Analysis of Pressure Losses of Selected Filtration Materials

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Abstract— *With the increasing demands on the efficiency of filtration materials, it is essential to pay attention to the study of pressure losses that occur during the flow of air through these materials. This article presents a device design for measuring pressure losses, followed by experimental verification of selected filtration materials. From the individual measurements, permeability and resistance coefficient are evaluated, which are key for determining the filter's pressure parameters and its performance under real operating conditions.*

Keywords— Pressure Losses, Filtration Materials, Permeability, Resistance Coefficient.

I. INTRODUCTION

The capture of aerosol particles using solid filters is the most widespread method of air purification, proven to be a simple, universal, and cost-effective way to separate particles. At low dust concentrations, fibrous filters are the most economical solution for effectively removing even very small microscopic particles. This technology is used in various areas, such as respiratory protection, air conditioning, air purification in industrial operations, and more. Although the basic principles of filtration are well studied, it remains a complex process in which discrepancies often arise between theoretical models and experimentally measured results [1].

Pressure loss is one of the main parameters determining the usability of different types of filters, as it affects their energy consumption, the efficiency of medium flow, and the overall requirements for their application in various areas of use.

II. DESIGN OF EXPERIMENTAL DEVICE

Effective filtration is a fundamental element in many technological processes, ranging from industrial applications to healthcare facilities. A key parameter in evaluating filtration materials is pressure loss, which arises due to the resistance the filtration material poses to the flowing medium. Determining this pressure loss is essential for the proper design and optimization of filtration systems.

When designing the experimental apparatus, it was necessary to propose and select components that ensure reliable, repeatable, and practically applicable measurements of the physical properties of filtration materials. The device was designed with an emphasis on accuracy, ease of operation, and the ability to be calibrated—an essential factor for long-term stability and measurement precision.

The basic principle of the device is to measure the pressure before and after the filtration material, based on which the filter's pressure loss is determined. To ensure measurement accuracy, it is necessary to select an appropriate manometer with a suitable range and sensitivity. A fan is used to generate airflow, creating forced air movement through the filter material. A critical aspect of evaluating pressure losses is the ability to regulate the fan's speed, which allows for varying the volumetric airflow through the filtration material and subsequently determining parameters related to the filter's properties.

The acquired pressure loss data must be systematically recorded and stored, which was achieved through the design of a suitable electronic solution and its integration with data acquisition software. The ambient air pressure was measured using an atmospheric pressure sensor, and the airflow velocity at the system's inlet was measured using an anemometer.

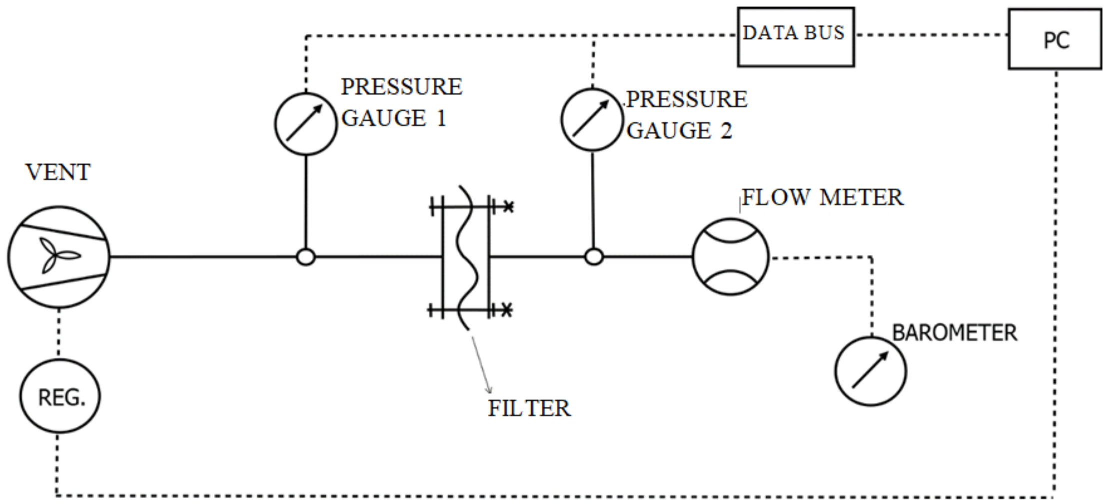

FIGURE 1: Measurement stand diagram

The piping system consists of simple tubes made using additive manufacturing technologies. Individual segments are connected by flanges, which are secured with bolts. This method of assembly ensures a strong connection while also allowing for easy disassembly and reassembly during maintenance or replacement of pipeline components. The connection interfaces are designed to minimize air leakage and ensure maximum system tightness. The tested filter is placed into a filter holder, which ensures its secure and stable positioning during testing. The holder is designed to allow quick and easy filter replacement without the need to disassemble the entire system.

III. DETERMINATION OF PERMEABILITY AND RESISTANCE COEFFICIENT OF FILTER MATERIAL

The pressure change across the filter can be described by a differential equation based on Darcy's law for laminar flow, supplemented by a term accounting for turbulent flow.

$$\frac{\mathrm{d}p}{\mathrm{d}x} = \frac{\eta}{k_f} \cdot w + \beta \cdot \rho \cdot \frac{w^2}{2} \tag{1}$$

$$\Delta p = \frac{\eta}{k_f} \cdot v \cdot \delta + \beta \cdot \rho \cdot \frac{w^2}{2} \cdot \delta \tag{2}$$

For a filter with an average thickness δ, a substitution can be made:

$$k'_f = \frac{k_f}{\delta}, \ \beta' = \beta \cdot \delta$$

equation (2) is then:

$$\Delta p = \frac{\eta}{k'_f} \cdot v + \beta' \cdot \rho \cdot \frac{w^2}{2} \tag{3}$$

where η is the dynamic viscosity (Pa·s), k'_f - is the permeability of the filter (m), β' - is the resistance coefficient (1), ρ – density of air (kg·m^{-3}), w – speed of sound (m·s^{-1}), Δp – pressure loss (Pa), δ – material thickness (m).

From two measurements of air velocity and pressure loss across the given filter, a system of two equations is formed, from which the permeability and the resistance coefficient of the filtration material can subsequently be calculated.

IV. EXPERIMENTAL MEASUREMENT OF PRESSURE LOSSES OF SELECTED FILTRATION MATERIALS

For the purpose of obtaining data on permeability and resistance coefficient, experimental measurements were conducted on four selected filtration materials: the AJ PRO and Promask PM2 respirators, a Type II surgical mask, and a textile mask.

AJ PRO AJ-01 FFP2

ProMask FFP2

Surgical mask type II

Textile mask

FIGURE 2: Selected filter materials

From each pair of measured pressure loss values at different air velocities through the filtration material, the permeability k'_f and resistance coefficient β' were calculated from the system of two equations. Subsequently, pressure losses were analytically calculated using equation (3), and their values were graphically represented as a function of the air velocity through the filtration material. To increase the accuracy of the measured data, each measurement was performed three times at different air velocities. All pressure loss measurements of the filters were carried out at an air dynamic viscosity of $1.82 \cdot 10^{-5}$ Pa·s and an air density of 1.167 kg·m^{-3}. The examined cross-sectional area of the filters was 2.715 mm² (bounded by attachment to the measurement stand).

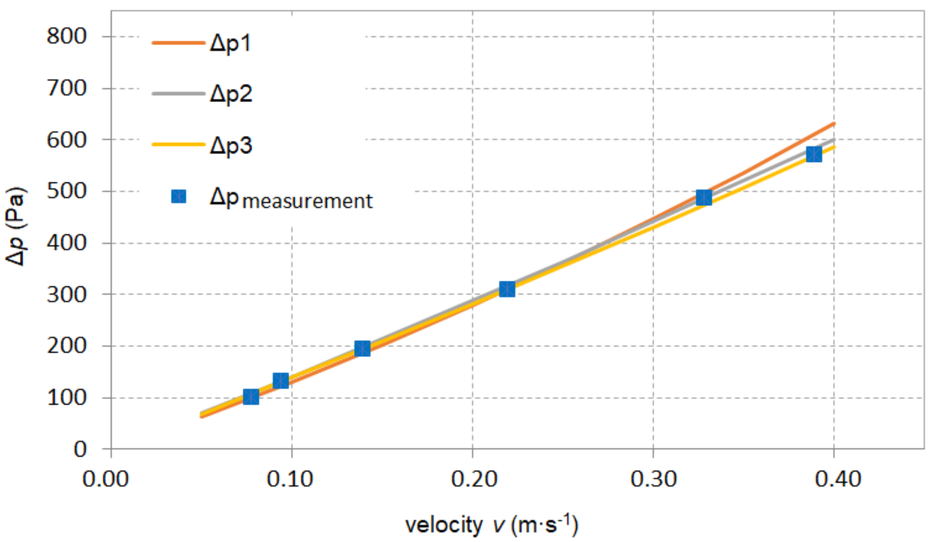

FIGURE 3: The course of pressure losses depending on the air velocity through the respirator's filtration material AJ PRO

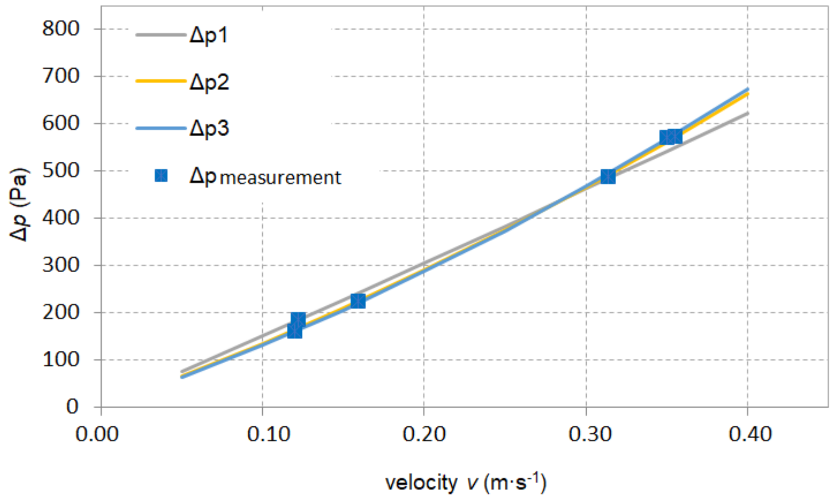

FIGURE 4: The variation of pressure loss depending on the air velocity through the filtration material of the Promask respirator

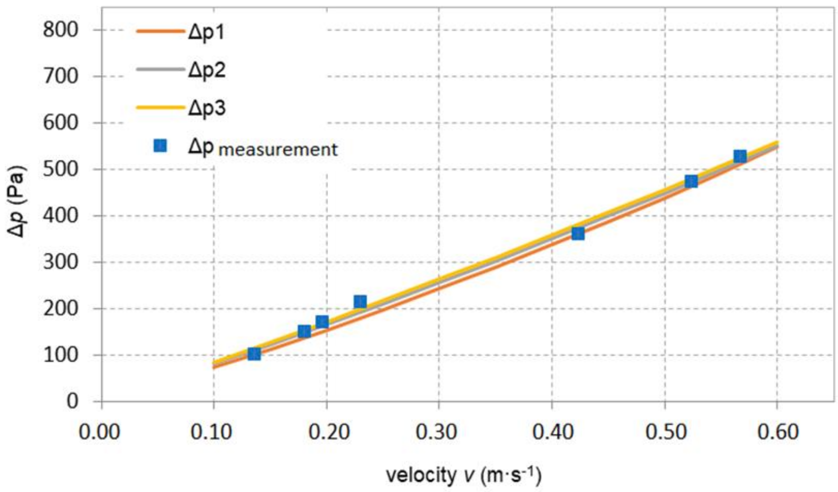

FIGURE 5: The variation of pressure loss depending on the air velocity through the filtration material of the Type II surgical mask

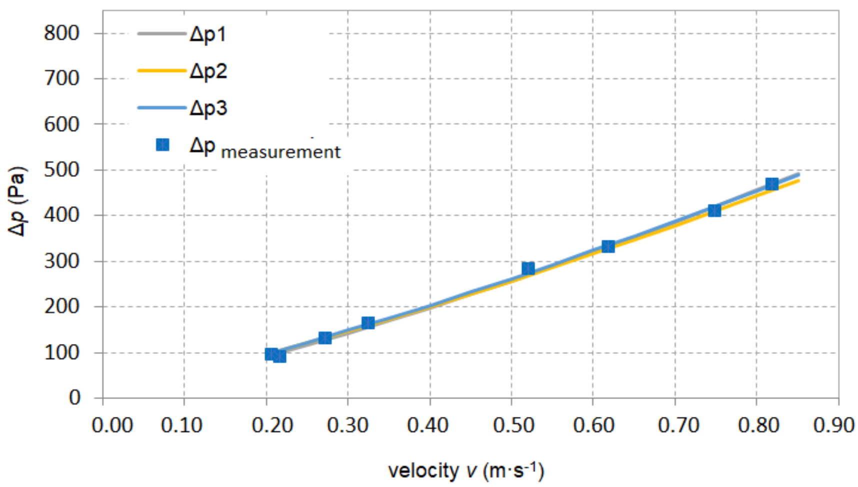

FIGURE 6: The variation of pressure loss depending on the air velocity through the filtration material of the textile mask

Based on the conducted measurements, it can be concluded that the textile mask exhibited the highest permeability, indicating its lowest resistance to airflow. This reflects the simplicity of the materials used and suggests its suitability for environments with coarse, dispersed particles. In contrast, both respirators showed significantly lower permeability, corresponding to their higher filtration efficiency but also resulting in higher pressure losses. The permeability of the surgical mask was between the values of the textile mask and the respirators. The distribution of resistance coefficient values corresponded with the pressure loss values, with the highest recorded for the respirators and the lowest for the textile mask. Among the FFP2-class respirators, no significant differences in permeability were observed; however, the Promask respirator exhibited higher resistance coefficient values, which may be attributed to differences in the material composition and structure of the filtration medium.

TABLE 1
MEASURED VALUES OF PERMEABILITY AND RESISTANCE COEFFICIENT OF SELECTED FILTRATION MATERIALS

Material	Permeability k'_f	Resistance coefficient β'
	(m)	-1
FFP2 respirator AJ PRO	$1.39 \cdot 10^{-8}$	$0.85 \cdot 10^{3}$
FFP2 respirator Promask	$1.41 \cdot 10^{-8}$	$1.42 \cdot 10^{3}$
Surgical mask	$2.36 \cdot 10^{-8}$	$0.42 \cdot 10^{3}$
Textile mask	$4.14 \cdot 10^{-8}$	$0.26 \cdot 10^{3}$

Based on the analysed dependence of pressure loss on the change in air velocity through the filtration material, it is subsequently possible to determine the minimum filtration area required to achieve the desired operational parameters while maintaining acceptable pressure losses.

The maximum allowable pressure loss for FFP2 respirator filters according to the EN 149 standard is 240 Pa during inhalation and 300 Pa during exhalation. According to the graphs presented below, these correspond to the maximum permissible air velocities w ($m \cdot s^{-1}$) (taken as the minimum of the measured values). The total required airflow according to the relevant standard is 95 $l \cdot min^{-1}$ during inhalation and 160 $l \cdot min^{-1}$ during exhalation. The required cross-sectional area of the respirator filter for inhalation, considering the maximum allowable pressure loss, is determined using the following relationship:

$$S = \frac{Q_V}{w} \quad (\mathrm{m}^2) \tag{4}$$

where S is the required filtration area (m^2), Q_V – required airflow according to the relevant standard ($l \cdot min^{-1}$), w – allowable air velocity ($m \cdot s^{-1}$).

Using the given formula, we can determine the minimum required filtration area for the AJ PRO AJ-01 FFP2 respirator as follows:

From the graph, we read the average air velocity at a pressure loss level of 240 Pa, which in this case is 0,17 $m \cdot s^{-1}$.

Calculation of the respirator filter's cross-sectional area for inhalation:

$$S_{\mathrm{inhalation}} = \frac{Q_{V_{\mathrm{inhalation}}}}{w} = \frac{0.001583}{0.17} = 93.14\ \mathrm{cm}^2$$

From the graph, we read the average air velocity at a pressure loss level of 300 Pa, which in this case is 0,21 $m \cdot s^{-1}$.

Calculation of the respirator filter's cross-sectional area for exhalation:

$$S_{\mathrm{exhalation}} = \frac{Q_{V_{\mathrm{exhalation}}}}{w} = \frac{0.00267}{0.21} = 126.98\ \mathrm{cm}^2$$

In a similar way, it is possible to determine the minimum filtration area for respirators subject to the EN 149 standard.

V. CONCLUSION

The results obtained from measurements on the designed device show that respirators achieved the lowest permeability and the highest resistance coefficient, as they are intended for use in environments with high concentrations of aerosol particles, bacteria, and viruses, where it is necessary to ensure the maximum level of filtration and respiratory protection for the user. To meet these conditions, materials with a very fine microstructure are required, which effectively capture even the smallest particles but at the same time increase the airflow resistance during breathing.

In contrast, masks exhibited higher permeability and lower resistance coefficients, indicating their lower ability to filter fine particles. This phenomenon is caused by their simpler fabric structure, which generally has larger pores and fewer layers compared to respirators. As a result, masks offer less resistance to the flowing air, which increases breathing comfort but simultaneously reduces their effectiveness in capturing aerosols and microorganisms. These properties make masks more suitable for use in ordinary, less risky environments where a high level of protection is not required.

The designed and constructed device is intended for testing various filtration materials, with its versatility lying in the possibility of adjusting components used to mount the filtration material—manufactured by 3D printing—as well as the fan that creates the required pressure in the system. Based on the measurement results obtained, it is subsequently possible to design the necessary filtration area that would meet the relevant standards or device requirements where the filtration materials will be applied. The simplicity and versatility of this device make it useful in various application areas as a preliminary step for verifying filter efficiency

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