

Assessment of the Thermal Insulation Characteristics of Clothing to Prevent Hypothermia Among Personnel

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Abstract. The paper evaluates the necessary thermal insulation of clothing to maintain the thermal balance of production personnel performing physical work of varying intensity in low-temperature conditions. An analysis of current research in the field of thermal insulation and personal protection of workers is conducted with the aim of improving the occupational safety of production personnel. Improvements to the methodology for assessing the thermal insulation characteristics of clothing are proposed, taking into account the ambient temperature, wind speed and vapour permeability of materials. It has been established that the main factor is the ambient temperature, which determines the level of insulation. The intensity of work reduces the necessary thermal insulation due to increased heat generation by the body. The vapour permeability of the material has less influence, but is important for comfort and heat balance regulation. The research was conducted within the following parameter ranges: ambient temperature $T = 253...268$ K, work intensity $q_m = 88...145$ W/m², clothing material air permeability $B = 10...40$ L/(m²·s). The conclusions obtained are of practical importance for the development of recommendations for the selection of special clothing, optimisation of work shifts, and reduction of the risk of hypothermia and injuries.

1 Problem Formulation

The impact of low temperatures on the efficiency of physical work performed by employees, especially in open environments, is a determining factor for several occupational categories. These include open-pit miners, oil and gas industry workers, housing and communal services workers, forestry workers, military personnel, and construction and road industry specialists [1]. The most common negative effects of cold on the human body are hypothermia, pain in the extremities, including frostbite, limited mobility, and reduced performance due to the need to wear heavy protective clothing. In addition, there is a general decline in physiological endurance, which directly affects labour productivity and the level of safety during production tasks [1].

Scientific research in the areas of equipment thermal insulation and human thermal protection is interrelated and critically important for ensuring safety, energy efficiency, and maintaining personnel performance in low-temperature conditions. Contemporary scientific literature convincingly demonstrates that optimising thermal insulation contributes to reducing energy costs and minimising the risk of accidents [2, 3, 4]. At the same time, adequate assessment and selection of clothing based on the amount of thermal insulation required protects workers from hypothermia and reduces the level of injuries [5, 6].

Today, thermal insulation is considered not only as a safety element, but also as a strategic investment in the energy efficiency of production processes. The results of recent studies [2, 3, 7] show that the right choice of materials and technologies can reduce heat loss by 20–40%, which directly affects energy savings and reduces the likelihood of accidents. Particular attention is paid to the development and application of new materials (nanocomposites, polymers, multilayer structures), as well as to the study of heat transfer processes in multilayer systems of various geometric shapes [7, 8, 9]. This opens up prospects for the integration of innovative solutions in the

field of technical insulation and personal protection, which is of key importance for industrial safety and sustainable development.

2 Analysis of Publications

Global experience shows that optimising thermal insulation and protective clothing is one of the key factors in improving energy efficiency and occupational safety in cold conditions. In Northern European countries (Sweden, Finland, Norway), the implementation of ISO 11079 standards has become the basis for planning work shifts in cold climates. This has made it possible to reduce the level of injuries associated with hypothermia and optimise the use of energy resources in production processes. Studies in Canada and the United States show that the right choice of multi-layer clothing systems with high vapour permeability reduces the risk of local cooling and increases worker productivity in cold regions. In the industrial sectors of Japan and South Korea, the emphasis is on the use of nanocomposite and membrane materials that provide a balance between thermal insulation and moisture wicking, which is critical for long-term work. European energy efficiency programmes emphasise that optimising the technical insulation of equipment can reduce heat loss by 20-40%, which directly contributes to energy savings and reduces the risk of accidents.

In [10], the authors investigated how changes in air velocity and walking speed affect the apparent thermal insulation of clothing sets, measured on a moving thermal manikin. The authors analysed static and dynamic modes using three air velocity levels (0.15, 1.55, 4.0 m/s) and three walking speeds (0, 0.75, 1.2 m/s), by performing a total of 486 tests to determine total and segmental thermal insulation. The results obtained are of practical importance for engineers and occupational safety specialists: when planning the necessary thermal insulation, it is necessary to take into account the resulting thermal insulation I_{cl} in dynamic conditions. It has been established that an increase in wind speed and the movement of the mannequin lead to a significant reduction in thermal insulation, with the torso and limbs reacting differently – the greatest losses are observed in open areas and in places where clothing fits tightly. Multi-layer sets showed a lower relative loss of insulation during movement, but the absolute losses remained significant. At the same time, it should be noted that the mannequin does not reproduce the physiological response of a human being (sweating, vascular reactions), and the test sets cover only a part of the possible designs and materials. In addition, laboratory conditions do not take into account changes in humidity and the processes of clothing wetting over time.

In [11], the effect of moisture on the 'wet' thermal insulation of clothing was investigated with the aim of quantitative assessment, in particular, how partial or complete wetting and fitting of clothing affect the apparent thermal insulation measured on a thermal mannequin. It was found that when wet, thermal insulation decreases because water fills the air pores in the fabric structure, reducing its insulating properties. The rate and degree of reduction depend on the fabric construction (loose structures lose more) and the fit of the clothing (looser clothing retains more air, providing better insulation even when partially wet). The effect is critical for prolonged work or intense sweating, when the 'wet' thermal insulation of clothing can decrease to such an extent that the actual thermal insulation becomes lower than the IREQ. The authors recommend taking into account the dynamics of changes in the 'wet' thermal insulation of clothing over time due to perspiration or external moisture when calculating the maximum permissible duration of an employee's stay in cold conditions, D_{lim} (given the available clothing and physical exertion, before the risk of hypothermia arises), and planning work shifts. The use of materials with better moisture-wicking properties and designs that prevent the inner layers from getting wet increases the safety of workers in cold conditions. At the same time, it should be noted that mannequin tests do not simulate active human perspiration with its local variations, and the study focused on individual materials, so the results cannot always be directly extrapolated to complex multilayer systems with membrane structures.

In [12], a critical analysis of practical problems and typical errors in the application of the IREQ model (ISO 11079) in field and engineering assessments of cold risk was carried out. Particular attention is paid to the influence of errors in input parameters (metabolism (M), wind speed (w),

actual thermal insulation of clothing (I_{cl}) on the results of IREQ and Dlim calculations. The authors identify inaccurate metabolism estimates (M), incorrect determination of clothing insulation (I_{cl}), especially when using static tables, as well as ignoring the vapour permeability of material B and the clothing area factor (f_{cl}), as the main sources of error. It is proposed to standardise input data collection procedures, use mannequin measurements to determine I_{cl} , and document all assumptions. The study is based on a review of existing models and theoretical approaches without experimental verification of their effectiveness in real conditions. This approach is useful for systematising knowledge, but limits the practical value of the results. Since IREQ/Dlim models are sensitive to the accuracy of parameters (metabolism, temperature, wind speed, actual thermal insulation of clothing), inaccurate or incomplete data collection can lead to distorted results. This creates the risk of incorrect clothing selection or work duration planning, which increases the likelihood of hypothermia and injury.

In [13], the influence of the clothing area factor (f_{cl}) and vapour resistance (R_{et}) on the IREQ and Dlim results was investigated. The authors performed simulations and provided empirical examples with different values of f_{cl} and R_{et} , comparing the results when they were ignored and when they were taken into account. The data obtained emphasise the need to expand standard IREQ assessment procedures by including measurements or estimates of f_{cl} and R_{et} , especially for modern multi-layer and membrane materials. Taking these parameters into account leads to significant changes in the IREQ and Dlim calculations, which are critical for prolonged or intensive work. Vapour permeability directly affects evaporation efficiency (E) and the body's heat balance: low vapour permeability of clothing material can significantly reduce the acceptable exposure time. Thus, the article provides compelling arguments for updating equipment assessment practices, as without taking f_{cl} and R_{et} into account, the risks of hypothermia may be underestimated. At the same time, the lack of experimental testing on thermal mannequins and humans limits the practical applicability of the conclusions, creating a risk of insufficient accuracy of recommendations in real, especially extreme conditions.

An analysis of recent studies [10–14] in the field of hypothermia assessment and protective clothing selection reveals a number of significant gaps that limit the practical application of IREQ/Dlim models in industrial settings:

1. The impact of vapour permeability and moisture. The vast majority of studies consider the thermal insulation properties of clothing in a dry state, whereas real working conditions are accompanied by intense perspiration and possible wetting of fabrics. This leads to a sharp decrease in effective thermal insulation (I_{cl}) and a reduction in the permissible wearing time (Dlim). Comprehensive studies are needed that integrate the effects of vapour permeability and moisture, including modelling of changes in thermal insulation at different levels of perspiration and external moisture.

2. Local cooling effects. There is limited data on the risks of local cooling of individual body parts (hands, feet, face), especially in conditions of uneven insulation distribution. This creates a risk of local injuries (frostbite), even if the overall heat balance of the body is maintained. Further research should focus on quantifying local effects and developing recommendations for specialised clothing items (gloves, footwear, protective masks).

3. Adaptation and individual factors. IREQ/Dlim models are mostly based on average physiological parameters and do not take individual differences into account. Age, gender, physical fitness, and thermoregulation characteristics significantly affect the body's ability to withstand cold stress. More research is needed to analyse these factors and propose adaptive models for personalised clothing selection, which will improve the accuracy of assessments and the safety of workers in cold conditions.

3 Aim of Paper

The purpose of the work is the improvement of methods for assessing the necessary thermal insulation of workers' clothing, taking into account the influence of ambient temperatures, work

intensity, dynamic conditions (wind), and vapour permeability of materials to reduce the risk of hypothermia, fatigue-related performance issues, and injuries.

4 Materials and Methods

The paper proposes a refinement of the methodology for assessing the necessary thermal insulation of workers' clothing, taking into account the influence of ambient temperatures, work intensity, dynamic conditions (wind), and the vapour permeability of materials.

The thermal insulation of the IREQ₀ workwear set is calculated using the formula [15]:

$$\text{IREQ}_0 = \frac{T_{sk} - T_{amb}}{q_f}, \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}, \quad (1)$$

where, T_{sk} – average human skin temperature, K; T_{amb} – ambient temperature, K; q_f – the average value of the density of the 'dry' heat flux from the surface of the human body, W/m².

To determine the amount of thermal insulation, data on the values of T_{sk} , the intensity of work q_m , and the ambient temperature T_{amb} , at which the workwear is used are required. If personal protective equipment is used in windy conditions and the workwear is made of breathable material, the required thermal insulation value of the clothing set is determined by the formula [15]:

$$\text{IREQ} = \frac{100 \cdot \text{IREQ}_0}{100 - C} = \frac{100 \cdot \text{IREQ}_0}{100 - (0.07 \cdot B + 2) \cdot \omega + 5}, \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}, \quad (2)$$

where, C – the reduction in thermal insulation of clothing, %; B – the air permeability of the outer layer of clothing, L/(m²·s); ω – the wind speed, m/s.

The calculation of the average value of the 'dry' heat flux q_f , which is necessary to determine the appropriate thermal insulation of a set of clothing, is calculated according to the heat balance equation [15]:

$$q_f = q_{conv} + q_{rad} = q_m - W - q_{c.breath} - q_{evap.breath} - q_{evap.h} \pm \Delta q_{h.c}, \text{ W/m}^2 \quad (3)$$

where, q_m – the energy consumption level depending on the category of work performed, W/m²; W – the effective power of mechanical work, W/m² (assume $W = 0$ W/m²); $q_{c.breath}$ – heat loss by convection during human breathing, W/m²; $q_{evap.breath}$ – heat loss by evaporation of moisture during human breathing, W/m²; $q_{evap.h}$ – heat loss by evaporation of moisture from the surface of the human body, W/m²; $\Delta q_{h.c}$ – change in heat content in the human body (difference between q_m and the sum of heat losses from the body) W/m².

The value of $q_{c.breath}$ can be determined using the formula [15]:

$$q_{c.breath} = 0.0014 \cdot q_m \cdot (T_{exh} - T_{amb}), \text{ W/m}^2, \quad (4)$$

where, T_{amb} – ambient temperature, K; T_{exh} – exhaled air temperature, K.

The value of $q_{evap.breath}$ can be determined using the formula [15]:

$$q_{evap.breath} = 0.0173 \cdot q_m \cdot (P_{evap} - P_{amb}), \text{ W/m}^2, \quad (5)$$

where, P_{evap} – pressure of saturated water vapour at the temperature of exhaled air, kPa; P_{amb} – pressure of water vapour in the atmosphere, kPa.

Vapour-permeable material is used to manufacture clothing. In this case, heat loss through evaporation from the surface of the human body is calculated using the formula [15]:

$$q_{evap.h} = \frac{8.816 + 0.39 \cdot q_m}{S} - q_{evap.breath}, \text{ W/m}^2, \quad (6)$$

where, S – surface area of the human body, m^2 (accepted that $S \approx 1.8 m^2$, which corresponds to a human body weight of 65 kg).

5 Research Results

Fig. 1 shows the effect of the intensity of physical work performed by employees (for categories Ib, IIa, IIa-IIb, IIb) on the required level of thermal insulation of clothing with a comfortable thermal sensation (without taking into account the air permeability of the outer layer) at different ambient temperatures in the range from $-5^\circ C$ to $-20^\circ C$ (253...268 K). The relationship between the intensity of physical work, the duration of the worker's exposure to low temperatures, and the body's heat balance is shown in Fig. 2.

Analysis of Fig. 1 shows that as the intensity of work (q_m) increases, the necessary thermal insulation of clothing decreases. This is because the human body produces more heat, and clothing can be lighter.

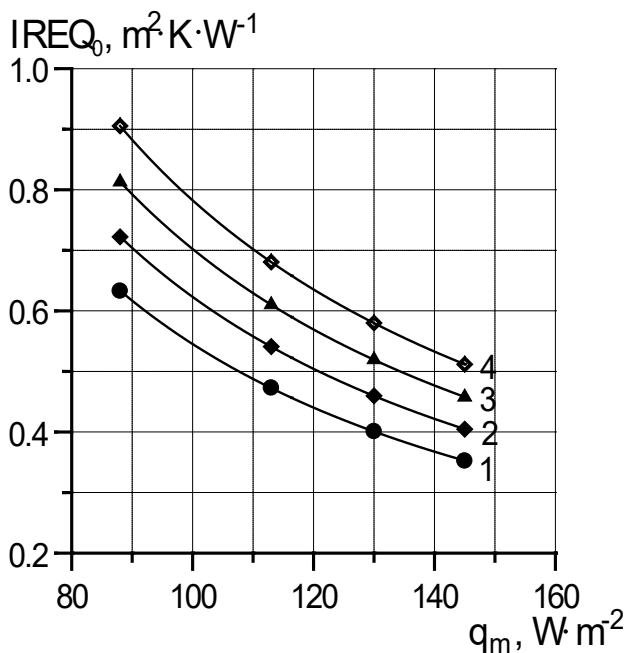


Fig. 1. Dependence of the required thermal insulation of clothing with a comfortable thermal sensation (without taking into account the air permeability of the outer layer of clothing) on the intensity of the worker's physical work (for work categories Ib, IIa, IIa-IIb, IIb) at different ambient temperatures:
1 – $-5^\circ C$; 2 – $-10^\circ C$; 3 – $-15^\circ C$; 4 – $-20^\circ C$

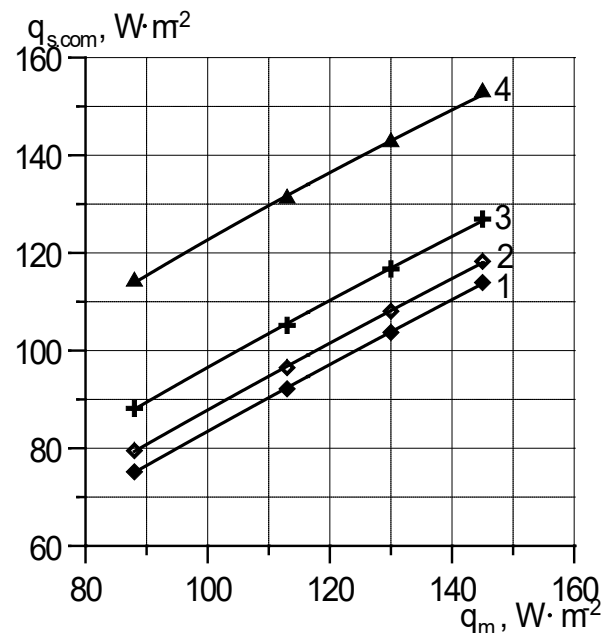


Fig. 2. Dependence of the average heat flux value ensuring comfortable working conditions on the surface of the worker's body from the intensity of his physical work (for categories Ib, IIa, IIa-IIb, IIb) for different durations of stay at an ambient temperature of $-5^\circ C$: 1 – 4 hours; 2 – 3 hours; 3 – 2 hours; 4 – 1 hour

As the ambient temperature decreases (from $-5^\circ C$ to $-20^\circ C$), the need for thermal insulation in clothing increases. Category Ia workers (security guards, indoor workers at industrial enterprises) are most vulnerable to cold stress, as their work involves little movement and their bodies produce little heat. For this category, the $IREQ_0$ value for comfortable thermal sensations is $0.6329...0.90534 m^2 \cdot K \cdot W^{-1}$, and as the ambient temperature decreases within the studied range, the thermal insulation of clothing increases by 1.43 times. Workers in category IIb involved in construction work (bricklayers, concrete workers, fitters, loaders), mining (miners, open-pit workers) and forestry (lumberjacks, woodworkers) and agricultural work (manual digging, soil cultivation, fodder harvesting) have a high work intensity, which contributes to significant heat release from the body, so the need for thermal insulation of clothing is lower than for categories Ia or IIa. However, at temperatures of $-5^\circ C$ to $-20^\circ C$, even workers in category IIb need protective

multi-layer clothing, especially when spending long periods outdoors. For this category of work with comfortable thermal sensations, the $IREQ_0$ value is $0.35237...0.51163 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$, and with a decrease in the ambient temperature in the studied range of its change, the thermal insulation of clothing increases by 1.45 times. The main risks of not complying with the requirement to use special clothing with the necessary thermal insulation are local cooling of the extremities (hands, feet, face), frostbite in strong winds, and reduced performance due to fatigue and cooling after work.

Curve 4 in Fig. 1, corresponding to an ambient temperature of -20°C , is the highest, which means a greater need for insulation. The categories of work (Ib, IIa, IIa-IIb, IIb) reflect different intensities of physical exertion. Heavier work (IIb) requires less thermal insulation than lighter work (Ib) at the same temperature: 1.8 times less at a temperature of -5°C and 1.77 times less at a temperature of -20°C .

The shape of the curves in Fig. 1 shows a nonlinear relationship: at low physical exertion (work category Ib), the difference between temperatures is significant, while at high physical exertion (work category IIb), the curves converge (the body compensates for the cold with its own heat).

Analysis of Fig. 2 shows that as the intensity of work (q_m) increases, the heat flow from the body surface increases. With an increase in the duration of the worker's stay in the cold (from 1 to 4 hours), the heat flow from the body surface required to maintain comfortable conditions at an ambient temperature of -5°C decreases: for work category Ib from 114.2 W/m^2 to 75.2 W/m^2 (1.52 times), and for work category IIb from 152.9 W/m^2 to 113.9 W/m^2 (1.34 times). This means that during prolonged exposure, the body gradually cools down, and less heat transfer from the body surface is required to maintain comfort. The curves are arranged sequentially: line 1 (4 hours) is the lowest, and line 4 (1 hour) is the highest. This demonstrates a gradual decrease in the permissible heat flow over time as the worker remains in the cold. The categories of work (Ib, IIa, IIa-IIb, IIb) reflect different levels of physical exertion. For more difficult work (IIb), the heat flow is higher, which makes it possible to maintain comfort for longer, even during prolonged exposure to cold.

Figures 3a–3d show the effect of the intensity of physical work performed by employees on the required level of thermal insulation of clothing, taking into account the air permeability of the outer layer ($B = 20 \text{ L}/(\text{m}^2 \cdot \text{s})$) at different ambient temperatures and wind speeds. The winter period in the Lviv region is characterised by moderate wind speeds, which usually range from 3 to 5 m/s. A wind speed of 1 m/s was used to model working conditions in enclosed production facilities, particularly in the food industry (dairy, fish, meat), food distribution, and pharmaceutical manufacturing.

Analysis of Figures 3a–3d showed that as the intensity of an employee's physical work decreases, the need for thermal insulation of clothing (with the air permeability of the outer layer of clothing $B = 20 \text{ L}/(\text{m}^2 \cdot \text{s})$) increases.

In conditions of wind, low ambient temperatures and physical work, the thermal insulation of the workwear set changes:

1. A decrease in ambient temperature leads to an increase in the required thermal insulation of clothing. The curves for a temperature of -20°C (Fig. 3a–3d) are higher than those for -5°C .
2. An increase in wind speed (from 1 to 5 m/s) significantly increases the need for thermal insulation in clothing, which is associated with an intensification of convective heat loss.
3. The intensity of physical work has a compensatory effect: at higher physical loads (category IIb), the required level of thermal insulation decreases because the body produces more heat.
4. The interaction of factors (temperature, wind, physical exertion) demonstrates a non-linear nature: at low physical exertion and high wind speed, the difference between the curves is more pronounced, while at high physical exertion, they converge.

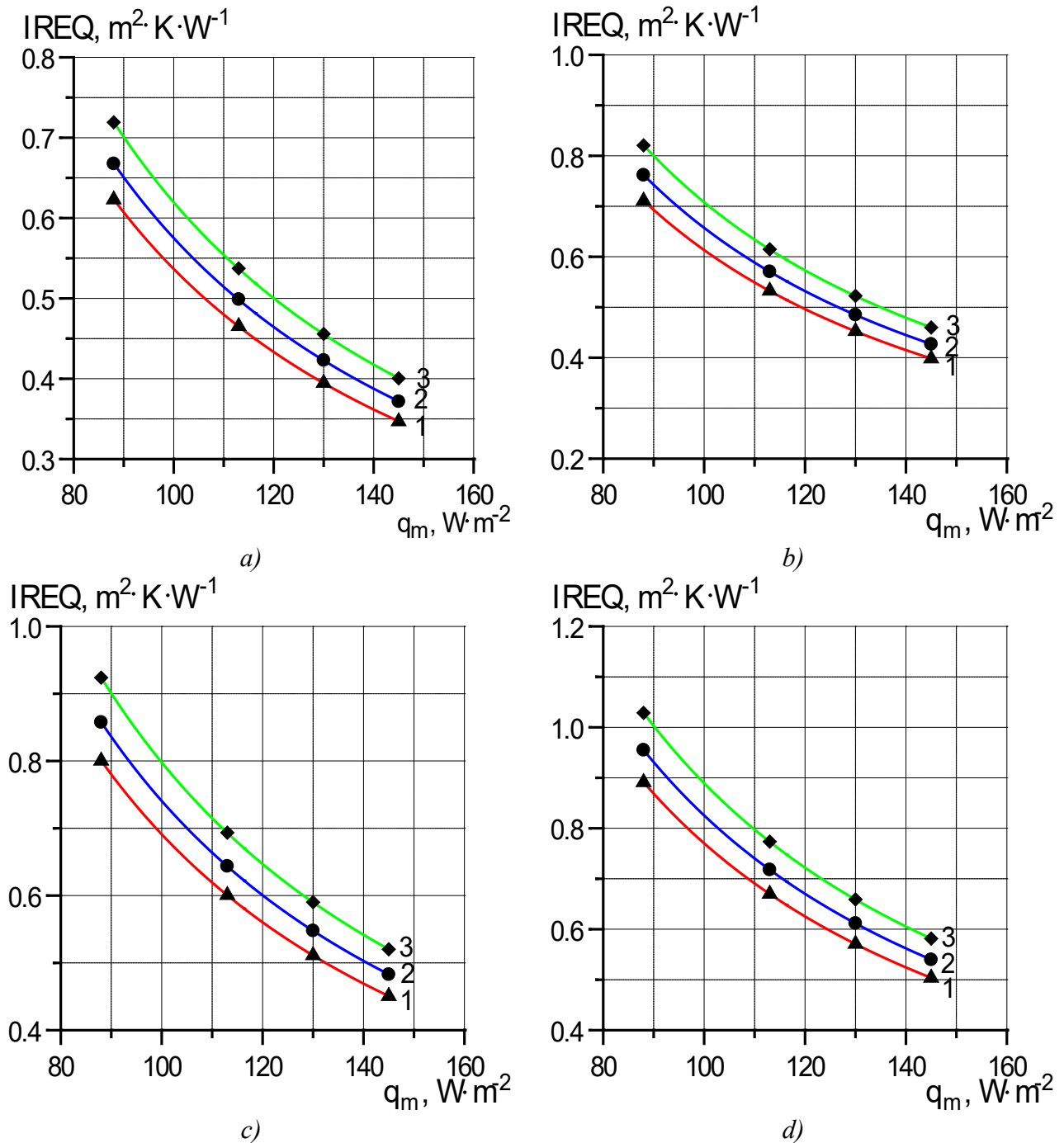


Fig. 3. Dependence of the required thermal insulation of clothing with a comfortable thermal sensation (taking into account the air permeability of the outer layer of clothing $B = 20 \text{ L}/(\text{m}^2 \cdot \text{s})$) on the intensity of the worker's physical activity (for work categories Ib, IIa, IIa-IIb, IIb) at different ambient temperatures and wind speeds:

a) -5 °C; b) -10 °C; c) -15 °C; d) -20 °C;

1 – wind speed 1.0 m/s; 2 – wind speed 3,0 m/s; 3 – wind speed 5,0 m/s.

The required thermal insulation of clothing can be generally represented by the equation:

$$\text{IREQ} = A \cdot B^m \cdot q_m^n \cdot T^k. \quad (7)$$

Based on the calculation results, unknown coefficients (A , m , n , k) were determined for the dependence $\text{IREQ} = f(B, q_m, T)$. Based on the results of assessing the necessary thermal insulation of clothing to maintain the worker's body heat balance with comfortable thermal sensations, an

empirical dependence of the necessary thermal insulation of clothing on the air permeability of the material, the intensity of work performance, and the ambient temperature at a wind speed of 3 m/s was determined. This dependence is described by the equation:

$$\text{IREQ} = 1.246 \cdot 10^{17} \cdot B^{0.028} \cdot q_m^{-1.1} \cdot T^{-6.25}. \quad (8)$$

The empirical dependence (8) obtained is reliable within the following parameters studied:

- ambient temperature: $253 < T < 268$ K;
- intensity of work performance: $88 < q_m < 145$ W/m²;
- air permeability of the material from which the clothing is made: $10 < B < 40$ L/(m²·s).

Analysis of empirical dependence (8) shows that the necessary thermal insulation of clothing increases with a decrease in ambient temperature and work intensity, and increases with an increase in the air permeability of the material:

1. Ambient temperature is the main factor determining the required thermal insulation of clothing, since the degree index is negative and equals $k = -6.25$. This means that when the ambient temperature T decreases, the IREQ value increases sharply.

2. Work intensity has a secondary but significant impact. The degree indicator at q_m is $n = -1.1$. That is, with greater physical activity, the body produces more heat, and the required thermal insulation of clothing decreases. At low work intensity (sedentary or light activity), the body's heat production is minimal, so greater thermal insulation of clothing is required.

3. The vapour permeability of the material has less influence, but its role is important for comfort and heat balance regulation through evaporation. The degree coefficient at B is $m = 0.028$. The more breathable the clothing is, the more thermal insulation is needed to compensate for heat loss through evaporation.

Comparison of calculated IREQ by Eq. (8) and theoretical values of IREQ by Eq. (2) of the required thermal insulation of clothing, taking into account the air permeability of the outer layer of clothing B , the intensity of the worker's physical activity (for work categories Ib, IIa, IIa-IIb, IIb), and different ambient temperatures at a wind speed of 3 m/s is shown in Fig. 4.

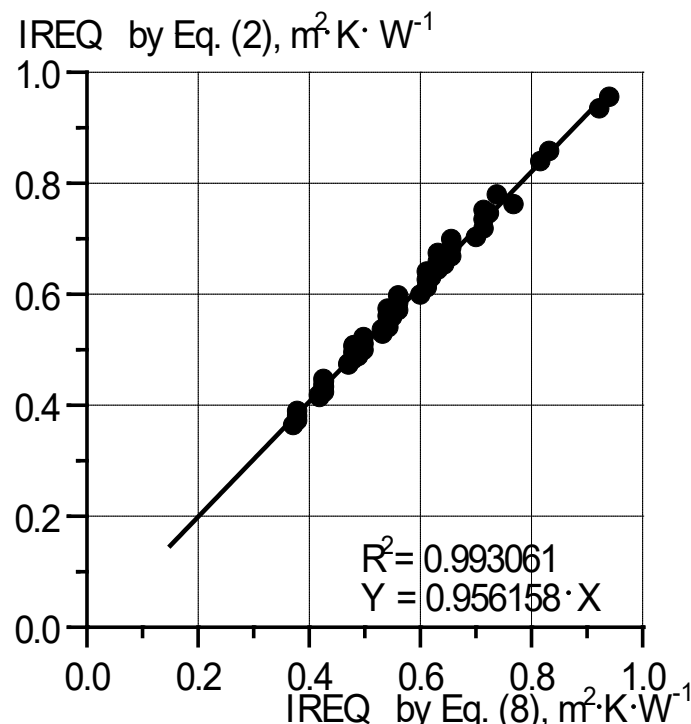


Fig. 4. Comparison of calculated IREQ by Eq. (8) and theoretical values of IREQ by Eq. (2), taking into account the air permeability of the outer layer of clothing B , the intensity of physical work of the employee (for work categories Ib, IIa, IIa-IIb, IIb), and different ambient temperatures at a wind speed of 3 m/s

Analysis of Fig. 4 showed good agreement between the calculated and theoretical IREQ data. The coefficient of reliability of the linear approximation is $R^2 = 0.993061$, which is quite acceptable. The obtained coefficients of dependence (8) are also statistically significant.

6 Conclusions

Based on the results of assessing the necessary thermal insulation of clothing to maintain the worker's body heat balance, an empirical dependence of IREQ on the air permeability of the material, the intensity of work performance, and the ambient temperature in cold conditions was determined. In this regard, the following conclusions can be drawn:

1. The study confirmed that the required level of thermal insulation of clothing depends on a combination of external and internal factors: ambient temperature, wind speed, vapour permeability of materials, and the intensity of physical work performed by employees.

2. It has been established that as the intensity of physical work increases, the amount of thermal insulation required decreases, since the body produces more heat, while as the temperature decreases and the wind speed increases, it increases.

3. Category Ia workers are most vulnerable to cold stress, as their work is sedentary and accompanied by low heat dissipation. They require a significantly higher level of thermal insulation in their clothing compared to categories IIa–IIb.

4. The proposed improvement of the methodology for assessing the required thermal insulation of clothing, taking into account the physiological parameters of the body and the properties of materials, makes it possible to more accurately determine the need for thermal insulation of clothing in real operating conditions.

5. Calculations were performed for a human body surface area of $S \approx 1.8 \text{ m}^2$, within the following parameter range: ambient temperature $253 \leq T \leq 268 \text{ K}$, work intensity $88 \leq q_m \leq 145 \text{ W/m}^2$, air permeability of clothing material $10 \leq B \leq 40 \text{ L/(m}^2 \cdot \text{s)}$.

6. The necessary thermal insulation of clothing is determined by the combined effect of three parameters: ambient temperature, work intensity, and vapour permeability of the material. The main influencing factor is the ambient temperature: as the temperature decreases, the thermal resistance of the insulation increases. The intensity of work has a secondary but significant impact: with greater physical activity, the body produces more heat, which reduces the required thermal insulation of clothing. The vapour permeability of the material has less impact, but its role is important for comfort and heat balance regulation through evaporation. Thus, when designing and selecting workwear, it is necessary to first consider the ambient temperature, adjusting the thermal insulation depending on the nature of the work and the properties of the fabric. The main risks of not complying with the conditions for using workwear with the necessary thermal insulation are frostbite in strong winds, reduced performance due to fatigue and cooling down after work.

7. The results obtained are of practical importance for the development of recommendations for the selection of workwear, optimisation of work shifts and reduction of the risk of hypothermia, fatigue and injuries, and can also be used to improve regulatory documents in the field of occupational safety.

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