Methods of formulation and theoretical solution of the mathematical problem of designing special clothing protective against high air temperature in the "human-special clothing-environment" system

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Abstract. The article presents the methods of formulating and theoretically solving the mathematical problem of designing special clothing that protects against high temperatures in the system "person-special clothing-outdoor environment". To solve the problem, the human body is assumed to be a deformable cylindrical body of limited size, and special clothing is assumed to be its soft shell. The developed mathematical model makes it possible to predict the dimensions of special clothing, material thickness, cross-sectional area of the underlayer (freedom of clothing) and thermal resistance indicators at the design stage, depending on the air temperature of the external environment.

1 Introduction

In the design of special clothes that protect against hot weather, changes in environmental conditions, on the one hand, and changes in the thermal and moisture characteristics of clothing materials, on the other hand, require long-term focused experiments on the reactions of the human body and the selection of special clothing materials suitable for them. In addition, there may be such extreme combinations of environmental conditions and clothing that it is impossible to conduct experiments in them, which in turn poses a risk to human health (fatigue, increased blood pressure, etc.)

In recent years, mathematical modeling methods have been widely and successfully used to solve such problems worldwide. Mathematical modeling is a method of studying physical phenomena by creating mathematical models. The first method is the human thermal system M. It was introduced by Donald and Widham [1] as a system with oriented parameters. Later, this approach was used to create analog models of human thermoregulation. The analysis of the literature on this issue allows dividing existing mathematical models into 3 groups.

The first group includes works in which mathematical models of thermoregulation of an unclothed person are presented.The second group includes works that consider the thermal condition of a person wearing clothes without a heating system in cold climates.The third

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group includes works devoted to the description of mathematical models of the thermal state of a person wearing clothes with a heating system.

Thus, in this field, there were attempts to create mathematical models of thermal processes of the human body and methods of calculating clothing packages based on these models. However, depended and took into account some components of the model in a very simplified way.

The protective functions of protective clothing against hot temperatures are determined by the composition and parameters of the material package.

2 Materials and methods

The main goal of the work is to develop a mathematical model of special clothing that protects against hot climatic conditions. From this point of view, the human body is a deformable cylindrical body of limited size (cylinder 1), special clothing (cylinder 3), air layer (cylinder 2) between the human body and special clothing (generally gas) and the catals are taken in the form of a cylinder (Figure 1).

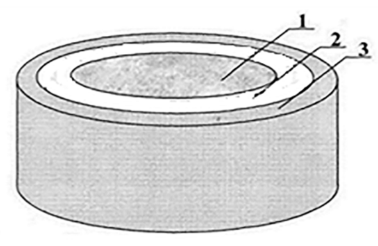


Fig. 1. Conventional cylinder view of the "Human-special clothing" system: 1- human body,2- air layer under clothing, 3- special clothing.

The problem under study is aimed at modeling deformations of a cylinder with a soft shell [2].

In this case, the "human-special clothing" system was conditionally adopted in the form of a cylinder, and in the process of mutual heat exchange between the air environment and the layers in it, the issue of temperature changes of the air and layer material in the underlayer of clothing was studied.

This formulation of the problem allows studying the deformation-stress state of the human body and special clothing (cylinder) under the influence of heat. The dynamics equations of a cylinder with a thin connected shell have the following form:

$$(k_m + \frac{4}{3}G_m) graddiv\vec{w}_m - G_m rotrot\vec{w}_m = \gamma_m \frac{\partial^2 \vec{w}_m}{\partial t^2},$$

$$\nabla^2\theta_m - (1/\chi_m)\dot{\theta}_m - \eta_m div w_m = -Q/_m, m = 1,2,3, \quad (1)$$

where km is volume module; Gm-displacement module; - temperature; ; and - Lame coefficients; - coefficient of linear thermal expansion; ; - specific heat in constant deformation; - fixed size; Q is a value that depends on the amount of heat; - density of cylindrical body material per unit volume; - displacement vector of cylinder points. If the above-mentioned two equations (1) are solved together for each m with boundary or conditions representing the condition of cylinders in contacts, then we will be able to theoretically study the distribution of external heat over time in special clothing and air, as well as in the human body (homogeneous body).

For this purpose, it is necessary to provide the coefficients, which represent the physical-mechanical parameters of each cylinder, found from the experiment [3].

Since the thickness of the studied special clothing is a small number compared to the thickness of the human body, m=1 special clothing (1) can be replaced by the (Krichhoff-Liav) equation based on the practical theory of elasticity.

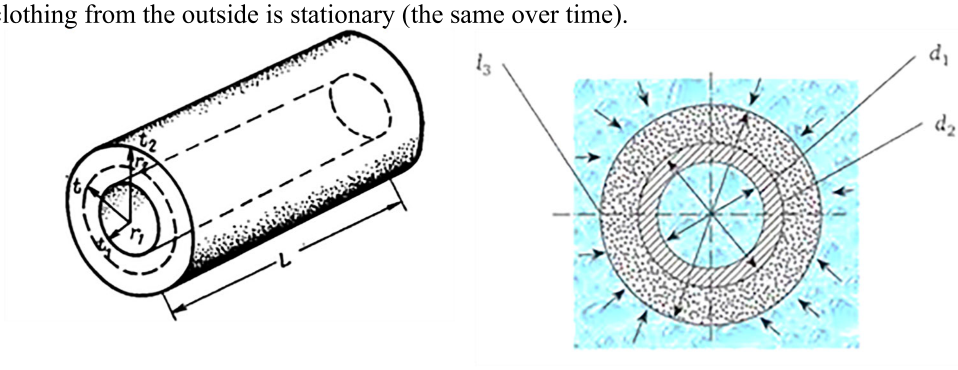
$$\frac{\partial^2 v}{\partial \theta^2}+\frac{1-\nu_0^{'}}{2}\frac{\partial^2 v}{\partial \alpha^2}+\frac{1+\nu_0^{'}}{2}\frac{\partial^2 u}{\partial \alpha \partial \theta}+\frac{\partial w}{\partial \theta}-\frac{m^{'}b^{'2}}{D^{'}}\frac{\partial^2 v}{\partial t^2}=0,$$
$$\frac{\partial^2 u}{\partial \alpha^2}+\frac{1-\nu_0^{'}}{2}\frac{\partial^2 u}{\partial \theta^2}+\frac{1+\nu_0^{'}}{2}\frac{\partial^2 v}{\partial \alpha \partial \theta}+\nu_0^{'}\frac{\partial w}{\partial \alpha}-\frac{m^{'}b^{'2}}{D^{'}}\frac{\partial^2 u}{\partial t^2}=0,$$
$$\nu_0^{'}\frac{\partial u}{\partial \alpha}+\frac{\partial v}{\partial \theta}+k^{'}\nabla^2\nabla^2 w+w-\frac{m^{'}b^{'2}}{D^{'}}\frac{\partial^2 w}{\partial t^2}=0, \quad (2)$$

in which - movement of special clothing points in three directions; - multilayer shell per unit area (A) of the neutral surface weight; b'-surface neutral radius [4].

The system of equations (2) allows finding displacement stiffnesses of material points in tension, torsion, and bending from the corresponding shell equations. This equation is easier to solve than equation (1) and quickly expresses the process under study. Does not require additional conditions. Equation (1) is solved for m=2.3 points for air and human body. For the case where m=3, the relationship between the deformation of the human body and the stresses in the cylindrical coordinate system has the following form [5]:

$$\sigma_{ij}=\tilde{\lambda}\theta\delta_{ij}+2\tilde{\mu}\varepsilon_{ij}\ ,$$
$$\theta=\varepsilon_{11}+\varepsilon_{22}+\varepsilon_{33}.$$
$$\varepsilon_{rr}=\frac{\partial u_r}{\partial r};\ \varepsilon_{\theta\theta}=\frac{1}{r}\left(u_r+\frac{\partial u_\theta}{\partial \theta}\right);\ \varepsilon_{zz}=\frac{\partial u_z}{\partial z};$$
$$\varepsilon_{r\theta}=\frac{1}{2}\left[\frac{1}{r}\frac{\partial u_r}{\partial \theta}+\frac{\partial u_\theta}{\partial r}-\frac{u_\theta}{r}\right],\varepsilon_{\theta z}=\frac{1}{2}\left[\frac{\partial u_\theta}{\partial z}+\frac{1}{r}\frac{\partial u_z}{\partial \theta}\right]. \quad (3)$$

In the given problem, if the mechanical effects and deformations occurring in special clothing and the human body under the influence of heat are considered to be small, then heat transfer equations can be used instead of (1). Let's assume that the heat applied to the special clothing from the outside is stationary (the same over time).



a) representation of the human body in the form of a cylinder

b) A person in the form of a b –cylinder cross section of the body

Fig. 2. Calculation scheme of modeled special clothing and human body.

In that case, as shown in Figure 2, the internal pressure is equal to the temperature of the human body. The external pressure is given to the temperature at which the special clothing should work. We define the surfaces to which the temperature (heat) is transferred as follows: Let the surface of the human body or , the surface affected by the external temperature, be the outer surface of the cylinder containing the air. Assume that ideal contact conditions are met between the cylinders. In that case, the external temperature affects the human bodyhrough the special clothing material and the air layer. The heat transfer coefficient of each cylinder () is as follows [6]

$$\lambda_t(r)=\lambda_{t1}+\sum_{j=1}^{J-1}(\lambda_{t(j+1)}-\lambda_{tj})H(r-r_j), \quad (4)$$

In this - Hevside's unit function, J- the number of cylindersdenotative Catalan. The heat transfer coefficientcan be assumed to be constant for a single-layer cylinder. Fure established a connection between the heat flux density on a unit surface and the thermal temperature gradient using an experiment. From this relationship, the heat transfercoefficient is found. In general, heat dissipation is the same for each layer

$$\frac{\partial T}{\partial t}=\frac{\lambda_t(r)}{c(r)\rho(r)}\left[\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2}+\frac{\partial^2 T}{\partial z^2}\right]=0(r_0<r<r_2). \quad (5)$$

in which the heat capacity.

If the symmetry of the cylindrical system is taken into account, then the following equations are used instead of (1)-(3):

$$\frac{d}{dr}\left[r\lambda_t(r)\frac{dT(r)}{dr}\right]=0(r_0<r<r_2); \quad (6)$$

By studying this heat transfer equation (6) and the boundary condition (7), the heat transfer to the modeled cylinders can be studied.

If the heat-temperature effect rate is very large and the unsteady process is studied in a shorttime interval, then the heat transfer equation is a hyperbolic type differential equation.

$$\frac{1}{c_{mq}^2}\frac{\partial^2 T}{\partial t^2}+\frac{1}{a}\frac{\partial T}{\partial t}=\nabla^2 T, \quad (7)$$

where is the rate of heat dissipation. For gas. For soft materials.

3 Results and discussion

Thus, the mathematical model of the "man - clothing - environment" system allows for the optimal choice of determining the condition of special clothing under external influences.

Methodology and algorithm for solving the problem of the heat exchange process in the "Man-clothing-external environment" system. A special dress of limited length is given. The length of the cross-sectional area is assumed to be constant. Let the elastic modulus of the clothing material be -, the coefficient of expansion from material heat.

The inner part of the clothing is free-standing or the cylinder shell and the inner part of the housing are in sliding contact. At the same time, heat flow is applied to the cross-sectional surface and heat exchange with the environment is increased (Figure.2). The area of temperature distribution along the length of the body should be determined by temperature. Naturally, the resulting temperature, movement, deformation and load fields are distributed non-linearly along the length of the structure.

Therefore, in a small part of the length of the structure, the distribution area of physical quantities is taken as a second-order curve. For example, let's consider the area of temperature distribution in the range, where - the last length of the considered partially thermally insulated rod; - length of clothes.

For a cylindrical system, the heat flux density can be written as follows

$$q_m=-\lambda_t(r)A_s\frac{dT}{dr}, \quad (8)$$

The last obtained first order differential equation (8) can be integrated

$$q_m\int_{r_1}^{r_2}\frac{dr}{r}=-2\pi\lambda_t(r)L\int_{t_{m1}}^{t_{m2}}dt \text{or} q_m=\frac{2\pi\lambda_t(r)L(t_{m2}-t_{m1})}{ln(\frac{r_2}{r_1})} \quad (9)$$

This last equation can be reduced to the following form using mathematical substitutions

$$q_m=\frac{2\pi\lambda_t(r)L(t_{m2}-t_{m1})}{ln(\frac{r_2}{r_1})}\cdot\frac{t_{1m}-t_{2m}}{r_2-r_1}=\lambda_t(r)\frac{A_{2m}-A_{1m}}{ln(\frac{r_2}{r_1})_1}\frac{t_{1m}-t_{2m}}{r_2-r_1}=\lambda_t(r)A_{nm}\frac{\Delta t_{m12}}{\Delta r_{21}}. \quad (10)$$

In this case, the parameter representing the surface, the average logarithmic surface, the difference in heat temperature. Thus, the relations determining the change of heat flow transfer depending on the direction were obtained [7].

In the calculation scheme shown in Figure 1 above, the thicknesses of the cylinders should be the thicknesses of the human body, air layer and special clothing. In the same way, the temperature change in the cylinders is also determined. Temperature changes in cylinders.

$$\Delta t_{T0} = q_m (\frac{\Delta r}{\lambda_t(r) A_s})_{T0}, \Delta t_{H1} = q_m (\frac{\Delta r}{\lambda_t(r) A_s})_{H1}, \Delta t_{M2} = q_m (\frac{\Delta r}{\lambda_t(r) A_s})_{M2} \quad (11)$$

Using this (11), we get the heat flow expression for a three-layer cylinder.

$$q_m = \frac{\Delta t_b}{(\frac{\Delta r}{\lambda_t(r) A_s})_{T0} + (\frac{\Delta r}{\lambda_t(r) A_s})_{H1} + (\frac{\Delta r}{\lambda_t(r) A_s})_{M2}}. \quad (12)$$

Here it is understood as the resistance to the flow of heat. Due to this, the heat flow is reduced.

Equations (6) and (7) are appropriate for stationary flow. The general solution of this equation is as follows:

$$T(r) = C_{1m} \int_{r_0}^{r} \frac{dr}{r\lambda_m(r)} + C_{2m}$$

It is also possible to switch from this solution to the three-layer cylinder solution, in that case

$$T(r) = C_{1m} \left[\int_{r_0}^{r} \frac{dr}{r\lambda_{1m}(r)} + \int_{r_1}^{r} \sum_{k=1}^{3} \left[\frac{1}{\lambda_{(k+1)m}(r)} - \frac{1}{\lambda_{km}(r)} \right] H(r - r_k) \frac{dr}{r} \right] + C_{2m}. \quad (13)$$

If we assume that the coefficients and are independent of the coordinate r, then (13) can be integrated

$$T(r) = C_{1m} \left[\frac{1}{\lambda_{km}} ln \frac{r}{r_0} + \sum_{k=1}^{3} \left[\frac{1}{\lambda_{(k+1)m}} - \frac{1}{\lambda_{km}} \right] H(r - r_k) \, ln \frac{r}{r_k} \right] + C_{2m}. \quad (14)$$

The expression (14) obtained as a result of the last interpolation involves arbitrary constants, we find them from the boundary conditions (13) and get the following solution

$$T(r) = \frac{\left[\frac{1}{\lambda_{km}} ln \frac{r}{r_0} + \sum_{k=1}^{3} \left[\frac{1}{\lambda_{(k+1)m}} - \frac{1}{\lambda_{km}} \right] H(r - r_k) \, ln \frac{r}{r_k} \right] (T_{S2} - T_{S1})}{\frac{1}{\lambda_{km}} ln \frac{r_m}{r_0} + \sum_{k=1}^{3} \left[\frac{1}{\lambda_{(k+1)m}} - \frac{1}{\lambda_{km}} \right] ln \frac{r_m}{r_k}}. \quad (15)$$

With the help of this formula, it is possible to study the thermal temperature distribution if the parameters of the cylinder layers are given.

Heat dissipation at the boundary of special clothing and air layer is also found by formula (15).

$$T(r) = \frac{\left[\frac{1}{\lambda_{1m}} ln \frac{r}{r_0} + \left[\frac{1}{\lambda_{2m}} - \frac{1}{\lambda_{1m}} \right] H(r - r_1) \, ln \frac{r}{r_1} \right] (T_{S2} - T_{S1})}{\frac{1}{\lambda_{1m}} ln \frac{r_2}{r_0} + \left[\frac{1}{\lambda_{2m}} - \frac{1}{\lambda_{1m}} \right] ln \frac{r_2}{r_1}}.$$

2. Suppose (as shown in Figure 1) a three-layered cylinder is exposed to a variable heat source. Let the heat source be under the influence of stationary and non-stationary heat temperature. This situation can be solved using classical equations of heat dissipation. When studying this problem, the time factor is taken into account. The mechanical system being trained determined by the heat transfer equation under unsteady heat distribution

$$\frac{\partial T}{\partial t} = \frac{\lambda_t(r)}{c(r)\rho(r)} \left[\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2} \right] = 0 (r_0 < r < r_2), \quad (16)$$

an initial condition is imposed to solve this equation

$$T_m | t = 0 = T_{0m}, \quad (17)$$

in thisT_{0m}- constant or invariant cat. In the same way, boundary conditions are set for r and z coordinates

$$T_m | r = r_0 = T_{0rm}, T_m | r = r_1 = T_{1rm}, T_m | z = 0 = T_{0zm}, T_m | z = l = T_{lzm}, \quad (18)$$

in this$T_{0rm}, T_{1rm}, T_{0zm}, T_{lzm}$quantities that come from the physical nature of the previously given path problem. We use the method of separation of variables to solve equation

$$T_m = Z_m(z) R_m(r) V_m(\tau). \quad (19)$$

If we put (19) into (18), then we get the following equation

$$\frac{V_{m\tau}^{'}}{V_m}=\frac{Z_{mzz}^{''}}{Z_m}+\frac{1}{a_m r R_m}\left[\frac{\partial}{\partial r}\left(r\frac{\partial R_m}{\partial r}\right)\right]=0, (r_0<r<r_2) \qquad (20)$$

The last equation depends on various variables, from which the condition (20) holds, i.e. $\frac{V_{m\tau}^{'}}{V_m}, \frac{Z_{mzz}^{''}}{Z_m}, \frac{1}{a_m r R_m}\left[\frac{\partial}{\partial r}\left(r\frac{\partial R_m}{\partial r}\right)\right]$ – it follows that the constant magnitude of the expressions is equal. Or the following relation is appropriate

$$\frac{V_{m\tau}^{'}}{V_m}=-\alpha_{m\tau}^2, \frac{Z_{mzz}^{''}}{Z_m}=-\gamma_{mz}^2, \frac{1}{a_m r R_m}\left[\frac{\partial}{\partial r}\left(r\frac{\partial R_m}{\partial r}\right)\right]=\delta_{mr}^2. \qquad (21)$$

Only then will the relationship be appropriate

$$\alpha_{m\tau}^2=\gamma_{mz}^2+\delta_{mr}^2.$$

Then the above equation $V_{m\tau}^{'}+\alpha_{m\tau}^2 V_m=0$the solutions are as follows $V_m=C_m e^{-\alpha_{m\tau}^2 \tau}$. Likewise $Z_{mz}^{'}+\gamma_{mz}^2 Z_{mz}=0$. The solution to this equation is general $Z_{mz}=A_{1m}cos(\gamma_{mz}z)+A_{2m}\,sin(\gamma_{mz}z)$.Let us assume that the beginning and end of the inner cylinders are homogeneously conditioned, then $A_{1m}=0$ ва $A_{2m}\,sin(\gamma_{mz}z)=0$will be.If we solve the last trigonometric equation$\gamma_{mz}=\pi r_0 k/h, k=0,1,2\ldots$.The solution obtained along the longitudinal axis$Z_{mzk}=A_{2mk}\,sin(\pi r_o kz/h)$is found. It follows from the obtained equation (21) along the radial coordinate

$$\frac{1}{r}\left[\frac{\partial}{\partial r}\left(r\frac{\partial R_m}{\partial r}\right)\right]+\delta_{mr}^2 a_m R_m=0.$$

The solution of the equation is as follows:

$$R_m=B_{1m}J_0(\delta_{mr}r\sqrt{a_m})+B_{2m}Y_0(\delta_{mr}r\sqrt{a_m}).$$

If we use the boundary conditions, we get the solution:

$$T_m=\frac{4k_m r_0^2\lambda_{mr}}{h}$$

$$\sum_{k,p=1}^{\infty}\frac{\gamma_{kz}}{(\gamma_{kz}^2+\beta_{mp}^2)(k_m^2 r_0^2+a_m\beta_{mp}^2\lambda_{mr}^2)J_0(\sqrt{a_m\beta_{mp}})}e^{-\alpha_{kmm\tau}^2\tau}\,sin(\gamma_{kmz}z)J_0(r\sqrt{a_m\beta_{mp}})$$

In the course of research, the mechanics of deformable solids, computational mathematics, mathematical modeling, programming methods, solving partial differential equations, separation of variables, Gaussian and finite element methods were used. In this example, results were obtained for a stationary thermal process of a mechanical system modeled mainly by a three-layer cylindrical body. The developed methodology and algorithm allows to study the unsteady heat process. MAPLE-18 software was used to solve the above equations.

Figure 3 shows the transfer of heat flow from the outside to the layer. As the heat decreases during the passage through the air layer. Figure 4 shows the distribution of heat flow by the thickness of three types of materials.

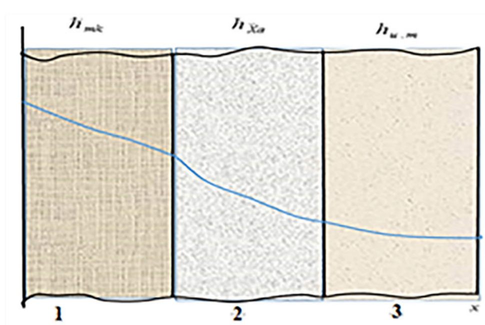


Fig. 3. Variation of the maximum value of heat according to the thickness of the "human-clothing-external environment" system: 1- clothing, 2- air layer under clothing, 3- human body.

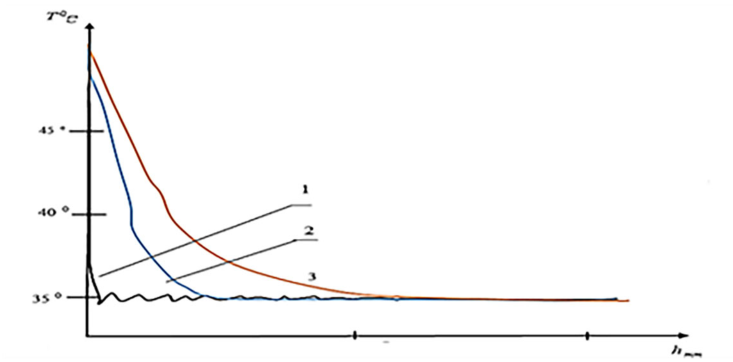


Fig. 4. Variation of the maximum value of heat depending on the thickness of the system depending on different materials: 1- air (nitrogen) in the underwear layer, 2- natural fiber material, 3- heat dissipation for synthetic fiber materials.

As can be seen from the diagram, the thermal conductivity of natural cotton fabric is much lower than other materials.

The obtained numerical results (accurate to 100%) correspond to the analytical solutions given in [7]. These comparisons show that the accuracy of the result of the given universal calculation algorithm method is the highest. It allows determining the components of deformation and stress caused by heat flow and external mechanical force in terms of cross-section and length. Numerical results were obtained for scores of 450 and 750. When using this method, it is taken into account that special clothing and the human body are not homogeneous or have variable parameters.

Determination of expansion and elongation deformations of layers under the influence of heat flow. A special garment of limited length is given a modeled air layer under the garment and the human body in cylinder let it be form. Longitudinal cross-sectional area $F_m$is constant. The coefficient of heat exchange with the environment is the right end $h_{mk}$of cross-sectional area, ambient temperature T_{ock}. Temperature distribution by special clothing the question of finding the area and expansion and extension of the air layer is put. The calculation scheme of the problem is shown below in Figure 5(q– heat flow) given of a three-node quadratic element T_{mi}, T_{mj}, T_{mk} node(i, j, k)we minimize the structured functionality in relation to the temperature values at the points.

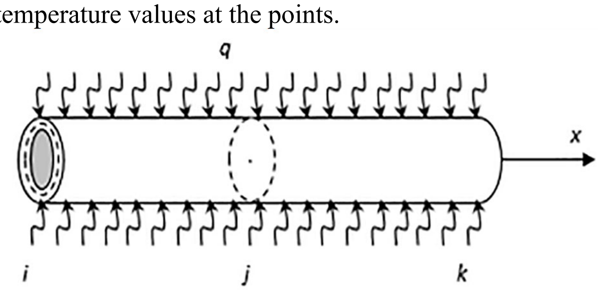


Fig. 5. Three-layer and nodal quadratic finite element scheme.

In addition, a calculation algorithm was created to determine the state of deformation of a garment of limited length under the conditions of heat flow and heat transfer. Taking into account the given heat flux, heat transfer and external (gravitational) force, a corresponding functional representing the total thermal energy of the particular garment under consideration is determined. A solution system of linear algebraic equations is constructed by minimizing heat transfer and gravity with respect to nodal temperature values.

Let's assume that along the side surface of the area, a layered cylindrical structure exchanges heat with the environment. Ambient temperature, - coefficient of heat exchange with the environment. The functional expression for boundary elements corresponding to this segment has the following form:

$$I_j = \int_{V_j} \frac{K_{xx1}}{2}\left(\frac{\partial T_{m1}}{\partial x}\right)^2 dV + \int_{S^j_{nбn}} \frac{h_{m1}}{2}(T_m - T_{oc1})^2 dS_1, \quad x_1 \le x \le x_2, \quad (22)$$

in this$j$- number of the final elements of the garment $x_1 \le x \le x_2$in the area;S_1- side surface area of clothing. Also, heat exchange with the environment takes place with the side surface of the cylindrical construction area.

Option I. $h_1 = h_2 = h_3 = 10(W/sm^{20}C), T_{OC1_1} = T_{OC2} = T_{OC3} = 20^0 C$.The number of boundary elements is 800. The number of nodes is 1601. Boundary elements have the same length:$\Delta l = 80(sm)/800 = 0.1(sm)$.

The temperature distribution along the length of the clothing is shown in Figure 4, the numbers of clothing knots are placed on the abscissa axis, and the temperature values are placed on the ordinate axis. As can be seen from Figure 5, in this option, the area of temperature distribution along the thickness of the clothing is represented by a smooth continuous curve.

4 Conclusion

It can be concluded from the above that the length of the special clothing $L = 80(sm)$, modulus of elasticity of special clothing material -$E = 2 \cdot 10^6(kg/sm^2)$, coefficient of thermal expansion of special clothing - $\alpha = 125 \cdot 10^{-7}(1/\circ C)$air temperature when equal to T=$30^0$from 50^0up tothe normal thermal condition of the human body is maintained, air temperature T=$60^0$when approaching , the balance of the human thermal condition is disturbed, that is, the person may overheat and become weak.

Thus, the developed mathematical model makes it possible to predict the dimensions (length), material thickness, cross-sectional area of the underlayer of clothing (freedom of clothing) and thermal resistance indicators of special clothing at the design stage based on the air temperature of the external environment. The next stage of our research was devoted to the development of the theoretical basis of the effective technology of special clothing processing.

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