MEASURING THE CARBON DIOXIDE CONCENTRATION UNDER PROTECTIVE FACE MASKS WITH A SENSOR SYSTEM

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Abstract. Wearing face masks is a way to limit the spread of viral particles. However, their usage leads to the creation of a microenvironment between the mask and the face as the heat and mass transfer processes through the masks are impeded. As a result, an increasing concentration of carbon dioxide (CO_2) is formed under the mask. Then the rich in CO_2 air is rebreathed again together with the fresh air, which penetrates the mask until a concentration balance is reached for the current user's activity. The paper aims to present a specially designed portable sensor system which allows continuous measurement of the CO_2 concentration, temperature and relative humidity in the microenvironment under protective textile face masks or respirators of a different type. The measurements with the device can be performed outside the breathing zone, which is a fundamental requirement for reliable results. The sensor system was applied in the test measurement of the microenvironment parameters under three protective respirators (FFP1, FFP2, and FFP3) and six cases. The obtained results showed the very fast impact of the mask barrier on the change in the CO_2 concentration, air temperature and air humidity in the breathing zone of the person.
Keywords: *sensors, masks, respirators, textiles, permeability, thermophysiological comfort*

Introduction

In a pandemic, wearing face masks is one of the main ways to limit the spread of viral particles (Spitzer, 2020). However, their use leads to a change in the dissipation of heat and moisture from the exhaled air to the environment, provided that approx. 25–30% of the heat of the human body is dissipated by respiratory processes in resting conditions and 15–20% in working conditions (Cain et al., 1990). As a result, a microenvironment with increased temperature is formed under the mask (Angelova and Velichkova, 2022). Due to the difficulty in free exchange with the surrounding air, the concentration of carbon dioxide (CO_2) in the microenvironment under the mask increases (Geiss, 2021), though Rhee et al. (2021) have claimed that this concentration remains below the short-term limits of the National Institute for Occupational Safety and Health (NIOSH). The increased CO_2 concentration under the face mask could cause an acceleration of the inhalation rate and heart rate (Geiss, 2021). In addition, headache has been reported by healthcare professionals (Ong et al., 2021), which may present with migraine characteristics or may be considered a subtype of external compression headache.

Face masks should provide protection against cough particles with a droplet size (5–10 μm), while the size of the saliva particles released during speech is approx. 1 μm

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(Asadi et al., 2019). Davies et al. (2013) have found that traditional fabrics filter 49% to 86% of particles in the air up to 0.02 μm, while surgical masks up to 89% of these particles. Van der Sande et al. (2008) and Rengasamy et al. (2010) claimed that textile masks filter 3%–60% of the particles in the exhaled air. Insufficient research has been conducted to assess the effectiveness of wearing a mask over time, the comfort of the individual and possible side effects. The editorial letter of Lazzarino et al. (2020) noted the difficulty of breathing when using masks and the possible inhalation of a fraction of carbon dioxide (CO_2), exhaled during the previous respiratory cycle. Spitzer (2020) and Lubrano et al. (2022) studied the effect of wearing masks on children, concluding that children below three years should not wear face masks. Though a lack of negative effects of mask-wearing on healthy people was reported (Shaw et al., 2020), recent studies showed evidence for a reduction of exercise time and perceived discomfort during exercise among healthy and trained participants (Driver et al., 2022; Egger et al., 2022).

Our literature survey showed that the parameters of the air under the face mask have not been studied in detail. The lack of such research can be attributed to the fact that the COVID-19 pandemic for the first time required long-term mask-wearing by different segments of the population.

Due to the fit of the protective masks, especially the very tight ones of type FFP2 and FFP3, a microenvironment is created under the mask. The prolonged wear could influence the temperature and humidity of the exhaled air and lead to an increment of the CO_2 concentration under the face mask due to the mask's low air permeability. The characteristics of the microenvironment under the face mask may be influenced by several factors, e.g. the type of the mask, the mask's heat and mass transfer abilities, the respiratory heat transfer mechanisms, the impact of nasal versus oral respiration, the metabolic activity of the person, the environmental conditions (temperature, humidity, air velocity), and the period of wearing of the mask.

The knowledge of the temperature and humidity of the microenvironment can also be useful in assessing the need of replacing the particular mask type, as they reflect the saturation of the fibers with exhaled air from the lungs. Exhaled air temperature can also be a useful biomarker for assessing exacerbations of diseases such as asthma and cardiovascular disease (Hoffmeyer et al., 2009).

In addressing the discussion above, the present work aims to present a specially designed sensor system which allows continuous measurement of the CO_2 concentration in the microenvironment under protective textile face masks and respirators. The sensor system also measures the air temperature and relative humidity of the microenvironment that change due to human breathing and the impeded heat and mass transfer through the face mask. The designed sensor system, presented in Section 2, was applied for the measurement of the parameters of the microenvironment under three protective respirators (FFP1, FFP2, and FFP3). The measurement method and the tested protocol are described in Section 3. The results from the tests and their discussion are presented in Section 4.

Design of a device for measuring the CO_2 concentration

The sensor module

The main component of the measuring device is a Sensirion AG (Stäfa, Switzerland) SCD30 sensor. Carbon dioxide is accurately measured using CMOSens® Infra-Red technology. The sensor automatically compensates for long-term deviations due to the

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dual-channel CO_2 concentration measurement principle. The sensor module also includes a module for measuring air humidity and temperature.

Figure 1 shows an image of the SCD30 sensor. The sensor's dimensions (35 × 23 × 7 mm) allow it to be easily integrated into the designed measuring device. To ensure high measurement accuracy across the entire range, the sensor employs a combination of two calibration methods: automatic self-calibration (ASC) and forced re-calibration (FRC).

Figure 1. *The SCD30 sensor*

The main characteristics of the SCD30 sensor are shown in *Table 1*. *Tables 2* and *3* summarize the features of the sensor for measuring the air temperature and air relative humidity respectively. Other features of the sensor include supply voltage (3.3–5.5 V); average rate of current measurement: 19 mA (for 2 s); maximum current: 75 mA.

Table 1. *Specifications of the SCD30 sensor for measuring the CO_2 concentration, ppm*

Parameter	Conditions	Value
CO_2 measurement range	I^2C, UART PWM	0–40000 ppm 0–5000 ppm
Accuracy	400–10000 ppm	± (30 ppm + 3%MV)
Repeatability	400–10000 ppm	± 10 ppm
Temperature stability	T = 0 … 50 °C	± 2.5 ppm / °C
Response time	$\tau_{63\%}$	20 s

Table 2. *Specifications of the SCD30 sensor for measuring the air relative humidity, RH, %*

Parameter	Conditions	Value
Humidity measurement range	-	0–100 %RH
Accuracy	25 °C, 0–100 %RH	±3 %RH
Repeatability	-	±0.1 %RH
Response time	$\tau_{63\%}$	8s
Humidity measurement range	-	0–100 %RH

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Table 3. *Specifications of the SCD30 sensor for measuring the air temperature, T, °C*

Parameter	Conditions	Value
Temperature measurement range	-	-40–70 °C
Accuracy	0–50 °C	± (0.4 °C + 0.023 × (T[°C] – 25 °C))
Repeatability	-	±0.1 °C
Response time	τ63%	>10 s
Temperature measurement range	-	-40–70 °C

The designed device

The designed device for measuring the CO_2 concentration is a 3D printed item in which the sensor, the controller and the battery are placed. The simulated 3D model is presented in *Figure 2a*. The device consists of two air ducts (1), which direct the air of the microenvironment under the face mask to the sensor system on the backside. The hooks (3) are located behind the ears and allow gripping with the mask' elastic straps. Another elastic band could pass through the head in front of the ears and hold firmly the device through the eyes (4). The electronic components of the measuring system (a sensor, a microcontroller, and a power source) are installed in the housing (2). The sensor was placed on the back side (the neck of the person) to fulfil the following requirements (Sofronova et al., 2021):

- The sensor does not disturb the airflow under the mask
- The sensor does not affect the heat and mass transfer processes in the microenvironment
- The sensor does not disrupt the mask fit
- The sensor readings are not influenced by the cycle "inhalation – exhalation", which can be the result when the sensor is stuck on the mask or is placed in the microenvironment under the mask (Escobedo et al., 2022)

Figure 2b presents the real device, made using 3D printing technology and thermo-plastic polymer (Acrylonitrile butadiene styrene). As the dimensions of the head of an adult person vary, two variants of the model were printed for performing the experiments. The dimensions and shape of the air ducts also vary by the head size and shape. *Figure 3* illustrates the placing of the device on the head: the 3D virtual fitting on the head (*Fig. 3a*) and the device during the measurements with a volunteer (*Fig. 3b*).

All components of the designed measuring system are shown in *Figure 4*. Apart from the SCD30 sensor, it involves the microcontroller (MCU) that assures the data management and communications between the electronic components. MCU supports both the Inter-Integrated Circuit (I2C) and Universal Asynchronous Receiver-Transmitter (UART) communication protocols to receive the data from the sensor, as well as a Bluetooth Low Energy (BLE) personal area network (PAN) to transmit the data to a personal computer or a smart device. Other requirements for MCU are low energy consumption, small size and low weight. The Adafruit Feather M0 Express microcontroller (Adafruit Industries LLC, New York, US) is used in the designed measuring system. *Figure 5* presents the connection diagram between the SCD30 sensor and the controller.

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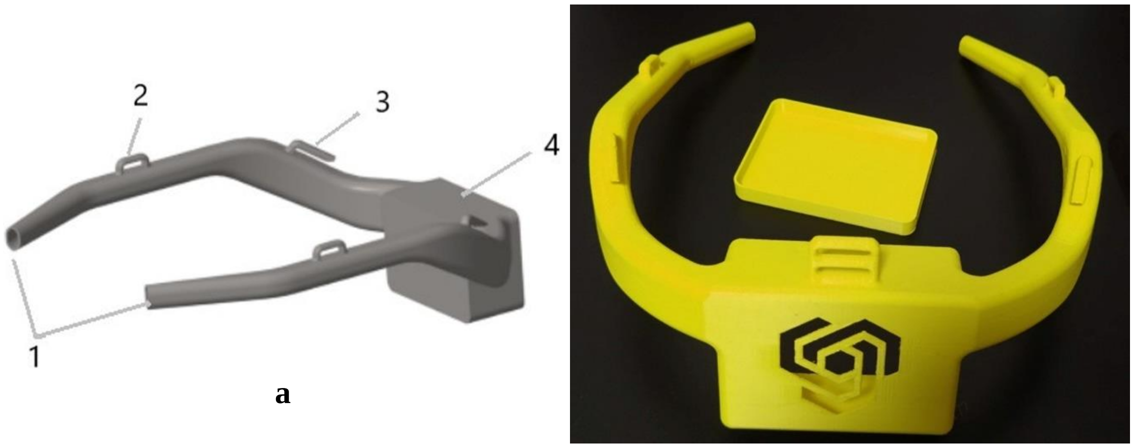

a

b

Figure 2. *Design of the device for measuring the CO_2 concentration under a protective face mask. (a) 3D virtual model of the device: (1) air ducts; (2) housing; (3) hooks; (4) eyes. (b) The printed prototype – view from the sensor box on the backside*

a

b

Figure 3. *Placing the device for measuring the CO_2 concentration under a protective face mask on the head: (a) 3D virtual model; (b) during the measurements*

The power supply of the device is provided with a rechargeable lithium-polymer3 battery with a nominal capacity of 1400 mAh and a nominal voltage of 3.7 V. Cable and wireless communications are used to build transmission between the components of the measuring system.

Because the device is required to be portable, communication between the MCU and the smart device is chosen to be wireless, via Bluetooth. *Figure 6* illustrated the scheme of the proposed interaction between the elements of the measuring system. The battery supplies power to the microcontroller. The connection between the controller and the

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sensor module is made via the I2C protocol. It uses only two two-way open-collector or open-drain lines: a serial data line (SDA) and a serial clock line (SCL), with pull-up resistors. The system uses a voltage of 3.3 V, although it is possible to operate at a voltage of 5 V.

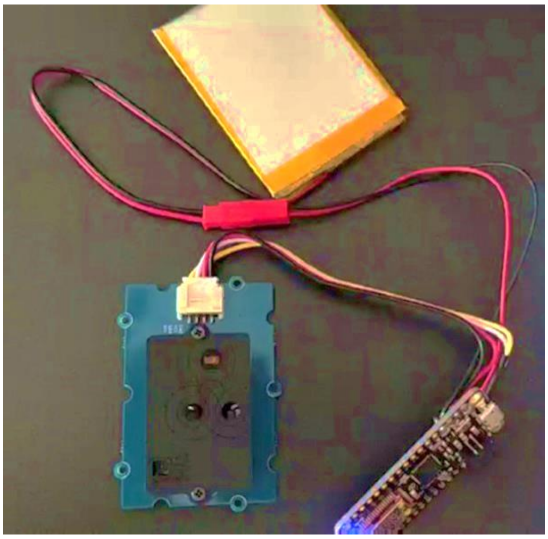

Figure 4. *Components of the measuring system*

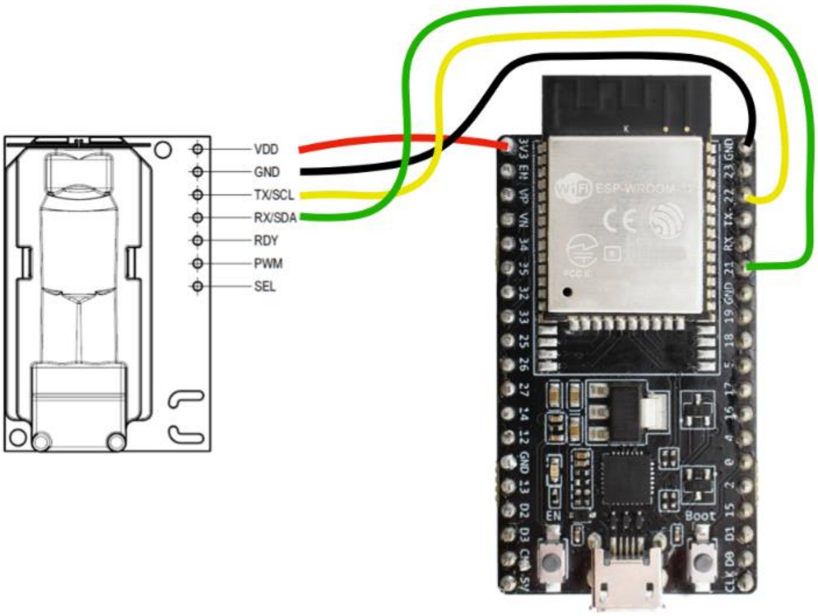

Figure 5. *SCD30 sensor connection diagram with the MCU*

According to the factory recommendation for continuous measurement of the SCD30 sensor (sampling interval from 2 s to 1800 s) the data acquisition speed is set to two seconds. This is the fastest limit for measuring and transmitting the sensor signals to the smart device. The sensor's accuracy is ± 30 ppm for CO_2 concentration from 400 to 10000 ppm and ± 50 ppm for CO_2 concentration above 10000 ppm.

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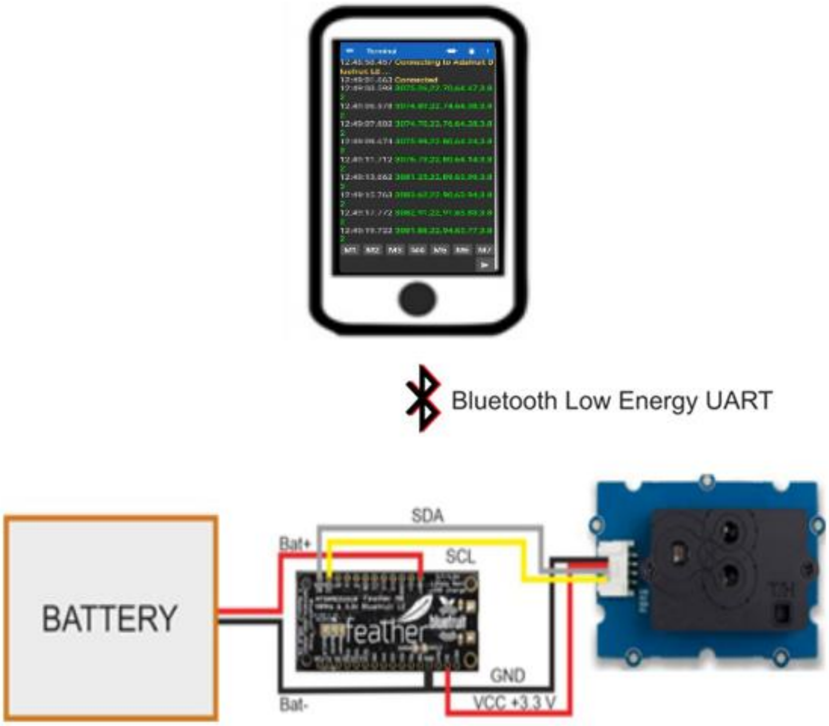

Figure 6. *Scheme of the built communication between the components of the measuring system*

The Sensirion Automatic Self-Calibration (ASC) is used for the calibration of the SCD30 sensor. The procedure is as follows: the sensor system is left to work in continuous measurement mode in a well-ventilated room with clean air over a period of 7 days. The lowest CO_2 concentration should be not less than the natural CO_2 concentration in the atmosphere, which in the year 2022 is 416.45 ppm (CO2 Records - CO2.Earth, 2022).

The collected data are saved in a smartphone in a sheet, as shown in *Figure 7*. The visual form of the data is presented in *Figure 7a*, and *Figure 7b* explains their reading. Column (1) contains the exact time of the measurement, and Column (2) is the CO_2 concentration. The next columns show the measured values for the air temperature (3), relative air humidity (4) and battery voltage (5).

```
17:51:11.373 2584.80,25.42,55.12,3.87
17:51:13.390 2582.51,25.43,55.03,3.87
17:51:15.376 2578.89,25.42,55.01,3.87
17:51:17.448 2577.14,25.46,55.02,3.86
17:51:19.435 2575.94,25.48,55.08,3.86
17:51:21.458 2572.87,25.52,55.10,3.87
17:51:23.477 2579.27,25.53,60.21,3.87
17:51:25.510 2580.20,25.57,60.85,3.87
17:51:27.532 2583.98,25.60,61.01,3.87
17:51:29.558 2586.02,25.63,61.70,3.87
17:51:31.578 2589.35,25.62,62.74,3.87
```

a

B

Figure 7. *Data collection via the smartphone: (a) the data set; (b) reading scheme of the data: (1) time of the measurement; (2) CO_2 concentration; (3) temperature; (4) air humidity; (5) battery voltage*

Materials and methods

The designed device with the sensor system was tested during pilot measurements in static conditions with two volunteers and three types of respirators that are widely used and meet the UNI EN 149: 2001 + A1: 2209 (2009) standard, as described below.

Materials

Three types of respirators were selected: FFP1, FFP2, and FFP3. These are filtering facepieces, having a filtration efficiency of 80% (FFP1), 94% (FFP2) and 99% (FFP3). FFP2 and FFP3 provide the same level of protection as the N95 respirator (O'Dowd et al., 2022). To mention only that according to the National Institute for Occupational Safety and Health (NIOSH), the N-series respirators, are not oil-resistant, and stop at least 95% of the airborne particles with 0.3 μm (Rengasamy et al., 2010).

Measurements protocol

The pilot measurements were performed with 2 adult volunteers in the age group 35-40 years (male and female). They declared the absence of symptoms of COVID-19, influenza or other respiratory diseases. The participants were provided with details about the purpose and methods of the study. Signing an informed consent was not applicable, as the measurements were not related to any change in the ordinary conditions of wearing a face mask or a respirator in enclosures.

All measurements were taken at rest in a sitting position of the person. The measurement started with 3 min of free sitting (no mask, no device) to evaluate the initial environment parameters. Then the device and the protective mask were placed on the participant's head. The fixing of the device was provided with a polyurethane elastic element. A reliable indicator of the proper performance of the measuring system was the rapid change in temperature and humidity compared to those in the environment.

Indoor environment parameters

The measurements were performed in an office room of the Technical University of Sofia. The temperature during measurements was 23.2 ± 0.2 °C, and the air relative humidity was 45.6 ± 1.9%. The environmental CO_2 concentration (inside the room) was between 1540 ppm and 2100 ppm during the measurement of the first volunteer and between 1420 ppm and 2000 ppm during the measurements of the second volunteer.

Results and discussion

Figures 8–13 present results for the CO_2 concentration measured under the three types of face masks (respirators) with different protection abilities: FFP1, FFP2 and FFP3. Two graphs are presented for each face mask: for the male and female participants.

The results obtained indicated a significant increase of the CO_2 concentration in the microenvironment, formed under the protective face mask. The increment was fast, for several seconds and reached 15000 ÷ 20000 ppm and even more. It should be noted that the sensor device can be used for assessment of the microenvironment under a particular face mask, allowing a comparison between different types of masks. However, the fit of the textile masks and respirators depends on the human face and its geometry; the same

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is valid for the designed sensor system. Therefore, a leakage can appear from the outer edges of the respirator. This could explain the differences between the results for the male and female participants, wearing the same type of respirator.

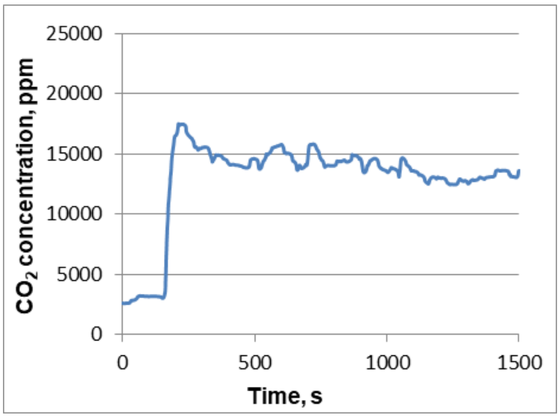

Figure 8. *CO_2 concentration under FFP1 mask, first participant (male)*

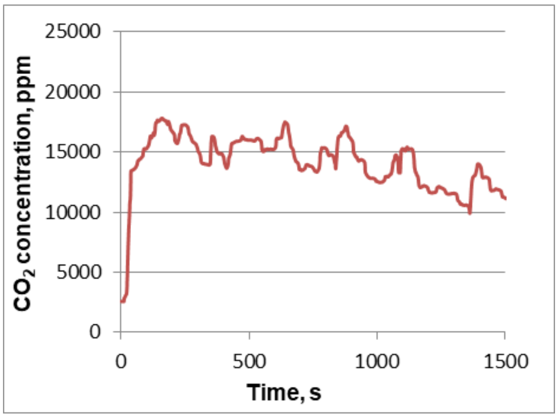

Figure 9. *CO_2 concentration under FFP1 mask, second participant (female)*

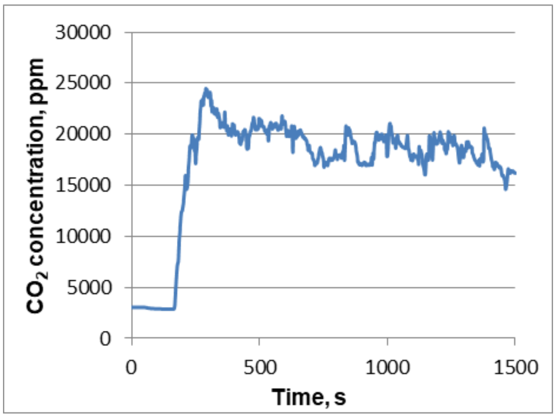

Figure 10. *CO_2 concentration under FFP2 mask, first participant (male)*

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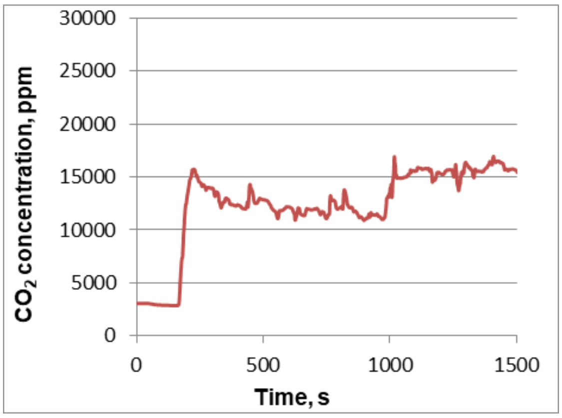

Figure 11. *CO2 concentration under FFP2 mask, second participant (female)*

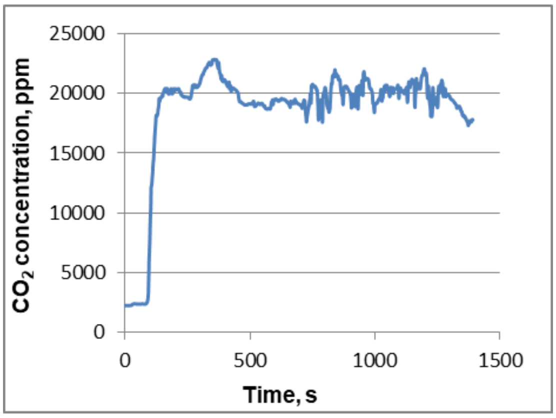

Figure 12. *CO_2 concentration under FFP3 mask, first participant (male)*

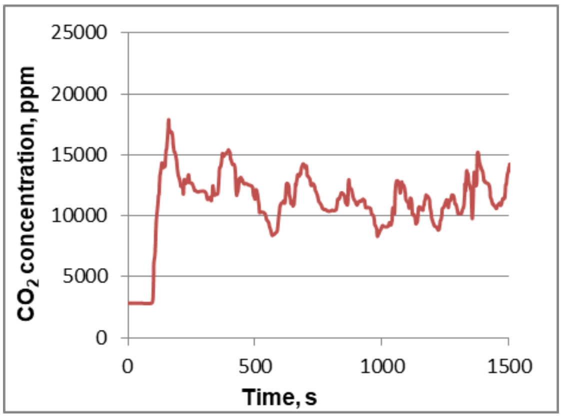

Figure 13. *CO2 concentration under FFP3 mask, second participant (female)*

Figure 14 shows a comparison between the results for the two participants: the average value of the CO_2 concentration in the microenvironment under each respirator was calculated together with the standard deviation. The CO_2 concentration was higher under the respirators of the male participant, but this cannot be attributed to the sex of the participants. It can be supposed that the fit of the respirators and the measuring

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device led to the difference (although special care was taken to ensure that the respirators and sensor system fit as snugly as possible on the participant's head).

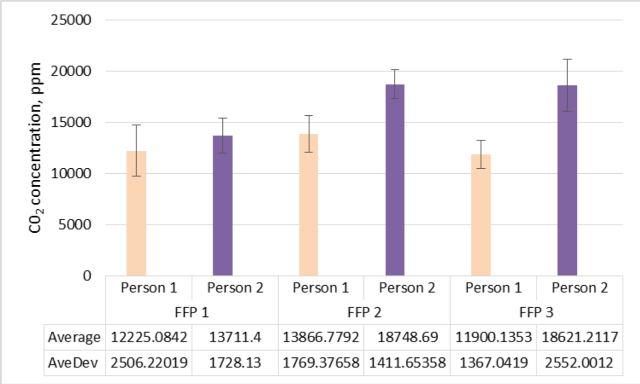

Figure 14. *CO_2 concentration: average values and standard deviations per mask type and participant (person 1 – female; person 2 – male)*

Figures 15–20 illustrate the measured changes in the temperature of the microenvironment under the respirators. For all three types of respirators, a temperature increment to 29÷30 °C was registered.

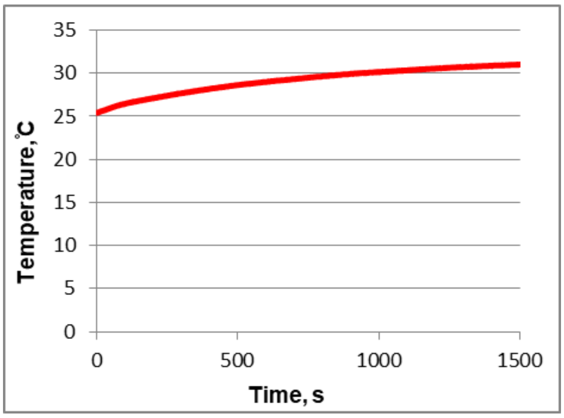

Figure 15. *Temperature changes under FFP1 mask, first participant (male)*

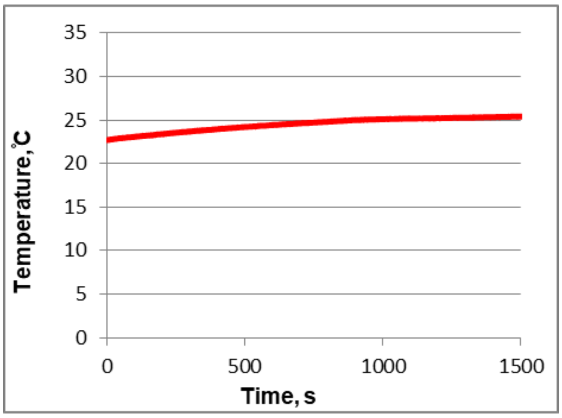

Figure 16. *Temperature changes under FFP1 mask, second participant (female)*

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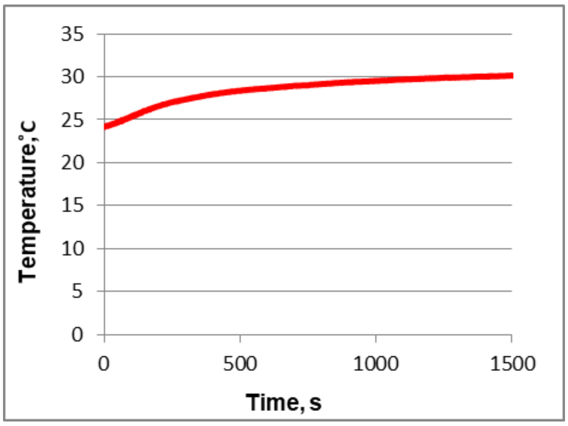

Figure 17. *Temperature changes under FFP2 mask, first participant (male)*

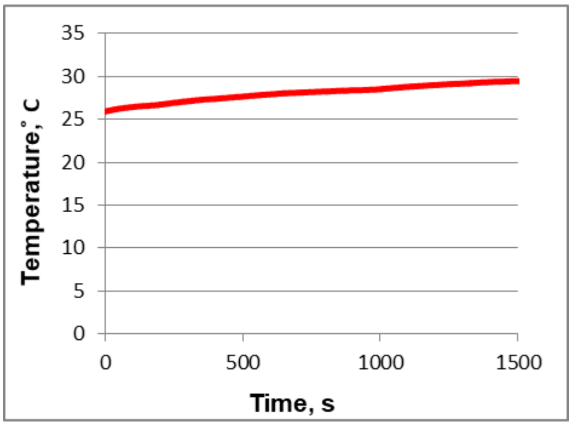

Figure 18. *Temperature changes under FFP2 mask, second participant (female)*

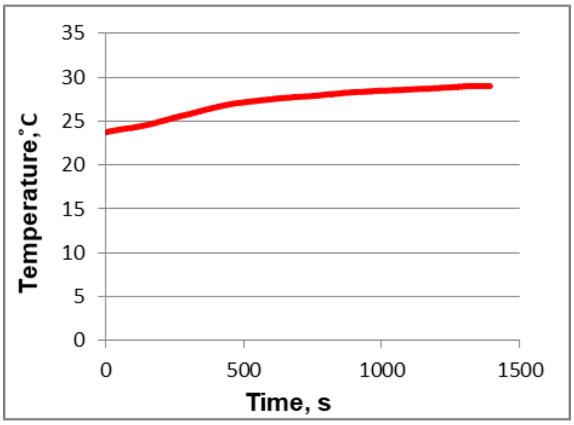

Figure 19. *Temperature changes under FFP2 mask, first participant (male)*

A comparison between the results for the two participants: the average value of the temperature in the microenvironment under each face mask and the standard deviation are summarized in *Figure 21*. The average value for all six cases is higher than the average indoor air temperature (23.2 °C). Previous research with an infrared camera has

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shown that the face skin temperature increased from 35.34 ± 0.92 °C to 36.84 ± 0.50 °C after the 2600 s period of surgical mask-wearing in a classroom (O'Dowd et al., 2022). In that study, the temperature of the microenvironment under the face masks was not measured, but the rise of the skin temperature of all participants was attributed to the temperature increment of the microenvironment under the mask. Another study (Rengasamy et al., 2010) reported that the temperature range of exhaled breath is 31.4–35.4 °C. The retention of exhaled air under the respirators also caused the temperature of the microenvironment to rise. Our present results confirmed that the face respirator would definitively be a reason for the air temperature increment under the mask.

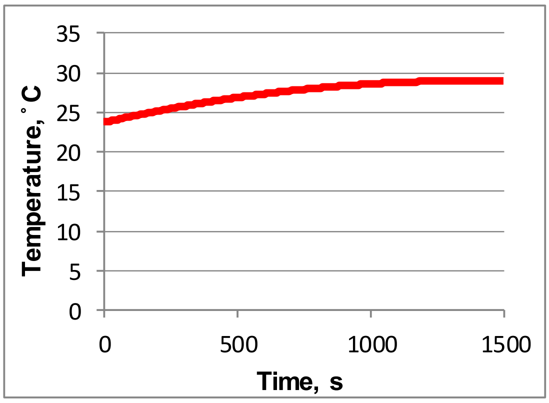

Figure 20. *Temperature changes under FFP3 mask, second participant (female)*

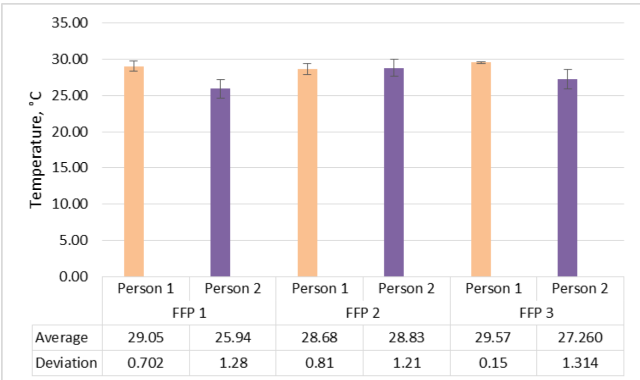

Figure 21. *Temperature under the face masks: average values and standard deviations per mask type and participant (person 1 – female; person 2 – male)*

The changes in the relative humidity under the respirators are presented in *Figures 22–27*. A comparison between the results for the two participants is summarized in *Figure 28* where the calculated average values and the standard deviation are shown. The results obtained showed that the average value of the humidity in the microenvironment under the respirators was varying between 70 and 85%. The increment of the air humidity can be explained by the impeded air transfer of exhaled air, which contains a high percentage of water vapor. Mansour et al. (2020) have found that the relative humidity of the exhaled air is between 65.0% and 88.6%, which corresponds very good with the measured values in our study.

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The environmental CO_2 concentration (inside the room) was between 1500 and 2000 ppm. Although the number of participants in these measurements is statistically insignificant, it is clear that metabolic processes in individuals with different physical activity (body mass index) have an impact on the measured indicators. For additional analyses, more experiments will be done in future.

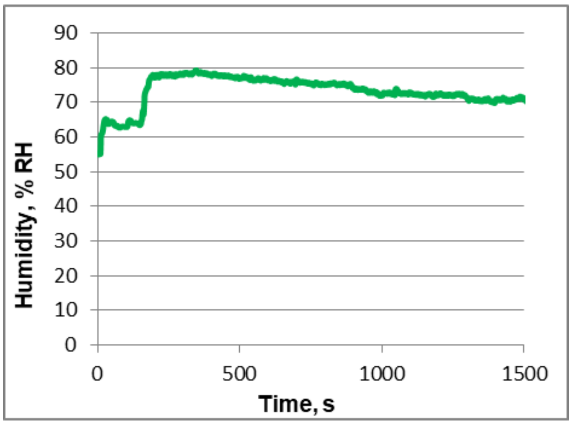

Figure 22. *Air relative humidity changes under FFP1 mask, first participant (male)*

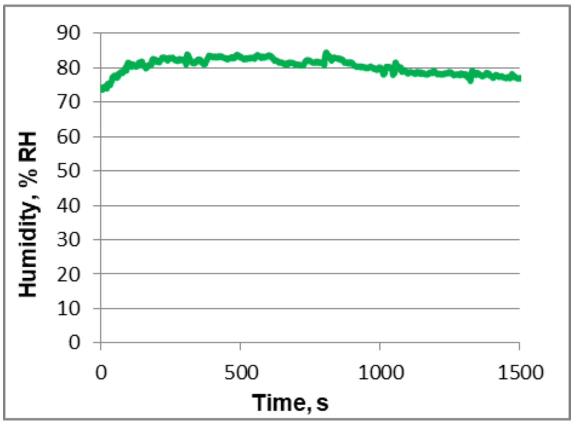

Figure 23. *Air relative humidity changes under FFP1 mask, second participant (female)*

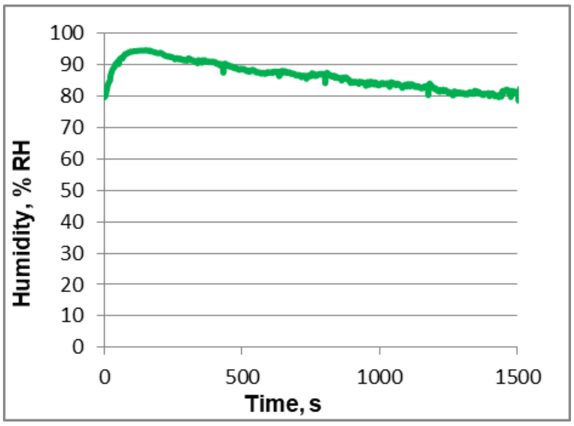

Figure 24. *Air relative humidity changes under FFP2 mask, first participant (male)*

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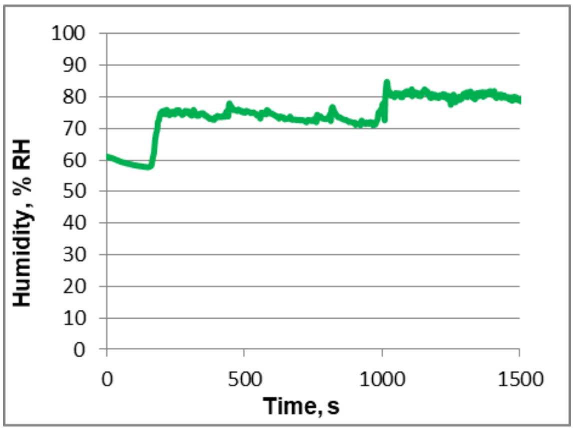

Figure 25. *Air relative humidity changes under FFP2 mask, second participant (female)*

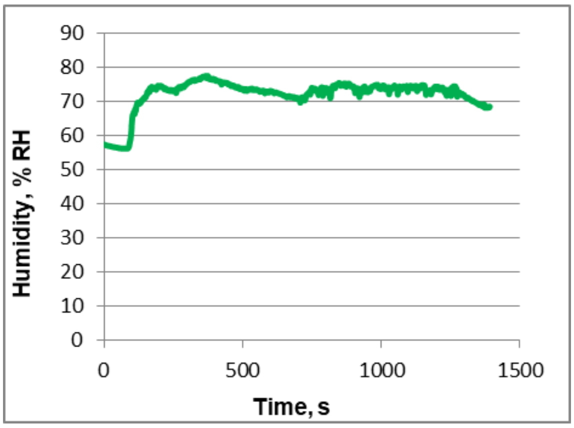

Figure 26. *Air relative humidity changes under FFP3 mask, first participant (male)*

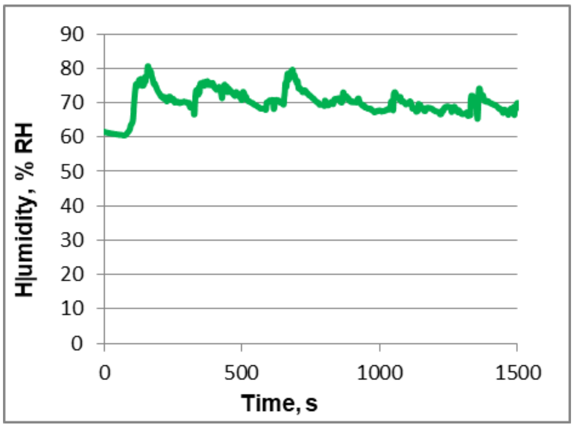

Figure 27. *Air relative humidity changes under FFP3 mask, second participant (female)*

The temperature increase in the microenvironment under the respirators was approx. 6 ÷ 7 °C, reaching about 29 °C, which is the approximate temperature of exhaled air by healthy people. The humidity was varying between 70 and 80% RH for the different types of respirators.

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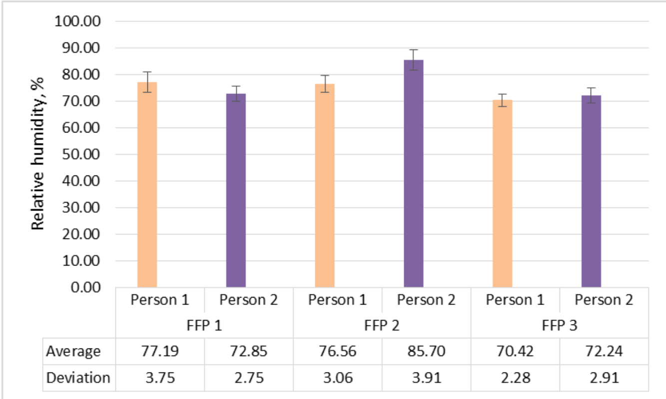

Figure 28. *Relative humidity of the air in the microenvironment under the face masks: average values and standard deviations per mask type and participant (Person 1 – female; Person 2 – male)*

Conclusions

In the present work, a new sensor system, specially designed for measuring the carbon dioxide concentration under protective face masks and respirators is discussed. The sensor system allows one to monitor in real-time three parameters of the microenvironment under a face mask/respirator: CO_2 concentration, air temperature and air relative humidity. The summary of the study's contribution is as follows:

- A sensor system for continuous measurement of the parameters of the microenvironment under a face mask/respirator was developed. The sensor system is light, portable and comfortable to wear: its weight is only 92 g including housing. The measurements are not disturbed by human breathing. The battery capacity is sufficient to ensure continuous measurement within more than 5 h.
- The study proves the changes in the microenvironment parameters under a face mask/respirator, compared to the surrounding environment in terms of air temperature, air relative humidity and CO_2 concentration.
- The CO_2 concentration in the microenvironment under the respirators increased rapidly and the average values were 9000÷16200 ppm higher than the CO_2 concentration in the room. The air temperature and relative humidity in the microenvironment under the respirators were considerably higher than the air temperature and relative humidity in the room.
- The measurements of the microenvironment parameters under the three different types of respirators showed different results, the most notable being the higher CO_2 concentration and relative air humidity under FFP2 and FFP3 respirators, compared to FFP1. However, the results are more pronounced in the male participant than in the other.

Henceforth, our future works will explore (i) the effect of the same types of respirators on more participants (both male and female); (ii) the air permeability and heat transfer through the layers of each of the three respirators to assess the influence of the heat and mass transfer impediment; (iii) the effect of other types of activities (i.e., walking) on the parameters of the microenvironment under the respirators.

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REFERENCES

[1] Angelova, R. A., Velichkova, R. (2022): Using face masks in the classroom: the effect on the indoor environment parameters and face thermophysiological reactions. – Appl. Ecol. Environ 20: 135-151.

[2] Asadi, S., Wexler, A. S., Cappa, C. D., Barreda, S., Bouvier, N. M., Ristenpart, W. D. (2019): Aerosol emission and superemission during human speech increase with voice loudness. – Scientific Reports 9(1): 1-10.

[3] Cain, J. B., Livingstone, S. D., Nolan, R. W., Keefe, A. A. (1990): Respiratory heat loss during work at various ambient temperatures. – Respiration Physiology 79(2): 145-150.

[4] CO2 Records - CO2.Earth (2022): https://www.co2.earth/co2-records. – Accessed 30th of November 2022.

[5] Davies, A., Thompson, K. A., Giri, K., Kafatos, G., Walker, J., Bennett, A. (2013): Testing the efficacy of homemade masks: would they protect in an influenza pandemic? – Disaster Medicine and Public Health Preparedness 7(4): 413-418.

[6] Driver, S., Reynolds, M., Brown, K., Vingren, J. L., Hill, D. W., Bennett, M., Gilliland, T., McShan, E., Callender, L., Reynolds, E., Borunda, N. (2022): Effects of wearing a cloth face mask on performance, physiological and perceptual responses during a graded treadmill running exercise test. – British Journal of Sports Medicine 56(2): 107-113.

[7] Egger, F., Blumenauer, D., Fischer, P., Venhorst, A., Kulenthiran, S., Bewarder, Y., Zimmer, A., Böhm, M., Meyer, T., Mahfoud, F. (2021): Effects of face masks on performance and cardiorespiratory response in well-trained athletes. – Clinical Research in Cardiology 111(3): 264-271.

[8] Escobedo, P., Fernández-Ramos, M. D., López-Ruiz, N., Moyano-Rodríguez, O., Martínez-Olmos, A., Pérez de Vargas-Sansalvador, I. M., Carvajal, M. A., Capitán-Vallvey, L. F., Palma, A. J. (2022): Smart facemask for wireless CO2 monitoring. – Nature Communications 13(1): 72.

[9] Geiss, O. (2021): Effect of wearing face masks on the carbon dioxide concentration in the breathing zone. – Aerosol and Air Quality Research 21(2): 200403.

[10] Hoffmeyer, F., Raulf-Heimsoth, M., Harth, V., Bünger, J., Brüning, T. (2009): Comparative analysis of selected exhaled breath biomarkers obtained with two different temperature-controlled devices. – BMC Pulmonary Medicine 9(1): 1-10.

[11] Lazzarino, A. I., Steptoe, A., Hamer, M., Michie, S. (2020): Covid-19: important potential side effects of wearing face masks that we should bear in mind. – The BMJ 369.

[12] Lubrano, R., Bloise, S., Testa, A., Marcellino, A., Dilillo, A., Mallardo, S., Isoldi, S., Martucci, V., Sanseviero, M., Del Giudice, E., Malvaso, C. (2021): Assessment of respiratory function in infants and young children wearing face masks during the COVID-19 pandemic. – JAMA Network Open 4(3): e210414-e210414.

[13] Mansour, E., Vishinkin, R., Rihet, S., Saliba, W., Fish, F., Sarfati, P., Haick, H. (2020): Measurement of temperature and relative humidity in exhaled breath. – Sensors and Actuators B: Chemical 304: 127371.

[14] O'Dowd, K., Nair, K. M., Forouzandeh, P., Mathew, S., Grant, J., Moran, R., Bartlett, J., Bird, J., Pillai, S. C. (2020): Face masks and respirators in the fight against the COVID-19 pandemic: a review of current materials, advances and future perspectives. – Materials 13(15): 3363.

[15] Ong, J. J., Chan, A. C., Bharatendu, C., Teoh, H. L., Chan, Y. C., Sharma, V. K. (2021): Headache related to PPE use during the COVID-19 pandemic. – Current Pain and Headache Reports 25(8): 53.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2104_27752792

[16] Rengasamy, S., Eimer, B., Shaffer, R. E. (2010): Simple respiratory protection—evaluation of the filtration performance of cloth masks and common fabric materials against 20–1000 nm size particles. – Annals of Occupational Hygiene 54(7): 789-798.
[17] Rhee, M. S., Lindquist, C. D., Silvestrini, M. T., Chan, A. C., Ong, J. J., Sharma, V. K. (2021): Carbon dioxide increases with face masks but remains below short-term NIOSH limits. – BMC Infectious Diseases 21: 1-7.
[18] Shaw, K., Butcher, S., Ko, J., Zello, G. A., Chilibeck, P. D. (2020): Wearing of cloth or disposable surgical face masks has no effect on vigorous exercise performance in healthy individuals. – International Journal of Environmental Research and Public Health 17(21): 8110.
[19] Sofronova, D., Sofronov, Y., Angelova, R. A. (2021): Design of a Device for Measuring the Parameters of the Microenvironment under Protective Face Masks. – In: 2021 6th International Symposium on Environment-Friendly Energies and Applications (EFEA). IEEE, pp. 1-4.
[20] Spitzer, M. (2020): Masked education? The benefits and burdens of wearing face masks in schools during the current Corona pandemic. – Trends in Neuroscience and Education 20: 100138.
[21] UNI EN 149:2001 + A1:2009 (2009): Facemasks. – International Council of Certification, Durrës, Albania.
[22] Van der Sande, M., Teunis, P., Sabel, R. (2008): Professional and home-made face masks reduce exposure to respiratory infections among the general population. – PloS ONE 3(7): e2618.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2104_27752792