Numerically modelling temperature deformations and stresses in the exhaust system of a gas compressor unit

Maryna Demianenko [1*], *Michal* Volf [1], *Myron* Banias[2] and *Oleksandr* Starynskyi [3]

[1] University of West Bohemia, 22 Univerzitni, Pilsen, 32600, Czechia
[2] NAEK Energoatom, 22-24 Hoholivska, Kyiv, 01032, Ukraine
[3] Sumy State University, 2 Rymskogo-Korsakova, Sumy, 40007, Ukraine

Abstract. During the operation of a gas compressor unit, the temperature of the exhaust system can cause failure or burnout of the inner facing sheets of the unit. The article describes a technique for determining the maximum temperature deformations of these elements. The technique enables more accurate calculation of the temperature deformations by determining the influence of the contacts between the inner facing and the power frame on the temperature distribution and mobility of the exhaust system. The temperature deformations and stresses of the exhaust system elements are determined, and the level of the permissible stresses is evaluated. The results of the work can be used to prevent possible ruptures and burning of the inner facing, as well as to calculate the design dimensions of the lens expansion joint.

1 Introduction

The operational reliability and efficiency of gas-turbine stations and gas compressor units (GCUs) depend on their main elements, which comprise the axial compressor, combustion chamber, and high and low-pressure turbines. But no less important for ensuring uninterrupted energy-efficient operation of the installation are the inlet air preparation device and the exhaust system of the unit [1]. The GCU exhaust system removes the exhaust gases from the gas turbine engine, reduces the concentration of pollutants into the atmosphere, lowers the noise levels and keeps the hydraulic resistance within the limits necessary for the normal operation of the gas turbine engine. The GCU exhaust tract is a steel casing (power frame) placed on movable and fixed supports, consisting of a gas duct, a diffuser, an adapter, a rotary device, and a vertical exhaust pipe.

Designing an exhaust system includes the calculation of hydraulic resistance and the degree of purification of gases, and strength calculations. The strength calculations consider the main loads acting on the elements of the exhaust system, i.e. thermal and dynamic loads. As indicated in [2], thermal loads are calculated at the design stage and checked in the launch process, which allows some design solutions to be specified (e.g. design of lens expansion

* Corresponding author: demianen@fst.zcu.cz

joint). The existing engineering methods for calculating thermal loads do not allow the precise determination of the deformations of the GCU exhaust system elements. This is primarily due to the complexity of the exhaust system, the presence of many detachable and non-detachable joints, as well as basalt and sound-absorbing plates, which contribute to the temperature distribution, overall mobility of the power frame, and consequently, the deformations of the exhaust system's structural elements.

The dynamic processes in the exhaust system, namely the vibroacoustic influence of the flow on the inner facing, have not been taken into account by researchers. In [2] it was found that the gas flow is highly unstable, which is associated with the formation of vortices and their passage through the GCU exhaust system. The gas pressure fluctuations reach an amplitude of 110 kPa with a frequency of 10-15 Hz. These factors can lead to failures during operation, where the inner facing sheets collapse and there are blowouts of the lens expansion joints.

Therefore, the research goal is to conduct refined calculations of thermal loads on the GCU exhaust system to determine its deformations and stresses. In the future, it will allow us to determine the optimal sizes of the lens expansion joints and avoid the collapse of the inner facing. It will therefore ensure the reliable operation of a GCU and its exhaust system in various microclimatic zones. The research will be divided into two stages, which will allow us to separately assess the effects of thermal and dynamic loads on the elements of the GCU exhaust system. This article describes the calculation of the effects of the thermal loads.

2 Literature Review

The influence of the thermal load on a GCU exhaust system can be determined using numerical methods. This is confirmed in many works devoted to the numerical research of various elements of a GCU, which show that numerical methods allow us to reliably determine the operating parameters of a unit [3-6]. One method which can be used is finite element analysis (FEA), which is implemented in many software packages, including the Static Structural module of ANSYS. This module has also proved to be applicable for estimating the strength of complex industrial structures [7-10].

In [11] FEA and computational fluid dynamics (CFD) are used to evaluate the thermomechanical fatigue life of a cylinder head. The cylinder head has a complex internal design (including water and air ducts, etc.), and a full simulation would be quite complex and time-consuming. Therefore a simplified model of the cylinder head was developed for the simulation to find the deformations and stresses.

In [12], FEA of the thermal load of a small piston engine cylinder was carried out in ANSYS. The complex design of the cylinder head was simplified at the geometry preparation stage. The geometry was divided into separate parts, which allows a mesh of higher quality to be built. In such cases, a certain type of contact is specified between the separate bodies, which determines their interaction.

In [13], the thermal load characteristics of a double dry clutch were studied using ABAQUS software. Because of the focus on the temperature field distribution of the friction plate, the pressure plate, and the intermediate master plate, these parts were divided into separate bodies. The "standard" contact type was set between these plates, which determines the interaction of the surfaces and the possibility of common temperature deformations.

It is necessary to develop a simulation technique for each design on the basis of the reviewed works, which will consider features such as geometry, types of mountings, and materials. CFD and the methods described in papers [14, 15] can be used to estimate the dynamic loads on the GCU exhaust system elements caused by the vibroacoustic effects of the gas flow.

3 Research Methodology

Simulating the temperature deformations and stresses of the GCU exhaust system elements requires data on the maximum possible temperature gradients during operation in a microclimatic region with a cold climate. The temperature of the internal facing of the exhaust system is +514°C, the minimum temperature of the outside air is -50°C, the maximum temperature of the outside air is +32°C. The material configuration of the exhaust pipe walls is shown in Fig. 1. The temperature deformations and stresses will be modelled using FEA using the Static Structural module of ANSYS 2019 R2.

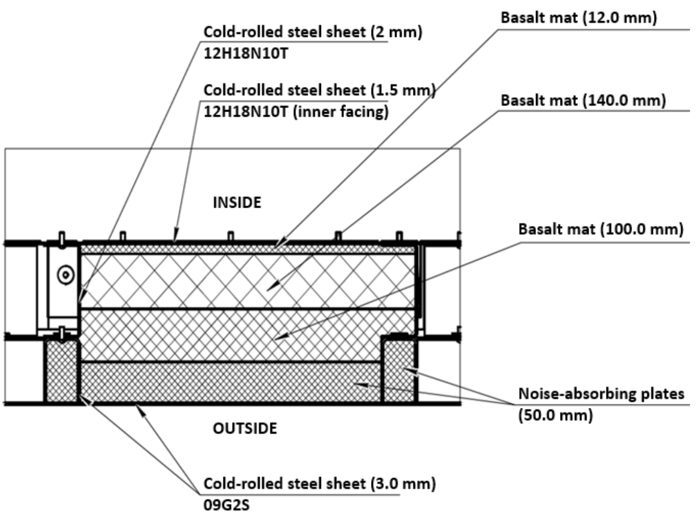


Fig. 1 – Design of the horizontal part of the GCU exhaust system

Due to the absence of fixed connections between the inner facing and the exhaust system power frame, as well as a large number of contacting surfaces, the numerical simulation of the temperature-stress state of the exhaust system horizontal section is extremely resource-consuming. Therefore, an analysis of the thermal stress state for each element was performed, and the total displacements were determined analytically according to these results.

During heating, the inner facing sheets expand, and the forces occurring in them can be divided into two types: forces resulting from constrained temperature deformations, and forces from outer loads (forces from the set-back reactions of the studs). The impact of the inner facing thermal deformations into the stress state of the power frame was evaluated by solving a test problem. The test section is shown in Fig. 2. The temperature of the inner facing equal to +514°C was set as the load, and the load from the weight of the power frame was set by including gravitational force in the calculation. The boundary condition "convection" was set on the outer walls of the outside facing of the exhaust system.

The contact type ‘Bonded’ is set between washer 1 and stud 2, meaning that the contact surfaces cannot move relative to each other, but joint temperature deformation is possible. The contact type ‘Frictional’ was set between washer 1 and facing 3, with a friction coefficient equal to 0.15, in which case slippage of the surfaces and their separation is possible. Stud 2, frame 4, and the outer facing 5 are fused into one body, as they are welded together. ‘Joint General’ joints were specified between stud 2 and facing 3, with the ability to move in all three coordinate axes and the ability to rotate about the axis of stud 2. Figure 3 shows the mesh, and the results of strain calculations are shown in Figure 4.

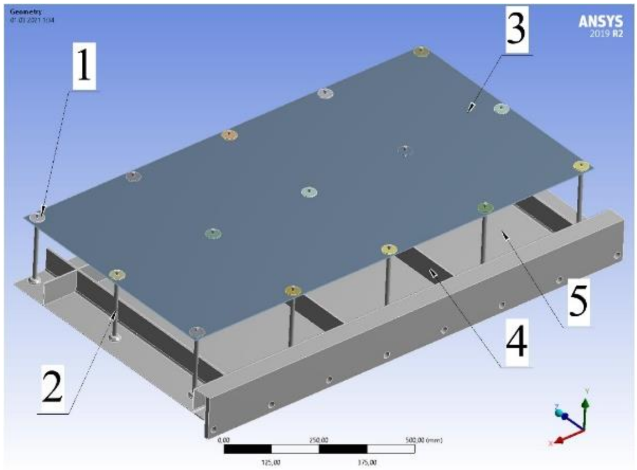


Fig. 2 – Design of the GCU exhaust system section for the test case: 1 – washer, 2 – stud, 3 – inner facing; 4 – power frame; 5 – outside facing

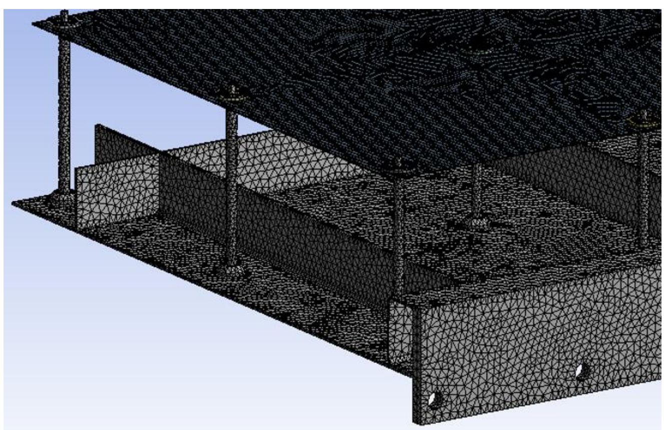


Fig. 3 – Computational mesh (Number of elements – 289 860)

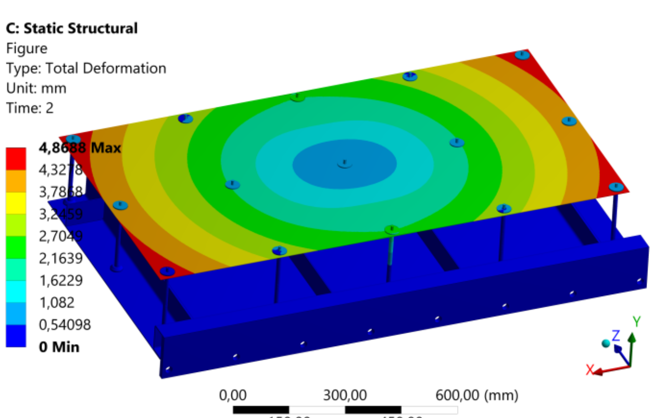


Fig. 4 – Temperature deformations of the section for the test case

The maximum calculated thermal deformations are detected in the corners of the facings and do not exceed 5 mm. The radial gap in the holes is 7 mm, so the temperature deformations of the inner facing are compensated for by the radial gap. Since the deformations of the inner facing are not constrained, it can be excluded from the calculation model of the whole exhaust system and only its weight is taken into account.

4 Results

Considering the placement and direction of the gaps in the sliding supports of the exhaust system, the outermost supports from the scroll housing side are fixed in the axial direction (Fig. 8). In this case, the adapter, diffuser, and the part of the gas duct from the left side of the fixed supports move towards the rotary device (to the left) under the action of thermal loads, and part of the gas duct from the right side of the support moves towards the scroll housing (to the right).

The maximum temperature differentials inside and outside the exhaust system were selected for the computations. The maximum temperature of the internal facing is +514°C and the minimum temperature of the outside air is -50°C. How was mentioned above, deformation of the inner lining does not affect to the deformations and stresses of the force frame. Hence, only weigh of the each plate of the inner lining was attached to this frame. This allows us to determine the maximum deformations and stresses of the exhaust system elements which may occur during operation.

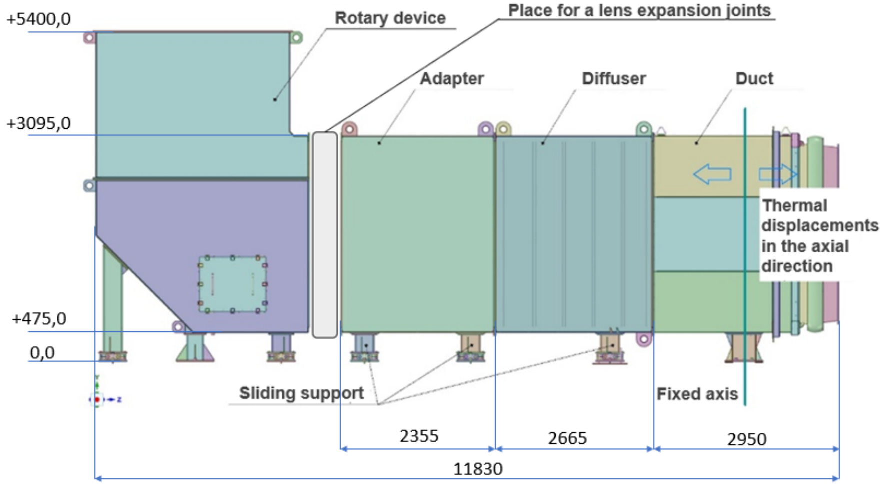
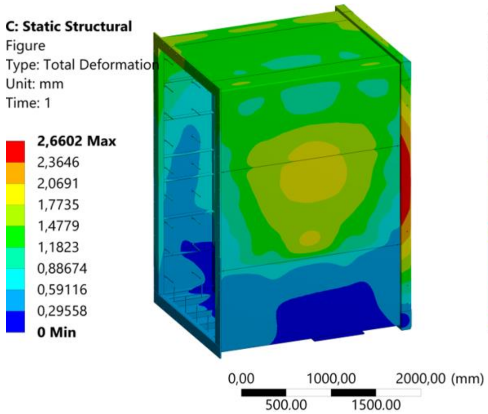
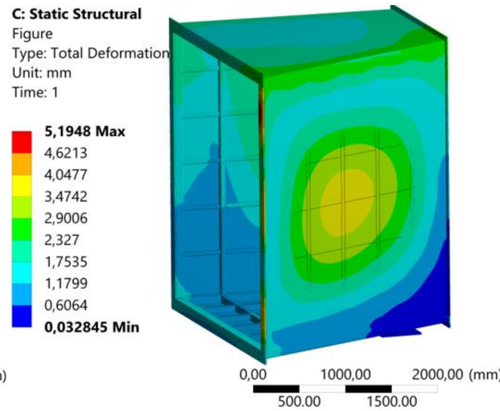


Fig. 5 – Design of the GCU exhaust system and location of lens expansion joint (dimensions in mm)

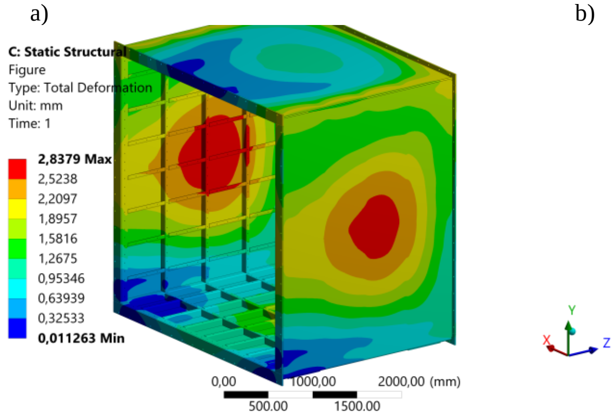
Figures 6a, 6b and 6c show the deformations of the gas duct, diffuser, and adapter. The thin lines show the initial state. The maximum total displacements are: gas duct flange 3 mm, diffuser flange 5.5 mm, and the adapter 3 mm. Table 1 shows the results of the calculation of thermal displacements of the diffuser and adapter flanges and the gas duct adjacent to the compensators under the action of thermal loads. Figures 7a, 7b and 7c show the locations of the control points on the flanges.



a)



b)

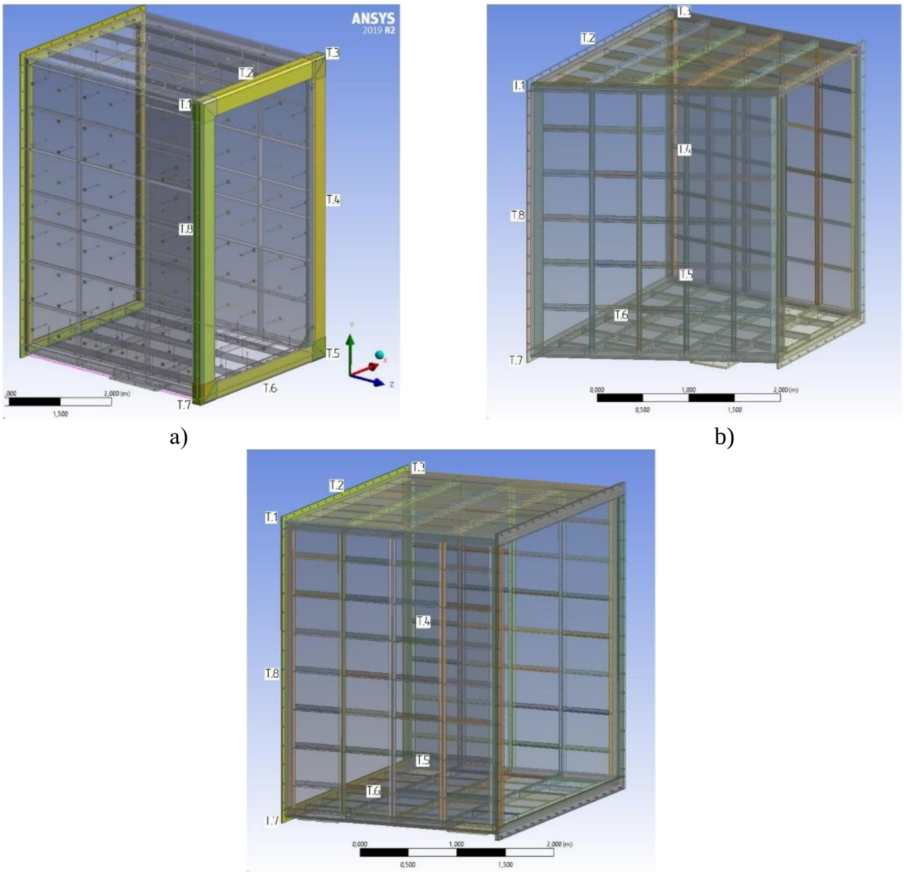


c)

Fig. 6 – Total deformations of the GCU exhaust system elements (a – gas duct; b – diffuser; c – adapter)

Table 1. Thermal displacements of the adapter flanges relative to the initial position.

	Flange 1 (from the scroll housing side)			Flange 2 (form the rotary device side)			Flange 3 (form the rotary device side)		
Direction	x	y	z	x	y	z	x	y	z
T. 1	1.0	0.9	0.3	-2.5	1.0	-1.8	-1.1	2.0	-3.0
T. 2	1.1	1.3	0.3	-1.7	0.4	-1.7	-0.1	2.0	-3.2
T. 3	1.3	0.8	0.2	-1.0	2.0	-1.5	1.0	2.0	-2.7
T. 4	0.3	0.5	0.5	-0.7	1.0	-1.6	-0.2	1.0	-3.1
T. 5	0.3	0.3	0.4	1.0	-0.4	-1.5	0.5	-0.2	-2.7
T. 6	0.1	-0.2	0.4	0.1	-0.4	-1.9	-0.1	-0.1	-3.4
T. 7	-0.3	0.4	0.4	-1.2	-0.5	-1.6	-0.5	-0.15	-2.9
T. 8	1.0	0.6	0.4	-2.1	0.5	-4.0	0.1	1.0	-5.5
Maximum displacement	1.1	1.3	0.5	-2.5	2.0	-4.0	-1.1	2.0	-5.5



a) b)

c)

Fig. 7 – The control points located on the flanges of the GCU exhaust system elements (a – duct from the scroll housing side; b – diffuser form the rotary device side; c – adapter form the rotary device side)

Figures 8a, 8b and 8c show the stress fields for the gas duct, diffuser, and adapter. It must be noted, that is no standards, which are determined allowable stress exactly for exhaust system of a gas compressor unit. In this case, was desisted to use for this purpose GOST 34233.1-2017 [16]. In its application area are written that, if the properties of materials, requirements for the design, manufacture and control of vessels and apparatus match the requirements of GOST 34347, them stress can be calculated according to GOST 34233.1-2017. This exhaust system of a gas compressor unit exact this case, it design, material properties manufacturing method are matched to requirements.

Hence, according to GOST 34233.1-2017 allowable stresses for carbon steel (09G2S) must be determined like:

$$[\sigma] = \eta \cdot min\left\{\frac{R_{elt}}{n_t} or \frac{R_{p0,2/t}}{n_t}; \frac{R_{m/t}}{n_b}; \frac{R_{m/10^n/t}}{n_d}; \frac{R_{p1,0/10^n/t}}{n_p}\right\},$$

where $R_{elt}, R_{p0,2/t}$, $R_{m/t}$, $R_{m/10^n/t}$, $R_{p1,0/10^n/t}$ - minimum yield strength at design temperature and minimum conditional yield strength at residual elongation of 0.2% at design temperature; minimum value of tensile strength (tensile strength) at design temperature; the average value of the limit of long-term tensile strength for a resource of 10n at design temperature; average 1.0% tensile creep strength in 10n at design temperature, respectively, MPa;

n_t , n_b , n_d, n_p - safety factor for yield strength; tensile strength (margin for tensile strength); limit of long-term strength; creep limit.

Allowable stresses for austenitic chrome nickel steel (12H18N10T) must be determined by GOST 34233.1-2017 like:

$$[\sigma] = \eta \cdot min\left\{\frac{R_{p0,2/t}}{n_t}; \frac{R_{m/t}}{n_b}; \frac{R_{m/10^n/t}}{n_d}; \frac{R_{p1,0/10^n/t}}{n_p}\right\}.$$

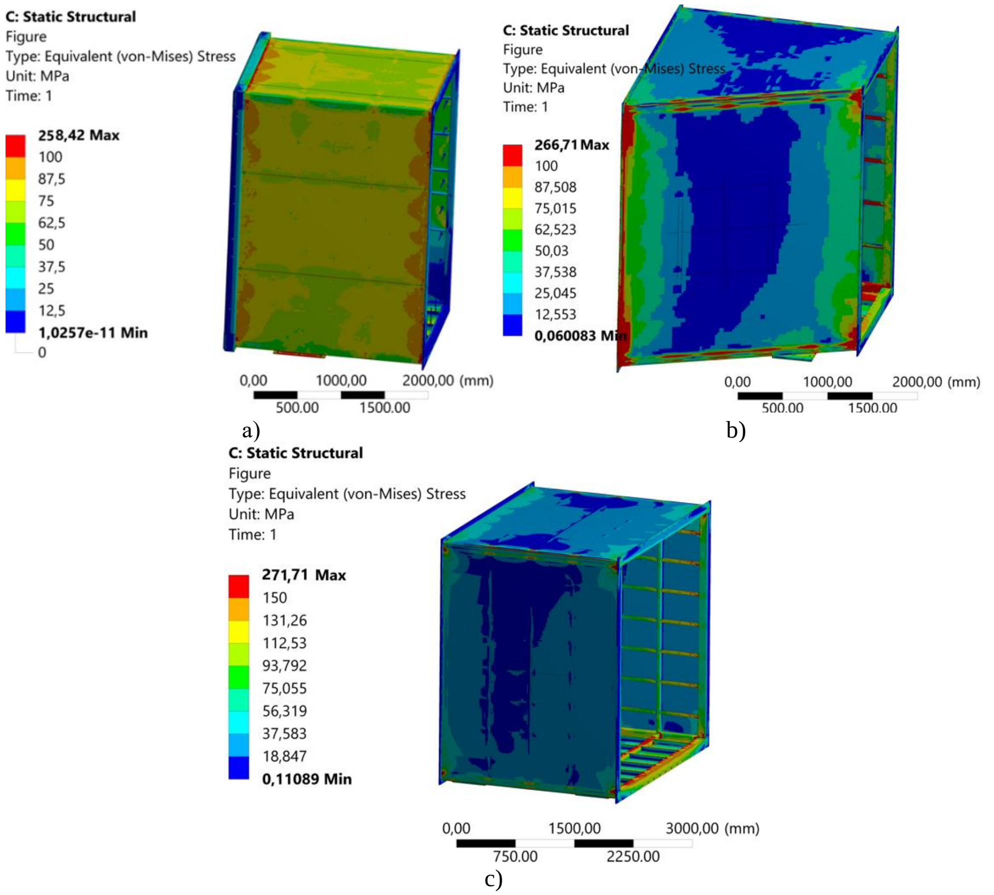


Fig. 8 – Equivalent Von-Mises stresses of the GCU exhaust system elements (a – gas duct; b – diffuser; c – adapter)

Determined values was written in table 2. These stresses were compared with those given in dangerous sections, determined by linearization according to third stress theory.

The linearized stress of the gas duct is 90 MPa, while the maximum stress in the flanges of the gas duct is 120 MPa. The stress is 50 MPa for the exhaust system diffuser, and the maximum stress in the diffuser flanges is 150 MPa. The linearized stress for the adapter is 70 MPa, and the maximum stress in the adapter flanges is 130 MPa.

Table 2. Stress analysis results according to GOST 34233.1-2017

Maximum stress location	Maximum stress	Temperature	Accepted allowable stress
gas duct flanges (12H18N10T)	120 MPa	76℃	180 MPa
diffuser flanges (09G2S)	150 MPa	82℃	177 MPa
adapter flanges (09G2S)	130 MPa	82℃	177 MPa

5 Conclusions

A technique for determining the temperature deformations and stresses in GCU exhaust system elements using numerical methods is designed. This includes carrying out a test problem to determine the influence of the mounting methods of the inner facing on the deformations of the power frame, and the subsequent selection of the calculation method for the elements.

The maximum temperature displacements of gas duct flange 1 adjacent to the lens expansion joint are determined to be:
- axial direction: 0.5 mm
- vertical direction: 1.3 mm
- exhaust system axial direction: ±1.1 mm

Maximum temperature displacements of the diffuser flange 2:
- axial direction: 4.0 mm
- vertical direction: 2.0 mm
- exhaust system axis direction: ±2.5 mm

Maximum thermal displacements of the adapter flange 3:
- axial direction: 5.5 mm
- vertical direction: 2.0 mm
- exhaust system axis direction: ±1.1 mm.

These results can be used to calculate the stress-strain state of the elements of a GCU exhaust system and to predict their further performance. These displacements make it possible to determine the dimensions of the lens expansion joint more accurately.

The strength of the flanges of the gas duct, diffuser and adapter is also evaluated and it can be confirmed that the strength conditions in the flanges of the exhaust system elements are satisfied.

References

1. A. Poletaev and A. Nedoshivina, “Investigation of characteristics and modernization of the design of exhaust tract gas turbine and gas compressors units”, Young scientists conference – 2017, UralENIN, «UrFU», pp. 123 – 124, 2017.
2. A. Lobanov, Evaluation of the exhaust system dynamic loads of a gas compressor unit by vibroacoustic characteristics: PhD Thesis. Perm: PNPU, 135 p., 2008.
3. O. Baturin, A. Krivcov, D. Kolmakova and V. Matveev, “Modeling, Analysis and Improvement of the Input Cleaning Device of a Gas Turbine Plant for Pumping Gas,” in Proceedings - 2019 21st International Conference; Complex Systems: Control and Modeling Problems; CSCMP 2019, vol. 2019–September, pp. 365–369, 2019.
4. E. Mekhonoshina and V. Modorskii, “Numerical modeling of aeroelastic behavior of GTU centrifugal compressor rotor,” in Procedia Engineering, vol. 201, pp. 655–665, 2017.

5. O. Kyrylash, V. Kostiuk, A. Smirnov, D. Tkachenko, and I. Loboda, Mathematical Simulation of the Gas Turbine Packages Thermal State, vol. Volume 5C: Heat Transfer. 2018.
6. A.A. Mesropyan and I.I. Mukhametzyanova, "Numerical Modeling of Gas Dynamics and Heat and Mass Transfer in the Cooling System of the GTE Box." USATU Bulletin Vol. 14 No. 1: pp. 25-31, 2010.
7. V. Anisimov, I. Zubrilin and M. Orlov, "Investigation of thermal and stress states of the annular combustion chamber flame tube walls," in Proceedings of the ASME Turbo Expo, vol. 4B, 2016.
8. A. Pugachev, A. Sheremetyev, V. Tykhomirov and A. Petrov, "Structural and dynamic optimization of a single axial compressor blade using the gradient-based method," in Proceedings of the ASME Turbo Expo, vol. 7B, 2014.
9. Micha Premkumar T. et al., "Optimizing the Design and Material used for Connecting Rod through Finite Element Simulation," International Journal of Vehicle Structures and Systems, vol. 13, no. 5, pp. 548–552, 2021.
10. A. Belhocine, D. Shinde and R. Patil, "Thermo-Mechanical Coupled Analysis-Based Design of Ventilated Brake Disc Using Genetic Algorithm and Particle Swarm Optimization," SAE International Journal of Passenger Cars - Mechanical Systems, vol. 14, no. 2, pp. 137–150, 2021.
11. W. Yang et al., "Thermo-mechanical fatigue life prediction based on the simulated component of cylinder head," Engineering Failure Analysis, vol. 135, p. 106105, 2022.
12. L. Lei and C. Bing-Wei, Finite element analysis of thermal load on cylinder head of small-sized piston engine, U.P.B. Sci. Bull., Series D, Vol. 81, Iss. 2, 2019.
13. C. Xie, G. Wu, S. He, Y. Zhang, and J. Tian, "Finite Element Analysis of Thermal Load Characteristics of Dry Dual Clutch," Journal of Physics: Conference Series, vol. 1748, no. 5, p. 52047, Jan. 2021.
14. O. Liaposhchenko, I. Pavlenko, K. Monkova, M. Demianenko and O. Starynskyi, "Numerical simulation of aeroelastic interaction between gas-liquid flow and deformable elements in modular separation devices," Lecture Notes in Mechanical Engineering, pp. 765–774, 2020.
15. M. Demianenko, M. Volf, V. Pavlenko, O. Liaposhchenko, I. Pavlenko, The solution of the stationary aeroelasticity problem for a separation channel with deformable sinusoidal walls. Journal of Engineering Sciences, Vol. 7(1), pp. D5–D10, 2020.
16. GOST 34233.1-2017, Vessels and apparatus. Norms and methods of strength calculation. General requirements, 35 p., 2018.