_v, universal gas constant R, gas temperature at the inlet and outlet of the seal T_2 and T_0, the angular velocity of rotation ω, the accuracy of the gasdynamic calculation ε.

The software package GasDin allows to perform two types of gasdynamic solutions: at a constant temperature of the gas layer, and taking into account heat generation and temperature changes in the gas layer. The non-linear differential equation of gas lubrication is solved (1). The system of nonlinear algebraic equations for unknown pressure and temperature at the nodes of the finite element grid is solved by the method of simple iterations, where the linearized system is solved at each iteration using the Gauss method. The end of the iterative process is determined by the user-specified accuracy of solution. Setting of gas temperature field at each iteration is carried out by specially created programs for automatic transfer of the temperature distribution to the software package GasDin, obtained by solving the heat transfer task for gas film and working rings.

The results obtained by gasdynamic calculation are recorded to special files. They contain the values of the pressure in the nodes, the coordinates of the nodes. The value of gas leakage through the seal, resulting gasdynamic force, are also calculated. The developed software package also allows for the initial selection of the working gap between the seals by aligning the gasdynamic and gasostatic resulting forces. The gasostatic force is calculated during the preparation of the initial data after thorough study of the working drawings, the method of sealing of non-rotating ring and setting the boundary conditions.

After gas-dynamic solution, the software package calculates the intensity of heat sources in the gas layer and exports them into the database to solve the heat transfer problem. Further, the temperature fields of rings and pressures in the gas layer are exported into the corresponding databases for solving the thermoelasticity problem in three-dimensional and axisymmetric simulations, taking into account the possible mismatch of grids. Recalculation of the working gap, taking into account the obtained strains of seal rings, is also performed automatically.

4.4 Testing and practical use of software package GasDin

Testing of the created software package GasDin was carried out by solving test tasks for special cases which have an analytical solution, such as the distribution of gas pressure in the gap without grooves. Also, test solutions were compared with solutions in literature and experimental studies [15].

To determine the gas pressure in the gap between the rings, the region of the gas layer is considered, taking into account the cyclic periodicity conditions, containing a groove and a land. The results of the gasdynamic solution were checked in two stages. It is known, that for gas layer with constant thickness and temperature, the gas lubrication equation (1) has an analytical solution.

$$P^2 = -\frac{1-P_0^2}{\ln r_0}\ln r + 1; P = \sqrt{1-\frac{1-P_0^2}{\ln r_0}\ln r}\ . \tag{4}$$

The solving results agreed with the results of the analytical solution up to the accurate to five decimal places and are shown in Figure 5. The exact solution values are marked with squares. For solutions, the following initial data were used: r_0=53.6 mm; r_1=68 mm; r_2=80 mm; P_0=1 atm; P_2=53 atm; the thickness of the gas layer outside the groove h_1=3 μm; in the groove h_2=11 μm.

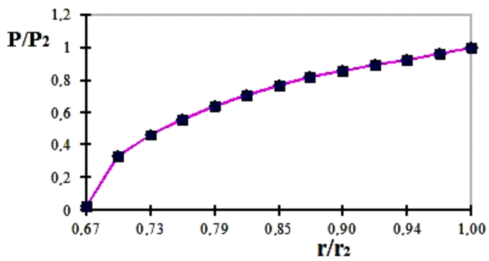

Fig. 5. Pressure distribution in the gas layer without grooves

Testing of the iterative solution algorithm and the created software package was also carried out for the real designs of dry gas seals used at the Joint Stock Company "Sumy Machine-Building Science-and-Production Association", Sumy, Ukraine. To determine gas pressure in the gap between the rings, the region of gas layer is considered taking into account the cyclic periodicity conditions. Solution model contains a groove and a land. Geometric and operating parameters of the seal with spiral grooves: r_0=101 mm; r_1=112.1 mm; r_2=125 mm; P_0=1.3 atm; P_2=60.8 atm; the thickness of the gas layer outside the groove h_1=3 μm; in the groove h_2=10 μm.

Figure 6a shows the distribution of gas pressure in the gap, taking into account temperature changes; Figure 6b the distribution of gas velocities in the gap.

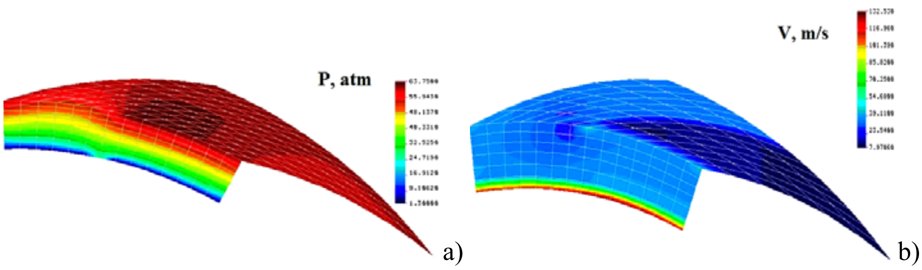

Fig. 6. For seals with spiral grooves: a) gas pressure distribution in the gap, taking into account temperature changes; b) the distribution of gas velocities in the gap

The developed solution algorithm and software package allows to find the gas pressure distribution for any type of grooves. Figure 7 shows the gas pressure distribution for seals with T-grooves under direct (Fig. 7a) and reverse (Fig. 7b) operation modes. The results of the gas pressure distribution in gap are in a good agreement with available in literature for seals with spiral grooves and T-grooves [6, 7, 8].

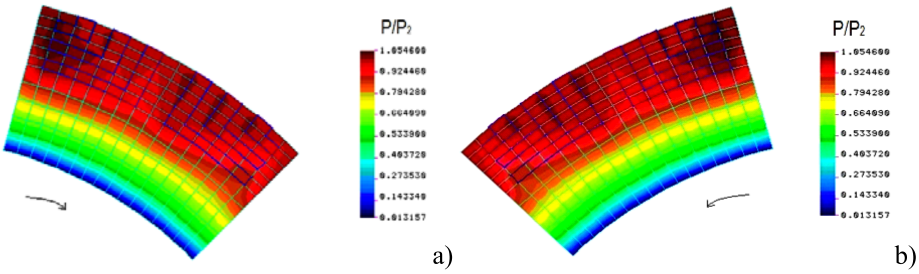

Fig. 7. Gas pressure distribution for seals with T-grooves: a) direct operation mode; b) reverse operation mode

An axisymmetric model of seal rings and gas layer is used for heat transfer solution. To determine the strain state of seal working rings, three-dimensional ring models are used taking into account the conditions of cyclic symmetry shown in Figure 8.

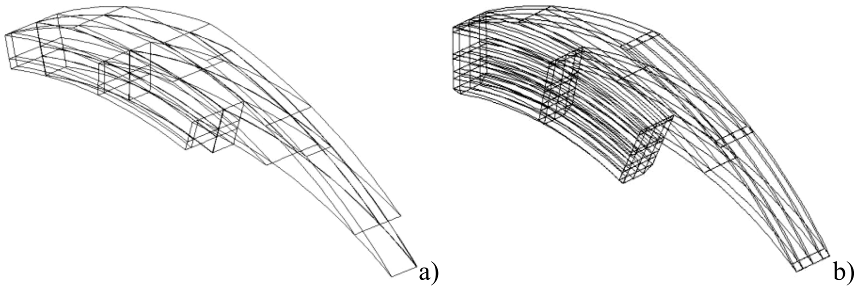

Fig. 8. The working rings models with spiral grooves: a) axially movable ring; b) rotating ring

It should be noted, that the Joint Stock Company "Sumy Machine-Building Science-and-Production Association" has created an experimental stand for dry gas seals. It determines the inlet and outlet pressure in seals, determines the gas velocities and temperature around seal rings, which can be used as the initial data for solutions. The gas temperature at the inlet and outlet of seals and the flow characteristics of seals are also determined.

As mentioned above, the heat transfer modeling for seal rings is done in axisymmetric setting. The resultant temperature distribution is shown in Figure 9.

Experiments for studied seals showed that gas in the gap heats up on average to 40-50°C, in the absence of contact of surfaces. As a result of computer modeling studies, the gas at the outlet is heated up to 46°C (319 K) for these seals. That is in a good agreement with experimental data.

The developed software package allows to determine the gas leakage through the seal, according to the integral expression for the gas leakage:

$$Q_r = \int_0^{2\pi} \frac{1}{12\mu RT} h^3 P \frac{\partial P}{\partial r} d\varphi \qquad (5)$$

The gas leakage obtained as a result of computer modeling of studied gas seals using developed software package GasDin is 1.03×10^{-3} kg/s. The changes of working gap caused by straining of seal rings are taken into account.

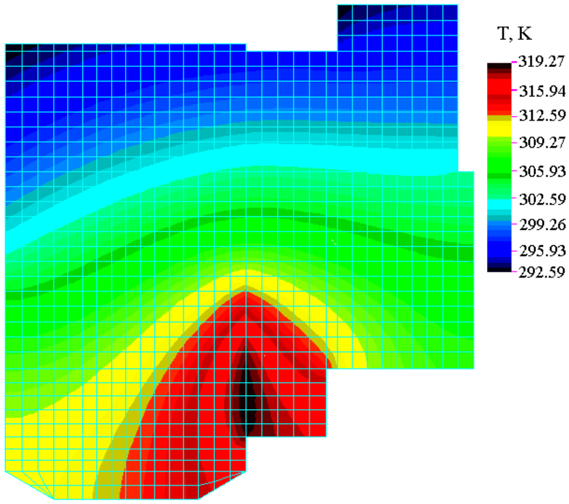

Fig. 9. Temperature distribution in gas seals

The calculated gas leakage differs from the experimental value for this seal design by 9%. It can be considered a good result.

The test modeling and solving confirm the reliability of results obtained using the developed software package GasDin.

5 Conclusion

Information technologies are widely used for computer modeling of various engineering facilities. Their use allows to improve the accuracy of designed facilities, reduce the service costs. Presented in this paper specialized software package allows to carry out computer modeling and solving of gas seals of centrifugal compressors.

The advantage of the developed software package GasDin is the ability to find the distribution of gas pressure in the gap between the seal rings at a constant temperature and taking into account of temperature changes. It is an advantage over existing general engineering software packages. Seeing that, the distribution of gas pressure in the gap is described by a non-linear equation related to particular part of gasdynamic, the theory of gas lubricant.

Also, the software package GasDin implements an iterative algorithm for modeling and solving of gas seals. It allows to make a model of working gap between the seal rings, which changes under the influence of gas pressure and temperature. This improved computer modeling can provide the reliable operation of dry gas seals.

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