A new principle for the development of workwear for constructing highways in the Siberian Federal District of the Russian Federation

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Abstract. The paper considered the problem of protecting workers from the biological factor during the construction of highways in the Siberian Federal District. A promising approach to meeting these requirements is proposed - the use of ventilated clothing. The authors developed a prototype of a protective overall. It was shown that when calculating its design, it was necessary to take into account the heat transfer in the air gaps.The authors worked out a numerical model of these processes and carried out calculations for the conditions in the warm season on the territory of the Siberian Federal District. It was found that with an air gap thickness of 20 mm, the additional heat removal provided by the air gap allowed maintaining the thermal comfort of a person when performing work with a load equivalent to 4 - 6 MET.

1 Statement of the research problem

Highway construction projects in the Siberian Federal District of the Russian Federation require a wide range of organizational tasks. Among them is the provision of workers with effective workwear.

An urgent problem when working outdoors on the territory of the Siberian Federal District is protection from a biological factor. Numerous species of blood-sucking insects, marked in the specialized literature as gnats, in the warm season complicate the development of a number of economic sectors in Western Southern Siberia. This problem is fully typical for implementing various stages of road construction.

Protection of a person from the bites of blood-sucking insects is provided by anti-mosquito outfits, which do not provide the necessary heat transfer with increased heaviness of labour. With excessive sweating, moisture accumulates in the shoulder area, condenses and is absorbed by the clothing. Human comfort in these conditions is ensured when changing clothes. Untimely change of wet clothes creates the risk of colds, even in comfortable temperatures.

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2 Problem solving method

The problem of developing effective overalls for workers, who are involved in the construction of highways in the Siberian Federal District, can be solved using the principles of ventilated clothing. Such outfits create conditions for free flow of colder air around the human body from the outside, providing additional cooling in conditions of increased physical activity.

The prototype of ventilated clothing for road construction workers (figure 1) contains ventilation mesh panels at the knee, elbow and waist (pos. 2-4). Due to the rigid frames (for example, at the knee level and in the straps on the bearers of the trousers – pos. 5, 6), the upper layer of clothing is removed from the body with the formation of an air gap of a given thickness. Due to the temperature difference between the human body and the available air, a natural convective flow is formed in it, which promotes the movement of air. For the removal of warm and humid air into the environment, a mesh panel (pos. 1) is provided in the neck of the product.

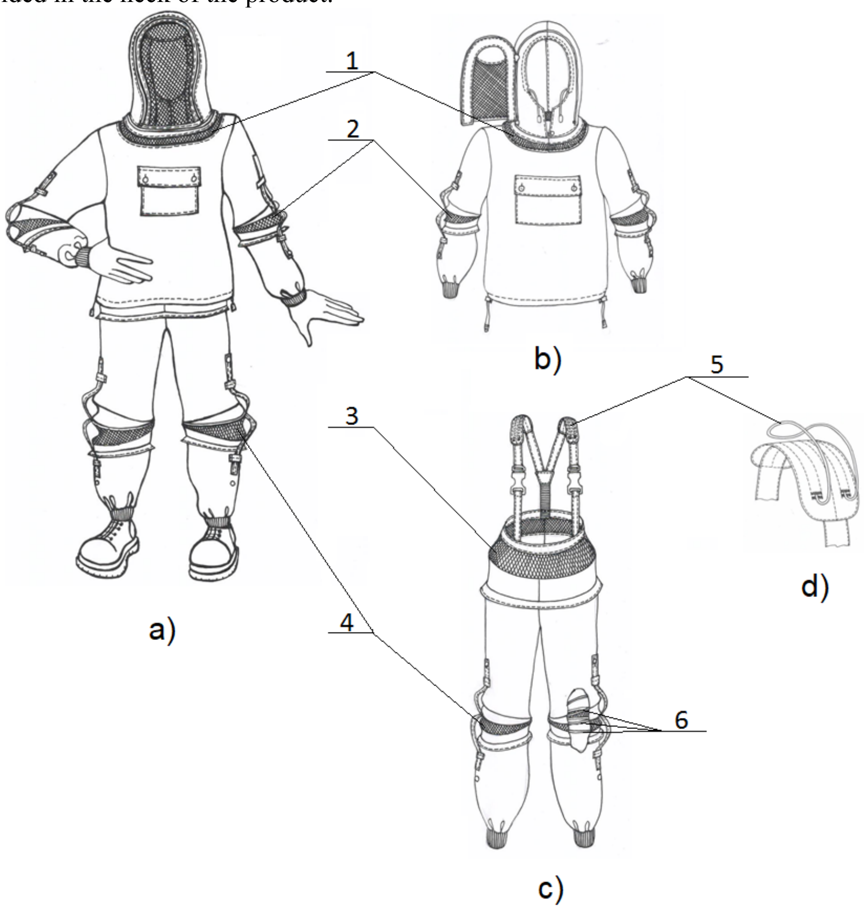


Fig. 1. Prototype of ventilated clothing for road construction workers (a – appearance of the kit; b - jacket; c - trousers; d – rigid frames at the knee level).

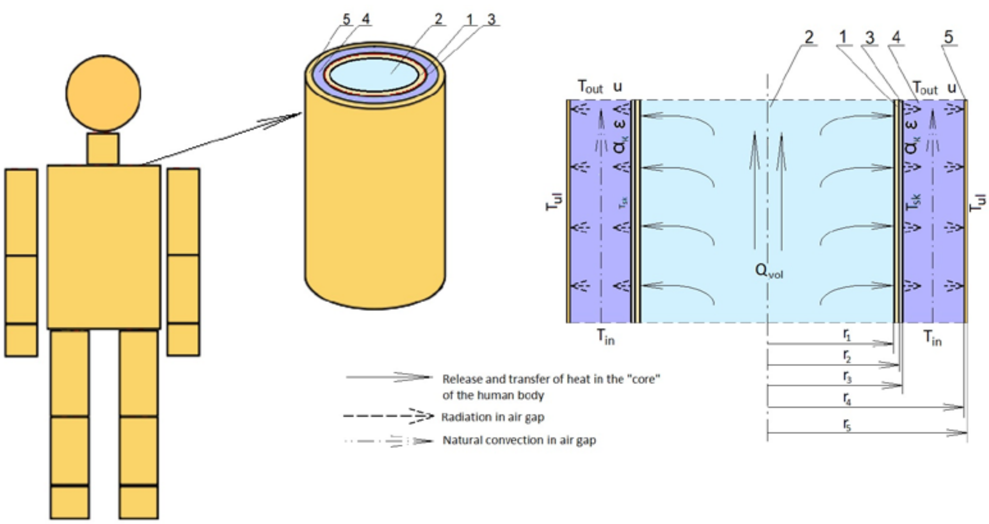
The calculation of the design of ventilated clothing is carried out taking into account the heat transfer in the air gap. Traditionally, these processes are studied by numerical methods. In most models, a homogeneous isolated air gap of regular geometric shape is considered [1-5, 9]. Its air exchange with the environment occurs due to an increase and decrease in air pressure under clothing, which occurs when a person moves [6, 8].

Natural convection in ventilated air gaps is taken into account in the Z. Kang model. The boundary conditions imply the maintenance of the skin temperature at a constant level twast (weighted average skin temperature) = 34 ºC [7]. Heat generation in body tissues is not considered in the model. The calculations were carried out for ambient temperatures above 25 ºC.

Thus, an important stage in the development of ventilated clothing for workers involved in the construction of highways in the Siberian Federal District is to work out a numerical model of heat transfer in the packages of materials with a ventilated air gap – it is a significant task.

3 Description of the mathematical model of heat transfer in ventilated clothing

The model of heat transfer in the air gap is based on a five-node body segment in cylindrical coordinates (figure 2, a). Despite the apparent simplicity, such models are widespread. The human body, 174 cm tall and weighing 70 kg, is represented by two nodes: “core” with a temperature of 37 °C (node 2, figure 2) and a “shell” (1 node, figure 2). The constancy of the temperature of the “core” of the body is ensured by the controlled release of heat:



a) b)

Fig. 2. Heat and mass transfer in a five-node body segment in cylindrical coordinates (a - the appearance of the package; b - calculated geometry of the five-node body segment in cylindrical coordinates: 1 – “shell” of the human body; 2 – “core” of the human body; 3 – underwear layer; 4 – air gap; 5 – upper layer).

$$Q_{vol} = \frac{100}{K_p}\left(\Delta T + \frac{1}{K_i}\int_0^1 \Delta T dt - K_d \frac{dT}{d\tau}\right)$$

where: K_p, K_i, K_d – respectively proportional, integral and differential coefficients (determined from the operating modes of the experimental setup); ΔT - "discrepancy" corresponding to the difference in the measured temperature of the" core T and its set value T_{set}=37 ºC.

The temperature of the “shell” of the body is provided by the supply of heat from the “core”. The intensity of this process:

$$\rho_w C_{pw}\left(\frac{\partial T_w}{\partial \tau} + u_w \cdot \nabla T_w\right) + \nabla \cdot q_w = \alpha_{pw} T_w\left(\frac{\partial p_w}{\partial t} + u_w \cdot \nabla p_w\right) + \tau_w : \nabla u_w + Q_{vol}$$

where: ρ_w – water density, kg/m^3; c_w – heat capacity of water, J/(kg·K); u_w – water velocity in the “core” of the human body, m/s; T_w – water temperature in the “core” of the human body, K; q_w – heat flux between “core” and “shell” of the human body, W/m^2; p_w – pressure in the “core” of the human body, Pa; Q_{vol} – heat generation in “core” of the human body, W.

In continuous areas (“shell” of the body, underwear and upper layers of the package of materials – nodes 3, 5) heat transfer is described by the conductivity model:

$$\rho_s C_{ps}\frac{\partial T_s}{\partial \tau} + \nabla \cdot q_s = -\alpha_s \frac{dS}{d\tau}$$

where: ρ_s – density of matter in the region, kg/m^3; C_{ps} – heat capacity of matter in the region, J/(kg·K); T_s – temperature of matter in the region, K; q_s – heat flux in region, W/m^2; α_s – heat transfer coefficient, W/(m^2·K); S – “core”-“shell” contact surface area, m^2.

Heat transfer in the air gap between the underwear and upper layers (node 4) is carried out by convection and radiation. According to E. Mert, the optimal thickness of the gap is $h_{ag\text{-}cr}$ = 20 mm [8]. When the thickness is less than this value, the ascending air movement dies out sharply; the gaps of greater thickness reduce the ergonomics of the clothes.

The calculation of convection in the gap is carried out according to the equations of continuity (4), motion (5) and energy (6):

$$\frac{\partial \rho_a}{\partial \tau} + \nabla \cdot (\rho_a u_a) = 0$$

$$\rho_a \frac{\partial u_a}{\partial \tau} + \rho_a (u_a \cdot \nabla) u_a = \nabla \cdot [-\rho_a I + \tau_a] + F_a$$

$$\rho_a C_{pa}\left(\frac{\partial T_a}{\partial \tau} + (u_a \cdot \nabla) T_a\right) = -(\nabla \cdot q_a) + \tau : S - \frac{T_a}{\rho_a}\frac{\partial \rho_a}{\partial T_a}\Big|_{p_a}\left(\frac{\partial p_a}{\partial \tau} + (u_a \cdot \nabla) p_a\right)$$

where: ρ_a – air density, kg/m^3; c_a – heat capacity of air, J/(kg·K); τ_a – viscous stress tensor in air, Pa; u_a – air velocity in the air gap, m/s; I – air consumption at the outlet from the interlayer, m^3/s; F_a – the force driving motion, N/m^3; q_a – heat flux in air gap by natural convection, W/m^2; T_a — air temperature in the air gap, K; S - cross-sectional area of the air gap, m^2

Radiant heat flux between the underwear and upper layers with temperatures T_b and T_{wall} is calculated according to the Stefan-Boltzmann law:

$$q = \varepsilon_g \sigma \left(\left[\frac{T_b}{100} \right]^4 - \left[\frac{T_{wall}}{100} \right]^4 \right)$$

where ε_g – reduced blackness between underwear and upper layers calculated according (8):

$$\varepsilon_{пр} = \frac{1}{\frac{1}{\varepsilon_u} + \frac{1}{\varepsilon_{wall}} - 1}$$

where ε_u – blackness of the underwear layer; ε_{wall} – blackness of the upper layer.

The numerical model is solved under combined boundary conditions. The law of convective heat transfer (h_c) from the surface of the underwear layer is determined by Nusselt number (Nu):

$$h_c = \frac{Nu \cdot k_a}{H}$$

where: k_a – air thermal conductivity coefficient, W/(m·K); H – body element height, m.

4 Analysis of research results

The calculation of heat and mass transfer in ventilated air gaps is carried out at t_{amb} = + 15º ÷ + 25 ºC, when the activity of blood-sucking insects is maximum. Figure 3 shows the dynamics of the temperatures of the model nodes. Changes in external conditions cause fluctuations in the temperature of the underwear by no more than 2.5 ºC. The temperatures of the upper layer of the package and the air in the gap change by 7.6 ºC and 9.4 ºC, respectively. At t_{amb}> 23 ºC, the air in the gap heats up sharply, which is associated with a change in the structure of heat transfer (figure 4).

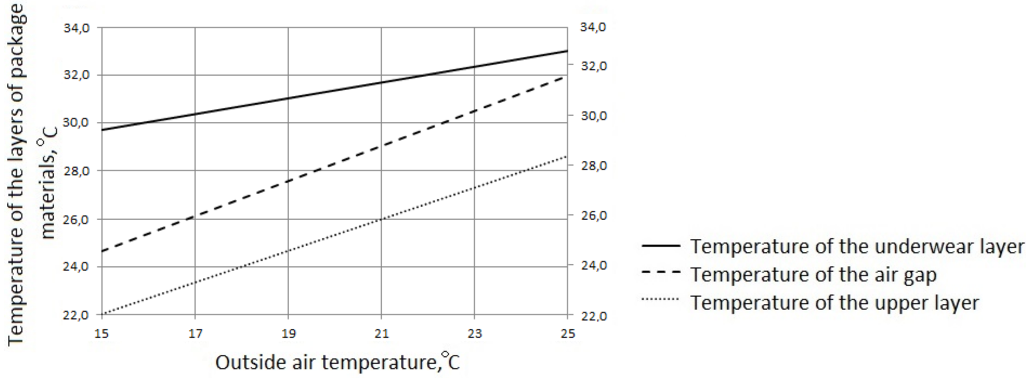


Fig. 3. Temperature field in the package of materials.

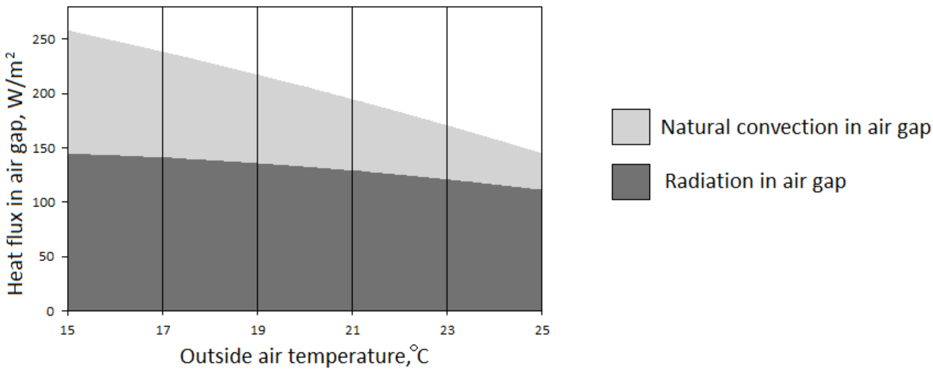


Fig. 4. Heat balance in air gap.

The temperature difference between the underwear and upper layers under the considered conditions changes slightly, due to which the radiant heat flux in the air gap also changes insignificantly.

The convection intensity in the gap is determined by the lifting force F_a, which depends on the change in the air density at the inlet (ρ_∞, kg/m^3) and at the outlet from the air gap (ρ_{out}, kg/m^3):

$$F_a = g(\rho_\infty - \rho_{out}) \tag{10}$$

where: g – gravity vector (acceleration of gravity), m/s^2

The air density field in the gap (ρ) is related to the temperature field distribution:

$$\rho = \rho_{out}\left(1 - \frac{T - T_{out}}{T_{out}}\right) \tag{11}$$

where: ρ_{out} – air density at ambient temperature T_{out} ; T – is the temperature at a given point in the air gap, K.

As the outside air temperature rises, the density differences along the height of the gap decrease, which reduces the lifting force. At the same time, the portion of convective flow in the heat transfer balance decreases from 49% at t_{amb} = 15 ºC, to 8% at t_{amb} = 25 ºC. In the region of higher temperatures, heat transfer in the gap occurs by radiation and conduction, but the portion of this mechanism is insignificant and rather constant.

Evaluation of the effectiveness of ventilated clothing is carried out by comparing the intensity of heat generation in the body with the heat flux on the body surface. For this, we developed an original method based on a linear relationship between the heaviness of the work performed and the heat release in the body. The method is based on calculating the metabolic equivalent of task (MET):

$$\mathrm{MET} = 1.162\mathrm{m[W]} = \frac{1.162 h_0 m}{m^{0.452} h^{0.725}}\left[\frac{W}{m^2}\right]$$

where: h_0 – reference height of a person (139 cm); m – is the weight of a person, kg; h – the actual height of a person, cm.

With light physical activity, for example, walking in a free mode, the heat production is 2 – 3 MET. With little effort, such as jogging it is 4 – 5 MET. When working that requires significant efforts, for example, moving loads weighing less than 10 kg, heat production is close to 6 MET, and with heavy physical efforts (carrying loads weighing over 10 kg), it is7 METs.

The heaviness of the labour process of work on the construction of highways belongs to IIb and III categories, which corresponds to an energy balance of 5-7 MET. To compare the heat production with the heat transfer of a person of the selected height and weight, a nomogram is proposed (figure 5).

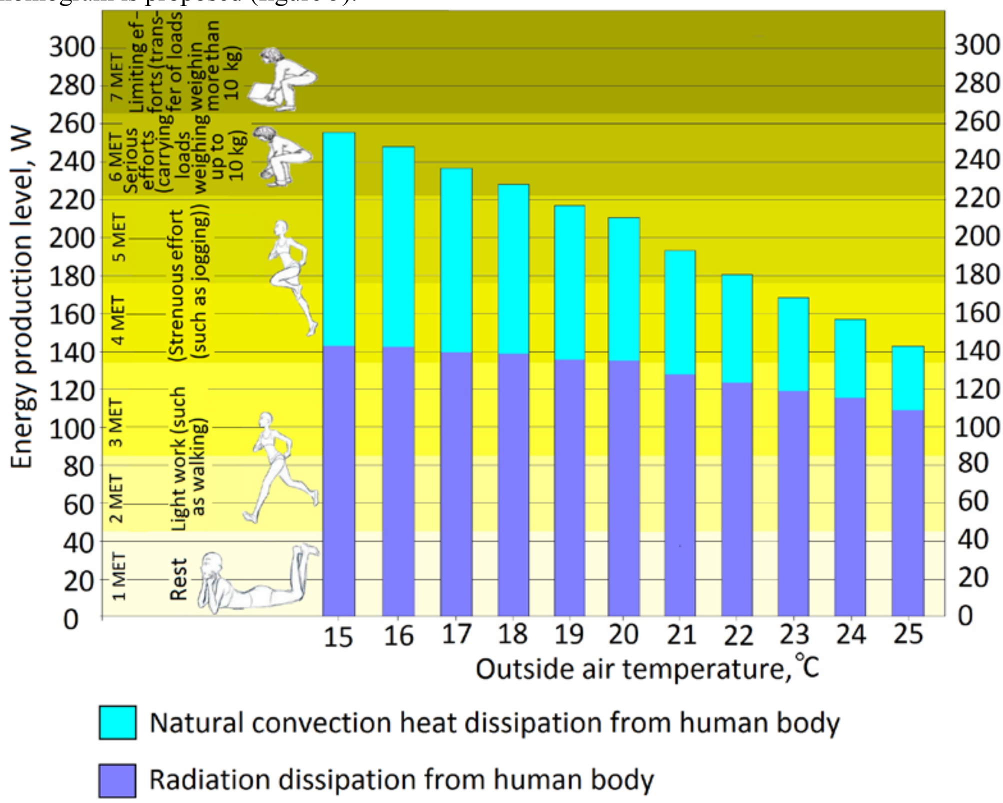


Fig. 5. Nomogram for determining the comfortable operating conditions for ventilated clothing.

As we can see, at t_{amb} = 15 – 18 ºC heat removal from the body surface, which is provided by an air gap of h_{ag} = 20 mm, helps to maintain the thermal comfort of a person when performing work that requires hard physical effort (6 MET). When the temperature rises to 22 ºC, the thermal comfort of the worker will be maintained due to the properties of ventilated clothing while performing sufficient physical efforts (4 –5 MET).

Thus, when calculating the outsizes for free fitting ventilated clothing, it is necessary to form an air gap with a thickness of 20 mm. This will ensure the thermal comfort of the worker at a load corresponding to the IIb and III categories of heaviness at t_{amb} = 15 – 18 ºC. At higher temperatures, uncomfortable sensations will form. However, the person’s thermal sensation when using ventilated clothing will be closer to optimal than when using traditional types of anti-mosquito clothing.

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