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Case Study: Measuring the Thermal Insulation of Heated Protective Gloves on a Thermal Hand Model

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Abstract

This paper presents a study on the thermal insulation of commercial protective gloves with passive and active heating systems considering different simulated temperatures (-15 °C, -10 °C, 0 °C and +5 °C). The insulation parameter was determined on a thermal hand model for two heated gloves supplied with different heat sources (active and passive) according to an originally developed procedure. The results confirmed that the use of an additional heat source (active or passive) makes it possible to obtain higher values of thermal insulation, expressed by a change in the performance level. In addition, the results indicate that active systems are more effective than the passive heat sources tested. The procedure shows how to evaluate the performance of heated products. It was found that active and passive systems differentially follow temperature changes, and thus differ in the levels of thermal insulation provided in the workplace. Depending on the degree of exposure of the worker to a cold environment, it is advisable to wear gloves additionally equipped with passive or active heat sources.

Key words: *heating protective gloves, cold work environment, thermal insulation.*

Introduction

Gloves protecting the user against low temperature should have a thermal insulation ability and a low transfer heat flux coefficient while maintaining flexibility and comfort of use [1]. Cold-resistant gloves significantly reduce the risk of contact with low temperature and cooling of the skin of the hands. The use of such gloves does not completely eliminate the risk of the user's loss of comfort – it only protects against quick cooling [2, 3]. However, there is still slow cooling of the hands and loss of the dexterity of fingers, intensified by the rigidity of the gloves [4, 5].

In workplaces where there is a risk of cooling of distal parts of the body, gloves with insulating properties are used [6]. This takes place in the case of the production, storage and distribution of food products, where it is required to carry out work in rooms where cold conditions are intentionally maintained (e.g., work in cold stores, freezing tunnels in meat, fish, milk and cheese processing, ice cream and frozen foods, sorting frozen vegetables and fruits) [7]. Traditional protective gloves are made of textile systems, possibly with the use of waterproof leathers or materials coated with polyvinyl chloride, nitrile rubber or polyurethane, and an increase in thermal insulation is achieved through the use of additional insulating inserts/linings. Despite the possibility of choosing gloves from traditional materials with different insulating properties,

it turns out to be insufficient to meet the expectations of users [8].

According to the current state of the art, modern protective glove designs are also being developed equipped with systems supporting heat preservation [9]. Such products can be divided by the way of heating and by the heat supply system for passive and active sources of heating used in protective gloves [10-12] (*Figure 1*).

Passive heat sources (PHS) can perform advanced functions, taking into account economic and environmental considerations. PHS include active mineral compounds that are a mixture of iron powder, alkali metal, alkaline earth or transition metal, active and inactive carbon, and additives used according to the specific application [12].

Active heat sources (AHS) include electrical power and phase transformation materials. Often in solutions using electrical heating, a single electric cable connected to the power source is used. These solutions make that the gloves can be rigid and heavy, especially due to the size and weight of the battery. Nowadays, more and more printed conductive paths are being used to provide heat to the various heating zones of a glove [13].

Another way to provide heat to a product is to use phase transformation materials that are characterized by an ability to accumulate and release large amounts

of energy. Application of these materials is made by using finishing techniques or direct application in the polymer matrix during the spinning process. Phase-change materials (PCM) can absorb energy when the phase changes from solid to liquid, and can also release energy when the phase changes from liquid to solid. In textile applications, the PCM is usually enclosed in small polymer spheres of only a few micrometers diameter The effectiveness of these solutions is not always sufficient to meet the expectations of users [14, 15].

Heated protective gloves, due to the release of additional heat from the active source, should be tested using an appropriate test method [16, 17]. At present, many of the solutions have disadvantages, such as the battery performance may not meet the requirements of long exposure in cold conditions for electrically heated gloves and footwear [18]. In the case of chemical heating, the temperature is not controlled and kept constant [18, 19]. Depending on the system used, researchers use different methods to assess the heat emission of heated gloves and footwear.

Currently, there is a scarcity of research on evaluation methodology for assessing the safety and performance of heated protective products in the workplace. The basic requirements specified in Directive 89/656/EEC and Regulation 2017/625 [20, 21] do not address to any large extent the actual workplace

conditions for which such products are intended. To make ensure that products containing heating elements, whether passive (e.g., mineral compounds, gels) or active (e.g., heating coils), effectively ensure worker safety in cold environments, and thus can be considered proper PPE, their performance in the workplace should be evaluated.

Standard protective gloves designed for use in cold environments should be characterised by appropriate insulation properties, expressed as a performance level (a measure of protection performance in the workplace). The study used a thermal hand model, in accordance with EN 511:2006 [22]. Protective gloves with active or passive heat sources are very promising products that can significantly improve worker safety in terms of maintaining optimum hand temperature during the execution of manual tasks in cold environments. However, little is known about their performance associated with the presence of heat sources [18]. Another question is whether their thermal insulation properties are maintained at the same level over time, and how they differ for various heat sources [12].

The objective of the work was to evaluate the thermal insulation properties of heated gloves containing passive and active heat sources using a thermal hand mode, in accordance with an originally developed protocol. Another goal was to establish the effectiveness of the thermal insulation of heated gloves and to determine their performance level. The important questions were whether passive
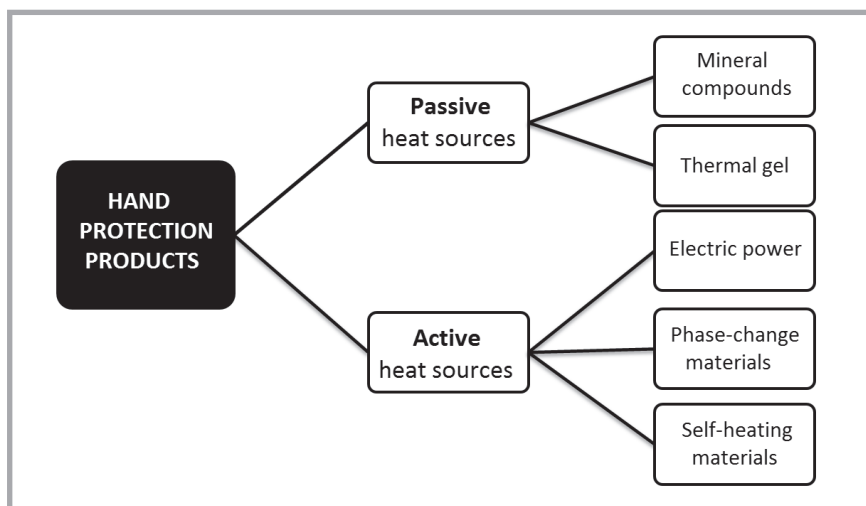

Figure 1. Types of hand protection products by heating system and heating medium.

and active systems follow temperature changes associated with the work cycle in the same way, and thus whether they ensure the performance level required. These problems are presented in a case study which shows a method for evaluating the thermal performance of gloves heated with passive and active sources in the context of user comfort and safety in cold environments.

Materials and methods

Experimental gloves and their components

Thermal insulation tests were made on two commercial models of glove of a similar construction with active and passive additional heat sources. The selection of gloves was dictated by the construction (five-finger model), similar

material used in the design (waterproof membrane, insulation and fleece lining) and comparable level of thermal insulation (1 or 2 levels of performance). The gloves are described in *Table 1*.

Methodology

Testing the thermal protective properties of the gloves

Protective gloves intended for use in cold environments should have adequate insulation properties, expressed in an appropriate level of this parameter. Thermal insulation is defined as resistance to dry heat loss, including the resistance of the protective glove and the air layer between the hand model and the glove. The test is carried out on a thermal hand model according to the EN 511 standard (*Figure 2*), which specifies the requirements for the value of the glove's param-

Table 1. Glove characteristics with passive and active heating systems.

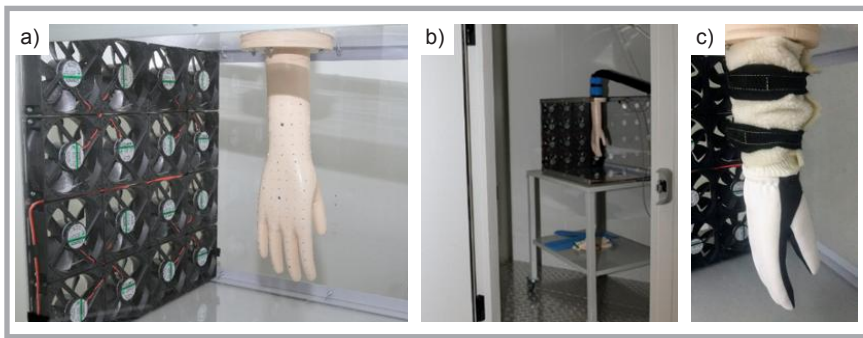| Name/Variant	Gloves/heating system	Type of heating system	Mass, g	Glove thickness, mm		Thermal effect
				Palmar part	Dorsal part	
Glove with passive heating system variant R_{PA}		Passive – use of a heating element in the form of a gel heater (Highlander, United Kingdom)	**Gloves**: 95.959 **Heating element**: 96.906 **Glove with heating system**: 192.866	3.28	3.97	Temp. 50-55 °C The time of heating depends on the temperature of use
Glove with passive heating system variant R_{AK}		Active – use of a carbon-based heating system with aLi-Poly battery (Glovii, Poland)	**Gloves**: 149.965 **Heating element**: 90.754 **Glove with heating system**: 243.126	1.29	2.21	Battery characteristics: 7,4V 2100 Ma 15.54 kWh

Figure 2. *a) Hand model used for testing the thermal insulation effectiveness of gloves according to PN-EN 511:2006, b) thermal hand model in the climate chamber, c) protective glove on the thermal hand model in the climate chamber.*

eters which provides protection against the cold.

The protective glove-specific properties of the laboratory test are classified into four different efficacy levels depending on the value obtained for given parameter (***Table 2***).

Tests were conducted for relative air humidity and 5 ambient temperatures: 10 °C, 5 °C, 0 °C, -10 °C & -15 °C, occurring in real cold work environments, which are described in detail in other authors' work [23]. After thermal stabilisation of the hand model and climate chamber, the measurements were registered.

Table 2. *Thermal insulation values with the level of effectiveness of the gloves (EN 511:2006) [22].*

Performance level	Thermal insulation, I_{TR} w m² K/W
1	$0.10 \le I_{TR} < 0.15$
2	$0.15 \le I_{TR} < 0.22$
3	$0.22 \le I_{TR} < 0.30$
4	$0.30 \le I_{TR}$

Concept of analysis of thermal protective properties of the gloves

Providing information on the thermal insulation of gloves expressed as a performance level is not sufficient for heated gloves. Therefore, it is important to provide other information on the additional amount of energy saved. The authors' own computer software for the thermal hand model was adapted to allow the analysis and measurement of additional heat generated by products equipped with additional heating systems.

The computer software uses the following parameters for evaluation of thermal properties of gloves with additional heating sources:

■ power changes resulting from placing an additional heating element, dP, W

$$dP = P_2 - P_1, \qquad (1)$$

where:
P_1 – the power supplied to maintain the preset temperature T_s during the reference measurement, W, and

P_2 – the power supplied to maintain the preset temperature T_s during the proper measurement, W.

■ insulation changes due to the placement of an additional heating element, dI, m²·°C·W⁻¹

$$dI = I_2 - I_1 \qquad (2)$$

where:
I_2 – insulation of the protective product during the proper measurement, m²·°C·W⁻¹;

I_1 – insulation of the protective product during the reference measurement, m²·°C·W⁻¹.

Based on the above parameters, it is possible to calculate the additional energy. This parameter informs about the amount of energy Et, J, saved during time (t) due to the use of an active or passive heating system:

$$Et = (P_1 - P_2)*t \qquad (3)$$

where:
t – time of measurement, s.

In addition, the Added Heat Index (AHI) was developed to assess the efficiency of the heating element used, which determines the increase in thermal insulation of the product tested, according to the formula proposed:

$$AHI = \frac{I_{eg} - I_0}{I_0} \times 100\% \qquad (4)$$

where:
I_{eg} – mean product insulation with passive and active heating systems,

I_0 – mean insulation of the product with passive and active heating systems but with the heating function disabled.

Statistical analysis

The data collected were subjected to statistical analysis using the SPSS Statistics 23.0 program to demonstrate the importance of the type of measurement and type of protective glove construction in the variant with a passive heating element (R_{PA}) and active heating element (RAK) for the mean thermal insulation and at four temperatures: +5 °C, 0 °C, -10 °C & -15 °C.

Student's t-test was applied for two dependent and independent samples by means of the posteriori Bootstrap method (sampling 1000). The significance of the results was assumed at the level of

Table 3. *Descriptive statistics of thermal insulation at +5 °C, 0 °C, -10 °C & -15 °C for a protective glove with a passive (R_{PA}) and active (R_{AK}) heating element.*

			Variant	N	M	Me	SD	Skewness	Kurtosis	Min	Max
Thermal insulation, m²*°C/W	Specific measurement	Temp. +5 °C	R_{AK}	8	0.21	0.22	0.05	-0.12	-1.93	0.16	0.28
			R_{PA}	8	0.16	0.15	0.02	0.59	-1.89	0.14	0.19
		Temp. 0 °C	R_{AK}	8	0.22	0.24	0.05	-0.49	-1.98	0.16	0.27
			R_{PA}	8	0.16	0.15	0.02	0.63	-1.98	0.14	0.19
		Temp. -10°C	R_{AK}	8	0.20	0.20	0.03	-0.40	-2.07	0.16	0.22
			R_{PA}	8	0.16	0.15	0.02	0.63	-1.72	0.14	0.18
		Temp. -15 °C	R_{AK}	8	0.20	0.20	0.02	-0.50	-1.87	0.16	0.22
			R_{PA}	8	0.15	0.14	0.02	0.82	-1.31	0.14	0.18
		Mean	R_{AK}	8	0.21	0.22	0.03	-0.49	-2.12	0.16	0.24
			R_{PA}	8	0.16	0.15	0.02	0.62	-1.93	0.14	0.18
	Reference measurement	Mean	R_{AK}	8	0.17	0.17	0.00	-1.96	3.89	0.16	0.17
			R_{PA}	8	0.14	0.14	0.00	-0.32	-1.05	0.14	0.14

p < 0.05. The normal distribution of variables was confirmed on the basis of skewness and kurtosis values not exceeding the range <-1; 1>.

Results

Test results of thermal protective properties of gloves

Table 3 presents descriptive statistics of the test results of thermal insulation tests, determined for 8 measurements (after 5, 10, 20, 60, 80, 120, 140 and 200 minutes of testing) during a 200-minute mode of gloves with a passive heating system (R_{PA} variant) and active system heating (R_{AK} variant) at all ambient temperatures tested: +5 °C, 0 °C, -10 °C & -15 °C. A summary of these results are presented in *Figure 3*.

The results of tests of the mean thermal insulation, expressed in performance levels, which were determined for 8 measurements (after 5, 10, 20, 60, 80, 120, 140 and 200 minutes of the test) were noted during a 200-minute mode of operation of the gloves with a passive heating system (R_{PA} variant) and those with an active heating system (RAK variant) at all ambient temperatures tested: +5 °C, 0 °C, -10 °C, -15 °C (*Figures 4*). The measurements for the zero test (with the heating function turned off) were marked in grey and yellow, and in green and orange colour in the measurements for gloves with an active heating element (function enabled).

Results of the analysis of thermal protective properties of the gloves

Additionally, in *Table 4* the Added Heat Index (AHI), which describes the efficiency of the heating system used and determines the percentage increase in the thermal insulation of the product tested, is defined.

Results of statistical analysis

Table 5 presents a summary of the T Test statistic for the effect of the construction of the protective gloves on the mean thermal insulation and at four temperatures: +5 °C, 0 °C, -10 °C & -15 °C.

A statistically significant effect of the construction of the protective gloves on thermal insulation was found in the mean specific measurement. In the case of protective gloves in the R_{PA} variant with a passive heating element, lower values of thermal insulation were ob-
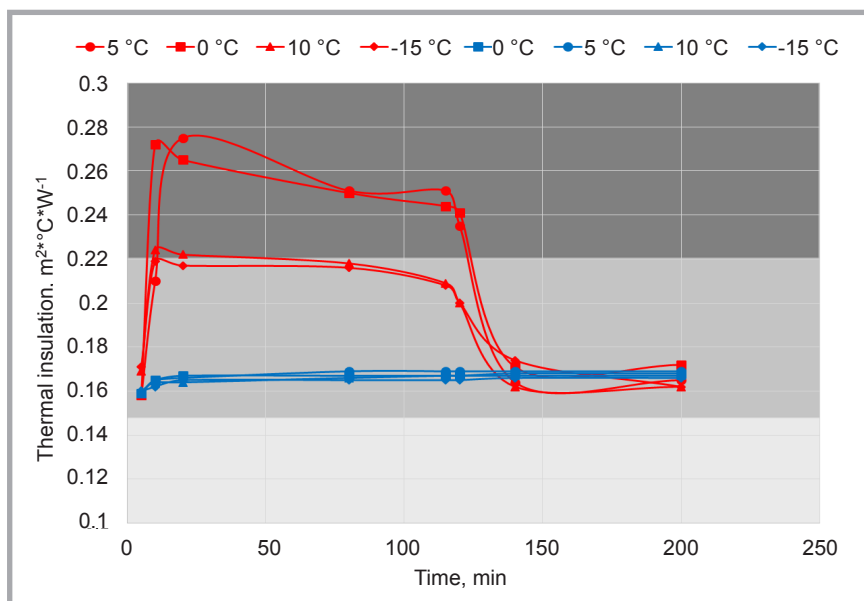

Figure 3. Dependence of thermal insulation as a function of time for protective gloves with the heating function turned off/on – R_{AK} model at all ambient temperatures tested.
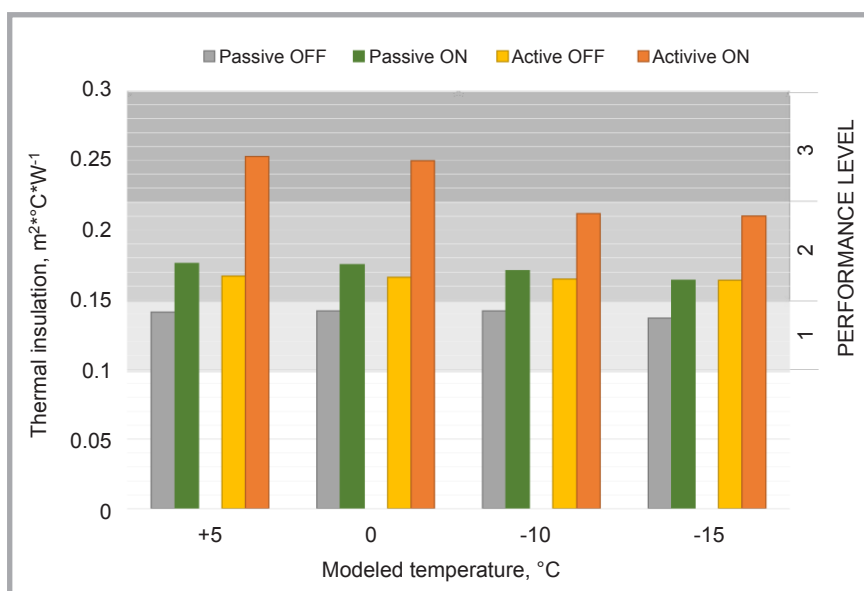

Figure 4. Increase in thermal insulation expressed by a change in the performance level of gloves with the heating system turned on compared to gloves with the heating system turned off.

Table 4. Additional heat, power changes, thermal insulation and the AHI index for the protective gloves (R_{PA} and R_{AK} variant) at temperatures of +5 °C, 0 °C, -10 °C and -15 °C.

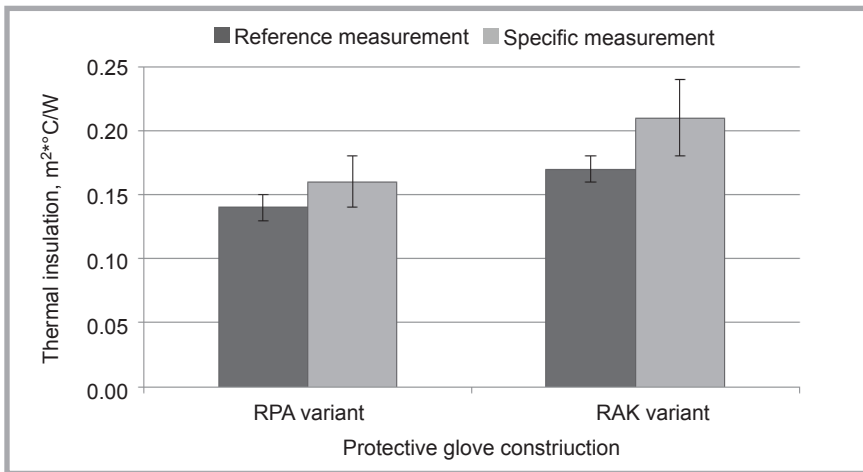| T, °C	I_{OFF}, m²*°C/W	I_{ON}, m²*°C/W	dP, W	dI, m²*°C/W	Et, J	AHI, %
Gloves with an active heating system						
+5	0.167	0.253	-2.839	0.086	56	51.6
0	0.166	0.250	-3.001	0.084	66	50.6
-10	0.165	0.212	-2.913	0.047	68.3	28.44
-15	0.164	0.210	-2.719	0.046	108.4	28.00
Gloves with an passive heating system						
+5	0.141	0.176	-1.140	0.035	45	24.25
0	0.142	0.175	-1.575	0.033	63	23.35
-10	0.143	0.171	-1.542	0.028	74	19.13
-15	0.137	0.164	-2.177	0.024	22	19.07

Figure 5. *Effect of the type of measurement on thermal insulation, $m^{2*}°C/W$ for protective gloves in the variant with a passive (R_{PA}) and active (R_{AK}) heating element.*

Table 5. *Test Statistic for the effect of the design of the protective gloves on the thermal insulation in a specific measurement at temperatures of +5 °C, 0 °C, -10 °C & -15 °C and for the mean thermal insulation.*

				Glove construction		T Test Statistic	
				Variant R_{PA}	Variant R_{AK}	t (14)	p
Thermal insulation $m^{2*}°C/W$	Specific measurement	Temp. +5 °C	M	0.16	0.21	3.09	$p < 0.05$
			SD	0.02	0.05		
		Temp. 0 °C	M	0.16	0.22	3.51	$p < 0.05$
			SD	0.02	0.05		
		Temp. -10 °C	M	0.16	0.20	3.37	$p < 0.05$
			SD	0.02	0.03		
		Temp. -15 °C	M	0.15	0.20	4.50	$p < 0.001$
			SD	0.02	0.02		
		Mean	M	0.16	0.21	23.68	$p < 0.001$
			SD	0.02	0.03		

Table 6. *Test Statistic for the effect of the type of measurement on the mean thermal insulation for protective gloves in the variant with a passive (R_{PA}) and active (R_{AK}) heating element.*

				Type of measurements		T Test Statistic	
				Reference	Specific	t (7)	p
Thermal insulation, $m^{2*}°C/W$	Glove construction	Variant R_{PA}	M	0.14	0.16	-2.58	$p < 0.05$
			SD	0.01	0.02		
		Variant R_{AK}	M	0.17	0.21	-3.40	$p < 0.05$
			SD	0.01	0.03		

served than in the case of protective gloves in the R_{AK} variant with an active heating element.

There was also a statistically significant effect of the construction of the protective gloves on thermal insulation in a specific measurement at four ambient temperatures: +5 °C, 0 °C, -10 °C & -15 °C. At each ambient temperature tested, in the case of protective gloves in the R_{PA} variant with a passive heating element, lower thermal insulation values were observed than in the case of protective gloves in the R_{AK} variant with an active heating element.

Table 6 presents a summary of the test statistics for the effect of the type of measurement on thermal insulation in general for protective gloves in the variant with a passive (R_{PA}) and active (R_{AK}) heating element.

There was a statistically significant effect of the type of measurement on the mean thermal insulation in the case of a protective glove in the variant with a passive (R_{PA}) and active (R_{AK}) heating element. In both construction variants of protective gloves, in the reference measurement, lower values of mean thermal insulation were observed than in the specific measurement, as shown in **Figure 5**.

Discussion

In workplaces where the risk of cooling of the distal parts of the body occurs, gloves with insulating properties are used. Traditional protective gloves are made of textile or leather materials, and an increase in thermal insulation is achieved through the use of additional insulating inserts/linings. In practice, this results in a deterioration of manual dexterity. An alternative may be the construction of gloves with a smaller number of insulating layers but equipped with additional heat-supporting elements (active or passive). These types of gloves can achieve a higher level of efficiency in terms of the thermal insulation required.

A cold work environment is characterised by a temperature of less than 10 °C. Work in such thermal conditions causes the cooling of hands and reduction of the manual worker's efficiency, which in turn reduces the effectiveness of work and may pose a risk of accident [24]. Moreover, the direct contact of fingers with a cold surface can cause a greater thermal injury than exposure to a cold atmosphere [25, 26]. Therefore, it is justified to use different types of protective gloves with good insulating properties. Gloves used to protect against heat loss should be characterised by high values of this parameter, which depends on the construction of the glove [23].

This fact is related to the type, surface mass and also number of layers of materials used in individual parts of the glove [27]. Alternative solutions, e.g. products equipped with active or passive heat sources, must have appropriate research methodology related to determining the added heat [28].

Currently, there is no literature describing the provision of protection to employees at an appropriate level by gloves equipped with additional heat sources. Own research confirms that the performance level of thermal insulation for gloves (R_{PA} variant) in simulated cold environment conditions (for all selected temperatures), without an active heating system, was at level 1, while in the case of R_{AK} – level 2. The mean thermal insulation for the R_{AK} gloves with the heating system turned on at temperatures of 5 and 0 °C was about 0.250 m^2K/W, which meant the achievement of the 3 rd performance level. In the other cases studied, the mean thermal insulation

for the gloves tested with the heating system turned on ranged from 0.15 to 0.22 m²K/W, which meant the achievement of the 2 nd performance level.

Therefore, the use of both passive and active heating systems in protective gloves in a cold work environment increases their thermal insulation, expressed by increasing the performance level, which is statistically significant. For the passive system, the added heat index (AHI) is +5 °C – 24.25%, 0 °C – 23.35%, -10 °C – 19.13% and 15 °C – 19.07%, and for the active system a heat indicator added (AHI) is +5 °C – 51,6%, 0 °C – 50,6%, -10 °C – 28,44% and 15 °C – 28,00%.

When comparing the results of the mean thermal insulation for the gloves (*Figure 5*), it can be clearly seen that the parameter decreases with the lowering of the temperature value. A small influence of ambient temperature on thermal insulation was observed mainly in the case of a five-finger glove with a passive heating system (R_{PA}), which is statistically significant. This is due to the location of the heating element, because only one zone in the glove is heated up. In addition, due to the construction and close adherence of the glove to the thermal hand model, there is a small convection of heat produced by the element inside the glove.

In turn, determination of the Added Heat Index (AHI), which evaluates the efficiency of the heating element used, helps to determine the increase in thermal insulation of the heated glove. The indicator values obtained show that an active heating system increases insulation by up to 52%.

Moreover, analysing the results of measurements of additional energy for variant R_{AK} (*Table 4*), it can be concluded that with a temperature decrease, E_t increases, which is related to maintaining the set temperature of 33 °C of the hand model. It can also be noted that the amount of heat added at temperatures to -10 °C is at a similar level (ranging from 5-68.3 J), while below this temperature, at -15 °C in the case of R_{AK}, the amount of heat increases by 37%, up to 108, 4 J. Which means that below -10 °C, it is more difficult to maintain thermal comfort in the glove.

In the case of a passive system, frequent local overheating was observed, caused by an uncontrolled temperature increase

due to the exothermic chemical reaction occurring in the gel heater and its large size. In addition, there was a large temperature drop in the finger zone, which could cause, for example, the risk of frostbite in working conditions [29].

The active heating system was characterised by very good thermal insulation and a constant, evenly distributed temperature inside the glove tested. Thermal insulation in the strategic finger zone did not differ from the average for the whole glove.

Based on the results obtained, when we consider the 8-hour work system, a glove with a passive heating system in the form of a gel heater would not work well, as the frequent necessity to replace the gel cartridges could impede the work. Moreover, the size of the contribution and the degree of hardness after the change of the phase to a crystalline one could cause discomfort at work.

In the case of using a glove with an active heating system placed on the whole surface of the glove, it can be stated that it would work if it is possible to replace the battery supplying the heating system during breaks. Due to the fact that the charging time of these batteries is 8 hours, the employee would have to have a set of a minimum of 3 pairs of batteries charged alternately.

Based on the results of the study, guidelines were developed for the use of gloves with passive and active heat sources in a cold environment. To improve the safety of workers wearing heated hand protection products, it should be borne in mind that:

■ in gloves with passive heat sources, the increment in thermal insulation is up to approx. 20%, corresponding to an increase in glove performance by 1 level, with a heating duration of approx. 70 min, which means that the heating elements must be replaced during work;

■ in gloves with active heat sources, the increment in thermal insulation is approx. 50%, corresponding to an increase in glove performance by 1 or 2 levels, with a heating duration of approx. 120 min, which means that the batteries may be replaced or charged during a break.

The procedure shows how to evaluate the performance of heated hand protection

products. The study indicates that active and passive systems differentially follow temperature changes, and thus differ in the levels of thermal insulation provided in the workplace. In a further study, the authors intend to compare findings from the methodological approach presented with results from experiments involving subjective evaluation by human participants.

■ Conclusions

The study evaluated the thermal insulation properties (as expressed by the thermal performance) of gloves with passive and active heat sources. The assessment approach proposed is useful in that it complements the standard procedure EN 511:2006 in terms of determining the thermal performance of heated gloves in cold work environments.

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