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Significance of Functional Studies Designing Filtering Half-masks with Superabsorbent Polymer

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Abstract
Functional studies of a range of personal protective equipment approved for distribution in European and international markets, conducted at different workplaces, showed that almost half of the participating workers did not find it comfortable. The objective of the work was to evaluate the comfort of use and functionality of a half-mask containing a superabsorbent polymer (SAP) designed for respiratory protection under harsh working conditions. The modifications implemented following functional studies were subsequently verified. The results of functional studies confirmed the hypothesis that nonwovens with SAP offer improved comfort of use. Filtering half-masks of modified construction fit users' faces much better, without causing skin irritation or chafing; the masks were also free of pungent or offensive odors, which contributed to good user experience. The results show the significance of functional studies involving workers in real-life workplaces.

Key words: *respiratory protective devices, filtering half-mask, superabsorbent polymer, comfort of use.*

Introduction

Personal protective equipment (PPE) is defined as devices used or donned by workers to protect themselves from one or more hazards potentially threatening their safety and health during work. In the European Union (EU), PPE is marked with the CE sign, which indicates that it meets the basic requirements of the design and manufacturing in relation to health and safety specified in Regulation (EU) 2016/425 of the European Parliament and of the Council of 9 March 2016 on personal protective equipment and the repealing of Council Directive 89/686/EEC [1]. Furthermore, such devices should be appropriate for existing hazards, should not increase or cause additional risk and they should correspond to the conditions occurring in the workplace. It is also important that they fulfil appropriate ergonomic requirements, take into account the health of the employee and fit the user in any necessary way [2].

In the process of CE certification, PPE is tested in terms of its functional and protective properties in laboratories. However, although laboratory testing is supposed to reflect real-life conditions in workplaces, complete simulation is rarely possible. It should be noted that workplace conditions are usually difficult to predict as they result from natural occurrences in the course of work. The designers and manufacturers of PPE often use advanced technologies to ensure compliance with construction principles, the relevant requirements stipulated in technical standards, internal regulations, the recommendations of OSH bodies, and with the expected levels of protection and functionality. Finally, the PPE models and prototypes developed need to be validated with respect to those specifications.

The process of product improvement, from developing a model to producing a prototype batch, should be accompanied by laboratory tests of the materials applied in the product, its components, and the final version of the product itself [3-7]. The validation of new personal protective devices designed for special applications requires workplace testing taking into account ergonomic principles [8]. The most common cause of discomfort are abrasions and bruising of the skin in the areas of adherence of the half-face mask to the user' s face (cheeks, nose, chin). Due to the tight fit, an unfavorable microclimate under the facepiece (i.e. high relative humidity and elevated temperature) occurs in a very short time [9]. Moist air causes water molecules to accumulate at the interface between the skin and brim of the facepiece resulting in skin irritation, which may lead to the rejection of protective equipment by the user, despite its high protection value.

According to the literature, in recent years there have been few studies evaluating the ergonomic properties of respiratory protective equipment in the workplace, as the majority of research efforts have dealt with protective clothing, footwear, and gloves, with some notable examples given below.

One paper reported that the PPE used by pineapple plantation workers while planting seedlings and harvesting fruits was ineffective [10]. The workers are at risk of venomous snake bites and punctures by pointed leaves. The study examined four sets of PPE, including protective footwear, gloves, and leggings, with each set consisting of three different models. Finally, only 5 models were approved for further functional testing (one model of footwear, two of leggings, and two of gloves). Only those devices were found to provide satisfactory protection against both leaf punctures and snake bites. According to the authors, the results of functional studies should be used as an input for developing PPE that would effectively protect workers on pineapple plantations. In addition to protective properties, in designing new devices one should also take into account such issues as comfort of use and type of work activity.

In the case of other agricultural work, including greenhouse cultivation, one of the major concerns is the use of pesticides. Since often exposure to pesticides is inevitable for the workers, PPE is needed to protect their health. The enclosed environment of the greenhouse increases the risks associated with pesticides, but the high temperature is conducive to inappropriate use of PPE. In this case, functional tests conducted in the workplace enabled the selection of the right protective devices and elimination of discomfort [11]. The authors of paper [12] also showed that rubber boots, trousers made of coated materials, hood-type face pieces, long-sleeved shirts, and rubber gloves are not appropriate for plant spraying at a tomato plantation due to thermal comfort issues. Thermal comfort was assessed by measuring the workers' pulse and body temperature. The functional study showed that the application of inappropriate personal protective devices may compromise the thermal regulation of the users and adversely affect their health. These studies were also confirmed in work [13].

A functional study conducted during manual sugar cane cutting, involving 47 workers, in Sao Paulo evaluated 4 models of protective gloves in terms of work safety, protection parameters, and user comfort. The results, as well as field observations, revealed that only one type of glove fully met the requirements of user comfort and resistance to damage. According to the authors, the study indicates the problem of the absence of convergence between laboratory testing and functional studies involving workers. In this way, the actual needs of the workers as well as the type of work performed are largely ignored [14]. A questionnaire survey conducted by Irzmańska in facilities where workers were exposed to mineral oils, lubricants, and mechanical factors confirmed the usefulness of functional studies in terms of the selection of appropriate glove protection levels for the manual tasks performed [15].

A functional study involving both male and female firefighters revealed construction defects in clothing as well as inadequacies associated with the materials used. Furthermore, the various personal protective devices used were not necessarily compatible, leading to work discomfort, limited movement, and thermal discomfort. It was found that further studies were needed to determine optimum modifications which could improve firefighter safety in terms of protective and economic parameters, and especially comfort of use [16].

PPE is also gaining wider applications in sports due to increasing training intensity and widespread injuries, often entailing costly treatments. Traditional personal protective devices often limit the user's movements, may be uncomfortable, cumbersome and heavy, and often adversely affect not only cognitive but also psychological aspects. Thus, user comfort and fit are considered to be very important factors in PPE construction.

Functional studies of PPE approved for distribution in the European and international markets, conducted in a variety of workplaces, have revealed that almost half of the workers involved did not find it comfortable. To ensure greater worker safety, more attention should be paid to the ergonomics, form, and style of PPE. It is therefore necessary to conduct further functional studies with a view to improving user comfort and providing effective protection to the users.

The objective of the present work was to evaluate the comfort of use and functionality of filtering half-masks containing a superabsorbent polymer (SAP) designed for respiratory protection under conditions of harsh physical work. The modifications of the construction conducted following the functional tests were subsequently verified.

Materials and methods

Filtering half-mask models

A developed fibrous composite with high filtration efficiency (98,53%), low air flow resistance (230 Pa) and good water sorption capacity was used to fabricate a filtering half-mask model for application in heavy working conditions. The model was positively evaluated according to the requirements of the new international ISO standards and EN European standards concerning filtering half-masks.

The filtering half-mask was developed as a planar construction, without high temperature moulding of the facepiece. The half-mask consists of the following basic elements:

- a nosepiece made of a nonwoven composite containing:
  1. a sorption layer with an area density of 26.66 g/m^2 responsible for drying the incoming air and stopping large particles suspended in it,
  2. an electret filtering nonwoven with an area density of 89.92 g/m^2 responsible for filtration proper,
  3. a sorption layer with an area density of 40.0 g/m^2, absorbing moisture from the user's face;

The individual layers of the composite produced were arranged in a system where, from the air inlet side of the polluted atmosphere, a sheath nonwoven fabric containing SAP with a particle size of 250 µm and electrostatic charge was used (1). The functions which this nonwoven fabric should meet are the drying of air entering and stopping of large particles from the surrounding atmosphere. The main layer is an electret filtering material, which is always responsible for the proper filtration of air (2). The non-woven fabric containing SAP with 30 µm granularity with electrostatic charge is designed to absorb moisture from the user's skin (3).

As a modifier, a polymer absorbent, type EK-X EN52 (SAP), with a grain size of 250 µm and 30 µm was used, which was added to the polymer mass in the amount of 3.5/m^2 of nonwoven fabric (approx. 3% by volume) – supplier: Toruńskie Zakłady Materiałów Opatrunkowych S.A.

- a head harness made of two elastic bands;
- a nose clip;
- a nose seal placed on the inner side of the nosepiece;
- an exhalation valve placed on the right side of the nosepiece.

The filtering half-mask model was subjected to full laboratory testing for conformity with the standard EN 149:2001+A1:2009 in terms of penetration by the test aerosols (sodium chloride and paraffin oil mist), breathing resistance, total inward leakage (TIL), dolomite liquid clogging, flammability, exhalation valve strength, CO_2 content in exhaust air, as well as functional tests under conditions similar to actual ones. The protective and functional tests of the half-mask model indicated that it met the required protection level FFP2.

The verified filtering half-mask model consists of the following basic elements:

- a half mask bowl made of a nonwoven composite containing:
  1. a sorption layer with an area density of 59.78 g/m^2 responsible for

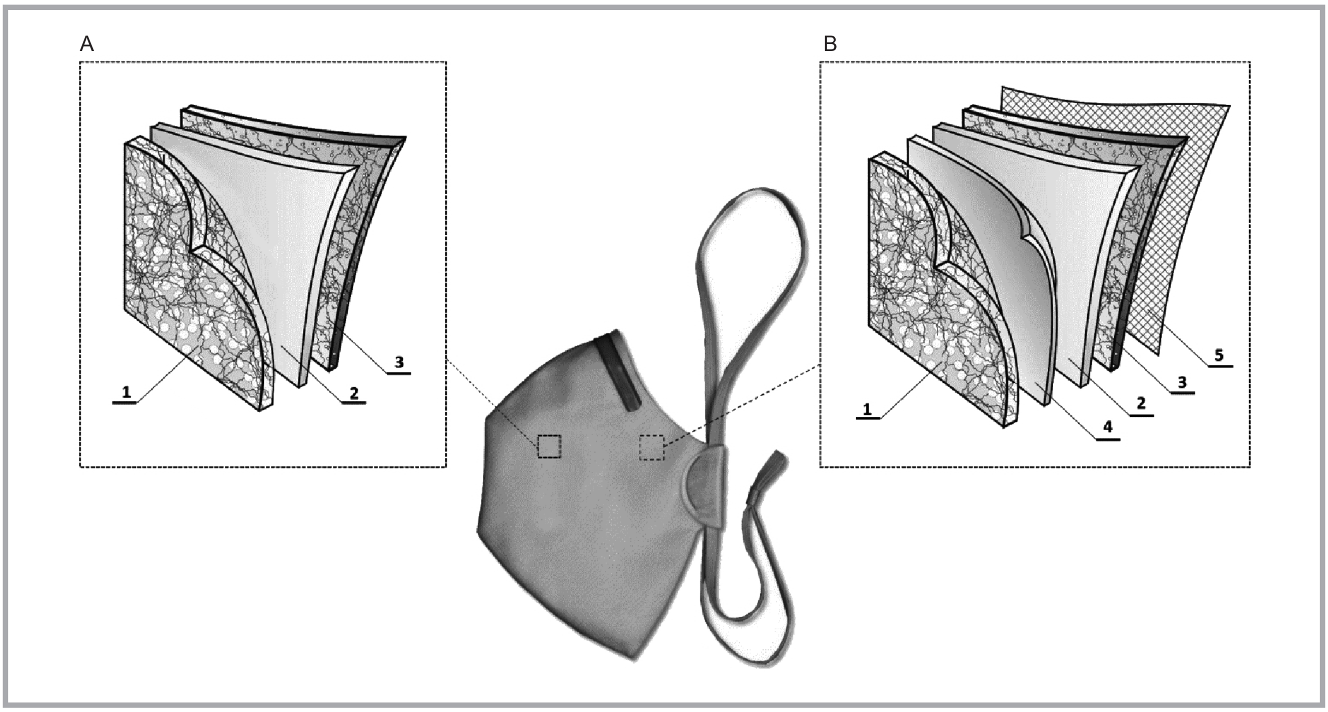

Figure 1. Comparison between the construction of the base filtering half-mask model and the verified filtering half-mask model (1 – sorption layer drying incoming air and stopping large particles, 2 – stiffening layer strengthening the construction, 3 – electret filtering nonwoven responsible for filtration proper, 4 – sorption layer absorbing moisture from the user's face, 5 – layer improving user comfort).

drying the incoming air and stopping large particles suspended in it,

2. a stiffening layer with an area density of 100 g/m^2, strengthening the construction,
3. an electret filtering nonwoven with an area density of 89.92 g/m^2 responsible for filtration proper,
4. a sorption layer with an area density of 23.03 g/m^2, absorbing moisture from the user's face,
5. a layer with an area density of 24.0 g/m^2, improving user comfort

- a head harness made of two elastic bands;
- a nose clip;
- a nose seal placed on the inner side of the nosepiece;
- an exhalation valve placed on the right side of the nosepiece.

Differences in the construction of both half-mask models are presented in ***Figure 1***.

Characteristics of the study group

The study involved 23 and 7 healthy male coal miners who tested the initial and modified filtering half-mask models, respectively. All of them were occupationally active and used filtering half-masks in their everyday work. The test group is characterised in terms of age, height, weight, and BMI in ***Table 1***.

Functional studies

The filtering half-mask model investigated, which had successfully passed laboratory tests, was subjected to functional studies under real-life conditions in the KWK Bobrek-Piekary coal mine, owned by Węglokoks Kraj Sp. z o.o. in Poland. The functional study involved 23 filtering half-masks and 7 verified half masks, which were evaluated by means of a questionnaire survey. Testing was conducted under conditions of high temperature (approx. 27 ± 2 °C) and high relative humidity (90 ± 10%), with the participants being operators of mining machines at an underground coal face. The tests were carried out in the following dustiness: carbon respirable phase concentration – 6.5 mg/m^3 with MAC equal to 2 mg/m^3 and silica respirable phase concentration – 0.25 mg/m^3 at MAC equal to 0.1 mg/m^3.

Questionnaire survey

Following a 6 h underground shift, the users were given a questionnaire in order to determine their subjective perceptions as to how comfortable the filtering half-masks were. The questionnaire included items concerning both the use of filtering half-masks and the specific half-mask model tested.

Results and discussion

Questionnaire on the comfort of use of filtering half-masks

The functional study involved 23 miners, of which 10 use half-masks 3x per shift, 15 use half-masks from 2 to 4 h per shift, and 21 remove half-masks several times per shift (3 to 10 times). Each miner was given a tested half-mask. The study was designed to evaluate various aspects concerning the comfort of use and functionality of the half-mask model tested based on subjective opinions of the users collected in the form of responses to questionnaire items. The items were closed-ended, with multiple-choice response options. A space for user comments was also provided. The results are

Table 1. Characteristics of the test group.

Basic statistics	M ± SD	Median (min-max)
Age, years	35 ± 8	35 (22-48)
Height, cm	178 ± 7	178 (167-191)
Weight, kg	85 ± 9	86 (69-101)
BMI, kg/m^2	27 ± 2	27 (23-32)

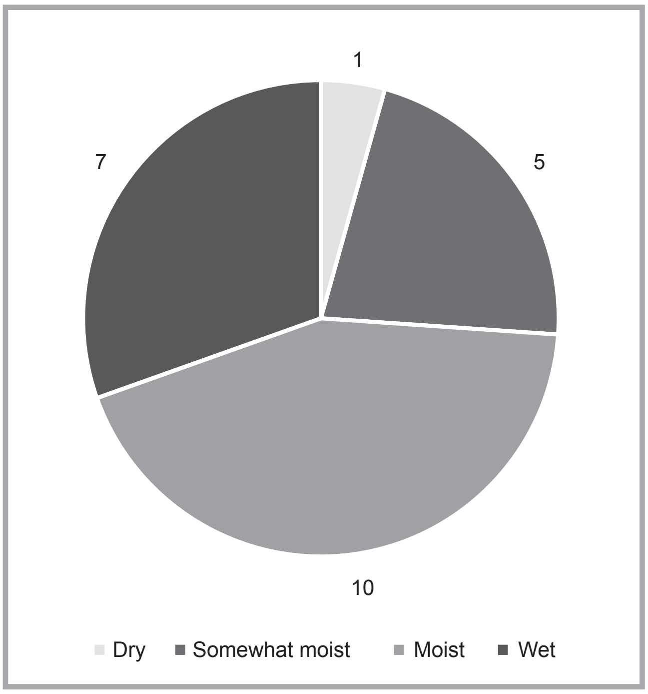

Figure 2. *Subjective evaluation of the thermal state of the user's face under the filtering half-mask model during hard physical work.*

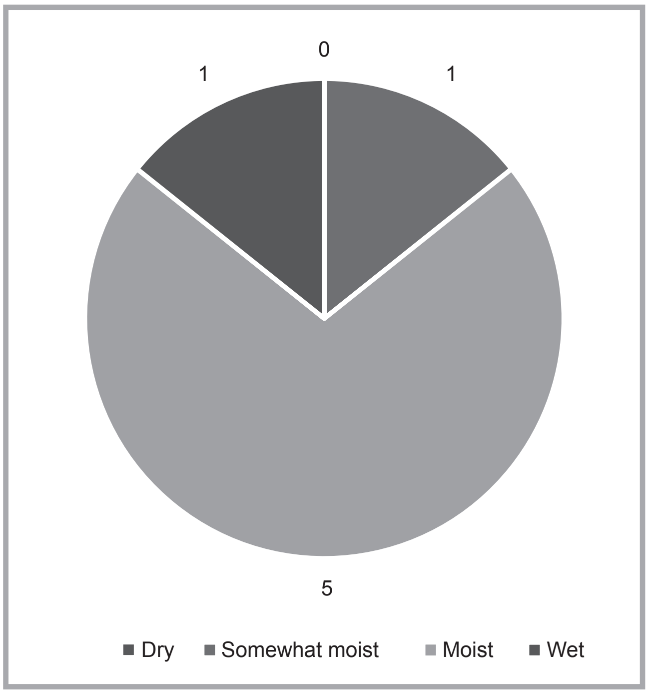

Figure 3. *Subjective evaluation of the thermal state of the user's face under the verified filtering half-mask model during hard physical work.*

presented in ***Table 2*** with the number of answers.

Analysis of questionnaire data made it possible to identify the most important issues reported by the participants with respect to the comfort of use and functionality of the filtering half-mask model tested. The questionnaire results are given below.

First of all, 13 out of 23 participants found the half-mask to be comfortable, while 15 stated that it absorbed perspiration from their face. According to 9 of the participants, the half-mask remained tight throughout use, 15 said that it did not cause skin irritation or chafing, and 20 reported no pungent or offensive odours. 19 of the participants confirmed that the half-mask enabled breathing dry air, and 13 stated that it did not increase its weight. Finally, 20 of the participants did not find any nonwoven fibres left on their face.

Evaluation of the thermal condition of the user's face under the half-mask also took into consideration the sensation of humidity associated with perspiration under harsh physical working conditions, as shown in the ***Figure 2***.

As can be seen from ***Figure 2***, the prevalent user sensation was that the face under the half-mask was moist.

Other comments reported by the users concerned difficulty in breathing associated with moisture absorption by the SAP and the sagging of the half-mask during breathing, rapid moisture absorption, causing the half-mask to become wet, making it impossible to use, and skin irritation.

The questionnaire showed that the construction of the half-mask was not rigid, and the external layer of the half-mask quickly absorbed moisture, but under harsh physical working conditions, the half-mask sagged, causing a dramatic increase in breathing resistance. The half-mask also caused skin irritation during use.

In view of the above, the construction of the filtering half-mask was modified by redesigning the nonwovens, that is, increasing the area density of the external layer by approx. 30 g/m^2 and decreasing that of the internal layer by approx. 20 g/m^2. While the filtering nonwoven remained in place, the polymeric mesh was replaced with a stiffening nonwoven with an area density of 100 g/m^2 to strengthen the construction. In addition, to improve user comfort, cotton gauze was added on the side of the user.

Table 2. *Number of positive and negative answers for filtering half mask model.*

No.	Question	Number of answer	
		Positive	Negative
4	Is the half-mask comfortable to use?	13	10
5	Does the half-mask absorb perspiration from your face?	15	8
6	Was the tightness of the half-mask compromised due to humidity (the nosepiece was not sealed on the user's face (e.g. there was a leak or it slipped away)?	14	9
7	Is your skin irritated or chafed where the half-mask made contact with it?	8	15
8	Does the half-mask produce pungent or offensive odours?	3	20
9	Does the half-mask enable breathing dry air?	19	4
10	Does the half-mask increase its weight during use?	10	13
12	Does the half-mask leave behind particles (nonwoven fibres or dust) on your face following removal of the mask?	3	20

Questionnaire on the comfort of use of the modified filtering half-masks

In the next step, the modified half-masks were subjected to functional studies in the Węglokoks Kraj coal mine, to be evaluated by means of a questionnaire study involving 7 workers. The quantitative results are given in ***Table 3***.

Analysis of questionnaire data made it possible to identify the most important issues reported by the participants with respect to the comfort of use and functionality of the modified filtering half-mask. The questionnaire results are given below (for 7 workers).

Following modification, 4 of the participants found the half-mask to be comfortable, while 6 stated that it absorbed perspiration from their face. According to 7 of the participants, the half-mask did not leak air throughout use, did not cause skin irritation or chafing, and did not produce any pungent or offensive odours.

As many as 4 of the participants confirmed that the half-mask enabled breathing dry air, and 2 stated that it did not increase its weight. Finally, all of the participants did not find any nonwoven fibres left on their face.

Evaluation of the thermal condition of the user's face under the half-mask also took into consideration the sensation of humidity associated with perspiration under harsh physical working conditions, as shown in ***Figure 3***.

As can be seen in ***Figure 3***, the prevalent sensation was that the user's face under the half-mask was moist.

Discussion of the questionnaire survey results

To compare user evaluation of the comfort of use of the filtering half-masks before and after modification, the percentage results for both models are given in ***Figure 4***.

The modified filtering half-mask, characterised by a substantially more rigid construction, gained much higher user approval. All participants stated that the modified half-mask did not leak air under humid conditions, did not cause skin irritation or chafing where it made contact with the user's skin, and did not produce any pungent or offensive odours.

However, as regards two questions concerning breathing dry air and increasing half-mask weight, the modified model received a more negative assessment than the initial one.

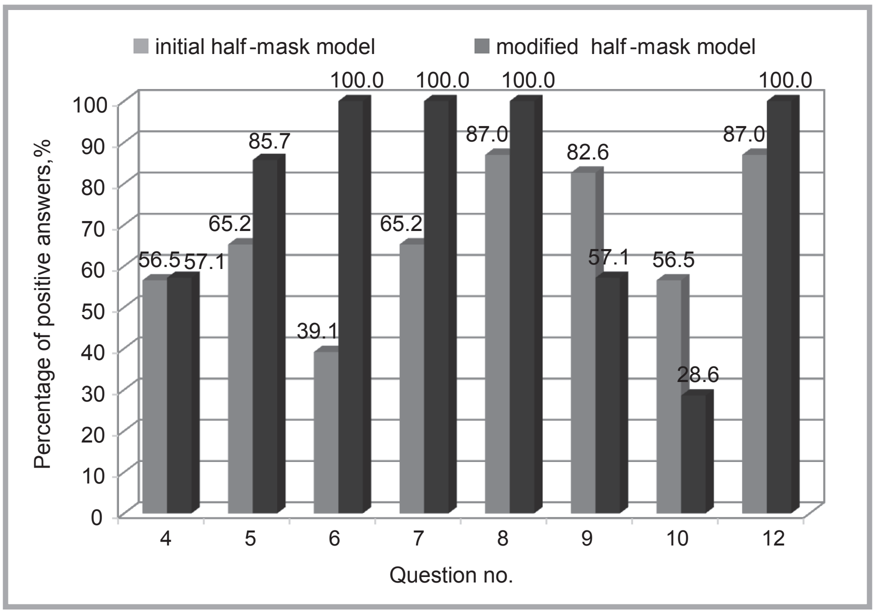

Figure 4. *Comparison of the results of questionnaire surveys evaluating filtering half-masks before and after modification.*

Table 3. *Number of positive and negative answers for modified filtering half-mask model.*

No.	Question	Number of answer	
		Positive	Negative
4	Is the half-mask comfortable to use?	**4**	**3**
5	Does the half-mask absorb perspiration from your face?	**6**	**1**
6	Was the tightness of the half-mask compromised due to humidity (the nosepiece was not sealed on the user's face (e.g. there was a leak or it slipped away)?	**7**	**0**
7	Is your skin irritated or chafed where the half-mask made contact with it?	**7**	**0**
8	Does the half-mask produce pungent or offensive odours?	**7**	**0**
9	Does the half-mask enable breathing dry air?	**4**	**3**
10	Does the half-mask increase its weight during use?	**2**	**5**
12	Does the half-mask leave behind particles (nonwoven fibres or dust) on your face following removal of the mask?	**7**	**0**

Table 4. *Comparative analysis of subjective evaluation of the thermal state of the user's face under the half-mask during harsh physical work.* ***Note:*** *B – absolute numbers, W – percentage results, %.*

Item	Multiple-choice options	Number of "YES" responses		Number of "YES" responses	
		Initial half-mask model		Modified half-mask model	
		B	W	B	W
Sensation of humidity on your face under the half-mask	Dry	1	4	0	0
	Somewhat moist	5	22	1	14
	Moist	10	43	5	71
	Wet	7	30	1	14

The two half-mask models were similar in terms of perceived user comfort, but the modified version revealed improved sweat absorption. Comparative results for subjective evaluation of the thermal state of the face under the half-mask are given in ***Table 4***.

As can be seen from ***Table 4***, the prevalent sensation for both the initial and modified half-mask models was that the user's face under the half-mask was moist.

To ensure greater safety under real-life conditions, one should thus pay greater attention to PPE ergonomics, form, and design. Further functional studies should be carried out with a view to improving comfort of use and safety in the workplace

Conclusions

Analysis of the studies and observations presented concerning the functionality of the filtering half-mask models developed confirms that the introduction of a superabsorbent polymer to the nonwoven material improved user comfort. The modified construction of the half-mask model, besides high protective performance, revealed a much better fit to the user's face and did not cause skin irritation or chafing, nor did it produce pungent or offensive odours, thus contributing to favourable user experience. Based on the functional study conducted under real-life conditions and organoleptic evaluation of the initial half-mask model following use by coal miners, guidelines were developed for the improvement of the construction of filtering half-masks designed for harsh physical working conditions.

The design process, which was informed by questionnaire data concerning user needs as well as the type and conditions of work performed by the end users, led to a product ensuring good user comfort. Introducing a stiffening layer that strengthened the construction and a layer improving user comfort or increasing the area density of the external layer by approx. 30 g/m^2 and decreasing that of the internal layer by approx. 20 g/m^2 resulted in improved comfort of use and functionalisation of the filtering half mask model containing the SAP polymer. The findings presented show the importance of conducting functional studies involving workers under real-life conditions in designing personal protective equipment. These results are in agreement with previously published studies that showed that only ergonomic tests carried out under real working conditions can show functional defects of protective equipment that affect its comfort of use. That is why it is necessary to consider human factors in the design of new products. Practical performance tests bring new knowledge that can be used to develop increasingly better and more comfortable designs of respiratory protective devices that would protect users in especially heavy working conditions.

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References

1. The Regulation (EU) 2016/425 of the European Parliament and of the Council of 9 March 2016 on personal protective equipment and repealing Council Directive 89/686/EEC, Official Journal of the European Union, L 81/51.
2. Graveling R, Araceli S-J, Lewis C, Groat S. Protecting Respiratory Health: What Should be the Constituents of an Effective RPE Programme? *Ann. Occup. Hyg.* 2011; 55, 3: 230-238.
3. Brochocka A, Makowski K. Filtering half masks for respiratory protection against nanoparticles containing aerosols. *Przemysł Chemiczny* 2014; 93, 1: 93-98.
4. Krucińska I, Strzembosz W, Majchrzycka K, Brochocka A, Sulak K. Biodegradable Particle Filtering Half-Masks for Respiratory Protection. *FIBRES & TEXTILES in Eastern Europe* 2012; 21, 6B (96): 77-83.
5. Brochocka A. Filtration Properties of Nonwoven Structures with Superabsorbents for Respiratory Protective Devices. *FIBRES & TEXTILES in Eastern Europe* 2017; 25, 3(123): 62-67. DOI: 10.5604/01.3001.0010.1691
6. Mazari FB, Mazari A, Havelka A, Wiener J. Effect of a Superabsorbent for the Improvement of Car Seat Thermal Comfort. *FIBRES & TEXTILES in Eastern Europe* 2017; 25, 2(122): 83-87. DOI: 10.5604/12303666.1228187.
7. Serweta W., Olejniczak Z., Matusiak M., Improve of Footwear Comfort Sensation with Material Packages and Knitted Fabrics, FIBRES & TEXTILES in Eastern Europe2019; 27, 3(135): 85-90. DOI: 10.5604/01.3001.0013.0747.
8. European Standard EN 13921:2007. Personal Protective Equipment – Ergonomic Principles.
9. Majchrzycka K, Okrasa M, Skóra J, Gutarowska B. Evaluation of the Survivability of Microorganisms Deposited on the Filtering Respiratory Protective Devices under Varying Conditions of Humidity. *International Journal of Environmental Research and Public Health* 2016; 13(1): 98.
10. Gonzaga MC, Abrahao RF, Tereso MJA. Effectiveness of Personal Protective Equipment for Farm Workers Who Grow Pineapples. *Advances in Physical Ergonomics and Human Factors – Advances in Intelligent Systems and Computing*. 2016; 489: 367-373. DOI: 10.1007/978-3-319-41694.
11. Barrasa M, Lamosa S, Macineiras J, Pineiro I. Study of the use of personal protective equipment (PPE) in greenhouses of Galicia. *VII Congreso Iberico De Agroingenieria Y Ciencias Horticolas: Innovar Y Producir Para El Futuro*. Innovating And Producing For The Future 2014; 513-518.
12. Ronaldo A, Castelo dos S. de Almeida, Motta M, Veiga F, Duarte J. de Castro Moura, Meirelles L A, Elabras Veiga L B. Thermal Comfort and Personal Protective Equipment (PPE), Work 41 2012; 4979-4982 4979. DOI 10.3233/WOR-2012-0042-4979.
13. Bartkowiak G, Greszta A. Determination of a Comfort Class for Protective Clothing Based on Ergonomic Tests. *FIBRES & TEXTILES in Eastern Europe* 2019; 27, 5(137): 65-74. DOI: 10.5604/01.3001.0013.2904.
14. Abrahão RF,Gonzaga MC, Braunbeck OA. Protective Gloves on Manual Sugar Cane Cutting are Really Effective? Work 41 2012; 4963-4966. DOI 10.3233/WOR-2012-0039-4963.
15. Irzmańska E, Okrasa M. Preliminary Study Evaluating Manual Dexterity Tests Assessing Gloves Protecting Against Cuts and Stabs by Hand Knives. International Journal of Industrial Ergonomics 2016; 56: 138-149.
16. Barker J, Boorady LM, Lin SH, Lee YA, Esponnette B, Ashdown SP. Assessing User Needs and Perceptions of Firefighter PPE. *ASTM International*. 2012; 1544: 158-175. DOI: 10.1520/STP104099.

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