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Calculation and research of the diaphragm compressor main elements

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Abstract. The article presents the experience of calculating and studying of the high-pressure membrane compressor main elements research experience, running on gaseous oxygen. The following issues are considered: determining the distribution and limiting disks surface profile, compressor main loaded elements strength calculation, modeling the temperature distribution in the membrane block during operation. These studies can be useful for further membrane compressor units development and can be used as a basis for calculations and new installations design.

Keywords: membrane compressor, high pressure, oxygen, membrane block, stress characteristics, temperature distribution.

1 Introduction

This article presents the main research in the most critical diaphragm compressor parts. The object of research is a membrane compressor unit with a suction pressure of 2.94 MPa, a discharge pressure of 29.4 MPa, and a capacity of 18 Nm³/h, designed for compressing oxygen gas and civil and industrial shipping needs. Diaphragm compressor design and production is a little studied and Russian compressor market complex branch. Membrane compressor production today in Russia is engaged in a small number of power engineering industries, one of them is JSC "Compressor", whose task was to produce a small-sized membrane compressor operating in a high-pressure zone, the working medium is high-purity oxygen [1-5]. This article subject is the membrane compressor strength characteristics study and the temperature distribution in the membrane unit.

2 Methods

The research purpose is to calculate and study the compressor units strength characteristics and temperature distributions in the membrane unit using modern software systems, namely ANSYS and SolidWorks [6, 7].

The following compressor elements strength calculations were performed:

1. The membrane strength calculation.
2. The crankshaft calculation dynamics and strength.
3. The plunger strength calculation.

A calculation was also performed to determine the temperature distributions in the membrane block

2.1 Initial data for the membrane strength calculation

Membrane verification calculation for strength begins with determining the minimum thickness of the membrane from the strength condition according to the method [1], p. 711, p. 46. We accept a membrane thickness of 4 mm.

The stresses that occur in the membrane during operation are determined by the formulas (2.1), (2.2) [1, p. 46]:

$$\sigma_{rp} = \frac{E \cdot \delta^2}{R^2} \cdot \frac{2 \cdot (q+1)}{(q-1)^2} \cdot \left[\frac{(3-\mu) \cdot (q+1)}{8 \cdot (1-\mu)} - \frac{2 \cdot (q+2-\mu)}{(q+3)(1-\mu)} + \frac{2 \cdot q+1-\mu}{4 \cdot q \cdot (1-\mu)} - \frac{q^{2q}}{4q} + \frac{2}{q+3} \cdot g^{q+1} - \frac{q+1}{8} \cdot g^2 \right] \quad (2.1)$$

$$\sigma_{tp} = \frac{E \cdot \delta^2}{R^2} \cdot \frac{2 \cdot (q+1)}{(q-1)^2} \cdot \left[\frac{(3-\mu) \cdot (q+1)}{8 \cdot (1-\mu)} - \frac{2 \cdot (q+2-\mu)}{(q+3)(1-\mu)} + \frac{2 \cdot q+1-\mu}{4 \cdot q \cdot (1-\mu)} - \frac{2 \cdot q+1}{4q} \cdot g^{2q} + \frac{2 \cdot (q+2)}{q+3} \cdot g^{q+1} - \frac{3 \cdot (q+1)}{8} \cdot g^2 \right] \quad (2.2)$$

where E - modulus for steel is assumed to be equal to $E=0,198 \cdot 10^6$ Pa;
 μ - the Poisson's ratio equal to be equal to $\mu=0,3$;
R - membrane radius in the seal, we take it equal to $R=0,05$ m.
g- relative radius, determined by the formula (2.3):

$$g = \frac{R_{current}}{R_{tightness}} \quad (2.3)$$

δ - deflection of the membrane at the Central point is assumed to be equal to $\delta = 1,3$ mm

2.2 Initial data for the crankshaft and plunger strength calculation

The crankshaft strength calculation will be performed in the ANSYS 19.2 software package using the StaticStructural and Model software packages [8, 9].

The crankshaft model is built using the KOMPASS 3D software package. The model definition starts with the grid construction. The grid model is constructed with the main element 8 mm size (fig. 1).

TABLE 5
Model (A4) > Mesh

Object Name	Mesh
State	Underdefined
Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	Mechanical
Element Order	Program Controlled
Element Size	8.0 mm

Fig. 1. Mesh characteristics the crankshaft

The main support surfaces and the shaft speed $\omega_1=78.5$ rad/s Fig.2.

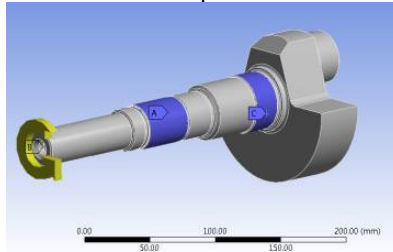


Fig. 2. Crankshaft fixation simulation

Similarly, with the preparation for the crankshaft calculation, the plunger model prepare. The grid model is constructed with the main element 8 mm size (fig. 3).

TABLE 5
Model (A4) > Mesh

Object Name	Mesh
State	Solved
Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	Mechanical
Element Order	Program Controlled
Element Size	8.0 mm

Fig. 3. Mesh characteristics the plunger

Setting the surfaces in the seal and the force action direction Fig. 4.

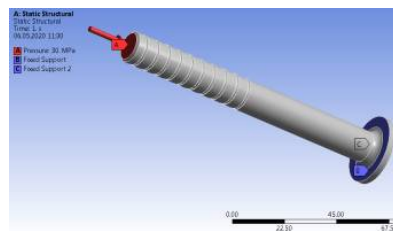


Fig. 4. Plunger fixation simulation

2.3 Initial data for the temperature distribution in the membrane block

When designing a membrane compressor, an important point is to study the temperature distribution in the membrane unit. Due to the small compression cavity volume, membrane frequent vibrations and a high compression ratio, the compressed gas temperature, and therefore the working parts, is high, so it is important to take into account the temperature distributions in the membrane block.

Temperature distributions are studied using the SolidWorks Flow Simulation software package [10-12].

The problem to be solved is internal we install plugs on all holes Fig.5.

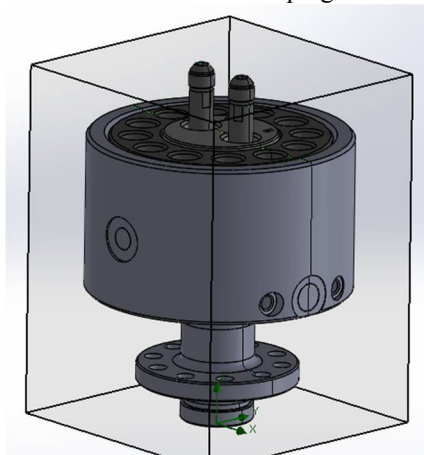


Fig.5. Membrane block simplified model with installed plugs

General system settings were set, and the data is shown in the table 1. The environment temperature, taken equal to normal conditions. The wall is assumed to be real, that is, capable of heat exchange with the environment.

Table 1. System general settings

Parameter	Value
Ambient temperature	20 °C
External ambient pressure	0,1 MPa
Wall heat transfer coefficient (for steel 38KHН3MFA GOST 4543-71)	$\lambda=34 \text{ kW/m}^2\text{K}$
Wall temperature	20 °C

Since the designed compressor is a membrane hydraulic drive, the working media oxygen and oil were selected (since its density is quite close to the direct working fluid PEF-130TU6-02-1072-86 characteristics). The flow of working media subdomains are determined Fig. 6.

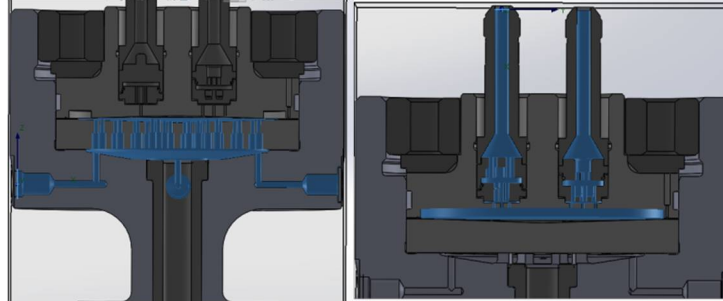


Fig.6. Flow subdomain for the liquid on the left and for the oxygen on the right

3 Results

3.1 Membrane strength calculation

The membrane strength calculations were performed using the Microsoft Excel software package. The results are shown in Figure 7.

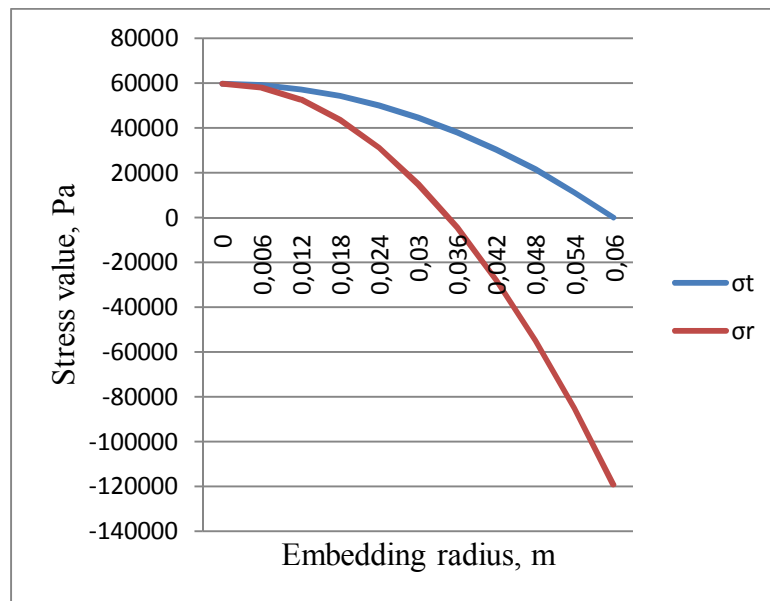


Fig. 7. Stress distribution (specify what these stresses are) from the center to the membrane periphery

From the data obtained, it can be seen that when working with a flat membrane, the most dangerous points are the membrane center and the sealing points. Comparing the

calculated and experimental data, we find that the obtained distribution does not contradict the thin shells theory.

3.2 Crankshaft and plunger strength calculation

Using the built-in ANSYS Static Structural module, consider the crankshaft strength, which accounts for the working environment main load [13-15].

The calculated values are total deformations and equivalent Mises stresses, Fig.8, 9.

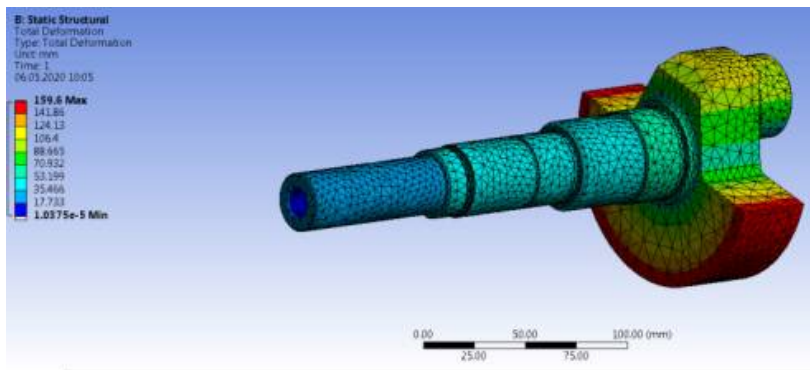


Fig. 8. The total strain

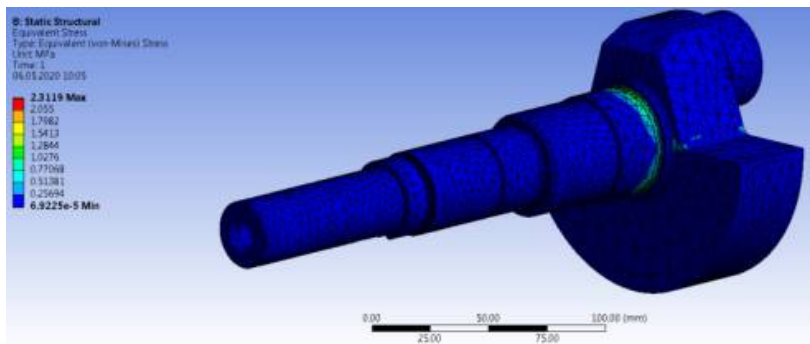


Fig. 9. Equivalent von Mises stress

An important condition in determining the strength crankshaft characteristics is to determine the critical speed, the speed at which the shaft occur greatest vibration amplitudes. ANSYS Modal has determined which shaft corresponds type to ours [16]. To do this, the number of harmonics for calculation was set to 12, since usually in practice only the most dangerous ones are paid attention to – bending ones, and all possible forms of vibrations (bending, transverse, longitudinal, rotational) will be modeled. It is enough to consider the first 3 harmonics for a complete picture.

The geometry, grid model, and research model are taken from the shaft analysis in ANSYS Static Structural [17, 18].

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To control the waveform, solutions in the form of Total Deformation are selected in the Solution tab. Animations of these values provide information about the oscillation shape [19-21].

The first three natural frequencies are shown in Fig. 10.

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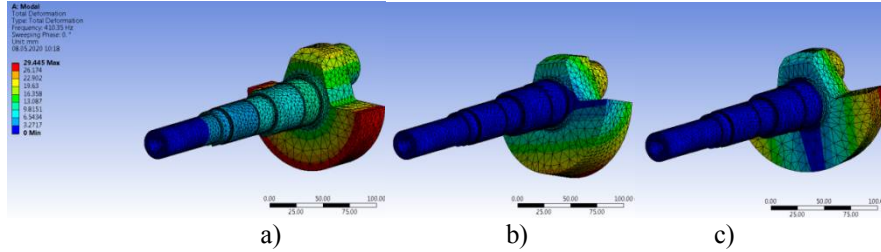


Fig. 10. natural frequencies: a) first harmonic b) second harmonic c) third harmonic

The study results are shown in table 2:

Table 2. Shaft natural frequencies

Harmonic number	Natural frequency, rad/s
1	410,3
2	3209,2
3	3368,2

The compressor shaft rotation speed is 12.5 rad/s, and the first critical frequency rotation frequency is 410.3 rad/s. thus, the designed high-pressure diaphragm compressor shaft operates at a sufficient distance from the first critical frequency and is rigid.

In the ANSYS Static Structural software module, consider the plunger strength, which accounts for the main load of the working environment [22, 23].

During the study, the following values were calculated: total deformations and equivalent Mises stresses, Fig. 11, 12.

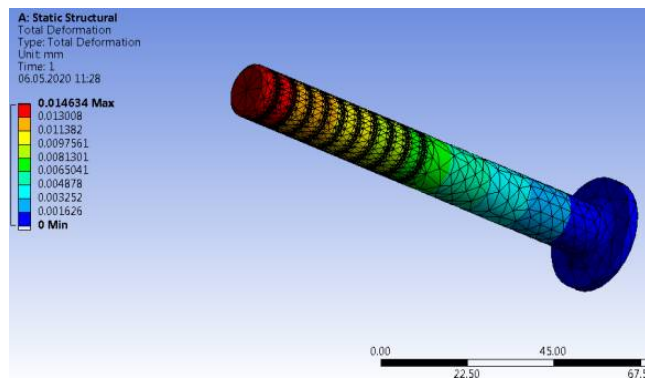


Fig.11. The total strain

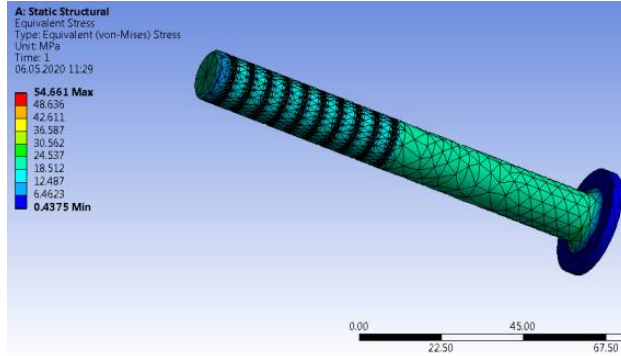


Fig.12. Equivalent von Mises stress

From the results obtained, it can be seen that the maximum deformations occur on the end plunger surface, where the maximum load falls. The maximum stresses arising in the plunger are 18.5 MPa, which satisfies the strength condition: $\sigma_{max} \leq \sigma$ for the steel material 38X2MYA GOST 4543-71 with $\sigma = 980$ MPa.

3.3 Temperature distribution in the membrane block

When setting the research task, it was found that it was necessary to find out how the temperature is distributed in the working area of the membrane unit, this temperature is transmitted to the elements of the membrane unit from the injected gas. During gas compression, the discharge temperature becomes 112 °C at the outlet of the membrane unit.

The limiting case was considered when the discharge temperature is constant and equal to 112 °C, i.e. the compressor unit operates at a given mode and the pressure and temperature of the suction and discharge are in equilibrium. The following conditions are set for the gas cavity, according to table 3:

Table 3. The boundary conditions for the gas chamber

Boundary condition	Values
«volume flow rate at the inlet»	0,0002 m ³ /s
«the volumetric flow rate at the exit»	0,00002 m ³ /s
«discharge pressure»	30 MPa (T _n =112 °C)

For the hydraulic cavity, according to table 4:

Table 4. The boundary conditions for the gas chamber

Boundary condition	Values
«inlet mass flow rate»	0,0665 kg/s
«inlet pressure»	3,0 MPa (T _n =40 °C)

Figure 13 shows a temperature distribution picture in the cross-section, which shows the temperature distribution at cross-section each point.

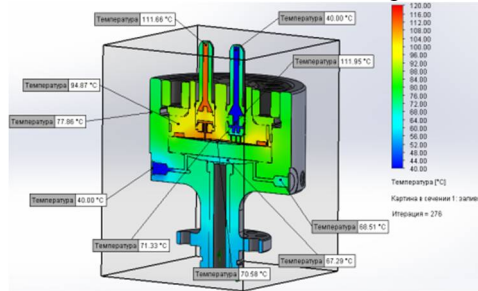


Fig. 13. Temperature distribution in the membrane block cross section

Heat exchange inside a metal membrane was considered. At the interface between hot oxygen and the membrane, the strongest heat exchange occurs. Due to the membrane small thickness, the temperature quickly becomes the same across the entire cross-section. Figure 14 shows the temperature distribution at the gas - liquid interface between a metal plate.

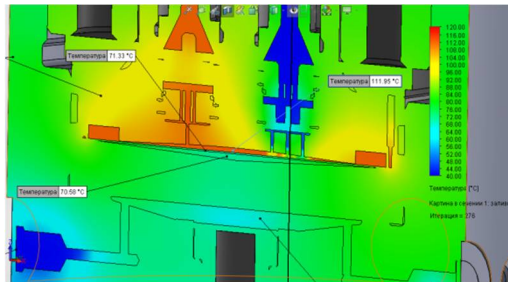


Fig. 14 Temperature distribution in the cross section at the gas-liquid interface between a metal plate

The greatest interest in the study is the change in the temperature of the working fluid. Entering the hydraulic cavity with a temperature of 40 ° C, the working fluid comes into contact with the distribution disk, through which a small volume for each revolution of the shaft enters the hydraulic cavity enclosed between the membrane and the disk. There is a liquid in the volume equal to $V = 0.000003 \text{ m}^3$ is in contact with the heated membrane and heat exchange occurs. Due to the large temperature difference and the working fluid small volume, rapid heating occurs. After moving the plunger to the lower dead center, the liquid from the volume between the membrane and the disk is again mixed with the total amount of liquid in the membrane block and heat exchange occurs Fig. 15.

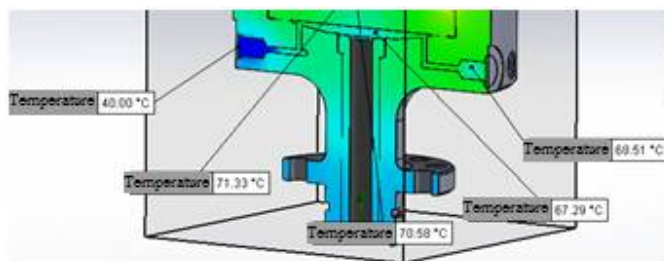


Fig. 15. Change in liquid temperature

Conclusions

The analysis of the main results of the calculations and studies allows us to note the following points for each of the studies.

An important point in the design is to determine the strength characteristics of the main loaded structural elements. It is necessary that these elements meet the strength conditions.

In terms of the strength calculation of the membrane, it is worth noting the importance of meeting the strength conditions of its main loaded places, namely the center and attachment in the sealing of the membrane block.

For the crankshaft, the most dangerous place was identified, namely the junction of the shaft and flywheel, which also meets all the requirements of the strength condition.

The plunger was subjected to an end load and it was found that it fully meets the strength conditions.

A simulation of the temperature distribution in the membrane block was also performed, which showed that oxygen entering the gas cavity of the membrane block heats the walls of the cavity, which at the initial stage have a temperature equal to the ambient temperature. When interacting with a hot gas, intense heat exchange occurs, due to which each point near the boundary changes its temperature. Heat exchange occurs unevenly due to the difference in the temperature parameters of suction and discharge, so the membrane unit will be heated unevenly.

Thus, the results obtained allow for more correct design of membrane compressor units and will be useful as an information base for future research in this area, as well as for use in design.

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