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# Investigation of thermomechanical processes in miniature membrane elastic elements

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## ABSTRACT

**Purpose:** The demand for the devices structures reliability and machines requires understanding elements operation, in particular elastic elements, under the effect of non-stationary temperature factors. Therefore, it is important to investigate the behaviour of these elements under variable temperature effecting.

**Design/methodology/approach:** In this article, the temperature field and the thermal stresses of the membrane type elastic elements, as well as the thermal deformation of its body part were investigated by the method of numerical analysis. The theoretical results have experimental confirmation.

**Findings:** The article shows possibilities significantly reduce the thermal stress in an elastic element, thereby increase its functional and structural reliability by varying the geometric parameters of the elastic element, the materials selection, and body shape.

**Research limitations/implications:** Numerical modelling of thermal processes requires accurate information about the physico-mechanical properties of materials and heat-exchange coefficient, which in practice may differ from the theoretical ones. Therefore, experimental confirmation of research and decisions is needed. The influence of the "hot" thermal shock was investigated. There is performed interest to investigate the "cold" thermal shock.

**Practical implications:** The obtained results allow creating elastic elements with better functional characteristics for operation in a wide temperature range. They can also be used in the designing of elastic elements not only of membrane type.

**Originality/value:** Performed investigation of thermomechanical processes in the membrane elastic element has revealed important features of its temperature deformations with non-stationary thermal influence. Namely, the nature of thermal deformations can be changed by selecting the geometrical parameters of the element, its material, as well as the conditions of heat-exchange conditions with mating member (body). In this way, it is possible to obtain a controlled deformation and to design the elastic elements with predetermined functional tasks.

On the other hand, the design of the membrane element body can create elastic hinges, which allows reducing the thermal stress in the membrane, which significantly increases the reliability of the element operation of this type in conditions of non-stationary temperatures. In general, the conducted investigations allow efficient design of elastic elements for devices, sensors and other precision mechanisms.

**Keywords:** Thermal stress, Thermal deformation, Thermal shock, Elastic elements, Elastic hinge

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PROPERTIES

## 1. Introduction

Today, miniature membrane elastic elements are widely used in precision instruments. They are used as precision mechanical sensors transducers (piezoelectric, piezoresistive, capacitive) (Fig. 1), or various mechatronic devices [1-6].

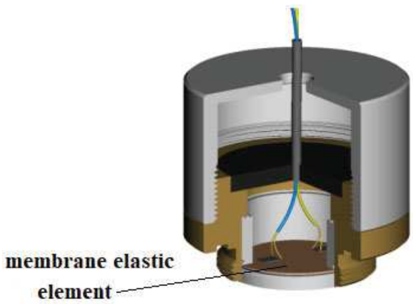


Fig. 1.Membrane elastic element in pressure sensor

The membrane in its function perceives some mechanical value (force, pressure, displacement, etc.), and the deformation of the membrane is an information signal or has a kinematic purpose. Therefore, the accuracy of the conversion function of a membrane element is crucial in the devices or systems where such element is used.

The expansion of the usage scope of these elements has given resulted in new operating conditions. Among other things, there is an increasing demand for elastic elements to be used in a wide range of non-stationary temperature influences, in particular sharper thermal shocks [7-10].

The membrane element usage showed that during "hot" thermal shock the membrane can thermally deflect to transient plastic deformations, and during "cold" thermal influence the membrane can break. In addition, if the membrane element is subjected to periodic thermal shocks, thermal membrane oscillations may occur. The described phenomena are the cause of the violation of the functional characteristics of the elastic elements, up to the loss of their structural reliability. Therefore, these relevant investigations aimed at improving the reliability of such elements.

In this article, on the basis of thermomechanical membrane element processes investigations, recommendations are given regarding the material and element parameters, as well as the design of its body part, which allows reducing the thermal stress in the membrane, which significantly improves the reliability of the operation of the elements.

## 2. Investigation of thermomechanical processes in the membrane

Scheme of the membrane elastic element contains the membrane in the round steel plate form, which is rigidly pinched in a massive cylindrical body (Fig. 2).

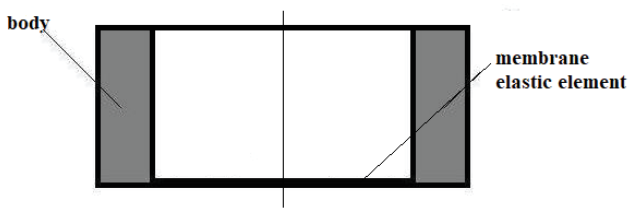


Fig. 2. Schematic diagram of a membrane elastic element

The temperature field in the membrane which contacts the medium with a non-stationary temperature on one side (Fig. 3) is described by the equation [11]:

$$\frac{\partial^2 T(r,z,t)}{\partial r^2}+\frac{1}{r}\frac{\partial T(r,z,t)}{\partial r}+\frac{\partial^2 T(r,z,t)}{\partial z^2}-\frac{1}{\chi}\frac{\partial T(r,z,t)}{\partial t}=0 \quad (1)$$

Boundary and initial conditions for this case

$$\left.\begin{aligned} &\frac{\partial T(r,z,t)}{\partial r}+l_3(T(r,z,t)-T_1)=0 \ \text{ at } \ r=R \\ &\frac{\partial T(r,z,t)}{\partial z}-l_1(T(r,z,t)-T(t))=0 \ \text{ at } \ z=0 \\ &\frac{\partial T(r,z,t)}{\partial z}+l_2(T(r,z,t)-T_1)=0 \ \text{ at } \ z=h \\ &T(r,z,t)=T_0=const \ \text{ at } \ t=0 \end{aligned}\right\} \quad (2),$$

Where $l_1$, $l_2$, $l_3$ are the normalized coefficients of heat exchange on the contact and inner surfaces and perimeter of the membrane; $T_0$ – the initial temperature of the membrane, which is the same throughout its body; $\chi=\frac{K}{\rho\cdot c}$ – coefficient of thermal conductivity; $\rho$ and $c$ – density and specific thermal conductivity; $R$ and $h$ – radius and thickness of the membrane; $T_1$ is the temperature of the medium in contact with the perimeter and the inner surface of the membrane; $T(t)$ – temperature of external influence; $r$ and $z$ are the coordinates along the radius and the thickness of the membrane.

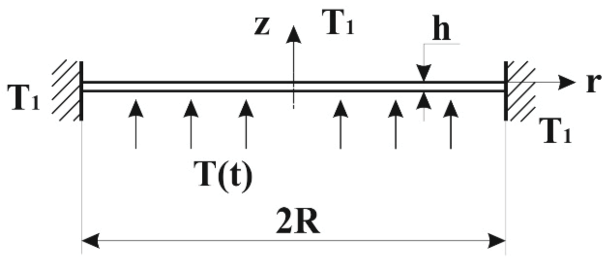


Fig. 3. The scheme of heat-exchange on the surfaces of the membrane

For the investigations, the membrane thickness varied within 0.1-0.5 mm and the radius 3-10 mm. Such membrane elements parameters are relevant in the designs of various sensors and mechatronic elements. The results of numerical simulation of heat transfer in the membrane at thermal shock 400°C at different coefficients of heat exchange on the perimeter are shown in Fig. 4-Fig. 6.

These investigations revealed important facts, namely: by the time of establishing a stable temperature field, there is a temperature gradient along the membrane thickness (Fig. 4) and there may be a gradient along the radius (Fig. 5), but under certain conditions of heat exchange at the perimeter and geometric parameters of the membrane it is practically absent along the radius (Fig. 6)

These facts explain the occurrence of the membrane thermal deflection under variable temperature. During the gradient in thickness and along the radius occurs thermal deflection. However, if there is no gradient along the radius at a temperature gradient along the membrane thickness, no thermal deflection occurs.

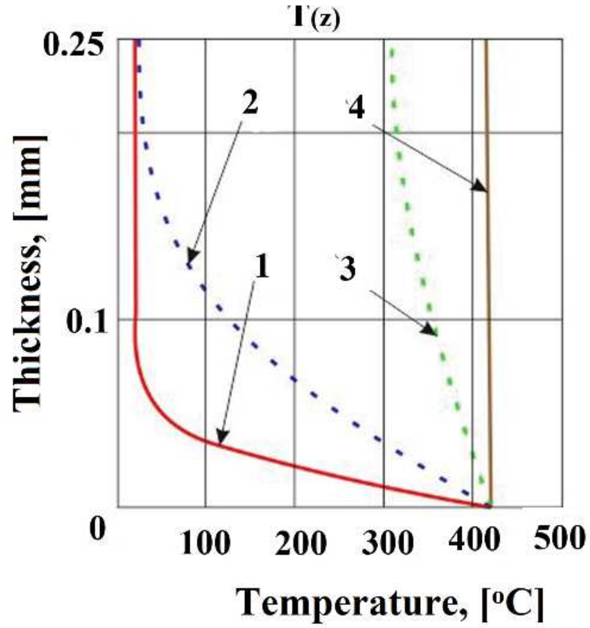


Fig. 4. Temperature dynamics along the thickness of the membrane, at its centre at discrete moments: 1 – at $t = 10$ ms; 2 – at $t = 0.1$ s; 3 – at t = 0.2 s; 4 – at t = 0.3 s

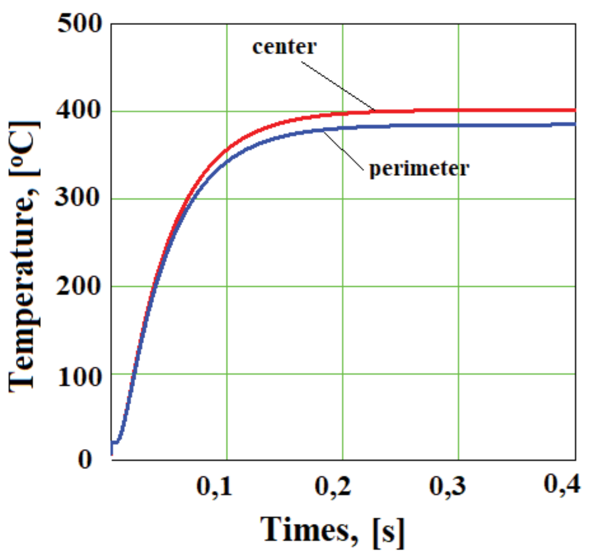


Fig. 5. Temperature dynamics at different points of the membrane at normalized coefficient of heat exchange on perimeter $l_3 = 200m^{-1}$

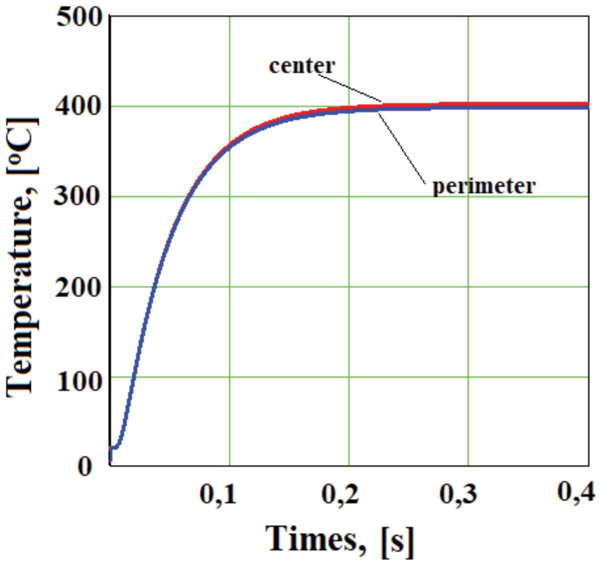


Fig. 6. Temperature dynamics at different points of the membrane at normalized coefficient of heat exchange on perimeter $l_3 = 225 m^{-1}$

a)

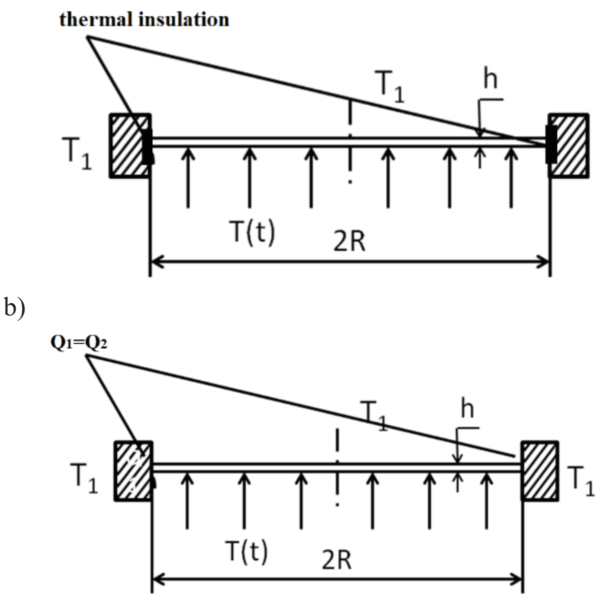


Fig. 7. Heat exchange diagrams at the perimeter of the membrane

It is possible to get rid of the temperature gradient along the radius of the membrane by minimizing the heat transfer at the place of its fixation in the body. The absence of heat exchange between the membrane and the body will be in the case of thermal insulation of the membrane around the perimeter (Fig. 7a), or if the body material has a thermal conductivity that will provide zero heat transfer ($Q_1 = Q_2$) at the place of membrane attachment in the body (Fig. 7b).

The obtained theoretical results were experimentally checked, namely, the temperature field linearity in the membrane and the dynamics of thermal deflection were investigated.

For this purpose, a membrane element with temperature-sensing elements attached along the radius of the membrane (Fig. 8) was suddenly mounted on a massive plate heated to 400°C.

Fig. 8. Membrane element with temperature-sensing elements

The results of the experiments are presented in Figure 9.

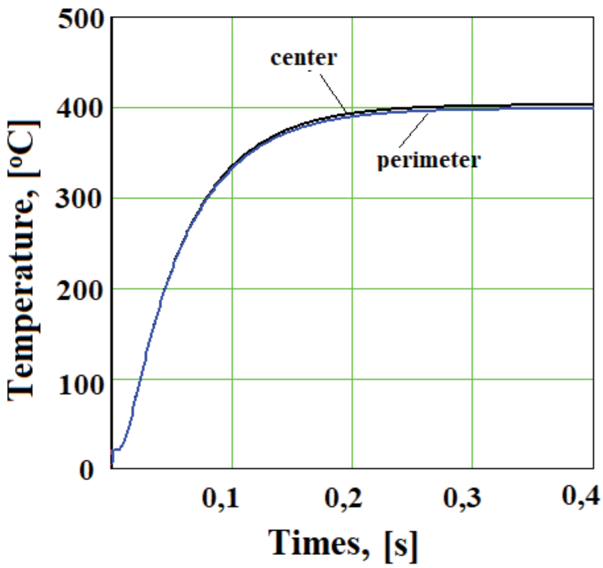


Fig. 9. Temperature dynamics in the centre and at the perimeter of the membrane during thermal shock

Thus, the maximum temperature difference in the centre and perimeter of the membrane was 1.2%. That is, the gradient along the radius was practically absent.

It is known that the membrane, in addition to possible thermal deformations, will undergo thermal stresses under temperature variable, which is described by the dependencies [12]:

$$\sigma_r(r,z,t) = \frac{E}{1-\nu^2}\left[\varepsilon_r + \nu\varepsilon_\phi - (1+\nu)\lambda_л T(r,z,t)\right] \quad (3)$$

$$\sigma_\varphi(r,z,t) = \frac{E}{1-\nu^2}\left[\varepsilon_\varphi + \nu\varepsilon_r - (1+\nu)\lambda_л T(r,z,t)\right] \quad (4)$$

where $E$ is elasticity modulus, $\mu$ – the Poisson ratio, $\alpha_0$ – the linear thermal expansion coefficient, $\varepsilon_r$, $\varepsilon_\phi$ – the radial and tangential deformations generated by the irregularity of the temperature field in the membrane, $T(r,z,t)$ – are the values of the temperature at the point of the membrane with coordinates $r$, $z$ and $t$ time.

During the hard membrane fixing, $\varepsilon_r = \varepsilon_\varphi = 0$ therefore:

$$\sigma_r(r,z,t) = \frac{E}{1-\mu}\left[-\alpha_0 T(r,z,t)\right] \quad (5)$$

$$\sigma_\varphi(r,z,t) = \frac{E}{1-\mu}\left[-\alpha_0 T(r,z,t)\right] \quad (6)$$

Obviously, in the case of $\varepsilon_r = \varepsilon_\varphi = 0$ voltage (3-4), is significantly smaller than (5-6). That is, if the membrane does not have the possibility of thermal expansion it can lead to membrane destruction under the influence of temperature and, thus, its low reliability. Therefore, if the mounting of the membrane allowed its temperature deformation in its plane, then in this case the membrane would have only the stresses generated by the irregularity of the temperature field in it. However, the membrane elastic element in its functional purpose inevitably has a rigid fixing.

## 3. Thermomechanical processes investigation in the membrane element body

It is obvious that the membrane element body, which has the form of a hollow cylinder, will also undergo thermal deformation under temperature. In order to find out the mutual influence of the membrane body thermal deformations, simulations of thermomechanical processes in the body of the membrane element were carried out.

If on all surfaces of the hollow cylinder (Fig. 10) there is a convective heat exchange with variable temperatures of mediums, and one end of the body is fixed, then the other undergoes the so-called "opening" (Fig. 11).

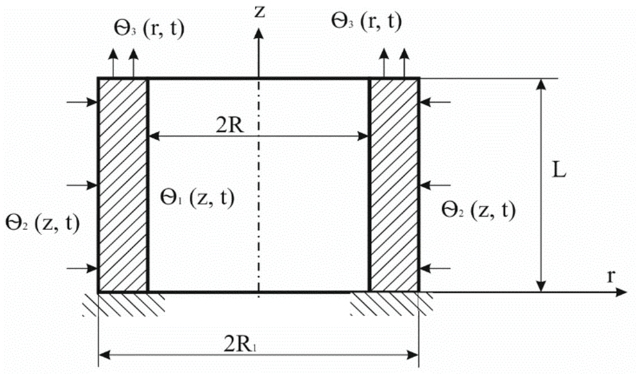


Fig. 10. Scheme of heat transfer on the cylindrical body surfaces of membrane elastic element ($L$, $R$, $R_1$ – height, inner and outer radii of the body, $\Theta_1(z,t), \Theta_2(z,t), \Theta_3(r,t)$ – temperatures of the media in contact with the cylinder surfaces

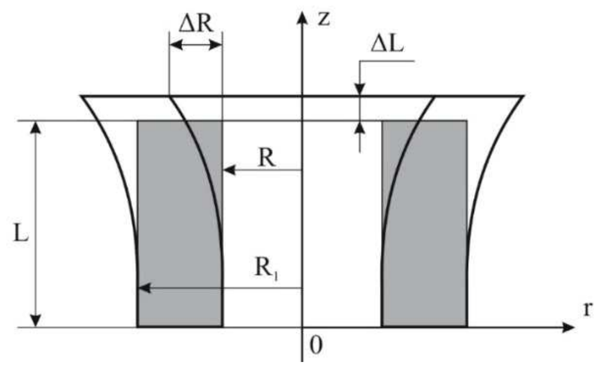


Fig. 11. Thermal deformation of the membrane element body

We obtain the axial $\Delta L$ and radial $\Delta R$ of the thermal point's displacements dynamics of on the inner body wall by numerical modelling.

For example, in the case of heat exchange in the inner body cavity with airspace, the absolute radial and axial thermal point's displacements on the inner body wall have the dynamics shown in Figure 12 and Figure 13. The most relevant body parameters of the membrane element were used for the calculation: $R = 2$ mm, $R_1 = 2.5$ mm, $L = 5.2$ mm.

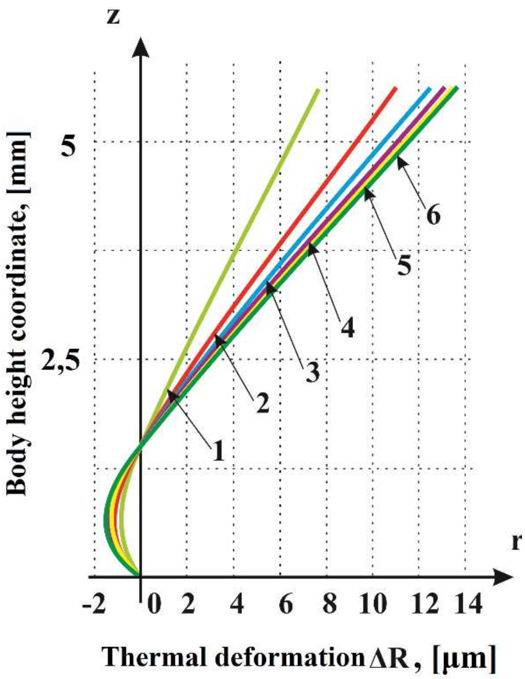


Fig. 12. The body wall thermal deformation of the membrane element in the radial direction at discrete moments of time: 1 – at $t = 10\ ms$; 2 – at $t = 50\ ms$; 3 – at $t = 0.1\ s$; 4 – at $t = 0.2\ s$; 5 – at $t = 0.3\ s$; 6 – at $t = 0.4\ s$

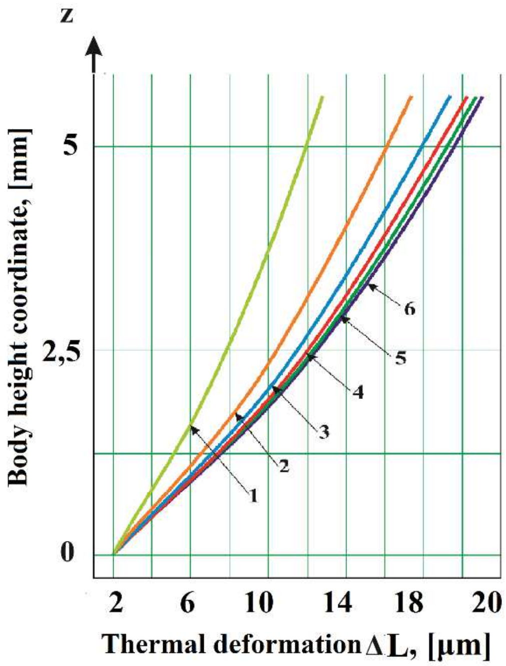


Fig. 13. Axial thermal deformation body wall of the membrane element at discrete moments: 1 – at $t = 10\ ms$; 2 – at $t = 50\ ms$; 3 – at $t = 0.1\ s$; 4 – at $t = 0.2\ s$; 5 – at $t = 0.3\ s$; 6 – at $t = 0.4\ s$

The modelling shows that the relative radial thermal body deformation in the area of attachment of the membrane reached 0.7%. It is this phenomenon that significantly affects the elastic element. Moreover, depending on the thermal deformation dynamics of the body, the membrane may initially shrink and then expand. Therefore, to reduce the thermal stresses in the membrane, it is proposed to complete the membrane element body (section A, Fig. 14) in the form of a torus quarter (torus ring).

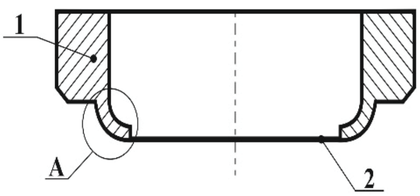


Fig. 14. Membrane element with a torus-shaped body edge

In addition, knowing that the housing is more massive than the membrane, it is suggested to make it of heat-resistant material with special heat treatment [13] and with linear thermal expansion coefficient bigger than membrane (for example, still the membrane made of 15X28 (10CrAl24, 446) alloy having a coefficient of linear temperature expansion $\lambda_1 = 10.1 \cdot 10^{-6}\ K^{-1}$, and the body made of XH60BT (Inconel 600) alloy having a coefficient of linear temperature expansion $\lambda_2 = 14.1 \cdot 10^{-6}\ K^{-1}$. The numerical modelling of thermomechanical processes in the membrane-body system selected the geometrical parameters of the torus part so that the dynamics of the radial expansion of the membrane and body were similar.

The theoretical results were experimentally checked.

As noted earlier, the membrane, which is rigidly fixed around the perimeter under the effect of non-stationary thermal influence, undergoes thermal stresses (5)-(6). Therefore, under pressure, the thermally stressed membrane deflection may be significantly different from the deflection of the membrane under normal conditions. This fact was used in the experimental efficiency verification of the torus body section of the membrane element.

Two devices were manufactured with identical membranes for research, but one device had a membrane 2 fixed in a cylindrical body 1 (Fig. 15), and in another device a massive body 4 had a torus edge 2 in which the membrane 1 were fixed (Fig. 16). In addition, thermocompensated piezoresistors 3 were fixed on the membranes. With the help of the piezoresistors the membrane deflection was fixed.

The membranes in both devices were identical. Based on the studies described above, the membranes parameters and the heat transfer coefficients on their perimeters were selected so that during the thermal shock action the membranes did not undergo thermal deflection.

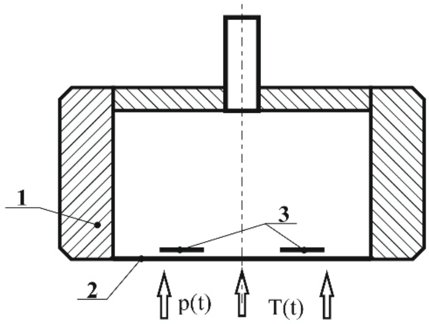


Fig. 15. Test device design with cylindrical body

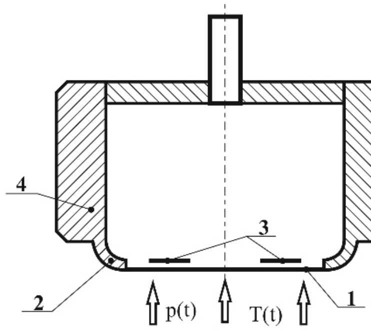


Fig. 16. Test device design with torus body edge

Further, the devices were placed in flasks (Fig. 17), which were sealed and air was pumped from them. Air was also pumped from the cylinder cavity to equilibration with an external vacuum.

Fig. 17. Vacuum flask with membrane elastic element

In the first experiments cycle, the flasks were mechanically destroyed and only a pressure shock under normal conditions acted on the membranes. The membranes deflection in this case was fixed by piezoresistors (Fig. 18).

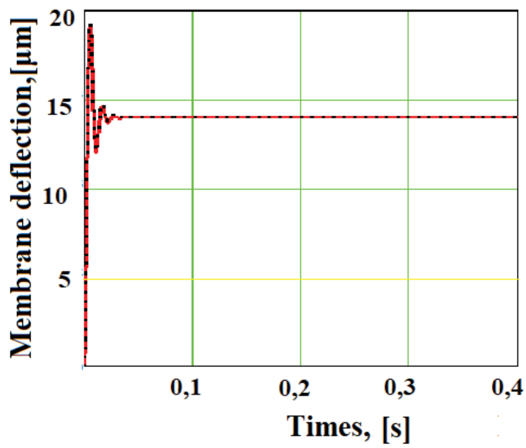


Fig. 18. Membrane deflection upon pressure impact

Since the output signals from resistive-strain sensors were almost similar (the maximum difference was 0.1%), it is possible to assert the characteristics identity of the membranes.

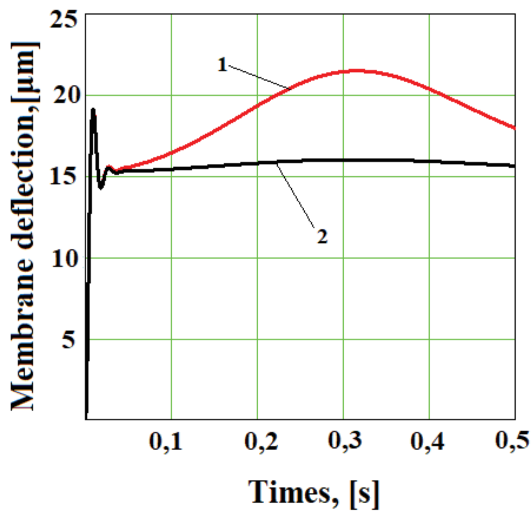


Fig. 19. Membranes deflection under thermal shock impact; 1 – membrane in cylindrical body, 2 – membrane in a torus-shaped body

Then the devices were again placed in the flasks, vacuumed, and then quickly immersed in a tank heated to a temperature of + 400°C with gas. Since the evacuation of the flasks was carried out in such a way that the flasks material was stressed at the tensile strength, than immersed in the hot gas they were immediately destroyed and the hot gas wave acted on the membranes. So, the pressure and heat shock have already effect on the membranes. Due to the fact that the flasks were pre-evacuated the front of the gas wave was more rapid. The results of the experiments are presented in Figure 19.

As we can see from the obtained results, the maximum membrane element deflection with a cylindrical body is 30% less than the maximum deflection under normal conditions. And in a membrane element with a torus-shaped body edge, the maximum deflection is only 4% less than the deflection under normal conditions.

The obtained experimental results show that the presence of a torus-shaped element creates an elastic hinge and allows the membrane thermal deformation in its plane, which significantly reduces the thermal stress in it during thermal shock. Obviously, this solution will increase the structural reliability of the elastic element and the efficiency of operation.

## 4. Conclusions

Thermomechanical processes investigations in a membrane elastic element have revealed important features of its temperature deformations in non-stationary thermal influences. Namely, the nature of thermal deformations can be changed by selecting the geometrical element parameters, its material, as well as the conditions of heat exchange with the coupled element-body. In this way, it is possible to obtain a controlled deformation and to design the elastic elements with predetermined functional tasks.

The body design of the membrane element can create elastic hinges, which allows reducing the thermal stresses in the membrane, which significantly increase the functional and structural reliability of elements in conditions of non-stationary temperatures.

Numerical thermal processes modelling requires accurate information on the physical and technical materials properties and heat transfer coefficients, which in practice may differ from the theoretical ones. Therefore, experimental research confirmation and decisions is required.

The influence of the "hot" thermal shock was investigated. There is performed interest to investigate the "cold" thermal shock.

The results obtained can be used in elastic elements design not only membrane type.

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