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Ergonomic and Olfactometric Assessment of Anti-Odour Filtering Half-Masks under Real-Life Workplace Conditions

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Abstract
The presence of vapours and gases of chemical compounds in the atmospheric air contributes to mental discomfort as well as irritation of the respiratory tract and eyes. The technical solutions applied, such as collective protection measures, namely the encapsulation of processes or local ventilation equipped with appropriate air filters, are often insufficient. In such a case, respiratory protective equipment (RPE) is the basic and, in many cases, the only technical means that protects humans against the harmful effects of this type of harmful substance. The study evaluated the ergonomic and anti-odour properties of a novel filtering half-mask model with an oxygen indicator in functional workplace tests. In addition, the subjective anti-odour assessment results from functional tests were statistically compared with the results of olfactometric tests. The differences identified are attributable to the fact that the olfactometric method excludes subjects with olfactory impairments. Moreover, statistical analysis indicated significant differences in anti-odour properties between a reference half-mask and the filtering half-mask model with a nonwoven adsorbent layer (91% odour reduction). The filtering half-mask developed was found to provide high and very high levels of user comfort and exhibited excellent protective and functional properties, with a filtration performance of 96% and breathing resistance of 147 Pa. Those parameters qualify the filtering half-mask presented for protection class FFP2. In addition, the half-mask effectively absorbed the vapours of malodorous substances up to 3 h and displayed oxygen concentration in the breathing zone. It should be noted that currently no such device is commercially available either in Poland or in the European Union.

Key words: *anti-odour half-mask; olfactometry; respiratory protective devices; degree of odour reduction; ergonomics.*

Introduction

Twenty-first-century technological advancement has brought about numerous hazards, with air pollution being of particular concern due to the intensive growth of the industrial and transportation sectors. The dynamic development of cities with their municipal infrastructures and the increasing use of renewable energy sources has led to more significant malodorous emissions. Odours may cause not only psychological discomfort but also respiratory and eye irritation. Repeated or long-term exposure to odorants may decrease one's sensitivity to a given stimulus, but if it subsides for some time, the sensitivity is often restored. Psychophysical analysis shows that olfactory adaptation results in elevated olfactory detection thresholds and diminished sensitivity to supraliminal stimulation. In order to maintain high sensitivity and, at the same time, respond to multiple stimuli at different concentrations, the olfactory system (as well as other sensory systems) has developed specific adaptation mechanisms for adjusting its responses to stimuli. Thus, the olfactory system can remain in equilibrium with the concentration of odoriferous substances in the surroundings while adequately reacting to new odours or changes in odorant concentrations significantly above the maximum allowable concentration (MAC) [1].

The application of collective protection measures to prevent odour pollution, such as sealing off technological processes or installing local ventilation systems, is challenging as those methods often fall short of expectations, and elevated odorant concentrations in workplaces have been reported [2]. In such cases, personal respiratory protective equipment (RPE) remains the basic, or indeed the only means of preventing the adverse effects of offensive or harmful odours. This was confirmed by the employees of small enterprises, i.e., mechanical, welding workshops, and printshops. Occupational exposures reported by users themselves were found to be high, including noise exposure (73.5%), smoke exposure (69.6%), and vapours and exhaust fumes (60.8%). Concerning the existing risks, the PPE used was positively assessed by the employees. The respondents readily use PPE such as protective glasses (33.3%), protective gloves (27.5%), protective masks (26.5%) and protective footwear (10.8%) [3]. The risk of volatile organic compounds (VOCs) is also present in beauty salons. This exposure can lead to negative health effects and an increased incidence of cancer among workers. In protection against VOCs occurring in beauty salons where the concentrations of toluene in rooms ranged from 26.7 to 816 mg/m^3, benzene – 3.13-51.8 mg/m^3, xylenes – 5.16-34.6 mg/m^3, and ethylbenzene – 1.65-9.52 mg/m^3, the workers used respiratory protective equipment in the form of a protective half mask. Based on the tests performed and questionnaires completed, it was shown that an improvement in comfort and decrease in the inhalation exposure of workers to VOCs occurs when respiratory protection equipment is used [4]. Most adsorption materials currently used in RPE contain activated carbon, but it should be noted that microporous zeolites (mineral nanosorbents) can remove higher amounts of volatile compounds from the air over a long time due to very large surface areas and unique physicochemical properties [2]. This study presents a novel anti-odour filtering half-mask intended to protect users from the effects of volatile compounds under variable workplace conditions. The half-mask proposed was designed to comply with the standard EN 149:2001+A1:2009 [5] for the protection level claimed. One of the standard requirements involves ergonomic evaluation in laboratory functional tests to check for product defects.

Figure 1. Anti-odour filtering half-mask with an oxygen indicator.

Nevertheless, as shown in publications [6, 7], ergonomic assessments can be best conducted under real-life use conditions in the workplace. In turn, the most advanced method of evaluating odour emission levels is olfactometry, in which the presence of odours is verified by a panel consisting of individuals with a 95% likelihood of having average olfactory sensitivity. The results obtained are subjective due to the individual physiological differences among panel members affecting their sensory accuracy [8-10]. This was also confirmed by the studies of Altunndag et al. [11], who showed that 15% of the population is characterised by complex olfactometric dysfunction, which results in a worse mood, including frequent headaches and migraines, as well as upper respiratory tract infections. Studies have also shown that in most cases, olfactometric dysfunction is more often shown by men. In the available world literature, various techniques are known to determine the level of smell perceptibility. In [12], the ability to recognise mammalian pheromones (androstenone) was identified among the Russian population. It was shown that women had a greater ability to detect pheromone than men. In addition, it was also found that the stimulants used (smoking), blood type, or origin do not significantly affect olfactometric abilities and olfactory perception. Hummel et al. [13] used the q-Sticks tool to compare and diagnose the ability to detect odorous substances in the population studied. This test allows the diagnosis of anosmia, i.e., loss of the sense of smell in a patient. This can significantly improve the clinical situation in which testing is often not performed due to the fast testing time and convenience of handling. On the other hand, functional olfactory surveys are conducted in workplaces with workers' participation, some of whom may exhibit very low odour sensitivity or none at all.

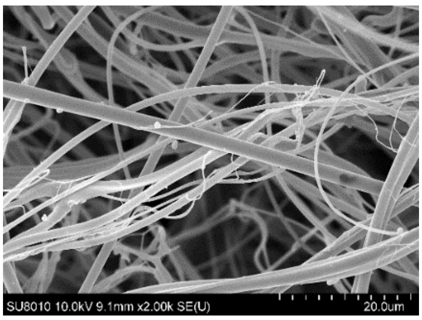
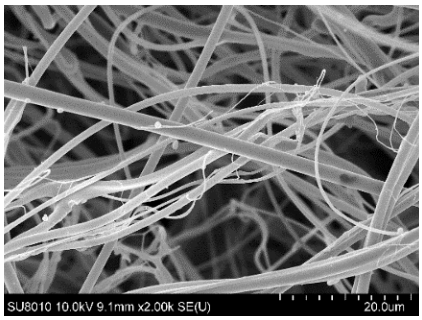
The study's objective was to evaluate the developed half-mask model in functional workplace tests in terms of user comfort. In addition, the study included a comparative analysis of odour-reduction assessment methods, that is, functional workplace tests versus olfactometric tests.

Materials and methods

Materials

Functional tests involved a filtering half-mask model designed to protect the respiratory system against volatile chemical compounds. It incorporated a zeolite and silica materials – containing nonwoven composite, and was equipped with an oxygen indicator (***Figure 1***), implemented in the half-mask model to measure the oxygen concentration level under the face piece. A characteristic feature of the solution proposed is the fact that the analyser detects a decrease in the oxygen concentration under the facepiece, which drops to a value of 15% while talking or performing heavy physical work. This affects the well-being (headaches, dizziness, fainting, etc.) and the comfort

Table 1. *Elements of the filtering half-mask and anti-odour filtering half-mask.*

	Reference filtering half-mask	Anti-odour filtering half mask
Structure of anti-odour half mask	Polypropylene filtering nonwoven without modifier	Polypropylene composite nonwoven containing zeolite and silica materials
	The construction of half-masks included a centrally located exhalation valve with dual filters with inhalation valves, two headbands holding the half-mask to ensure the right position and seal on the user's head, a seal fitted along the inner rim of the facepiece, and an oxygen sensor holder fixed on the right filter connector	
Layout of the filtering material layers	Polypropylene filtering nonwoven with area density 80 g/m^2 (filtering layer) 	Polypropylene nonwoven composite including zeolite and silica materials with area density (300±40) g/m^2 (filtering layer) 
	GW-20/160 needle-punched nonwoven with an area density of (160 ± 15) g/m^2 (outer layer)	
	GW-20/160 needle-punched nonwoven with an area density of (160 ± 15) g/m^2 (inner layer)	
Total weight	36.0 g + 146.5 g (oxygen indicator)	50.68 g + 146.5 g (oxygen indicator)

of the user's work. The oxygen sensor signals the sound and light alarm and begins to vibrate when there is a threat to the health and life of the user. Two bright flashing LEDs on the top and bottom of the device make the alarm visible from all sides. The device has a small size, which allows the employee personal use. Thanks to this, high comfort of work is ensured as required by international standards, which can improve the safety of users in a dynamically changing work environment. Tests were conducted to determine user comfort and the degree of odour reduction.

The filtering half-mask developed, shown in ***Figure 1***, consisted of the following elements (***Table 1***).

A multifunctional material containing polypropylene fibres with zeolite and silica additives was used in the construction of the filtering facepiece respirator. The adsorption performance of the material against both organic and inorganic compounds (ammonia, acetone, and cyclohexane) had been previously confirmed and discussed in [14]. These additives are known to be safe to ingest orally. Because the additive particles agglomerate when introduced into the polymer structure, they may become detached from the base materials during breathing. For this reason, the system of materials used in the construction of the half-mask can be optimised in a way that prevents the modifier particles from getting into the respiratory system at the moment of their uncontrolled detachment from the filter fabric elementary fibres, i.e., on the respiratory side, a high-performance melt-blown nonwoven fabric can be used.

Table 2 shows data on the protective and functional properties of filtering and anti-odour half-mask.

The anti-odour filtering half-mask equipped with an oxygen sensor had a detector attached to the user's protective clothing. This impacted the comfort of using the half-mask and did not burden the human skeletal and muscular system. This is confirmed by surveys, in which 48% of respondents rated the half-mask as highly comfortable.

Figure 2. *Municipal waste segregation station.*

Table 2. *Protective and functional parameters of the filtering half-mask and anti-odour filtering half-mask.*

	Paraffin oil mist penetration, %	Sodium chloride aerosol penetration, %	Breathing resistance, Pa	
			inhalation	exhalation
Mean value	2.70	1.78	151.2	165.0
Standard deviation	0.91	0.27	6.04	15.26
Minimum value	1.50	1.32	134.9	131.5
Maximum value	3.80	2.06	157.9	192.8

Methods

Functional test

The functional test involved 30 workers in three manufacturing facilities. Their occupational tasks mostly involved solid waste segregation, operating and cleaning production lines, and maintaining machinery. Nearly 50% of the subjects were 46-60 years old, approx. 7% were 60 or older, and approx. 13% were 18-25 years old. Most of the subjects were experienced workers, 83% of which were males.

The test's primary objective was to determine the degree of perceived user comfort with respect to the filtering half-mask with an oxygen sensor developed and its odour-reduction performance. Due to the absence of previous studies on the subject, the investigations were largely pioneering and exploratory. The subjects were asked to complete a questionnaire following an approx. 2 h period of work while wearing half-masks.

The professional work performed by the testing group consisted mainly of municipal waste segregation, cleaning work and ongoing work on production lines, as well as the servicing of the machinery stock of production plants (***Figure 2***). The environmental tests performed allowed us to identify a highly flammable organic substance (isobutylene) at the level of 6 ppm.

Olfactometric test

The odour-reduction performance of the filtering half-mask model was also evaluated by the olfactometric method, consisting of three consecutive steps:
- determination of the individual olfactory sensitivity of volunteers,
- performing the odour-reduction test,
- recording the participants' subjective perceptions on a form.

The olfactometric test involved 18 subjects, all of whom exhibited excellent olfactory sensitivity. Before the test, the volunteers completed a short ques-

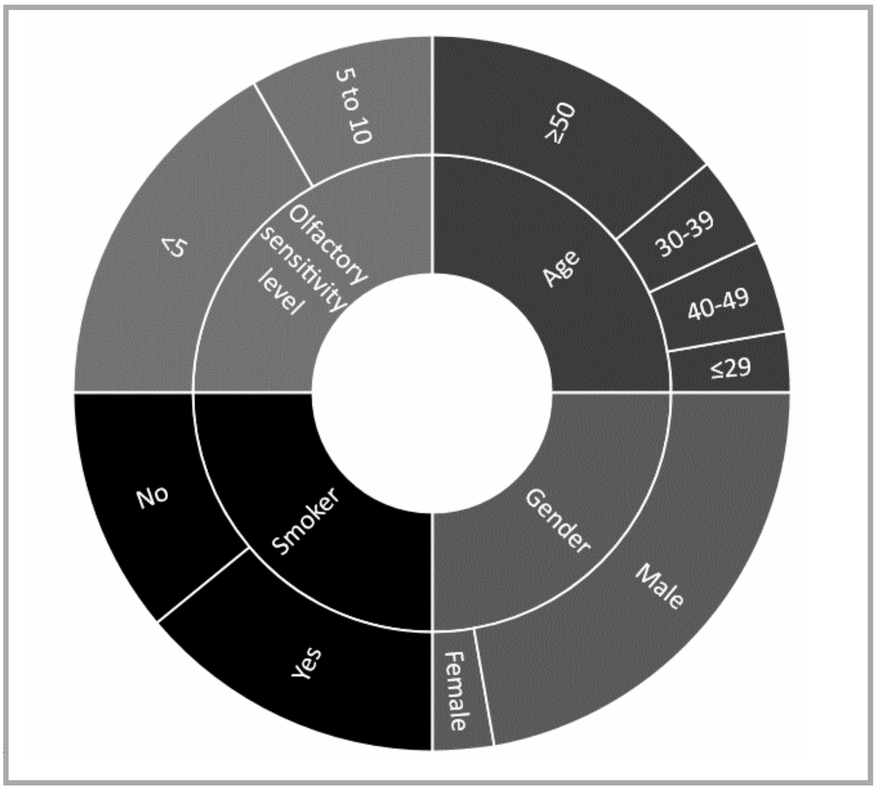


Figure 3. *Characteristics of the study group.*

tionnaire concerning their age, gender, current occupation, and health. They were requested not to consume food or beverages half an hour before the test. The study group was heterogeneous in terms of age (23-62 years), gender, and occupation (see ***Figure 3***). The study involved two filtering half-mask models: one with anti-odour properties and another without an odour-adsorbing layer (reference). Otherwise, the two models were identical in terms of shape and construction.

A two-step method of assessing anti-odour properties of half-masks was described in detail in publication [15]. In the first step, the olfactory sensitivity of individual subjects (without half-masks) was determined to establish the baseline individual olfactory sensitivity levels according to the procedure described in [16] using an Odor Pen Test Kit (St. Croix Sensory, Inc. Stillwater, MN, USA). Volunteers with depressed olfactory sensitivity were excluded from further study.

Subsequently, an odour-reduction test (while wearing half-mask) was conducted using an Odor Pen Kit and procedure based on a combination of the ascending concentrations method, which uses 14 pens containing increasing concentrations of the test substance [17], and three-alternative forced choice (3-AFC) method [18], which requires the participant to indicate which of the three pens generates odours, even if they are unable to sense them.

The study was performed in two consecutive rounds. In each round, three pens were presented: two blind ones and one containing n-butanol at a distance of 1cm from the surface of the half mask in an area situated circa 5 cm below the nose clip. The order of pen presentation was determined randomly. The presentation time was adjusted each time to a period necessary for the participant to take two full inhalations through the nose. Participants were supposed to indicate the pen number at which they detected the odorant. Next, pens from successive dilution levels were presented. The rounds ended when the subject correctly detected two pens of successive dilutions. The test result was determined as the number of the first of two consecutive correct detects. An arithmetic mean of the results was obtained in both rounds. The testing time for each test subject varied from 20-35 min depending on the individual odour perception capabilities.

The degree of odour reduction was calculated as the difference between the olfactory sensitivity of individual subjects (without the half-mask) and the results obtained while wearing the half-mask. The odoru reduction efficiency (W) was calculated from the following equation:

$$W = \frac{degree\ of\ odor\ reduction}{individual\ olfactory\ sensitivity\ level} \cdot 100\% \quad (1)$$

Odor reduction efficiencies were compared with the results obtained on the basis of a questionnaire assessing the subjective degree of odour reduction. Answers to the questions were ranked using the 5-point Likert scale, and then percentage values were assigned to each of the ranks, respectively (very high – 100%, high – 80%, medium – 60%, low – 40%, very low – 20%) [19].

Breakthrough time measurements

The test stand consisted of six essential elements, i.e., 2 Dräger X-am 7000 gas detection analysers, a pneumatic test chamber, an airflow control system equipped with Red-y for gas flow controllers, a humidifier, and a circulation cooler equipped with a HAAKE SC 100 thermostat and vaporiser.

The gas detector was used to measure the concentration of test vapours in a pneumatic test holder upstream and downstream of the sample. In the case hydrogen sulfide, the gas was dosed straight from the gas cylinder and mixed with air to obtain the concentration required. While in the case of cyclohexane, acetone and ammonia, the concentration required was obtained by mixing vaporised liquid with the stream of clean air. The airflow was regulated by flow controllers. The variation in the challenge concentration did not exceed 5 ppm at (70 ± 5)%

Table 3. *MAC value for testing substances.*

No.	Group of chemical compound	Name of substance	MAC level, ppm
1.	organic	acetone	235.00
2.		cyclohexane	81.00
3.	inorganic	ammonia	18.70
4.		hydrogen sulfide	4.77

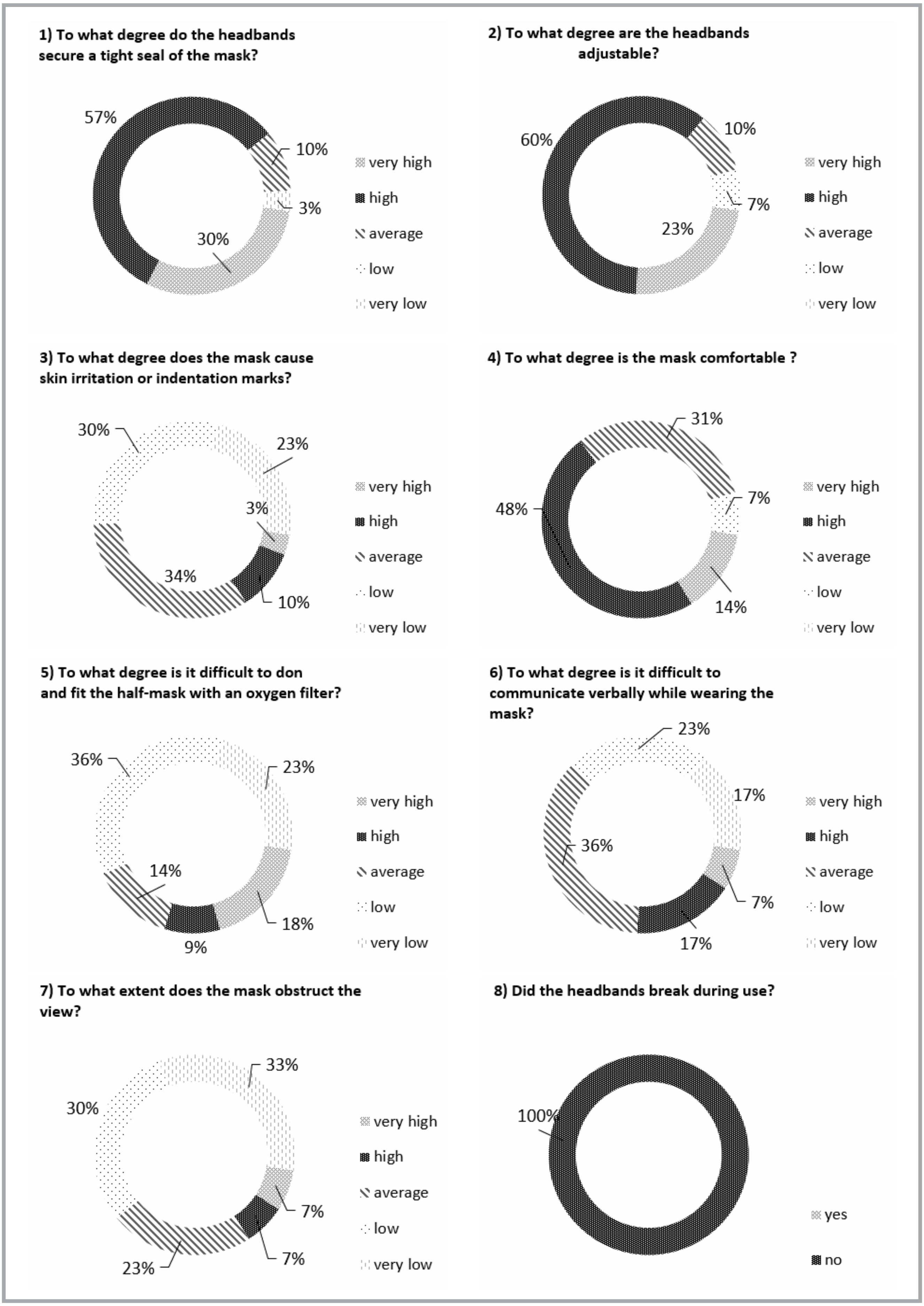
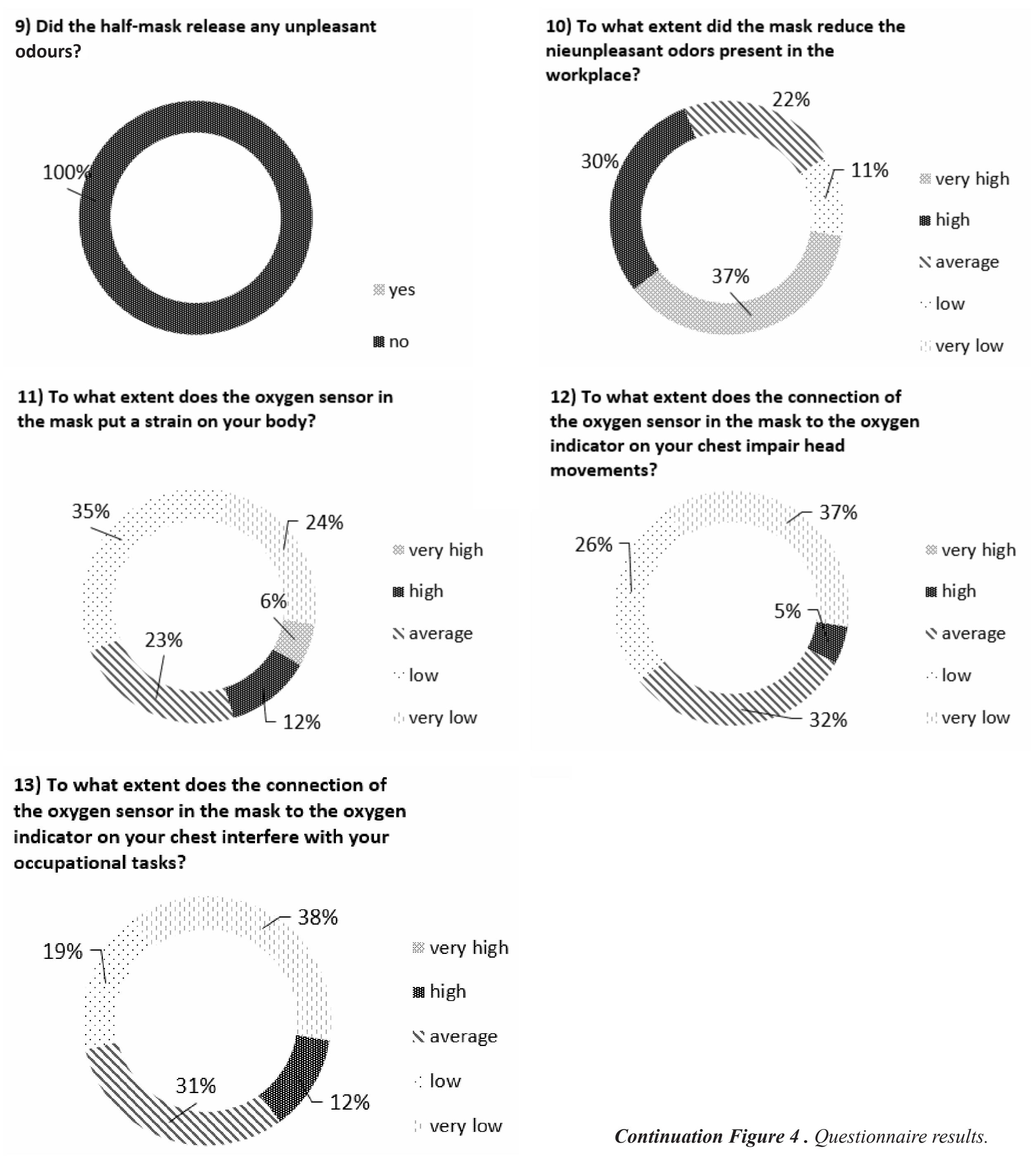


Figure 4. *Questionnaire results.*



Continuation Figure 4 . *Questionnaire results.*

relative humidity and (21 ± 1) °C temperature [20]. The tests were carried out at a volumetric flow rate of 30 l/min.

Results

Functional tests

During all functional tests, the level of oxygen under the facemask was monitored. Interestingly, the oxygen concentration under the facepiece decreased to 17% and during speech even to 16-15% vol.

The functional workplace test was concluded by completing a questionnaire consisting of three general items and 13 items concerning the ergonomic and anti-odour properties of the facemask model studied (***Figure 4***).

Responses to questions 1 and 2 indicated that the headbands were well received by the subjects; they were mostly reported to secure a good or very good seal (57% and 30% of responses, respectively). Similarly, headband adjustability was deemed high by 60% and very high by 23% of the subjects. As can be seen, while 33% of the subjects reported medium levels of skin irritation or indentation marks, as many as 53% indicated low or very low degrees of those physiological phenomena. The half-mask model tested was rated as highly comfortable by as many as 48% of the respondents. The oxygen sensor attached to the filtering half-mask was intended to display the percentage of oxygen concentration in the breathing zone. The participants were explicitly asked how difficult it was to don and fit the mask with the sensor. According to most subjects, the degree of difficulty was low (36%) or very low (23%). Furthermore, most workers (73%) did not report any significant issues with communicating while wearing the masks in the workplace, reporting only very low, low, or average problems. According to 86% of the respondents, the mask did not obstruct the view, and nobody reported broken headbands, which indicates that the design and technological solutions applied in the mask were of very high quality. The filtering half-mask model tested contained a zeolite and silica composite responsible for adsorbing malodorous vapours. Given the nature of the subjects' work and their exposure to such substances in the workplace, the survey included questions about odour emission and reduction. No subjects reported odour emission from the half-mask (0%), while more than half of them (67%) stated that the half-mask provided high or very high odour reduction levels, proving its effectiveness. Of particular significance in the filtering half-mask is the oxygen sensor, which is directly connected to an analyser displaying oxygen concentration in the breathing zone. In response to the questions about the strain on their body, head movement impairment and interference with occupational tasks caused by the oxygen sensor and display, most participants (over 55%) stated that the equipment tested did not adversely affect user comfort, which indicates that the solution proposed may enjoy substantial popularity among workers.

Olfactometric evaluation of odour reduction

Figure 5 shows the individual olfactory sensitivity levels revealed by the participants.

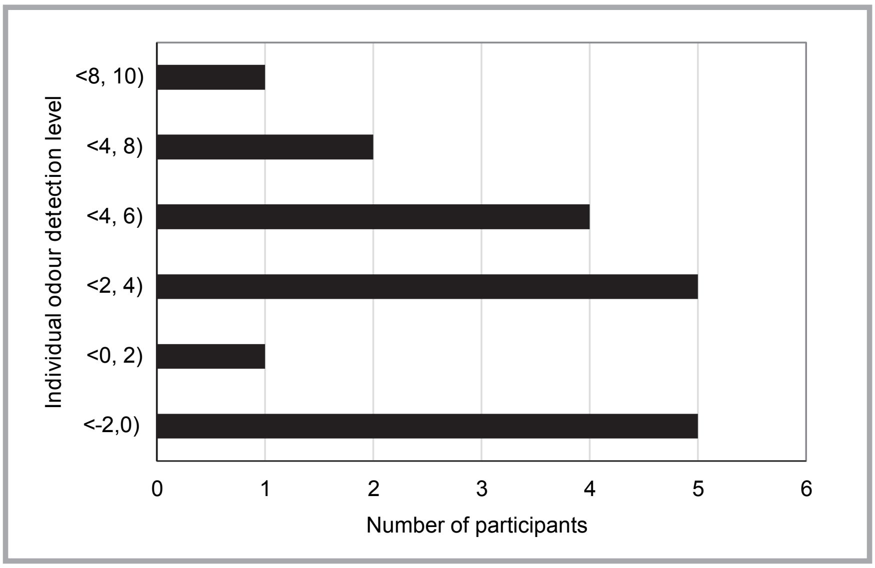


Figure 5. *Individual olfactory sensitivity levels revealed by the participants.*

The five volunteers who did not detect any odour level and one who detected only the highest n-butanol concentration (pen 2) were excluded from further study. The twelve volunteers exhibiting higher olfactory sensitivity levels took part in the tests.

Table 4 shows the basic statistics describing the half-masks tested in terms of odour detection levels as well as the degree of odour reduction and odour reduction efficiency.

The olfactometric test showed that the reference half-mask without an absorbent layer led to a 41% odour reduction, while the anti-odour half-mask led to an almost 91% reduction, which proves its high effectiveness for the applications intended. On the other hand, the subjective assessments of workers described in subsection 3.1. indicate an approx. 68% odour reduction (item 10 in the questionnaire). The difference between the functional tests and olfactometric results may be attributable to the fact that workers with low olfactory sensitivity were not excluded from the functional test. Their subjective odour-reduction assessment might have distorted the overall functional test results.

Breakthrough time results

The breakthrough time results obtained for the anti-odor filtering half mask model studied against test substances are given in ***Figure 6***.

One of the organic compounds used in the tests was acetone (***Figure 6.a***). A rapid increase in acetone vapour concentration in the breathing zone occurred already within the first minutes of the experiment, with a gradual stabilisation after approx. 20 min, which may indicate the saturation of the sorbents responsible for the removal of offensive odours. Acetone breakthrough, marked by exceeding its MAC, occurred in 46 min. Compared to acetone, cyclohexane vapour concentration in the breathing zone rose less rapidly but steadily (***Figure 6.b***). Cyclohexane levels began to stabilise after 30 min of the experiment, with a breakthrough after another 36 min (in 66 min). The results show that the filtering half-mask model proposed may effectively protect users from inhaling harmful organic substances as long as their concentrations in the air remain below their respective MAC levels.

The breakthrough time against ammonia vapour at a nominal concentration equal to MAC was 42 min (***Figure 6.c***). In the first minutes (2-3 minutes of exposure of the test sample to vapours of the test substance), the sorbents implemented constituted an effective barrier to the test gas, completely adsorbing

Table 4. *Odour-reduction performance of half-masks studied.* ***Note:*** *N – number of participants tested, M – mean value, SD – standard deviation.*

Half-mask model	Parameter	N	M	SD
Reference filtering half-mask	Individual odour detection level	12	2.92	1.90
	Degree of odour reduction		2.04	1.47
	Odour reduction efficiency, %		41.35	27.92
	Subjective degree of odour reduction, %	–	–	–
Anti-odour filtering half-mask	Individual odour detection level	12	0.33	0.49
	Degree of odour reduction		4.63	2.23
	Odour reduction efficiency, %		90.71	14.79
	Subjective degree of odour reduction, %	28	67.86	27.40

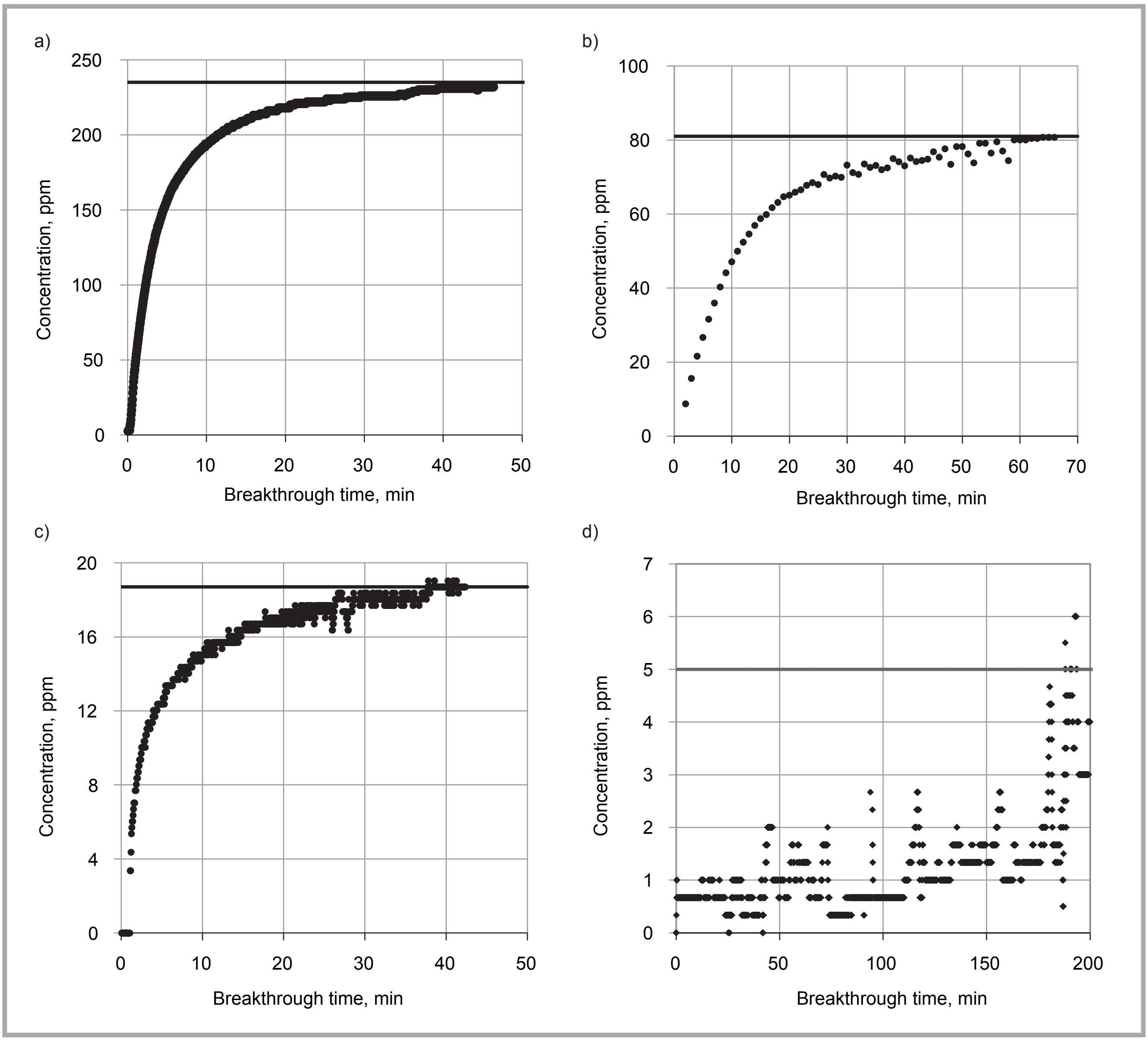


Figure 6. *Breakthrough times against: a) acetone; b) cyclohexane; c) ammonia and d) hydrogen sulfide.*

the ammonia/air aerosol permeating the nonwoven (0 ppm in the breathing zone). Subsequently, after the complete saturation of the sorbents contained in the filtering layer of the half-mask, a breakthrough was observed, and the test was concluded. Among all the test substances, the longest breakthrough time was recorded for hydrogen sulfide. As can be seen, the time-concentration plot for that gas is markedly different from those for the other vapours, with a gradual and irregular increase in concentration (*Figure* ***6.d***). This irregularity may be attributed to the fact that the test gas applied had a very high initial purity (H_2S 99.9%) and concentration, which was controlled by means of specially designed valves. A breakthrough occurred after 3 h and 20 min.

It is worth noting that the breakthrough times described in the literature for steady-state flow are usually shorter than those obtained for pulsating flow [21-23], which is associated with the sinusoidal changes in the flow rate of the challenge mixture through the sample and the removal of the adsorbate from the polymer/carbon material by the exhaled air. Thus, the results described above represent the worst-case scenario. The breakthrough times might be much longer in the real-life use of the respiratory protective devices developed.

As can be seen, the filtering half-mask model proposed may be used as an effective respiratory device against harmful or malodorous inorganic compounds as long as their concentration in the air does not exceed their MAC levels. The innovative filtering half-mask proposed was demonstrated to improve user safety under variable workplace conditions. The novel half-mask revealed excellent protective and functional properties: filtration efficiency of 96% and a breathing resistance of 147 Pa, conforming to protection class FFP2. In addition, the half-mask absorbed odorant vapours for up to 3 h and displayed oxygen levels in the breathing zone.

Discussion

The application of filtration composites made of zeolite-containing melt-blown nonwovens in respiratory protective devices designed for variable workplace conditions reduces the hazards and risks associated with exposure to malodorous substances adversely affecting human health and well-being. Large amounts of such compounds are released, amongst others, by the increasing numbers of large-scale animal farms, which exert a substantial adverse effect on the natural environment and the quality of life of the people residing in their vicinity.

The questionnaire survey showed that the anti-odour filtering half-mask model provides a high level of protection against offensive and harmful odours that may occur in workplaces. It is also characterised by very good functional properties in terms of the fit and adjustment of headbands and user comfort (in particular, it does not obstruct the view or hinder occupational tasks). Furthermore, the olfactometric evaluation showed the odour reduction effectiveness of the half-mask model studied to be 91%, which makes it suitable for the intended applications. The half-mask exhibited excellent protective properties in terms of filtration performance and the adsorption of offensive odours below MAC levels at low breathing resistance levels, indicating good functional performance. Last but not least, the half-mask is equipped with a system displaying oxygen levels in the breathing zone.

Conclusions

The article presents an assessment of the comfort of use and degree of reducing odour nuisance by filtering half-masks with absorbing properties in workplace conditions. The result of the research conducted revealed that the development of respiratory protective devices based on zeolite filtering composites obtained with the melt-blown technique, for use in respiratory protection in conditions of a dynamically changing work environment, could reduce risks associated with exposure to odorogenic, as well as with the odorous and foul substances that affect both the environment and human well-being.

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Conflicts of interest

The authors declare no conflict of interest.

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