ISSN 1738-8716(Print)
ISSN 2287-8130(Online)
Particle and Aerosol Research
Par. Aerosol Res. Vol. 19, No. 1: March 2023 pp. 1-11
http://dx.doi.org/10.11629/jpaar.2023.19.1.001

다양한 호흡기 보호용 면체 마스크의 서브 마이크론 입자에 대한 여과 성능 평가

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(투고 2023년 3월 14일, 수정 2023년 3월 25일, 게재확정 2023년 3월 26일)

Filtration Performance Evaluation of Various Respiratory Face Masks Against Sub-Micron Particles

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(Received March 14 2023; Revised March 25 2023; Accepted March 26 2023)

Abstract

Respiratory face masks are protective facepieces that are designed to filter inhaled air. They are easy-to-use devices that can protect the wearer against various hazardous particles in the air. Respiratory face masks also prevent the spread of viruses and bacteria-containing droplets that are released from the coughing or sneezing of the infected people. During the COVID-19 pandemic, various types of face masks have circulated on the market. Their ability to filter sub-micron particles, which are the sizes of harmful particulate matter and airborne viruses, needs to be investigated. Their breathability, the easiness of breath through the mask, also needs to be considered. In this study, wwe evaluated the performance of filters used for different types of face masks certified by different standards including Korean (KF94, KF80, KF-AD), USA (N95), and Chinese (KN95) standards. We also tested the filters of nanofiber masks and surgical masks for which there are no standards for filtration test. The N95 mask filters showed the highest quality factor for capturing virus-sized particles. The other types of mask filters have acceptable performance except for nanofiber mask filters whose performance is very low.

Keywords: mask, filter, performance, quality factor, airborne virus

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1. Introduction

COVID-19 has become a global pandemic that affects various aspects of human life. It has infected more than 759 million people and caused more than 6.8 million deaths (WHO, 2023). Before that, there was an influenza pandemic in 2009 with more than 18,449 officially confirmed deaths by August 2010 (Simonsen et al., 2013). These viruses are transmitted from human to human through the air (Kutter et al., 2018). Therefore, face masks have become an essential device to protect humans from airborne pathogens.

Face masks can inhibit the spread of dangerous diseases by trapping the pathogen expelled by an infected person through coughing or exhalation, so they do not spread in the air. Face masks also protect the uninfected wearer from pathogens that are already in the air by filtering the inhaled air. These two-way protections make face masks very effective in reducing the spread of airborne pathogens (Prather, Wang, and Schooley, 2020).

Several types of face masks are available in the market with different price points and performances. Some face masks are sold as certified face masks that pass a standardized test such as N95 (USA), KN95 (China), and KF (Korea). N95 standard requires the filter to have 95% efficiency at a filtration flow rate of 85 l/min (HHS, 2020). The KN standard requires 95% efficiency at a flow rate of 85 l/min (GB2626-2019). The KF standard requires the filtration efficiency of 94% for KF94 mask and 80% for KF80 mask respectively at a filtration flow rate of 95 l/min (MFDS, 2020). The detail of the filtration performance criteria for each mask test standard is summarized in Table 1.

There are also face masks that are certified based on a less strict standard which doesn't require certain filtration performance. KF-AD masks and surgical masks are the examples for which filtration test is not included in the their certification standards.

Other types of face masks besides standardized face masks have also emerged due to the high demand for face masks during the COVID-19 pandemic. Some face masks use advanced materials such as nanofiber and claim to be more comfortable and washable. Nanofiber masks were marketed as face masks that can be used multiple times without degradation in their performance. There are also clothes masks that can be used multiple times by using cloth as their material.

The quality of a mask is determined by its ability to filter airborne particles and its easiness to breathe through. Therefore, it is important to assess the quality of available face masks to ensure their protectiveness and their comfortability. Rengasamy et al. (2010) has

Table 1. Filtration performance criteria for different respiratory face mask test standards.

Standard	KF80	KF94	N95	KN95
Test particle	NaCl	NaCl	NaCl	NaCl
Particle neutralization	No	No	Yes	No
Particle size (μm)	MMD*: 0.6(0.04-1.0)	MMD*: 0.6(0.04-1.0)	CMD*: 0.075±0.02	CMD*: 0.075±0.02
Flow rate (l/min)	95	95	85	85
Filter performance (%)	≥ 80	≥ 94	≥ 95	≥ 95
Inhalation pressure drop (pa)	≤ 60**	≤ 70**	≤ 343	≤ 210

*MMD : Mass Median Diameter, *CMD : Count Median Diameter
**For the pressure drop test of KF standard, the flow rate is 30 l/min.

studied the performance of various cloth mask material and found that the penetration range varies from 40 – 90 % against standard polydisperse NaCl particle. Shakya et al. (2016) compared the performance of surgical masks and clothes masks against monodisperse latex particles. They conclude that surgical masks are more effective in reducing particulate exposure. MacIntyre et al. (2015) came to a similar conclusion in a randomized trial in hospital settings. Ho et al. (2020) conclude that cotton masks can be a substitute for a surgical masks to prevent droplet exposure. The comparison between N95 masks and different types of cloth mask materials including their combination to improve their performance has also been studied (Konda et al., 2020; Zangmeister et al., 2020). A study comparing N95 and surgical masks for various particle sizes has also been conducted (He et al., 2013).

However, to the best of our knowledge, no study compared the filtration performance of various masks that adhere to various standards around the world. Additionally, the performance of commercially available surgical and nanofiber masks needs to be tested. This study tests the collection efficiency of the mask filters against submicron particles. This particle size is important because they correspond to the size of the COVID-19 (coronavirus disease of 2019) (Zhu et al., 2020). It also corresponds to the size of most exhaled droplets from humans (Papineni and Rosenthal, 2009) which can be a potential medium for virus spreading. The breathability of tested masks is also assessed by measurement of pressure drop through mask filters.

2. Materials and method

Face masks used in this study were standardized masks with KF94, KF80, KF-AD, KN95, N95, and surgical face masks certifications. Nanofiber masks were tested too as a comparison. For each mask type, three different brands of commercially available masks were used. All masks tested in this study were within 3 months from the date of manufacture, and were used for test on the same day after opening from their packages. Table 2 lists the masks. I, II, and III

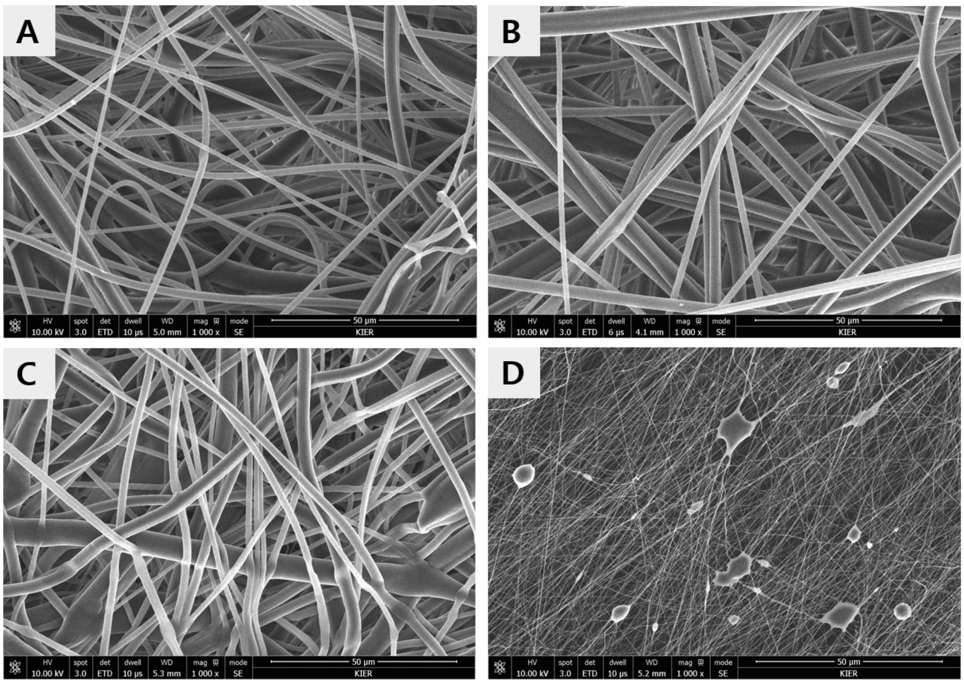

Figure 1. SEM images of filtration layer of tested masks. (A) KF94 mask, (B) KF80 mask, (C) Surgical mask, (D) Nanofiber mask.

Table 2. Filter layer structure of tested masks.

Mask ID	No. of filter layers	Overall thickness (μm)	Filtration layer thickness (μm)
KF94-I	4	980	220
KF94-II	4	680	350
KF94-III	3	800	170
KF80-I	4	1010	190
KF80-II	3	580	250
KF80-III	3	810	190
KF-AD-I	3	620	-*
KF-AD-II	2	480	120
KF-AD-III	2	540	-*
Nanofiber-I	3	480	-*
Nanofiber-II	3	490	-*
Nanofiber-III	3	490	-*
Surgical-I	3	360	130
Surgical-II	3	420	110
Surgical-III	3	320	120
N95-I	3	830	220
N95-II	3	760	170
N95-III	3	780	170
KN95-I	3	740	180
KN95-II	3	790	200
KN95-III	3	800	210

*The filtration layer was strongly bonded to other layers, so the thickness of only the filtration layer could not be measured.

followed by mask ID simply represent different brands.

Among the filter layers, filtration layer mainly contributes to the filter performance of masks. Figure 1 shows the SEM images of filtration layer for selected masks. The fiber size and the inner structure of filtration layers for N95, KN95, KF-AD, and surgical masks are very similar to KF94 mask, for which the mean fiber diameter is about 2 μm. On the other hand, the nanofiber masks have a filtration layer composed of very thin fibers of around 100 nm in diameter.

In this study, a uniform shape of mask filter cut-out instead of the whole face mask is used as a test sample to compare the filtration performance of masks. The mask filters were cut into a circular shape with a diameter of 50 mm as depicted in Figure 2. All the layers of mask filters including the support layer were used in the experiment.

Polydisperse test particles were generated from 1.0 wt% KCl solution using a single jet atomizer (Model 9302, TSI). Generated particles have a size range of 15 – 660 nm with a mode size of around 50 nm.

The experimental apparatus to test mask filters is shown in Figure 3. Test particles generated from the atomizer were dehumidified with silica gel. To control the particles' concentration, they were diluted with dried air in a mixing chamber. Then, the particles are neutralized by a radioactive particle neutralizer (Am-241, Model 5.522, GRIMM). Then, they were fed to a filter holder by air suction provided by a vacuum pump downstream of the filter holder. The flow rates used in the test is depicted in Figure 3.

The filter holder held the 50 mm diameter filter sample with an effective filtration area diameter of 40 mm. The filter that was held in the filter holder filtered the KCl particles. The filtration flow rate was adjusted by a mass flow controller. The filtration flow rate was adjusted so that the filtration velocity was 15 cm/s. This filtration velocity corresponds to an 85 l/min flow rate on a full face mask which is the flow rate used in most of the standards for testing masks filtration performance. Pressure difference between upstream and downstream of filter sample was measured by a differential pressure transmitter. In order to calculate the collection efficiency, particle concentration at the upstream and downstream of filter was measured by a SMPS (Scanning Mobility Particle Sizer) that consists of an electrostatic classifier (Model 3080, TSI) connected to DMA (Differential Mobility Analyzer) (Model 3080, TSI) and CPC (Condensation Particle Counter) (Model 3775, TSI). The aerosol sampling flow rate was 0.3 l/min with a sheath flow rate of 3.0 l/min.

3. Result and Discussion

The collection efficiencies of Korean standard mask filters as a function of particle size are shown in Figure 4. All the tested brands of KF94 mask filters showed efficiencies above 90% in all particle sizes. The efficiency curves of all the tested brands were similar. Meanwhile, the KF80 mask filters had efficiencies of above 80% in all particle sizes for the

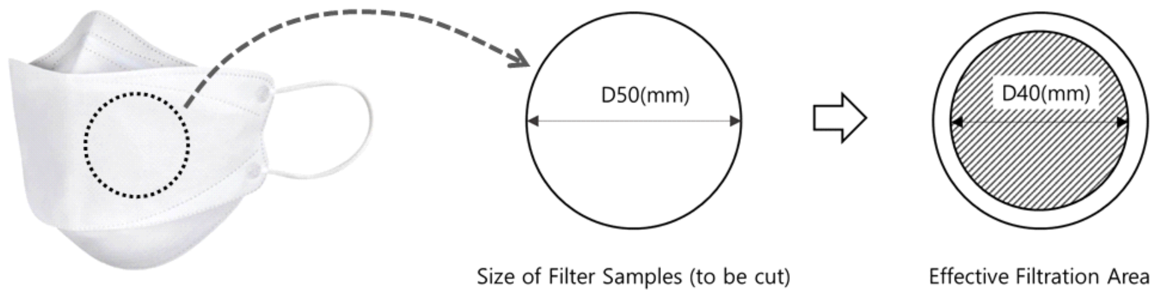

Figure 2. Preparation of filter samples from commercial masks

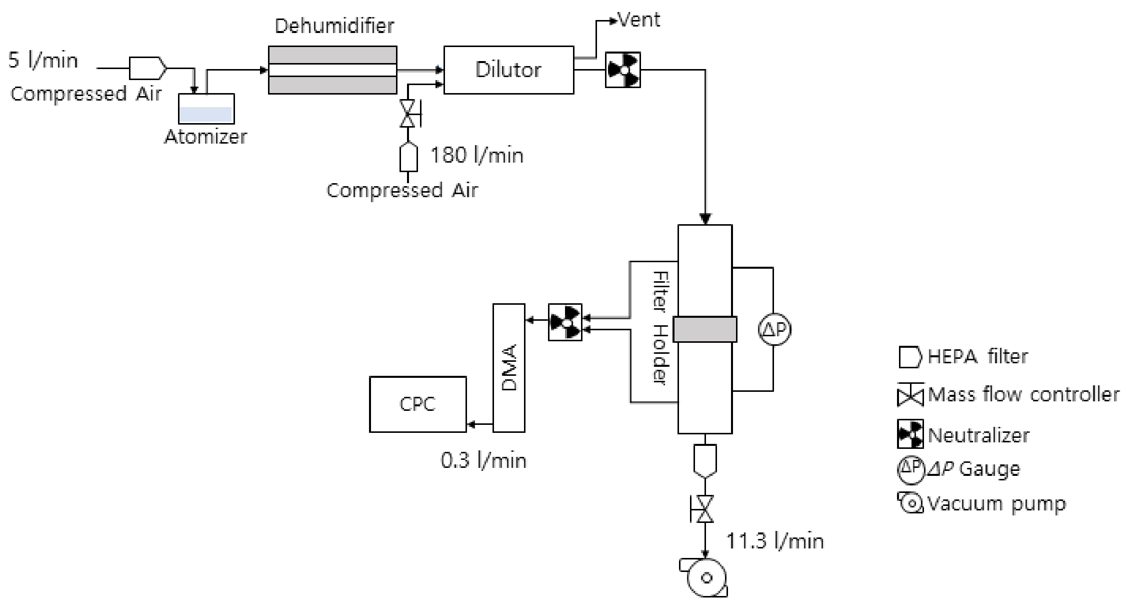

Figure 3. Experimental apparatus for testing filtration performance of mask filters.

KF80-I and KF80-III. However, the KF80-II showed slightly lower efficiencies at all particle sizes compared to the other brands. The KF-AD mask filters had the lowest efficiency of the three Korean standard masks. The KF-AD also had the largest spread of efficiency curves among the tested brands. The KF-AD-I and KF-AD-III showed efficiencies of around 70% and 80% respectively for all particle sizes. The KF-AD-II showed around 50% efficiency for all particle sizes. The KF-AD standard has the loosest requirement among all Korean standards. The standard doesn't require any filtration performance. On the other hand, the KF94 masks have the strictest criteria on the filtration efficiency among all Korean standards. Therefore, the implementation of KF94 masks is similar among the tested brands, leading to similar performances.

The KF94 and KF80 face masks had the most penetrating particle size (MPPS) around 40 nm. The efficiency was higher for particles smaller than the MPPS due to an increase in particle capture by diffusion. The efficiencies continued to increase for particles above the MPPS due to an increase in capture by interception, and electrostatic attraction. The KF-AD has two valleys in the efficiency curve at 45 nm and 165 nm. The two valleys are likely to be caused by the weak electrostatic forces of mask filters and their thin filtration layer.

The efficiencies of N95 and KN95 face masks are shown in Figure 5. The three brands of tested N95 face masks had similar efficiencies. All the tested brands of KN95 mask filters also had similar efficiencies. Among the KF94, N95, and KN95 masks, the N95 mask filters had the highest efficiency at almost all particle sizes. The KN95 was the second highest and KF94 had the lowest efficiencies.

The collection efficiencies of nanofiber masks, and surgical masks are shown in Figure 6. The efficiencies of nanofiber masks showed significant differences among brands. The efficiencies of the nanofiber-I and nanofiber-III were lower than 60% in all particle sizes. For the nanofiber-II, the efficiencies were around 60%

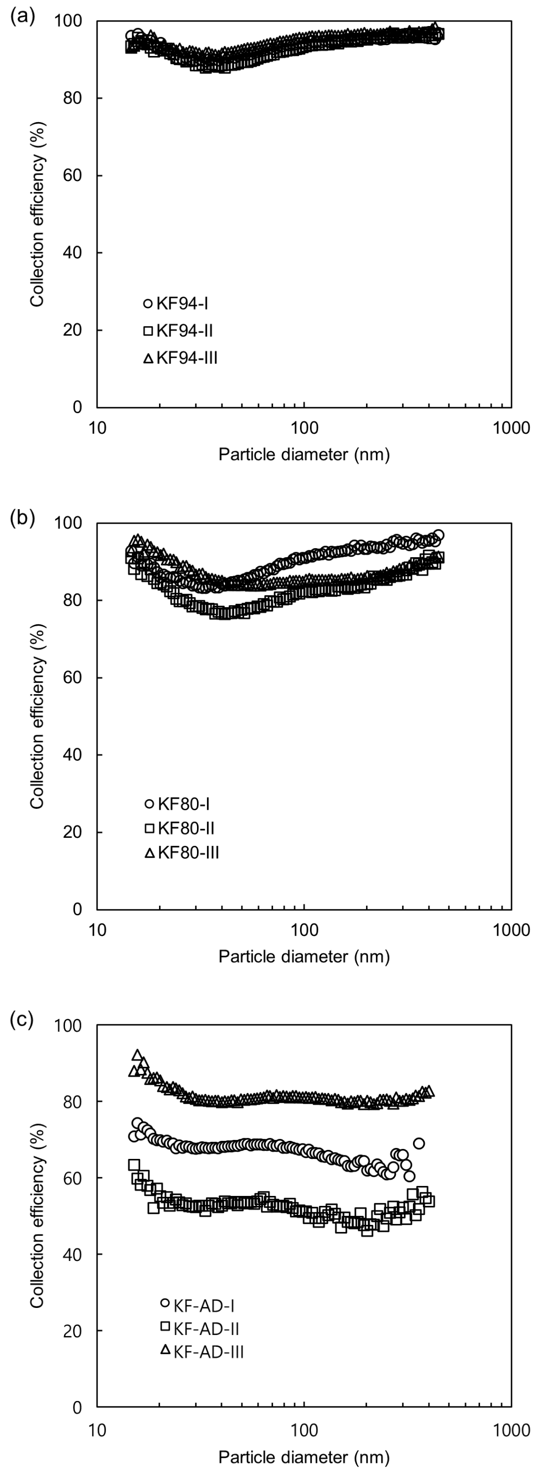

Figure 4. Collection efficiency of mask filters with Korean certification: (a) KF94, (b) KF80, (c)KF-AD.

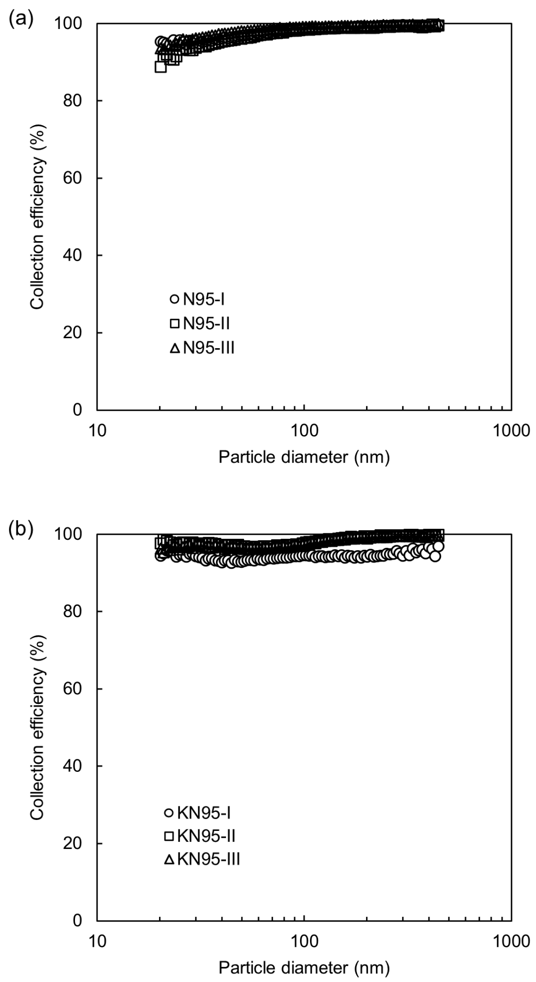

Figure 5. Collection efficiency of (a) N95 mask filters and (b) KN95 mask filters.

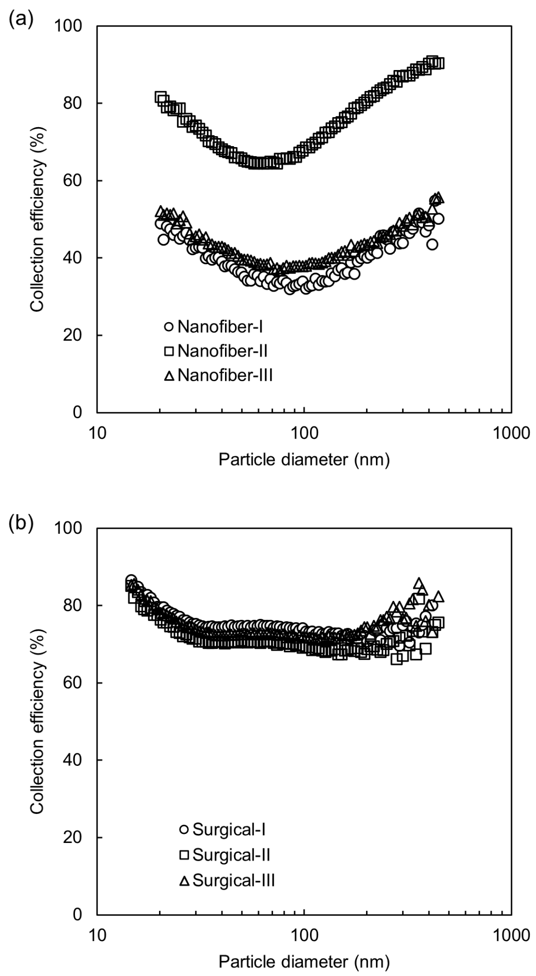

Figure 6. Collection efficiency of (a) Nanofiber mask filters and (b) Surgical mask filters.

at particle diameters of 70 nm, and around 80% at particle diameters of 20 nm and 400 nm. This difference in performance between brands can be attributed to the lack of filter test standards for nanofiber masks. The MPPS of the nanofiber masks was between 70–100 nm, which is larger than other type of masks. This is because there is no electrostatic charge on the nanofiber masks. Filtration for nanofiber masks is solely relying on the mechanical capture of particles.

The three brands of tested surgical masks had similar efficiencies. The efficiencies were above 70% for all particle sizes and are comparable to the KF-AD-I. The surgical face masks were not standardized in term of filtration efficiencies. However, the efficiencies of the tested brands were very similar to each other. The efficiency curves of surgical mask filters were w-shaped with two valleys. These curves have a similar shape to KF-AD masks. The curves may signify weak electrostatic forces in the mask filters.

The collection efficiency of each mask filter in capturing the KCl particles with diameter of 90-110 nm at filtration velocity of 15 cm/s is shown in Figure 7. These particle diameters are of great interest since they correspond to the size of SARS-CoV-2 virus particles (Zhu *et al.*, 2020). N95 filters show the highest efficiency with 98% for all tested brands,

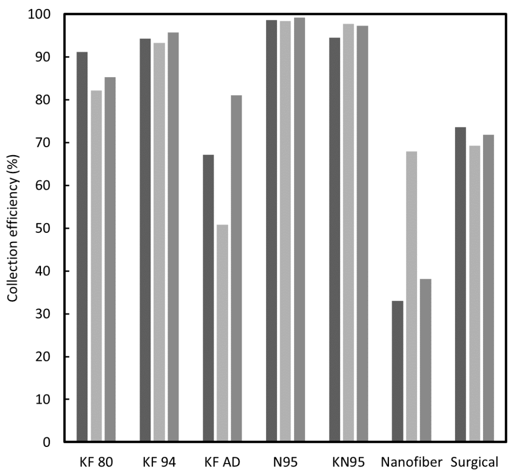

Figure 7. The efficiency of each mask filter against particles with diameter of 90–110 nm.

slightly higher than KF94 masks which have efficiency of around 94%.

All tested brands of KF80 masks had collection efficiencies higher than the 80% efficiency. KF-AD masks showed different efficiencies for each brand. The efficiency of KF-AD-I was 65%, the KF-AD-II was 50% and the KF-AD-III was 80%. The KF-AD standard is designed to certify a mask that is able to protect the user from water droplets produced by coughing or sneezing. The droplet size is larger than 1 micrometer (Smith et al., 2020). Therefore, its performance in submicron particle size was lower compared to different standardized masks.

The surgical face masks had efficiencies of around 70% for the 90-110 nm particles. The efficiencies were higher than KF-AD-I and KF-AD-II masks even though it was lower than the KF-AD-III. The nanofiber mask filters showed very low efficiency in capturing virus-sized particles. The nanofiber-I and nanofiber-III had efficiencies of only around 35%. Meanwhile, the nanofiber-II had the highest efficiencies at 65%. However, it was still lower than the efficiency of surgical masks. These results show that nanofiber masks has poor performance in protecting the user from submicron particles.

To better compare the performance of each mask filter, the quality factor of each mask filter type was compared. The quality factor, Q, is determined by

$$Q = -\frac{\ln(1-E_f)}{\Delta P} \qquad (1)$$

while E_f is collection efficiency of a filter and ΔP is pressure drop across the filter. The higher value of the quality factor is preferable. The pressure drop of all tested mask filters is plotted in Figure 8 and the quality factor is shown in Figure 9. The pressure drops of all tested mask filters were below the N95 limit of 343 Pa and KN95 limit of 210 Pa. This means that all tested face masks will be comfortable to wear. The quality factors of N95 mask filters were the highest among all tested mask filters. The very high efficiency with relatively low pressure drop of N95 masks is possibly attributed to high electrostatic density in the filtration layer. The quality factor of KN95 masks was the second highest. Meanwhile, KF94 and KF80 had similar quality factors. The quality factor of KF-AD and surgical masks varied between brands. On average, their quality factors were lower than KF94 and KF80 masks.

Nanofiber masks had the lowest quality factor among all tested mask filters. Their pressure drops were lower than all other mask filters, however, their efficiencies were also very low, so their quality factor remain low. The nanofiber-II had higher efficiency compared to the rest of the nanofiber mask filters. However, its pressure drop was significantly higher than those of other brands. Therefore, the quality factor of nanofiber-II was also low.

4. Conclusion

In this study, the filtration performance of various commercial mask filters was evaluated. The tested masks include standardized face masks certified by Korean standards (KF94, KF80, KF-AD, and surgical masks), American standards (N95), and Chinese

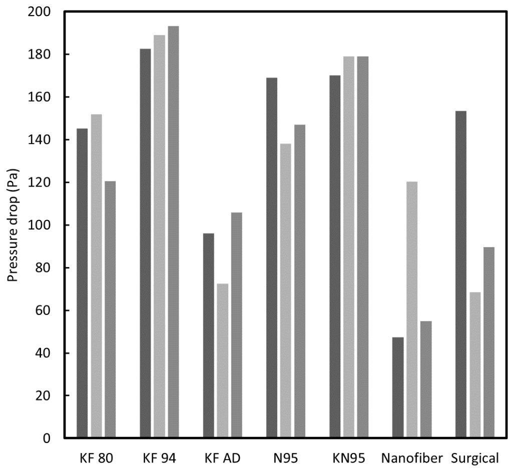

Figure 8. Comparison of pressure drop of tested mask filters.

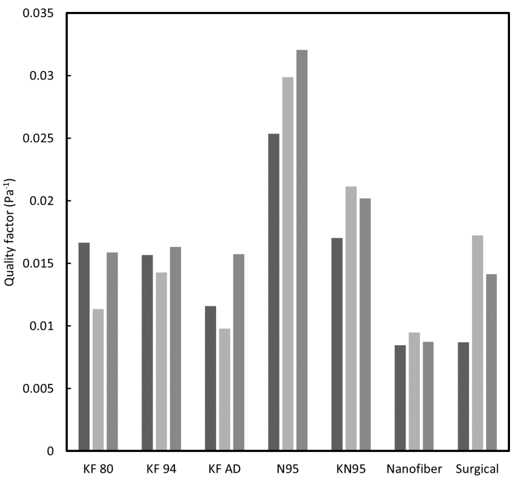

Figure 9. Comparison of quality factor of tested mask filters.

standards (KN95). Nonstandard face mask filters, which are the nanofiber masks, were also tested. The performance parameters were the collection efficiency of each mask filter in capturing submicron particles and their pressure drop or breathability. The ability of the mask filters to capture virus-sized particle and their quality factor were compared.

All of the standardized mask filters had met the efficiency criteria that are requested each mask test standard, even though the test condition and method used in this study was not exactly same with those of standards. To compare the filtration performance of all mask filters used in this study, the quality factor representing the ratio of collection efficiency to air resistance was calculated for particles with a diameter of 90-110 nm corresponding to the size of corona virus. The quality factor differences between brands were found on masks with a loose standard such as KF-AD and surgical masks or on non-standardized masks such as nanofiber masks. The N95 mask filters show the highest quality factors indicating that they have higher collection efficiency even with lower air resistance. This result can be attributed to the fact that the electrical charge of the N95 mask filters has a greater effect on collection efficiency than the KF94 and KN95 mask filters. The other types of mask filters have similar quality factors that are lower than N95 but are acceptable except for nanofiber mask filters whose efficiency and quality factors are very low.

Acknowledgment

This work was conducted under framework of the research and development program of the Korea Institute of Energy Research (GP2020-0018-08), Republic of Korea.

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