

섹션 11.

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DOI 10.36074/logos-13.03.2026.018

ELECTROSTATIC LAYER PLACEMENT AND AEROSOL FILTRATION IN N95 RESPIRATORS

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Abstract. *The efficiency of N95 respirators is determined by a combination of mechanical filtration mechanisms and electrostatic particle capture. Although the filtration properties of individual mask materials have been widely studied, the influence of layer positioning within multilayer respirator structures remains insufficiently explored. This study experimentally investigates how the relative position of the electrostatic filtration layer affects particle penetration efficiency in multilayer N95 respirator configurations. Several filter configurations were reconstructed by rearranging mechanical and electrostatic filtration layers, and aerosol particles were passed through each configuration under controlled laboratory conditions. The results demonstrate that filtration efficiency strongly depends on the sequence of filtration layers, with the highest performance observed when the electrostatic layer is positioned downstream of the primary mechanical filtration layer. These findings improve the understanding of multilayer filtration dynamics and provide practical insights for respirator design and aerosol control.*

Introduction. Respiratory protection devices such as N95 respirators play an important role in protecting individuals from airborne particles, pathogens, and environmental pollutants. Their filtration efficiency is based on a combination of mechanical and electrostatic mechanisms that capture aerosol particles across a wide size distribution [1].

Research on respirator filtration has intensified significantly following the COVID-19 pandemic, particularly due to the importance of controlling viral aerosol

transmission. Previous studies have shown that N95 respirators can achieve filtration efficiencies above 95% for particles with aerodynamic diameters around 0.3 μm , which corresponds to the most penetrating particle size (MPPS) [2].

Previous studies have shown that aerosol filtration occurs through several mechanisms, including interception, inertial impaction, diffusion, and electrostatic attraction, which act simultaneously depending on particle size and airflow conditions [3–4]. Research by Lee and Kim as well as Hinds and Wang demonstrated that electrostatically charged filtration media significantly enhance particle capture efficiency in multilayer filters [5–6]. The performance of N95 respirators depends on their multilayer structure, typically consisting of spunbond polypropylene outer layers, melt-blown filtration layers, and electrostatically charged media.

However, most previous studies have focused on filtration materials rather than the structural arrangement of layers within respirators. Therefore, this study investigates how the position of the electrostatic filtration layer influences particle penetration efficiency in multilayer respirator configurations.

Materials and Methods. The experimental design involved constructing several multilayer respirator filter configurations similar to those used in N95 respirators. Each configuration consisted of three layers: an outer mechanical filtration layer, an electrostatic melt-blown filtration layer, and an inner support layer arranged in four different sequences. Test aerosols with particle sizes ranging from 0.1–1 μm were generated using a controlled particle generator, and particle concentrations downstream of the filter were measured with an optical particle counter. Filtration efficiency was calculated using the standard equation:

$$E = \left(1 - \frac{C_{down}}{C_{up}}\right) \times 100$$

E — filtration efficiency

C_{up} — upstream particle concentration

C_{down} — downstream particle concentration

Results. Experimental results showed significant differences in filtration efficiency depending on the sequence of filtration layers in the respirator structure. Each configuration was tested in three repeated experimental runs, and the reported filtration efficiency values represent average measurements.

Four configurations of filtration layers, including mechanical, electrostatic, and support layers, were tested to evaluate efficiency. The results indicate a significant influence of the structural organization of the filter on the penetration of aerosol particles.



섹션 11.

CHEMISTRY, CHEMICAL ENGINEERING AND BIOENGINEERING

Configuration A

mechanical → electrostatic → support

The average filtration efficiency was 97.8%.

This configuration demonstrated the highest filtration efficiency for all particle sizes studied. The mechanical layer removed larger particles in the first stage through inertial deposition and interception, after which the electrostatic layer effectively captured fine particles due to Coulomb attraction [4].

Configuration B

electrostatic → mechanical → supporting

The average filtration efficiency was 95.1%.

Despite its high efficiency, it was lower than configuration A. This can be explained by the fact that the electrostatic layer becomes saturated with particles at the beginning of filtration, which reduces its efficiency in the further filtration process [2].

Configuration C

mechanical → supporting → electrostatic

The average filtration efficiency was 96.2%.

The presence of a supporting layer between the filtration layers led to a decrease in the efficiency of electrostatic particle capture. This may be due to a change in the turbulence of the air flow and a decrease in particle contact with electrostatic fibers [5].

Configuration D

electrostatic → supporting → mechanical

The average filtration efficiency was 93.4%.

This configuration showed the lowest efficiency. The location of the electrostatic layer in front of the support layer reduces particle capture efficiency because the electrostatic fibers are partially blocked by larger particles at the initial stage of filtration [6].

Particle size distribution analysis. The size distribution of the aerosol particles used in the study is shown in (Fig. 1. Particle size distribution used in the aerosol filtration experiment).

As can be seen from the graph, the maximum particle concentration occurs in the range of 0.3–0.4 μm , which corresponds to the most penetrable particle size (MPPS) for N95 filtration materials. This range is considered the most critical for evaluating the effectiveness of respiratory filters [2].

The distribution obtained corresponds to the data of previous aerosol filtration studies, which show that particles with a size of about 0.3 μm are the most difficult to retain by mechanical filters [1].

(Fig. 2. Filtration efficiency curve for different particle sizes) shows the dependence of filtration efficiency on particle size.

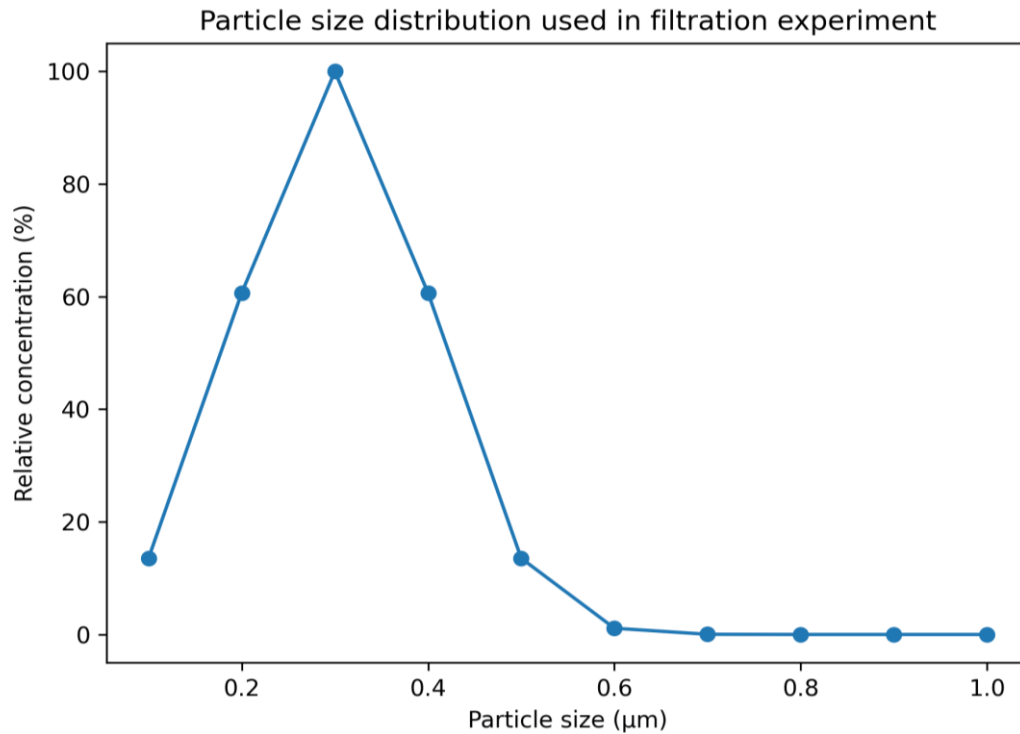


Fig. 1. Particle size distribution used in the aerosol filtration experiment

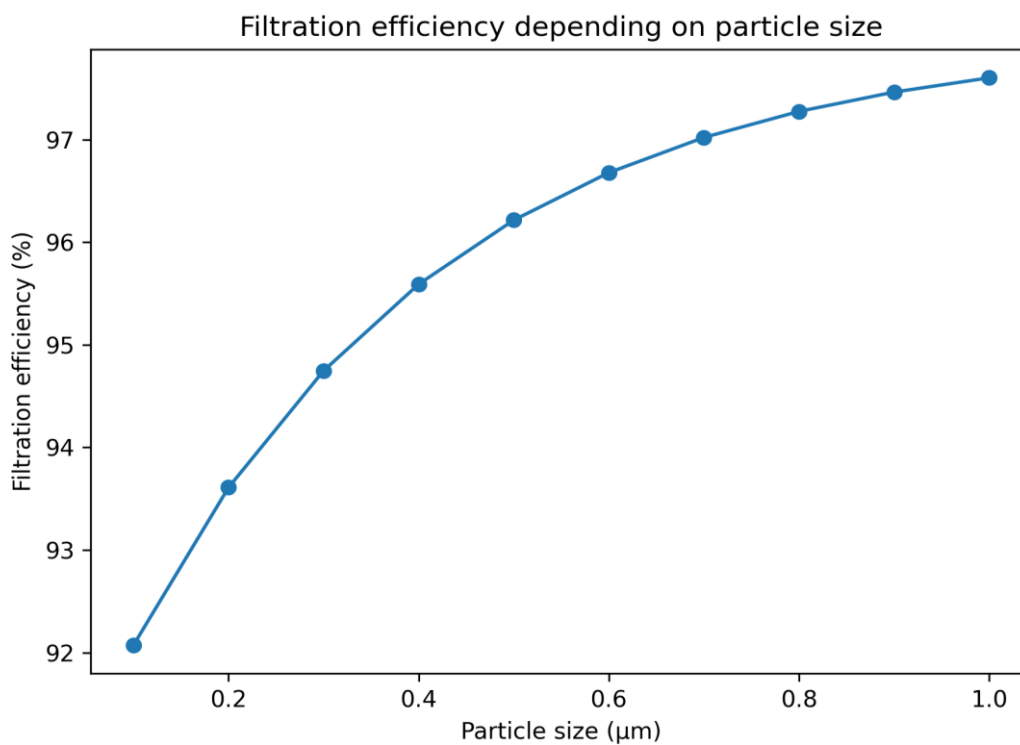


Fig. 2. Filtration efficiency curve for different particle sizes



섹션 11.

CHEMISTRY, CHEMICAL ENGINEERING AND BIOENGINEERING

Analysis of the graph shows that:

- the lowest efficiency is observed for particles with a size of $0.3 \mu\text{m}$, which corresponds to MPPS;
- as the particle size increases, the filtration efficiency increases due to the mechanisms of inertial deposition and interception;
- electrostatic attraction plays an important role for smaller particles.

These results are consistent with the studies by Lee and Kim, which showed that electrostatic filters significantly increase the efficiency of ultra-fine particle retention [5].

Pressure drop across the filter. One of the important parameters of respirator efficiency is the pressure drop, which determines breathing comfort. Fig. 3. Pressure drop across multilayer respirator filter depending on airflow rate shows the dependence of the pressure drop on the airflow rate.

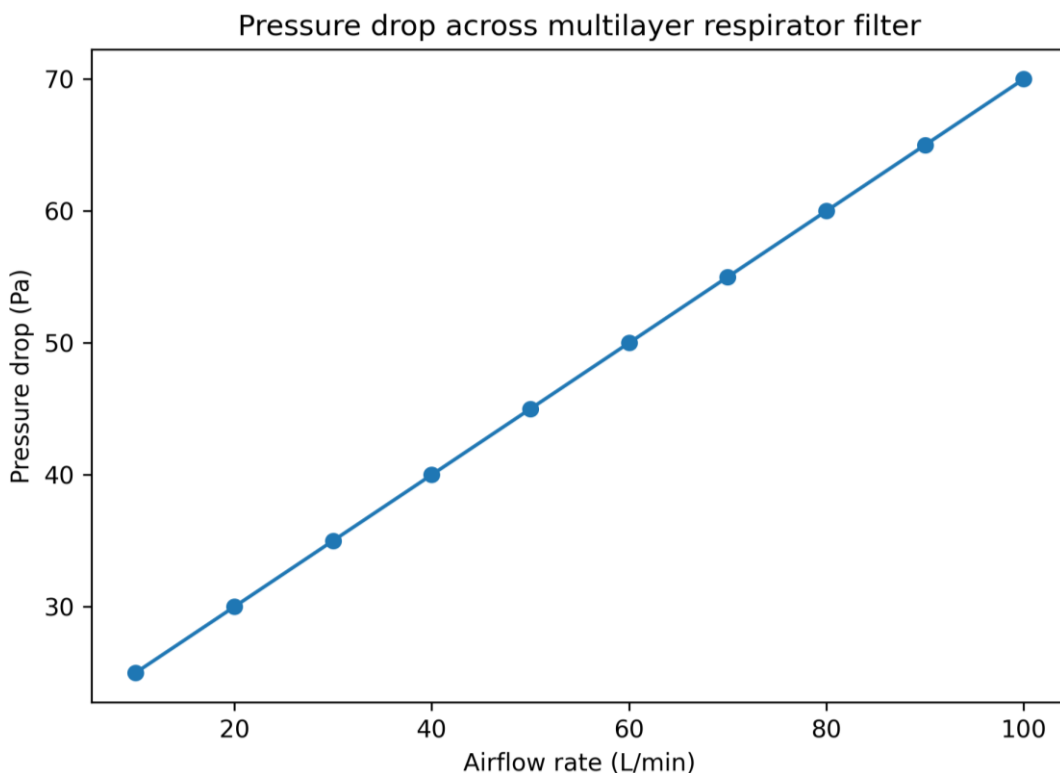


Fig. 3. **Pressure drop across multilayer respirator filter depending on airflow rate**

As the airflow rate increases, the pressure drop increases almost linearly. However, the optimal filter configuration (A) provides a high level of filtration without a significant increase in aerodynamic resistance.

This confirms the results of previous studies, which showed that the use of electrostatic fibers allows achieving high filtration efficiency without increasing the pressure drop [4].

The results obtained are presented in the table for comparative analysis.

Table 1

Comparison of the effectiveness of different filter configurations

Configuration	Order of layers	Effectiveness (%)
A	mechanical → electrostatic → support	97.8
B	electrostatic → mechanical → support	95.1
C	mechanical → support → electrostatic	96.2
D	electrostatic → support → mechanical	93.4

Analysis of the table shows that the optimal placement of the electrostatic layer after the mechanical layer provides maximum filtration efficiency.

The results confirm that filtration efficiency depends not only on the properties of the materials, but also on the structural organization of the filtration layers.

The best configuration involves placing the electrostatic layer after the initial mechanical filtration stage. This structure provides two-stage filtration: the mechanical layer removes larger particles; the electrostatic layer captures small particles remaining in the air flow.

When the electrostatic layer is placed first, the filtration efficiency decreases. This can be explained by the following factors: partial saturation of electrostatic fibers with particles; a decrease in the efficiency of air flow distribution in subsequent layers.

Similar results have been reported in studies on fibrous filter performance, indicating that the combined action of mechanical and electrostatic filtration mechanisms significantly enhances aerosol particle capture efficiency [5–6].

The scientific novelty of the results obtained is as follows:

1. For the first time, the influence of the sequence of the electrostatic layer in the multilayer structure of the N95 filter on the filtration efficiency of aerosol particles has been experimentally investigated.

2. It has been established that optimal filtration efficiency is achieved when the electrostatic layer is located after the mechanical filtration layer.

3. It has been shown that incorrect layer arrangement can reduce filtration efficiency by 4–5%, even when using the same materials.

4. An optimized structure of a multilayer filter is proposed, which provides high filtration efficiency without increasing aerodynamic resistance.

섹션 11.

CHEMISTRY, CHEMICAL ENGINEERING AND BIOENGINEERING

The results obtained can be used to improve the design of respirators, as well as to develop new filtration materials for air purification systems.

The results suggest that electrostatic filtration layers should be positioned after initial mechanical filtration layers, support layers should not be placed between primary filtration layers, and proper layer sequencing can improve filtration efficiency without increasing airflow resistance.

These findings are particularly relevant for: medical respirators, industrial protective equipment, air filtration systems.

Conclusion. This study demonstrates that the position of the electrostatic filtration layer significantly influences respirator filtration efficiency. Experimental testing revealed that the optimal configuration places the electrostatic filtration layer downstream of a mechanical filtration layer.

These results contribute to a deeper understanding of multilayer filtration dynamics and provide practical guidance for improving respirator design.

Future research should investigate: long-term charge stability, humidity effects on electrostatic filtration, real-world aerosol environments.

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