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EXPERIMENTAL STUDIES OF HYDRAULIC LOSSES AND CARBON DIOXIDE CONCENTRATION IN THE SPACE UNDER THE FACE MASK PROTECTING AGAINST COVID-19

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Abstract

Masks are the primary tool used to prevent the spread of COVID-19 in the current pandemic. Tests were carried out to determine the total pressure drop through the materials from which the masks are made and the correlation of these results with the concentration of carbon dioxide in the inner space of the mask. The results showed that a parameter representing hydraulic losses of the mask material has a significant influence on the concentration of carbon dioxide in the inner space of the mask. Masks with higher hydraulic resistances accumulated a higher concentration of carbon dioxide, and generated greater fluctuations of carbon dioxide as a function of time, which may be caused by compensation of the respiratory system. For example, in a two-layer mask (mask no. 3) the hydraulic resistance values are about three times higher than in a single-layer mask

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(mask no. 1). The study also noticed that the inscriptions and prints placed on the masks increase the hydraulic resistance of the material from which the masks are made, which may also contribute to the accumulation of carbon dioxide in the space between the mask and the face. To reduce the accumulation of carbon dioxide within the inner space of the mask, the results of this work suggest searching for mask materials with the lowest possible hydraulic resistance.

Keywords: face masks, COVID-19, hydraulic losses, mask material, carbon dioxide concentration

1. INTRODUCTION

Masks are the primary tool used to prevent the spread in the pandemic. The current sanitary measures during the Covid-19 era solutions by means of effective ventilation and air quality are investigated [1-3]. The most common symptoms of COVID-19 are fever, cough, shortness of breath, and breathing problems. Muscle aches and fatigue can also accompany the disease. For example, in Poland, a mask or visors must be worn in the following places [4]: on buses, trams and trains; in a passenger car, if you are traveling with someone you do not live with on a daily basis; in shops, shopping malls, banks, markets and post offices; at cinemas and theaters; at doctor’s clinics and hospitals; in massage and tattoo parlours and in church, school, university, offices and other public buildings (until April 2021). Many researchers are concerned with the quality of the air that people breathe.

Air pollutants e.g., carbon dioxide (CO_2) [5, 6] particulate matter PM 2.5, PM10 [7, 8] etc. have a serious impact on human health. Out of these pollutants, the concentration of carbon dioxide is one of the most dominant one [9, 10]. Currently, in the natural environment outside buildings, the concentration of CO_2 in the air usually does not exceed 400 ppm and it is recommended for the breathing person. Too high concentration of carbon dioxide in the air may have a negative impact on human health. In confined and unrestricted spaces, the concentration of carbon dioxide tends to be higher. This applies to both rooms and industrial sites. Usually air has a constant composition. However, as pollutants, including CO_2, increase, the amount of oxygen in the air decreases. Oxygen is essential for life, which is why it is so important to monitor air pollutants. Measurements are performed indoors in buildings [11, 12], but also in other closed or open spaces [13-15]. The masks stop the above pollutants from the outside air (also bacteria and pathogenic viruses), but also trap the carbon dioxide inside them, which is a product of respiration. Depending on physical activity, a person exhales different amounts of carbon dioxide. For example, when resting in a lying position, a person exhales 10 - 12 l/h CO_2, in a sitting position 12 - 15 l/h CO_2, with light office work 19 - 24 l/h CO_2, while in medium-heavy work or gymnastics, a person exhales 33 - 43 l/h CO_2 [16].

Filtering facepiece respirators are usually tested on the basis of the EN 149:2001/AC:2002 standard [17], while surgical masks are tested according to the EN 14683:2019+AC standard [18].

The aim of the present study is to measure and analysis was made of the hydraulic losses of the materials from which the masks are made, and the correlation of these results with the concentration of carbon dioxide. Carbon dioxide in the inner space of the mask it is only from human respiration while working at the computer. It should be emphasized that the aim of the study is not to assess the impact of wearing masks on human health, and the work did not assess the effectiveness of the masks in preventing viruses, bacteria and dust from entering the respiratory system.

2. RESEARCH METHODOLOGY

The tests of five masks involved determination of the carbon dioxide concentration in the inner space of the mask and measurement of the pressure drop (local pressure loss) through the material of the mask.

2.1. Description of the tested masks

The research was carried out on five different popular masks. They are shown in general view in Fig. 1a–e, and their technical parameters are given in Table 1. Mask 1 and masks 3–5 were bought in local stores in Poland, while mask 2 was made by the researcher from cotton material.

Table 1. Description of the tested masks

Number	Material	Description of the mask
Mask 1	non-woven polypropylene	type I, acc. to [18], three layers of fabric (Fig. 1a)
Mask 2	100% cotton, weight: 125 g/m^2	made of three layers of material (Fig. 1b)
Mask 3	non-woven polypropylene	two layers of fabric (Fig. 1c)
Mask 4	polypropylene	type FFP2 (according to [17] GB2626-2006 KN95), mask equipped with a metal buckle at the level of the nose, very densely woven materials, five layers of fabric (Fig. 1d)
Mask 5	polypropylene	half mask with an exhalation check valve, type FFP2 (according to [17]), mask equipped with a metal clip at the level of the nose, very densely woven materials (Fig. 1e)

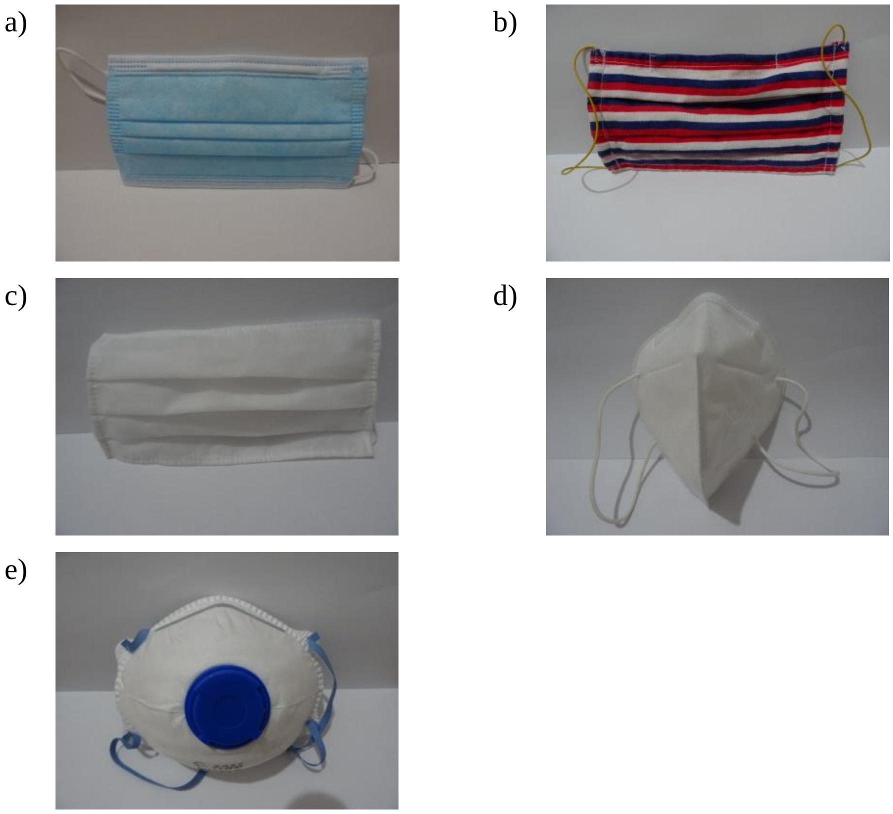

Fig. 1. General view of the tested masks

2.2. Carbon dioxide measurements in the space between mask and face

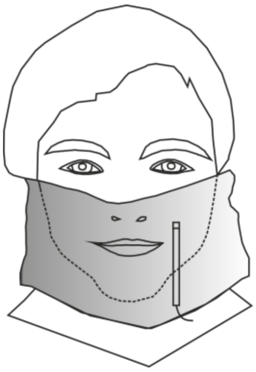

Fig. 2. Location of the measuring probe under the mask during measurement of carbon dioxide concentration

Carbon dioxide measurements were made using a Testo IAQ probe connected to a Testo 435 recorder, for which the error is ± 3% of the measured value for the range 0–5000 ppm [19]. Results were recorded every second. The measuring point was located as shown in Fig. 2. All masks were tested by four participants and each participant performed 10 measurement series for each mask.

2.3. Measurement of pressure drop through the mask material

The hydraulic losses generated by the mask can significantly affect comfort. Any additional hydraulic resistance appearing around the mouth and nose increases the discomfort of breathing. To determine the characteristics of the total pressure drop for the materials from which the masks were made, tests were performed on a test stand compliant with the PN-EN 13141-5 [20] and CR 14378:2002 [21] standards. It should be noted that due to the lack of guidelines for measuring the pressure drop through a mask material, use was made of standards [21, 20] applicable to the testing of ventilation elements such as air intakes and launchers. A diagram of the stand used for measuring the total pressure drop and the output is shown in Figure 3.

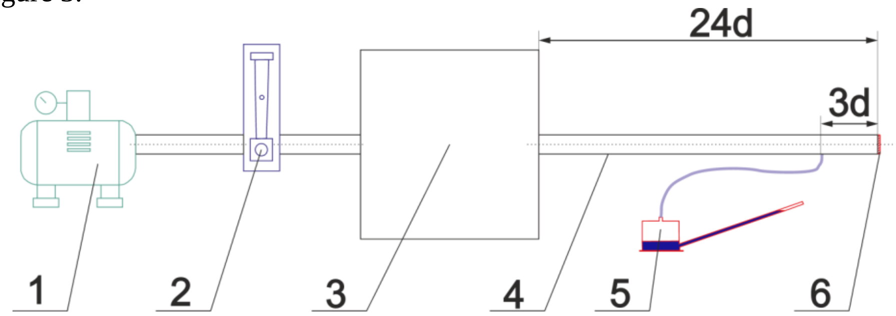

Fig. 3. Diagram of the stand for testing the pressure drop of the mask material: 1 – compressor, 2 – rotameter, 3 – air chamber, 5 – static pressure manometer, 6 – mask material sample

The air flow through the test pipe (4) with diameter d = 34 mm is generated by the compressor (1). To stabilize the flow, a cubic air chamber was used, the side length of which is equal to 10 diameters. The volumetric flow Q was measured with the Veb MLV LD rotameter, which has a measurement error of ± 5 l/h. The tests were performed for volumetric flow rates ranging from 300 to 2000 l/h. Static pressure p_s was measured at a distance of 3 diameters from the material sample (6) using an MPR-3 manometer, of which the measurement error is ± 0.3 Pa. The total pressure was determined as the sum of the static pressure p_s and dynamic pressure p_d (2.1):

$$p_c = p_s + p_d \quad ; \quad p_d = \frac{\rho u_m^2}{2} \quad ; \quad u_m = \frac{Q}{A}, \tag{2.1}$$

where u_m is the average air velocity in the test tube, ρ is the air density, and A is the test cross-sectional area.

The uncertainty of the measured values was calculated according to Moffat [22] as follows (2.2):

$$\delta x = \sqrt{B_{inst}^2 - \left(2\sigma_{ran}\right)^2} \ , \tag{2.2}$$

where B_{inst} is the overall fixed error uncertainty of the measurement equipment, and σ_{ran} is a random error caused by various factors.

3. RESULTS AND DISCUSSION

Table 2 shows the mean values of carbon dioxide concentration for different masks for all test participants from 10 measurement series for each mask [23].

Table 2. Average carbon dioxide concentrations for various masks **Błąd! Nie można odnaleźć źródła odwołania.**

Average carbon dioxide concentration for various masks [ppm]						
Mask 1	Mask 2	Mask 3	Mask 4	Mask 5	Measurement without mask	Inside the laboratory
2629	2209	1236	4199	6035	859	539

In order to thoroughly understand the effect of the mask on the carbon dioxide levels in the space between the mask and the face, carbon dioxide concentration tests were performed without the mask with the carbon dioxide probe positioned in the same way as when measuring carbon dioxide with the mask. The results of the measurements are presented in Table 2. Table 2 also shows the average values of carbon dioxide concentration in the room where the tests were carried out.

In literature [24], the carbon dioxide concentration in the breathing zone was determined by sucking air through a silicone tube into the mask space, where the sampling point was on the bridge of the nose, just above the tip. Placing the inlet of the tube over the tip of the nose may result in an additional supply of fresh air, so the results for the mask carbon dioxide concentration may be understated.

Very high values of carbon dioxide concentration in N95 masks were obtained in literature [25], as high as 30,000 ppm. Such high carbon dioxide concentration values can be influenced by the position of the probe between the nose and mouth, which can result in the measurement of exhaled air. High CO_2 concentrations have also been obtained in cloth and paper masks [26].

For the purpose of testing the hydraulic losses of the mask materials, the tested masks were divided into homogeneous masks, which have filtration surfaces made of a homogeneous material, and non-homogeneous masks, with a check valve or painted surfaces on the filtering surface.

Figure 4 compares the average values of the total pressure drop for flows ranging from 300 to 2000 l/h through the materials of the homogeneous masks (masks 1–4), while Figure 5 shows the pressure losses of the elements included in the non-homogeneous mask 5. Mask 5 has the most complex structure of all of the tested masks, in which the air flows through the following three areas: material without inscriptions, material with inscriptions (painted), and a check valve. The greatest hydraulic resistance among the homogeneous masks is generated by mask 4, which has the largest number of layers (5 layers) and the highest material density. The lowest hydraulic resistance is generated by mask 3, with only two layers of material. This test confirms the dependence of hydraulic resistance on the density of the filtering material and the thickness of the filtering layer. Similarly, filters used in ventilation systems with a significant wall thickness and a material of higher density are characterized by greater hydraulic resistance [27]. It should also be emphasized that thicker filters are most often characterized by higher filtration efficiency [28]. In the case of mask 5, the smallest average pressure losses for the flow range from 300 to 2000 l/h are generated by the check valve, and the largest by the printed (painted) filter material. The painted filter material generates a 5.6 times greater hydraulic loss than the unprinted material. Locally printed inscriptions or drawings can significantly increase the hydraulic resistance in the mask. The increase in pressure loss may make using the mask uncomfortable, due to the increased breathing resistance [29].

Figure 6 shows the hydraulic characteristics of the mask materials for flows ranging from 300 to 2000 l/h. As the flow increases, the pressure losses increase.

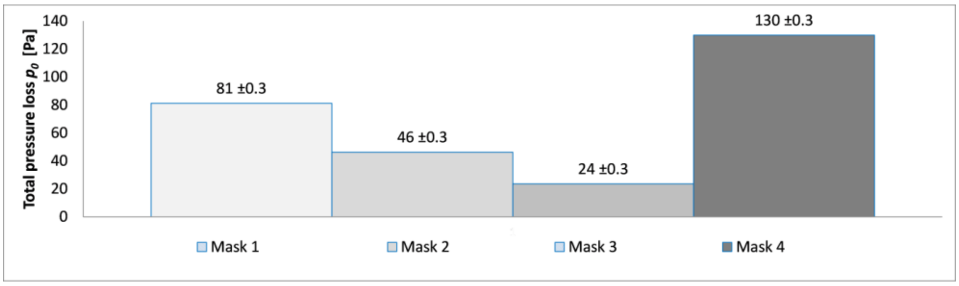

Fig. 4. Comparison of the average total pressure drop for the materials of masks 1–4, for flow rates from 300 to 2000 l/h

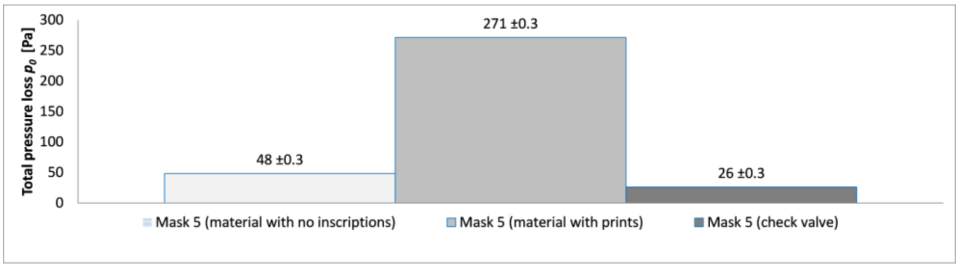

Fig. 5. Comparison of the average total pressure drop for the materials of mask 5 (material without inscriptions, material with inscriptions, check valve) for flow rates from 300 to 2000 l/h

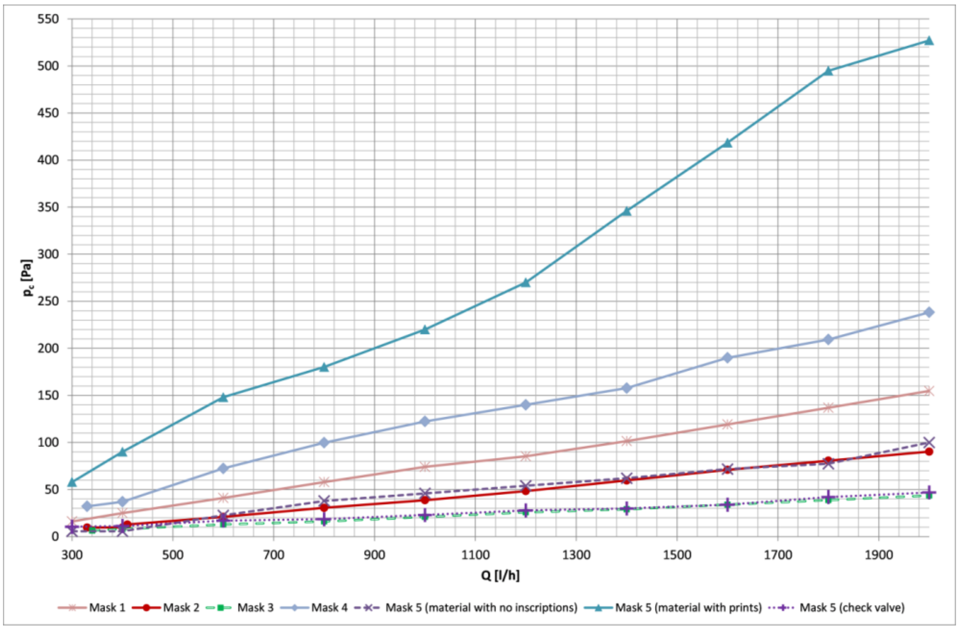

Fig. 6. Total pressure drop curves for masks 1–5, for flow rates from 300 to 2000 l/h

Figure 7 shows a linear correlation ($R^2 = 0.92$) between hydraulic losses and the concentration of carbon dioxide for homogeneous masks (masks 1–4). As the hydraulic resistance increases, the concentration of carbon dioxide in the mask increases. The increase in carbon dioxide concentration as a function of total pressure drop can be explained in two ways:

1) Using the analogy of room ventilation systems, it can be seen that an increase in hydraulic resistance in ventilation ducts or diffusers is usually associated with a decrease in air flow. A decrease in indoor air flow causes a decrease in indoor air quality and leads to an increase in carbon dioxide concentration. The situation may be similar in the case of the respiratory system, in which

the additional hydraulic resistance caused by the mask reduces the efficiency of the lungs and contributes to an increase in the carbon dioxide concentration.

2) The second explanation for the increase in the concentration of carbon dioxide as a function of the drop in total pressure is related to the recirculation of carbon dioxide from the mask to the human respiratory system. In literature [30], a series of simulations of air flow in the mask space was performed [31], on the basis of which a vortex was identified in the air space between the human face and the mask during exhalation. This may cause the accumulation of carbon dioxide in the space under the mask [32].

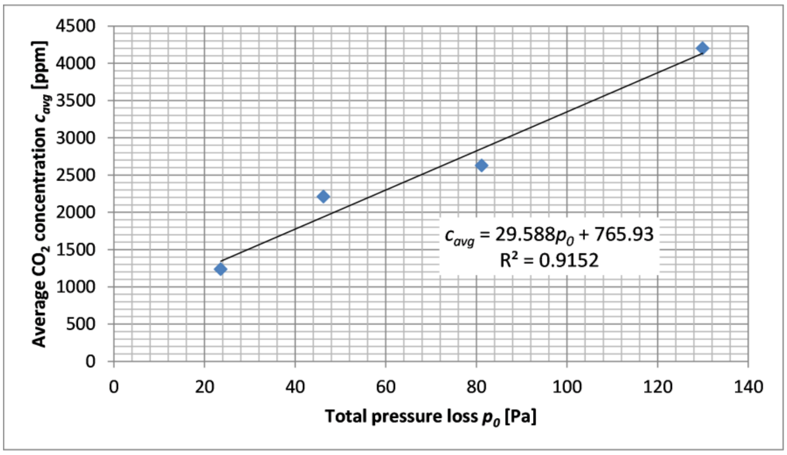

Fig. 7. Relationship between CO_2 concentration and total pressure drop for masks 1–4

4. CONCLUSIONS

This paper has described measurements of carbon dioxide concentration in five different masks and their relationship with the hydraulic losses generated by the mask materials. The following conclusions are drawn from the research:

1. The values of hydraulic losses of the mask materials depend on the number of layers the masks are made of. The greater the number of layers of material in the mask wall, the greater the pressure drop through the mask material. The material of the two-layer mask generates up to three times lower hydraulic resistance compared to the material of which the three-layer mask is made.
2. The values of carbon dioxide concentration in the mask space depend on the total pressure drop through the mask material. The lower the pressure drop through the mask material, the lower the carbon dioxide concentration values in the mask space, so it is preferred to use

materials with low hydraulic resistance. It should be emphasized that this study did not conduct research on the effectiveness of human protection against virus transmission as a function of the hydraulic resistance of the mask material.

3. The hydraulic losses of the mask materials may be affected by prints made on the mask, which locally generate significant hydraulic resistance. The research showed that the tested printed material generated 5.6 times higher hydraulic resistance compared to the material without printing. The increase in hydraulic resistance in the printed material was due to the reduction of gas permeability through the paint surface, which is locally an additional layer added to the mask.

The development of effective masks, is essential to contain the spread of COVID-19. The correlation between the concentration of carbon dioxide in the mask space and the pressure losses of the mask material may provide valuable guidance in the design of new materials for the manufacture of masks.

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