Investigation of the stress state of the connecting rod of the oppositional compressor and evaluation of the probability of its trouble-free operation

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Abstract. Calculating and experimental methods were used to study the stress-strain state of the connecting rod of the oppositional compressor operating in the chemical industry. Computational and experimental methods for assessing the stress-strain state of the compressor connecting rod head were previously tested on models, since the connecting rods are large and conducting research on a running compressor is extremely difficult. Similarity criteria are defined that allow the methods and results of studies obtained on models to be applied to the assessment of the stress-strain state of connecting rods. The dependence of the contact angle between the connecting rod and the connecting rod finger on the load, the gap in the coupling and the geometric characteristics of the head was obtained. For the connecting rod head, a numerical experiment was used to calculate the stress state under loads and gaps in the connecting rod – pin, corresponding to the operational ones. Analysis of the stress distribution obtained by the calculation allowed us to estimate the dependence of stresses on the magnitude of the applied load, the magnitude of gaps in the interface and the change in the angular coordinates of the sections with the maximum stress values. Taking into account the obtained results, a method has been developed and a study of the stress distribution of the compressor head in operation has been carried out. For the maximum loaded sections of the connecting rod head, the fatigue resistance characteristics and the characteristics of regular variable loading in operation at rated load are determined. Based on the results obtained, the probability of failure depending on the magnitude of the loads and the size of the gaps was evaluated.

In the chemical industry, machines and units operate in aggressive environments, at high pressures and temperatures. Processed reagents are explosive and toxic substances. Under these conditions, equipment failures can cause extremely dangerous situations. Consequently, machines and units must be reliable to ensure safe operation. At a number of enterprises operating nitric compressors, there were cases of destruction of connecting rods. Examination of the destroyed machines showed that all cases of breakdowns are identical and were the result of fatigue cracks in the piston heads. As a rule, the formation of cracks began with the inner surface of the head in its middle section. Experimental studies of the performance of structural elements, characterized by large sizes and working in chemical production, present great difficulties. In this regard, to assess the life of the connecting rod, it is advisable to study the stress state of the connecting rod head by experimental and computational methods using numerical experiment. When loading the connecting rod, two characteristic areas can be distinguished: the contact zone of the cylindrical surfaces of the connecting rod pin and the connecting rod head, where the distributed load operates, and the area with a clearance between the
cylindrical surfaces, where there is no contact pressure (figure 1). Practice has shown that all the cases of formation and development of fatigue cracks, destruction of heads in operation accounted for the cross section of heads with coordinates 80-100° from the longitudinal axis of symmetry of the connecting rod, which indicates the action of maximum stresses in these sections, therefore, the greatest interest is the distribution of stresses in these zones. As noted in [1], radial force $N_B$, tangential force $Q_B$, and bending moment $M^*$ occur at the contact and clearance boundary of the pin with the connecting rod bore. Since the stiffness of the finger is several orders of magnitude greater than the stiffness of the connecting rod head, as shown in [2], a constant bending moment $M = M^*$ will act on the contact area of the BO. In accordance with [2, 3], using the boundary conditions of the contact angle $\alpha_0$, it is possible to determine the values of the force factors $N$ and $Q$ as a function of the angle $\alpha_0$.

![Figure 1. Forces acting in the connecting rod head.](image)

To assess the influence of the geometric characteristics of the connecting rod head on the stress distribution, a computational and experimental evaluation of the stress – strain state of the connecting rod models was carried out. Ring models with internal diameter $d$ from 62 to 71 mm were considered, the wall thickness of the ring $h$ varied from 4.35 to 22.1 mm. To ensure compliance of the stress-strain state of the connecting rod head model and the real connecting rod head, criteria adequately describing the model and the full-scale part were used. It is obtained that the ratio of $P/lz$, where $P$ is the current load, $l$ is the length of the bearing, $z$ is the amount of clearance, satisfactorily describes the influence of loads and clearances; the ratio of $0.5d/h$ the effect of geometrical dimensions in the calculation of the contact angle in the coupling of the finger with models of different thickness rings. Figure 2 shows the dependence of the contact angle on the $p/lz$ ratio for the connecting rod head and its model with a ratio of $0.5d/h = 3.2$, which shows their practical coincidence. Analysis of stress distribution in models with different ring wall thickness allowed to estimate the trends of stress changes depending on the magnitude of the applied load, the values of gaps in the coupling, to find the coordinates of the sections with maximum stresses. The dependence of the contact angle $\alpha$ on the load value, the gap in the coupling and the geometric characteristics of the head was established, which allows using the algorithm and the results of calculating the contact angle obtained for models in the calculation of full-scale parts. For the model and the connecting rod head, stresses for the internal surfaces were calculated under the conditions of geometric similarity, that is, at the same $p/h$ and $P/lz$ ratios and the same contact angle. The calculation showed that the average error in determining the design stresses for the model and the connecting rod head for the area where there are maximum stresses and defects in operation does not exceed 2.4%.
For the connecting rod head, a numerical experiment was used to calculate the stress state for sections within the range of the angle $\alpha_0$, corresponding to the end of the contact zone, to the angle $\phi = 135^0$, corresponding to the transition of the head to the rod. The loads and clearances in the connecting rod-pin varied. The specified loads matched operating ones: 180kN at nominal mode; 250KN when working with overload; 100kn when the machine was under loaded. The clearances in the connecting rod pin-boring rod is also set in accordance with the operational parameters: 0.10 mm, with the extreme values of 0.05 mm, 0.15 mm. Analysis of stress distribution obtained by the calculation allows us to estimate the trend of changes of stress depending on the load applied, the clearances in the coupling, and the change in angular coordinates of cross sections with extreme values of stresses. It is found that the increase in the clearance from the minimum to the maximum value causes an increase in stresses by 20-30%. It is established that the maximum values of stresses acting on the inner surface of the connecting rod head are 2.7...2.9 times higher than the stresses acting on the outer surface of the head.

For experimental evaluation of the stress state of the connecting rod, full-scale strain tests were carried out at different operating modes of the compressor. The main objectives of experimental studies of the stress-strain state of the connecting rods of the compressor were: to determine the magnitude and nature of changes in the loads acting on the crank mechanism of the compressor during its operation; to establish the nature of the stress distribution in the elements of the connecting rod with determination of the most loaded sections; comparison of calculated and experimental results; search for the most rational design forms and technological solutions; improving the reliability of connecting rod elements. Conducting studies of the stress state of connecting rod elements in compressors in production conditions is a significant challenge. Large dimensions and weight of the connecting rod, the presence of plane-parallel and rocking movement, work in an oil environment and at elevated temperatures and with a very limited time of testing require careful preparation of studies. Therefore, strain gauge studies of the models were previously carried out in order to perform the subsequent industrial tests in the conditions of continuously operating production in the shortest possible time. Tests of the models allowed to study the effect of clearances on the magnitude of stresses by choosing a landing on a mandrel that simulates a finger. Landing was chosen in accordance with the clearances characteristic of the investigated compressors, which can’t be done on a running compressor. Operating load was varied. Processing of experimental data was carried out by methods of dispersion analysis [4, 5].

Comparison of the numerical experiment data and the model test results showed that the accepted calculation scheme, tested on the models, with a sufficient degree of accuracy allows to determine the stress distribution outside the contact angle. To study the stress-strain state of the connecting rod heads, 70 sensors were glued to one of the serial connecting rods. Sensors were glued in seven sections of the connecting rod head with an interval of 45$^0$ from the vertical axis of the connecting rod by five sensors in the axial direction on the outer and inner surface of the head, so that their longitudinal axes were oriented in the direction of the measured deformation. To exclude the influence of temperature deformations, compensation sensors were used, which were placed near the active sensors parallel to their axis. Necessary measures have been taken to protect load cells from corrosion, temperature influences and electrical interference.
Before the tests, the insulation resistance, the integrity of the load cells and the absence of a short circuit to the mass of the connecting rod were monitored. Before loading, the measuring path was calibrated, zero sensor readings were recorded, and then the compressor was started. When the compressor enters the operating mode (32 MPa in the discharge line), the load cell readings in the studied sections of the connecting rod head were recorded. Further, the compressor was unloaded step by step and the load cell readings were recorded at 90% (30 MPa) of the operating pressure as well as 75% (24 MPa), 50% (16 MPa) and idle. After stopping the compressor, a control calibration of the measuring path was carried out. The obtained data were processed by statistical methods [4, 5]. During the tests, the values of the loads acting on the crank mechanism of the compressor in operation, and the nature of their changes were determined, while the most loaded sections were identified. Tests have shown that the greatest influence on the stress distribution had: the type of load (tension-compression) and the magnitude of the force acting on the connecting rod. Figure 3 and figure 4 show the stress distributions depending on the load for the inner and outer surfaces of the connecting rod. And on the inner surface they are much larger, which explains that all cases of cracking and destruction began from the inner surface.
The dependence of stresses on the type and magnitude of the load shows that tensile loads have a greater impact on the growth of stresses than compressive ones.

The distribution of stresses in the angular sections of the head depending on the applied load (tension or compression) are shown in figure 5 under tension, in figure 6 under compression. Figure 5 shows that the maximum values of the stresses acting on the inner surface are 2.2 times higher than the stresses arising on the outer surface. The coordinates of the sections where the maximum stresses are applied differ for the outer and inner surfaces. For internal surfaces this section, located at angles $\pm 90^\circ$ for exterior section, located at angles $\pm 135^\circ$ counted from the longitudinal axis of symmetry of the connecting rod. The stresses in these sections are decisive for the evaluation of the fatigue resistance of the connecting rod, it is obvious that these calculations must be carried out for the inner surface of the connecting rod head. It is found that when the tensile force increases from 100 to 250 kN, the stress values in these sections increase from 40 to 80 MPa, whereas for other sections such a large increase in stress does not occur. Tensile loads affect the stress-strain state of the connecting rod more than the compressive forces.

Some unevenness of the stress distribution over the angular cross section of figure 5 and figure 6 can be explained by errors in the manufacture of the connecting rod and the errors of the load cells. The stress distribution under the action of the compressive force is shown in figure 6.
Figure 6. Stress distribution over angular section of the connecting rod head at compression, load 250 kN; 1 - inner surface of the head rod's; 2 - outer surface of the head rod's.

Figure 7. Stress distribution on the inner surface of the connecting rod head obtained by calculation (1) and experimentally (2). Load 250 kN, and the gap in the coupling. Load: 1-250 kN; 2 - kN 180; 3 -100 kN.

Figure 8. Probability of failure of connecting rods, depending on the load

It is found that in the upper part of the head the compression stresses retain the same level equal to 20 MPa when the load changes from 100 to 250 kN. It is almost impossible to conduct experimental studies of the change in the clearance value to increase the stresses on the running compressor, but a good correlation of studies of the stress-strain state on the models allows the dependences obtained on the models to be applied to the connecting rod. On the basis of the computational and experimental studies, the following conclusions can be drawn: the main influence on the stress-strain state of the connecting rod head have tensile forces; maximum stresses act on the inner surfaces of the connecting rod heads and they occur in sections located in the middle of the head (+ 90° from the longitudinal axis of symmetry of the connecting rod). Comparison of numerical and field experiment results (figure 7) shows that the stresses in the connecting rod head of the opposition compressor, determined by numerical methods, exceed the stresses determined experimentally by 7 ... 22% and give a more conservative estimate of the stress state. Strain tests of the operating compressor showed that the connecting rod operates at a regular variable load with an asymmetric cycle. Experimental data and results of numerical experiment allowed to find stress values in the most loaded sections of the compressor head. For dangerous sections (angle 90°) at nominal load of the compressor (32 MPa in the discharge line) was determined as the cycle characteristics of the alternating stress: amplitude cycle \(\sigma_a = 54\text{MPa}\), the mean stress of the cycle \(\sigma_m = 68.2\text{ MPa}\), the average value of equivalent amplitude of the given cycle to symmetric cycle \(\sigma_{ae}=57.6\text{ MPa}\), the coefficient of variation of equivalent amplitude cycle...
\[ \theta_{\sigma_3} = 68.2. \] The endurance limit of the connecting rod head was determined by the recommendations of [6] and GOST 25 504. For rod it is equal to \( \sigma_{-1} = 84 \text{ MPa} \). On the basis of the obtained results, algorithm and methodology of resource estimation given in [7] with the use of tables of mathematical statistics [8] the probability of failure depending on clearances and operating loads is estimated [9]. According to the calculation results, methods of surface hardening of the connecting rod head were recommended to maintain the required level of probability of failure-free operation [9].

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