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AN ANALYTICAL SOLUTION TO THE PROBLEM OF THE THERMOMECHANICAL STATE OF A ROD OF LIMITED LENGTH WITH SIMULTANEOUS PRESENCE OF END TEMPERATURES AND LATERAL HEAT EXCHANGE

Abstract. This article deals with the problems of numerical study of the thermomechanical state of rods. On the basis of the fundamental law on the change in the amount of heat, an equation of the established thermal conductivity for a horizontal rod of limited length and a constant cross section is constructed through a fixed cross-section in a time $\partial\tau$. In this case, different temperatures are set at the two ends of the investigated rod, and heat exchange with the surrounding medium takes place through the lateral surface. In addition, the investigated rod is made of thermal protective material ANV-300. The determining law of the distribution of temperature, of all the corresponding deformations and stresses, and also of the displacement along the length of the investigated rod. The values of the thermal elongation and the resulting axial force are calculated.

Keywords:temperature, rod, thermal energy, algorithm.

In a complex thermal zone, bearing components of reactive and hydrogen engines, nuclear and thermal power stations, processing lines of processing industries, as well as internal combustion engines operate. The reliable operation of these structures will depend on the conditions of the thermoelectric power of the bearing components. Therefore, this study is devoted to a numerical study of the state of the thermoelectric power of the structural components in the form of rods of limited length, bounded at both ends.

The proposed computational algorithm is based on the principle of energy conservation. In this case, all types of integrals in the functional energy formulas are integrated analytically. In this case, the numerical solutions obtained will have high accuracy.

1. Statement of the problem

We consider a horizontal rod of limited length and a constant crossed section which area is$F(cm^2)$. The axis ox of the rod is directed from the left to the right which coincides with the axis of the rod.At the left end of the rod, the temperature$T_1[c^0]$, is given, and the direction $T_2[c^0]$. In this case $T_1 > T_2$. Through the lateral surface of the rod, heat exchange takes place with its surrounding medium. In this case, the heat transfer coefficient $h\left[\frac{watt}{cm^2 \cdot c^0}\right]$, and the ambient temperature$T_{oc}[c^0]$. The calculation scheme of the process is shown in Fig. 1

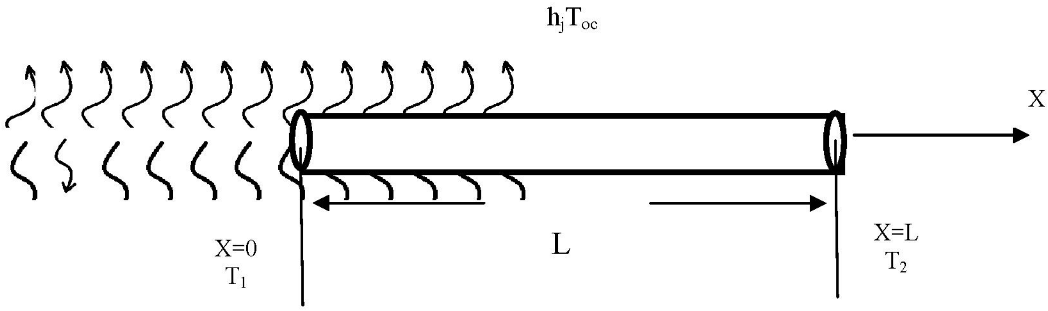


Figure 1 - The calculation scheme of the problem

It is required to determine:

1) The law of temperature distribution along the length of the investigated rod.
2) The amount of thermal elongation of the test rod.

In case of pinching the two ends of the rod, it is necessary to determine:

3) The arising axial forces.
4) The field of distribution of the components of deformations and stresses.
5) The field of distribution of displacement.

The physical and mechanical properties of the material of the rod under investigation are characterized by the coefficients of thermal conductivity $K_{xx}\left[\frac{watt}{cm^2\cdot c^0}\right]$, thermal expansion $\alpha\left[\frac{1}{c^0}\right]$ and elastic modulus $E\left[\frac{kg}{cm^2}\right]$. If we take into account that the investigated process of the rod material is much larger than the cross-sectional area, then it is possible to neglect the temperature gradients in the directions perpendicular to the axis of the rod without significant error, and take the temperature constant at each point of the cross section perpendicular to the axis. With this assumption, a temperature with a function of only one independent variable$x$, and the field of temperature distribution along the length of the rod can be described by an ordinary differential equation.

According to the fundamental law of thermophysics, the amount of heat passing through the time dt through the cross sections of the rod at a distance of x [cm] from its left end will be

$-K_{xx}F\frac{dT}{dx}d\tau$ (1)

where$T(x)$ – is the temperature distribution field, which is still unknown.

At that time, the amount of heat passing through the time dt through the cross section, located at a distance $x+dx$[см] from the left end of the rod, will be equal to

$$-K_{xx}F\left(\frac{dT}{dx}+\frac{d^2T}{dx^2}dx\right)d\tau \quad (2)$$

In addition, the portion of the rod enclosed between the sections spaced from the left end of the rod at a distance of x and $x+dx[cm]$, due to the thermal conductivity process, acquires during the time dt the amount of heat equal to the difference of the indicated quantities (1) and (2) e.

In addition, the portion of the rod enclosed between the sections spaced from the left end of the rod at a distance of x and $x+dx$[cm], following the heat conduction process, acquires in the time dt the amount of heat equal to the difference of the indicated amounts (1) and (2),

$$K_{xx}F\frac{d^2T}{dx^2}d\tau \quad (3)$$

It should also be noted that during this same time, a heat loss is equal to

$$hPdx(T-T_{oc})d\tau \quad (4)$$

where $P[cm]$ is the cross sectional.

But since the process we are investigating is steady-state, i.e. stationary, then the from (3-4) we have

$$K_{xx}F\frac{d^2T}{dx^2}dxd\tau = hPdx(T - T_{oc})d\tau \quad (5)$$

From this, for the problem under consideration, we determine the equation for the steady-state heat conductivity

$$\frac{d^2T}{dx^2} = \frac{hP(T - T_{oc})}{K_{xx}F} \quad (6)$$

For convenience, we introduce the notation

$$a^2 = \frac{hP}{K_{xx}F} \quad (7)$$

considering that the ambient temperature$T_{oc} = const, 0 \le x \le l$, then we have

$$\frac{d(T - T_{Oc})}{dx} = \frac{dt}{dx} \quad (8)$$

hence we also obtain

$$\frac{d^2T}{dx^2} = \frac{d^2(T - T_{oc})}{dx^2}, 0 \le x \le l \quad (9)$$

Taking (7) and (9) into account, we rewrite (6)

$$\frac{d^2(T - T_{oc})}{dx^2} - a^2(T - T_{oc}) = 0 \quad (10)$$

This equation is an ordinary differential equation with constant coefficients. Then its general integral will be

$$T - T_{oc} = C_1e^{ax} + C_2e^{-ax}, \quad 0 \le x \le l \quad (11)$$

where$C_1$and$C_2$are constants of integration. Their values are determined from the boundary conditions at the ends of the rod.

$$T(x = 0) = T_1[c^0];T(x = l) = T_2[c^0]; \quad (12)$$

$$\left.\begin{aligned} T_1 - T_{oc} &= C_1 + C_2 \\ T_2 - T_{oc} &= C_1e^{al} + C_2e^{-al} \end{aligned}\right\} \quad (13)$$

From these systems, the valuesC_1 and C_2.

$$\left.\begin{aligned} C_1 &= \frac{(T_2 - T_{oc}) - (T_1 - T_{oc})e^{-al}}{2sh(al)} \\ C_2 &= \frac{(T_1 - T_{oc})e^{al} - (T_2 - T_{oc})}{2sh(al)} \end{aligned}\right\} \quad (14)$$

Substituting (14) into (11), we determine the field of temperature distribution along the length of the rod under consideration, taking into account the operating conditions [2]

$$T(x,h,K_{xx},P,F,T_{oc}) = T_{oc} + \frac{(T_2-T_{oc})sh(ax)+(T_1-T_{oc})sha(l-x)}{sh(al)},0 \le x \le l \quad (15)$$

On the basis of the fundamental theory of thermal physics, it is possible to determine the elongation of the rod under consideration if it is pinched by one end and the other is free

$$\Delta l_T = \int_0^l \alpha T(x)dx = \alpha \int_0^l T(x)dx = \alpha\{T_{oc}l + [(T_2 - T_{oc})(ch(al)-1)/a - (T_1 - T_{oc})(1 - ch(al)/a)]/sh(al)\} \quad (16)$$

In the event that both ends of the rod are clamped, an axial compressive force R is produced in it, which will be directed along its axis ox. Its value is determined by the corresponding Hooke law [3]

$$R = -\frac{\Delta l_T EF}{l} = -\frac{\alpha EF}{l}\{T_{oc}l + [(T_2 - T_{oc})(ch(al)-1)/a - (T_1 - T_{oc})(1 - ch(al)/a)]/sh(al)\} \quad (17)$$

In this case, according to the length of the investigated rod, the distribution law of the thermoelastic component of the voltage t can be determined according to the generalized Hooke law

$$\sigma = \frac{R}{F} = -\frac{\alpha E}{l}\{T_{oc}l + [(T_2 - T_{oc})(ch(al)-1)/a - (T_1 - T_{oc})(1 - ch(al)/a)]/sh(al)\} \quad (18)$$

Then the distribution law of the corresponding thermo-elastic component of the deformation is also determined according to Hooke law

$$\varepsilon = \frac{\sigma}{E} = -\frac{\alpha}{l}\{T_{oc}l + [(T_2 - T_{oc})(ch(al)-1)/a - (T_1 - T_{oc})(1 - ch(al)/a)]/sh(al)\} \quad (19)$$

Further, according to the theory of thermal physics, the law of distribution of the temperature component of deformation

$$\varepsilon_T(x) = -\alpha T(x) = -\alpha\left\{T_{oc} + \frac{(T_2 - T_{oc})sh(ax) + (T_1 - T_{oc})sha(l-x)}{sh(al)}\right\}, 0 \le x \le l \quad (20)$$

Then the temperature component of the voltage is already determined according to Hooke law

$$\sigma_T(x) = E\varepsilon_T(x) = -\alpha E\left\{T_{oc} + \frac{(T_2 - T_{oc})sh(ax) + (T_1 - T_{oc})sha(l-x)}{sh(al)}\right\}, 0 \le x \le l \quad (21)$$

After this, according to the theory of thermo elasticity, it is possible to determine the law of distribution of the elastic component of deformation

$$\varepsilon_x(x) = \varepsilon - \varepsilon_T(x) = -\frac{\alpha}{l}\{T_{oc}l + [(T_2 - T_{oc})(ch(al)-1)/a - (T_1 - T_{oc})(1 - ch(al)/a)]/sh(al)\} +$$
$$\alpha\left\{T_{oc} + \frac{(T_2 - T_{oc})sh(ax) + (T_1 - T_{oc})sha(l-x)}{sh(al)}\right\}, 0 \le x \le l \quad (22)$$

Then, according to Hooke law, we can determine the law of distribution of the elastic component of the voltage

$$\sigma_x(x)=E\varepsilon_x(x)=\sigma-\sigma_T(x)=\frac{\alpha E}{l}\{T_{oc}l+[(T_2-T_{oc})(ch(al)-1)/a-(T_1-T_{oc})(1-ch(al)/a)]/sh(al)\}+$$
$$\alpha E\left\{T_{oc}+\frac{(T_2-T_{oc})sh(ax)+(T_1-T_{oc})sh(a(l-x))}{sh(al)}\right\},0\le x\le l \quad (23)$$

Finally, we can determine the law of distribution of the displacement of the cross-section of the rod. ItisdeterminedfromtheCauchyrelations

$$\varepsilon_x(x)=\frac{\partial u}{\partial x};\Rightarrow U=\int\varepsilon_x(x)dx+C \quad (24)$$

Here the value of the constant C is determined from the pinning conditions $U(x=0)=0$. Then we have

$$U(x)=-\alpha\left[T_{oc}+\frac{chal-1}{alshal}(T_1+T_2-2T_{oc})\right]x+\alpha\left\{T_{oc}x+\frac{1}{ashal}[(T_2-T_{oc})chax-(T_1-T_{oc})]\right\}$$
$$+\frac{\alpha}{ashal}[(T_1-T_{oc})chal-(T_2-T_{oc})] \quad (25)$$

Then we have l=100см, $K_{xx}=100\frac{\text{Вт}}{\text{смс}^0}$; h=10$\frac{\text{Вт}}{\text{см}^2\text{с}^0}$; $T_{oc}=20^0C$; α=125·10^{-7} $\frac{1}{c^0}$; E=2·10$^6\frac{kg}{cm^2}$; T_1=600^{0}C; T_2=100^{0}C; r=1cm.

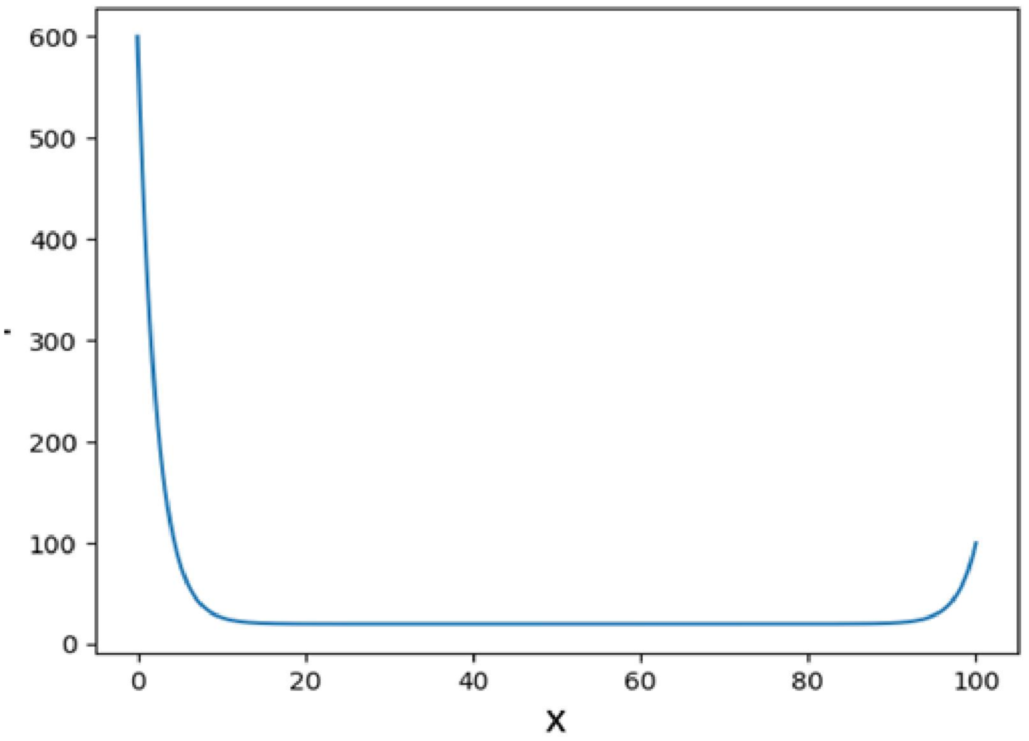
Then we get the results shown in Figure-2. In Figure-2, a) the law of the distribution of temperature along the length of the rod is given. The resulting law of distribution of deformation components is given in Figure-2, b). It can be seen from the figure that the thermo-elastic component of the deformation Ɛ-is constant along the entire length of the rod.

At that time, the elastic component of the deformation $\varepsilon_x(x)$, on stretches near the jamming, has a stretching character. In the middle section of the rod, $\varepsilon_x(x)$ has a compressive character. The temperature component of the deformation $\varepsilon_T(x)$ along the entire length has a compressive character. Its maximum value corresponds to the highest temperature.

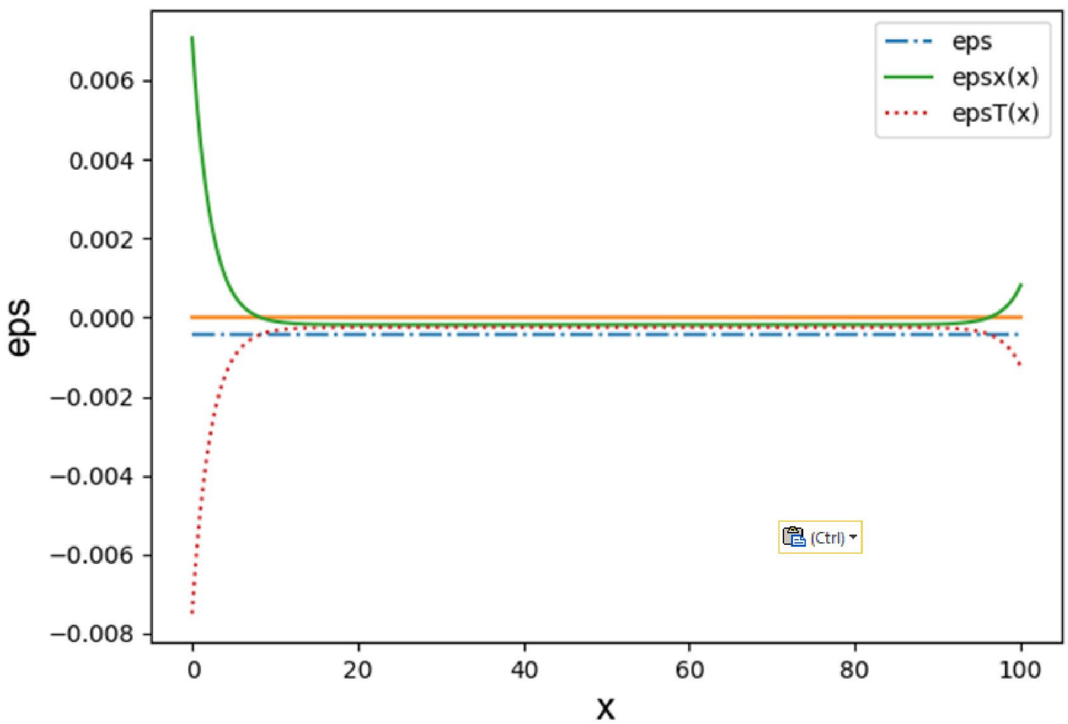
The nature of the component stresses is similar to the corresponding deformations. This is clearly seen from Figure-2, c). In Figure-2, d) the distribution field for the displacement of the cross-sections of the rod is given. It can be seen from the figure that the cross-sections of the rod in section $0<x\le 6{,}9$ are moving in the direction of the x axis. At that time, the largest displacement Umax1 = 0.0043092 cm corresponds to the coordinate cross-section of which x = 8 cm;

The cross sections of the rod located in the section 70 <x <l = 100 cm move against the direction of the axis ox. Here, the largest displacement U_{max2}=-0,0016472 cm corresponds to a cross section whose coordinate is x = 94 cm. Moreover, $|U_{max1}|/|U_{max2}|=2{,}61639$;

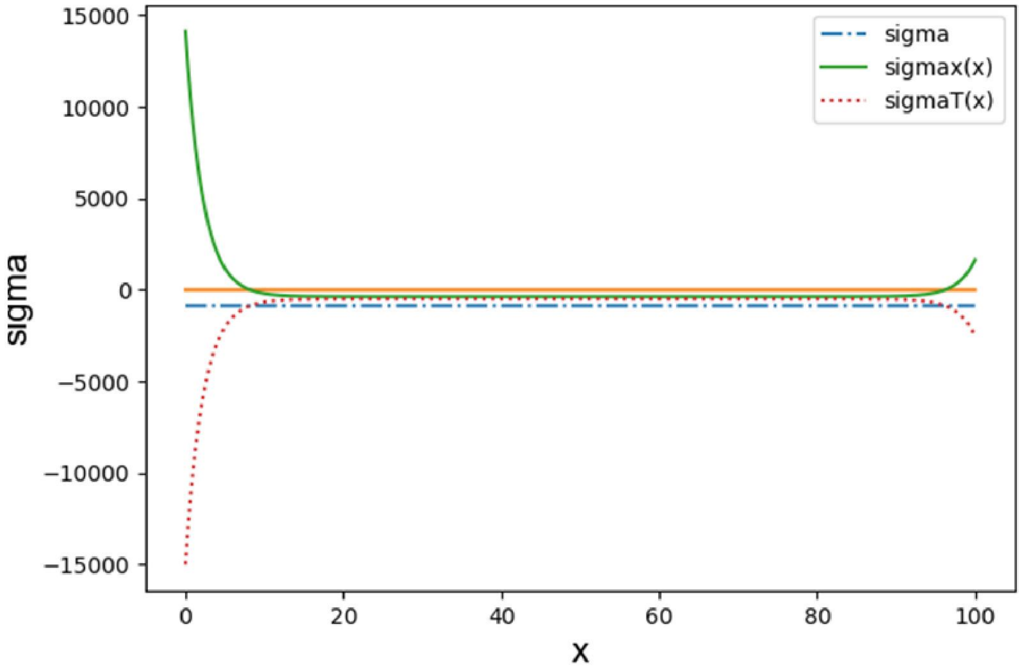
a) The temperature



b) the deformation



c) voltage



d)move

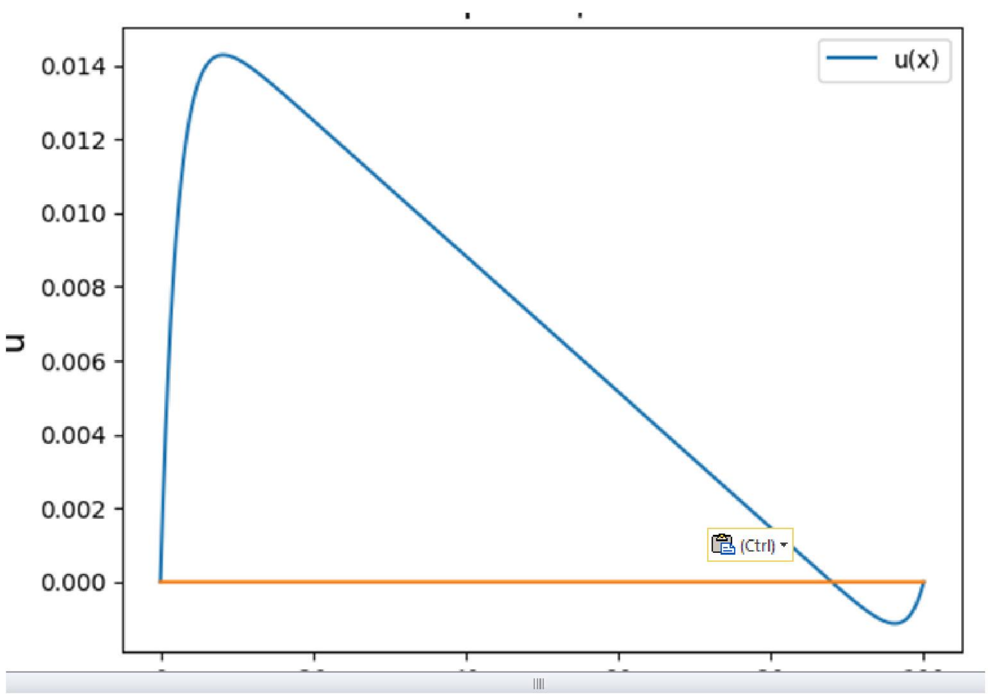


Figure - 2. The laws of distribution of temperatures, strains, stresses and displacements

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ҰЗЫНДЫҒЫ ШЕКТЕУЛІ ТҰРАҚТЫ ТЕРМОМЕХАНИКАЛЫҚ КҮЙДІҢ БІР МЕЗГІЛДЕ ШЕКТІК ТЕМПЕРАТУРАНЫҢ ЖӘНЕ БҮЙІРЛІК ЖЫЛУ АЛМАСУ ӘСЕРІ ЕСЕБІН ТАЛДАМАЛЫҚ ШЕШУ

Аннотация. Бұл мақалада өзектің термомеханикалық күйін сандық зерттеу проблемалары қарастырылады.

Көптеген өндіріс орындарында негізгі құрылым элементтері күрделі жылу көздері әсерінде тұрақты жұмыс жасайды. Өндірістің үздіксіз жұмыс жасауы әрине сол элементтердің сынып қалмауына тікелей байланысты. Сондықтанда алдын – ала негізгі құрылым элементтердің әр түрлі жылу көздері әсерінде қандай термо-механикалық жағдайда болуын терең зерттеу өндірістің үздіксіз, тұрақты, сапалы жұмыс жасау тұрғысынан өте өзекті мәселе болып табылады.

$\partial\tau$ уақытта тұрақты көлденең қима арқылы өтетін жылу мөлшерінің өзгеруі туралы іргелі заңның негізінде шекті ұзындықты және қимасы тұрақты көлденең өзектің жылу өткізгіштігінің теңдеуін құруға болады.

Бұл жағдайда қарастырылған өзектің екі ұшында әртүрлі температура белгіленеді, ал қоршаған ортамен жылу алмасуы бүйірлік бет арқылы өтеді. Сонымен қатар, зерттелетін өзек ANV-300 термиялық қорғаныш материалынан жасалған. Барлық орын алатын деформациялар мен кернеулерге байланысты, сондай-ақ зерттелген өзектің ұзындығы бойынша қозғалу кезіндегі температура таралуын анықтайтын заң. Жылулық ұзартудың және осьтік күштің мәндері есептеледі.

Реактивті және сутегі қозғалтқыштарының компоненттері, ядролық және жылу электр станциялары, өңдеу өнеркәсібінің өңдеу желілері, сондай-ақ ішкі жану қозғалтқыштары бар күрделі жылу аймағында жұмыс істейді. Осы құрылымдардың сенімді жұмыс істеуі мойынтіректер компоненттерінің термоэлектрлік қуатына байланысты болады. Демек, бұл зерттеу екі жағында шектелген шектеулі ұзындықтағы өзектер түріндегі құрылымдық компоненттердің термоэлектрлік қуатының жай-күйін сандық зерттеуге арналған.

Ұсынылған есептеу алгоритмі энергия үнемдеу принципіне негізделген. Бұл жағдайда функционалдық энергетикалық формулалардағы интегралдардың барлық түрлері аналитикалық түрде интегралданған. Бұл жағдайдаалынғансандықшешімдержоғарыдәлдіккеиеболады.

Тірек сөздер: жылу ағыны, жылу беру, жылу өткізгіштік, жылу алмасу, жылу оқшаулау.

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АНАЛИТИЧЕСКОЕ РЕШЕНИЕ ЗАДАЧИ О УСТАНОВИВЩЕГОСЯ ТЕРМОМЕХАНИЧЕСКОГО СОСТОЯНИЯ СТЕРЖНЯ ОГРАНИЧЕННОЙ ДЛИНЫ ПРИ ОДНОВРЕМЕННОМ НАЛИЧИИ КОНЦЕВЫХ ТЕМПЕРАТУР И БОКОВЫХ ТЕПЛООБМЕНА

Аннотация. В данной статье рассматриваются проблемы численного изучения термомеханического состояния стержней. На основе фундаментального закона об изменении количества тепла, прошедшее за время $\partial\tau$через фиксированного сечения строится уравнение установлившегося теплопроводности для горизонтального стержня ограниченной длины и постоянного попереченного сечения.

При этом на двух концах исследуемого стержня заданы разные температуры, а через боковой поверхности происходит теплообмен с окружающей ее средой. Кроме того, исследуемый стержень выполнен из термозащитного материала ANV-300. Определяющийся закон распределения температуры, всех соответсвующих деформации и напряжений а также перемещения по длине исследуемого стержня. Вычисляются величины термического удлинения и возникающего осевого усилия.

В сложной термической зоне работают подшипниковые компоненты реактивных и водородных двигателей, атомных и тепловых электростанций, технологических линий перерабатывающих производств, а также двигателей внутреннего сгорания. Надежная работа этих конструкций будет зависеть от условий термоэдс компонентов подшипника. Поэтому это исследование посвящено численному изучению состояния термоэдс несущих компонентов конструкций в виде стержней ограниченной длины, ограниченных с обоих концов.

Предлагаемый вычислительный алгоритм основан на принципе сохранения энергии. При этом все типы интегралов в функциональных формулах энергии интегрируются аналитически. При этом полученные численные решения будут иметь высокую точность.

Ключевые слова: тепловой поток, теплообмен, теплопроводности, теплообмена, теплоизоляция.

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