Assessment of the loaded state of the piston unit cylinder stage taking into account of temperature exposure

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Abstract. The article assesses the stress-strain state of the cylinder low-speed stage long-stroke piston unit are loading with an internal pressure of the working medium taking into account the temperature loads of its walls. The results of the analysis of the long-stroke piston unit low-speed stage cylinder are compressor unit show a significant effect of the temperature of the cylinder wall on their deformation. The analysis allows for optimal design of the piston unit low-speed stage cylinder stages under conditions of temperature loads, taking into account its actual deformed state.

1. Introduction

Currently, one of the promising areas of development of compressor technology is the use of low-speed piston units for solving specific problems: reducing vibration and noise effects on equipment; the possibility of using piston seals for compressors without lubricants; high operating efficiency and low cost of exploitation when low capacity (up to $5 \cdot 10^{-3}$ m$^3$/s) and increased discharge pressure (over 3 MPa) [1], [2].

The article discusses the stress-strain state of the cylinder low-speed stage long-stroke piston unit. A feature of the functioning of a piston unit, such as a piston compressor or pump, is a periodic change in pressure and temperature of the working fluid in the cylinder [3], [4], which determine its loaded state. Peak values of pressure in the working cavity of the unit and temperature effects arising from the compression of the working fluid in the cavities of the unit contribute to the formation of fatigue surface cracks in the cylinder walls [5].

In articles [6], [7], [8], the results of theoretical and experimental studies of the gas parameters for the cylinder long-stroke piston unit are presented. In particular, it was shown that the average temperature of the injected gas reaches 450 K without cooling and up to 350 K with water cooling of the cylinder walls. Thus, the actual temperature of the cylinder wall long-stroke piston unit can reach significant values. Temperature effects lead to an increase in radial deformations of the cylinder walls of the compressor, and therefore affect the gaps in the cylinder-piston pair, and, consequently, the efficiency of the working process, implemented in the unit [9].

Thus, the assessment of the deformations of the cylinder for the piston stage of the unit is an important task, since without accurate information about the resulting gaps between the piston seals and the inner wall of the cylinder, it is impossible to model new versions of the stages of low-speed units [10], [11], [12], [13], [14].

2. The problem formulation

The paper discusses the combined effect of pressure acting in the discharge zone of a low-speed unit, and the temperature of the compressible gas on the radial movement of the cylindrical shell, as well as on the magnitude of the stresses in the cylinder wall.

The study was performed using the ANSYS Workbench Mechanical software package (ANSYS WM) [15], [16]. This program allows you to take into account the change in the internal pressure along the length of the cylinder for any the piston position, while simulating various conditions of contact between the moving elements of the unit [17], [18], [19], [20], [21].

The stress-strain state analysis of the piston unit cylinder (the compressor) was carried out for the following design: cylinder diameter $D = 0.05$ m; piston stroke $\Delta X = 0.5$ m; the wall thickness of the
cylinder was taken $\delta = 2.5$ mm. The design pressure in the discharge zone is $p_n = 10$ MPa with the piston position $X = 490$ mm (Figure 1).

To create a finite-element geometric model in the ANSYS WM program, the graphic editor DesignModeler was used. The design model is simplified compared to the actual design of the compressor (Figure 1). The main elements of the deformable model of a low-speed piston stage are: thin-walled cylindrical shell, two bearings, a piston with sealing rings. Figure 2, by way of illustration, shows a finite-element mesh of a piston unit cylinder. The finite element mesh was generated in the "Mesh Sizing" procedure automatically by standard ANSYS WM software using user-defined finite element parameters: the element type is a 10-node tetrahedron; the size of the tetrahedron ranged edge of the from 0.5 mm to 2 mm.

![Figure 1. The design scheme of the long-stroke low-speed stage piston unit](image1)

To improve the accuracy of modeling the deformation gradient over the thickness of the cylinder, the mesh of elements is made of three layers. Each of the cylinder elements is modeled by a separate three-dimensional body (solid) with the possibility of changing its mechanical characteristics. The material of the cylinder wall of the unit is Steel 40X, the material of the seal in the cylinder-piston pair is Floubon 20 (Table).

![Figure 2. The finite element grid of the piston unit](image2)

Connections and interactions between individual unit details were modeled by assigning contacts between them (Connections – Contacts). In the zone of injection and suction, the connection of the
ends cylinder was simulated with the support plate by setting the indissoluble contact at the interface of the solid bodies – Bonded - Solid To Solid. The movable contact between the inner wall of the cylinder (Steel 40X) and the seal (Flubon 20) of the piston unit is set by the boundary condition "Frictional (friction coefficient \( f = 0.2 \)). In the design model, the supports stiffness was not taken into account, and their rigid support was modeled by the Fixed Support team.

### Table 1. Materials characteristic

| Material      | Density, \( \text{kg/m}^3 \) | Elastic Modulus, MPa | Poisson's Ratio | Linear Temperature Expansion Coefficient, \( \text{1/°C} \) |
|---------------|--------------------------------|----------------------|-----------------|-----------------------------------------------------|
| Steel 40X     | 7850                           | 2.0 \( \times \) 10\(^5\) | 0.3             | 1.2 \( \times \) 10\(^5\)                           |
| Floubon 20    | 2130                           | 1300                 | 0.4             | 6.6 \( \times \) 10\(^5\)                           |

### 3. Theory

Figures 3 and 4 show the results of calculating the radial displacements and equivalent stresses \( \sigma_{eq} \) for the cylinder walls in the discharge zone with the piston position \( X = 490 \text{ mm} \) and discharge pressure \( p_n = 10 \text{ MPa} \) without taking into account the temperature effect from the working gas of the piston unit.

![Figure 3. Radial displacements of the cylinder walls without taking into account the temperature effect from the working gas of the piston unit](image-url)
Figure 4. Equivalent stresses in the cylinder walls without taking into account the temperature effect from the working gas of the piston unit

To analyze the effect of temperature effects on the development of deformations and stresses in the cylinder walls of the unit, the design model provides a preliminary solution to the thermostatic task in the ANSYS WM software package using the standard Steady-State Thermal module (Figure 5). The resulting temperature distribution of the cylinder walls (45° – 70°C), of the piston (~ 50°C) and of the ring seals (~ 60°C) (Figure 6), which depend on the temperature of the working medium [22], [23], is transmitted to the Static Structural module for assessing the stress-strain state of the piston unit cylinder wall.

Figure 5. Scheme of the draft computational model for calculating the temperature and estimating the stress-strain state of the piston unit cylinder wall
Figures 7 and 8 show the results of calculating the radial displacements and equivalent stresses $\sigma_{eq}$ for the cylinder walls in the discharge zone with the piston position $X = 490$ mm and discharge pressure $p_n = 10$ MPa, taking into account the temperature effect from the working gas of the piston unit.

**Figure 6.** Compressor cylinder temperature distribution

**Figure 7.** Radial displacements of the cylinder walls taking into account the temperature effect from the working gas of the piston unit

**Figure 8.** Equivalent stresses in the cylinder walls taking into account the temperature effect from the working gas of the piston unit
4. Results discussion
The results of the calculations shown in Figures 3 and 7 (radial movements of the cylinder walls of the piston unit) and Figures 4 and 8 (equivalent stresses in the cylinder walls of the piston unit) show a significant temperature effect from the working gas on the stress-strain state of the cylinder low-speed stage long-stroke piston unit. In particular, there is an increase in the radial displacements of the walls of the cylinder walls from 14 \( \mu \text{m} \) to 25 \( \mu \text{m} \) in the injection zone and 19 \( \ldots \) 26 \( \mu \text{m} \) in the suction zone (excluding and taking into account temperature effects) and the growth of equivalent stresses in the cylinder walls from 120 MPa to 225 MPa suction zone. There is also an increase in equivalent stresses in the rigid support to 260 MPa.

5. Conclusion
The results of the analysis of the stress-strain state of the cylinder of a low-speed stage of a long stroke piston compressor unit show a significant influence of the temperature of the cylinder wall on their deformation in the radial direction, resulting in gaps between the internal wall of the cylinder and the piston. The size of the gaps reaches a significant value, which exceeds the allowable conditional gaps for low-speed stages of piston units, indicated in the sources [24] – from 0.5 \( \mu \text{m} \) to 10 \( \mu \text{m} \). The temperature effect of the working medium of the piston unit also causes a significant increase in the level of stresses in the material of the cylinder wall adjacent to the supports.

Thus, an analysis of the results shows that in order to reduce the deformation of the cylinder wall to acceptable values of the gap between the internal wall of the cylinder and the piston and reduce the level of stresses in the wall material, it is necessary to intensify the cooling processes of the cylinder wall of the piston stage unit.

6. References
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