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# Nanofibers in face masks and respirators to provide better protection

C. Akduman[1] and E. P. Akçakoca Kumbasar[2]

[1] Pamukkale University, Denizli Vocational School of Technical Sciences, Department of Textile Technology, 20100, Denizli, Turkey

[2] Ege University, Faculty of Engineering, Department of Textile Engineering, 35100, Izmir, Turkey

*perrin.akcakoca@ege.edu.tr*

**Abstract** A facemask is a loose-fitting, disposable device that creates a physical barrier between the mouth and nose of the wearer and potential contaminants in the immediate environment. They are generally labelled as surgical, isolation, dental or medical procedure masks. On the other hand, respirators are personal air purifiers. They are designed to protect the wearer from inhaling dangerous substances such as toxic chemicals and infectious particles. Respirators are designed to help reduce the wearer's respiratory exposure to airborne contaminants such as particles that are small enough to be inhaled - particles less than 100 microns (μm) in size. A face masks or a respirator consist entirely or substantially of filter material or comprises a face piece in which the main filter(s) form an inseparable part of the device. Nanofibers could be the key elements for filter materials in face masks or respirators. They have a very high surface area per unit mass that enhances capture efficiency and other surface area-dependent phenomena that may be engineered into the fiber surfaces (such as catalysis or ion exchange). They could enhance filter performance for capture of naturally occurring nanoparticles such as viruses, as well as micron-sized particles such as bacteria or man-made particles such as soot from diesel exhaust.

***Keywords*— face masks, filtration, nanofibers, respirators.**

## I. INTRODUCTION

THIS study summarizes the general information about face masks and respiratory devices, face mask and respirator types, some related standards, and finally application of nanofibers in these devices.

Filtering face piece particulate respirators and facemasks are widely utilized for reducing inhalation exposure to airborne particles that may be associated with various health effects [1]. They are considered to prevent or slow down the transmission of airborne particles possibly causing adverse health effects. A simple definition for facemask is "a loose-fitting, disposable device that creates a physical barrier between the mouth and nose of the wearer and potential contaminants in the immediate environment". A face mask generally labelled as surgical, isolation, dental or medical procedure mask [2]. A conventional face mask consists of one, two or three layers of flat or pleated fabric, affixed to the head with ear loops [3]. A surgical mask is generally used as a physical barrier to body fluids and larger droplets in healthcare activities [4].

The most common facemasks are the surgical masks but the main differences are; simple face masks are not used to prevent infectious diseases but a surgical mask should have a minimum of 80% bacteria filtration efficiency, a conventional face mask consists of one, two or three layers of flat or pleated fabric [5], usually made from paper or cotton fabric but a "surgical mask" is made of at least a three-ply layer of material like polypropylene [3]. However surgical masks do not have either adequate filtering or fitting attributes to provide respiratory protection for the wearer. They are not intended to be used more than once [2] and are usually designed to help prevent contamination of the work environment or sterile field from large particles generated by the wearer (e.g. spit, mucous). Surgical masks may also be used to help reduce the risk of splashes or sprays of blood, body fluids, secretions and excretions from reaching the wearer's mouth and nose [6].

On the other hand, a respirator is a device designed to protect the wearer from inhaling dangerous substances such as toxic chemicals and infectious particles [5]. Respirators especially help to reduce the wearer's respiratory exposure to airborne contaminants such as particles that are small enough to be inhaled - particles less than 100 microns (μm) in size. Respiratory protective equipment (RPE) is a particular type of personal protective equipment (PPE) [7]. RPE is divided into two main types: 1. Respirator (filtering device), 2. Breathing apparatus (BA) [7]. Respirators use filters to remove contaminants in the workplace air and help reduce the wearer's respiratory exposure to airborne contaminants. This includes airborne particles that may contain biological material, e.g. mold, Bacillus anthracis, Mycobacterium tuberculosis, the virus that causes Severe Acute Respiratory Syndrome

(SARS), Avian Flu, Ebola Virus etc. or even PM2.5 (particulate matter with diameter of 2.5 micron or less) [6].

## II. Standards And Classification

Surgical masks are cleared by the Food and Drug Administration (FDA) [2]. FDA does not do any testing; but reviews the information supplied by the manufacturers in their 510(k) premarket application. Manufacturers submit test results for fluid resistance, filtration efficiency for polystyrene latex and Staphylococcus aureus bacterial aerosol particles, differential pressure and flammability for Surgical masks clearance usually in accordance with ASTM F2100-11 [4]. ASTM F2100-11 specification covers testing and requirements for materials used in the construction of medical face masks that are used in providing health care services such as surgery and patient care. It provides performance classes for face mask materials as bacterial filtration efficiency (ASTM F2101), sub-micron particulate filtration efficiency (ASTM F2299), differential pressure (MIL-M-36954C), fluid penetration resistance (ASTM F1862) and flammability (16 CFR Part 1610) [8].

Medical face mask materials covered under this specification shall be designed as one or more of the following performance classes as based on the barrier performance properties of the materials used in medical face masks: Level 1 Barrier, Level 2 Barrier, and Level 3 Barrier. The properties of the medical face mask material shall conform to the specifications requirements in Table 1 [8].

TABLE I
Medical Face Mask Material Requirements by Performance Level (ASTM F2100-11) [8]

| Characteristic | Level 1 Barrier | Level 2 Barrier | Level 3 Barrier |
|---|---|---|---|
| Bacterial filtration efficiency, % | ≥95 | ≥98 | ≥98 |
| Differential pressure, mm $H_2O/cm^2$ | <4.0 | <5.0 | <5.0 |
| Sub-micron particulate filtration efficiency at 0.1 micron, % | ≥95 | ≥95 | ≥95 |
| Resistance to penetration by synthetic blood, | 80 | 120 | 160 |
| Flame spread | Class 1 | Class 1 | Class 1 |

Besides, the respirators must provide protection at the highest concentration the person will experience. In the United States, the National Institute for Occupational Safety and Health (NIOSH) tests the filtration efficiency of particulate filtering, air-purifying respirators for certification purposes. NIOSH approves N-, R-, and P-series non-powered air-purifying respirators, each at 95, 99, and 99.97% filtration efficiency levels under 42 CFR Part 84 as shown in Table 2 [9].

TABLE II
NIOSH 42 CFR Part 84 Particle filter classifications [6]

| Minimum Efficiency | N-Series | R-Series | P-Series |
|---|---|---|---|
| 95% | N95 | R95 | P95 |
| 99% | N99 | R99 | P99 |
| 99.97% | N100 | R100 | P100 |

According to NIOSH 42 CFR 84, the three efficiency levels are 95, 99, and 99.97%, tested at a flow rate of 85 L/min at the most penetrating particle size (generally about 0.1 to 0.3 μm). The three degradation resistance series were established by the choice of either charge-neutralized NaCl (sodium chloride salt), which is only mildly degrading to filter media (N series of filters), or DOP (dioctyl phthalate) liquid oil, which is highly degrading (R or P series) [10]. Then filters are rated as N, R and P series to indicate the filters are 'not oil resistant', 'resistant to oil' and 'oil proof' respectively [11]. Accordingly, N series filters tested with NaCl aerosol are recognized as not highly resistant to degradation and only appropriate for use with solid aerosol in the workplace. Among the respirators certified under 42 CFR Part 84, the N95 respirators are the most commonly used [6], [11]. Because the filter efficiency is based on the physical parameters of the particles to be filtered, any biologic particles can be expected to be filtered at no less efficiency than the test aerosol (ie, at least 95% efficient for an N95 filter [9]. The penetration, P, of such particles through a certified N95 respirator cannot exceed 5%; thus, the efficiency, E, of the respirator, which is calculated as E = 100% - P, must be at least 95% [12].

In Europe, the Personal Protective Equipment directive (89/686/EEC) requires that PPE placed within the European market should be certified by European Norm (EN) and marked with 'Conformité Européen'(CE), indicating European Community (EC) conformity. All respirators must be approved and tested to the performance requirements of the corresponding European Standard, which forms the following categories: filtering half masks, half masks and quarter masks, full face masks, powered air respirators, and supplied air respirators [12].

Legislation of European Standards for "filtering half masks" (also called filtering face pieces (FFP)) is covered by EN 149:2001 [13], [14]. They usually marked with EN 149:2001 and an additional sub category such as FFP1 (low efficiency; 80%), FFP2 (medium efficiency; 94%) and FFP3 (high efficiency; 99%) (Table 3) [6]. They are designed to protect against solid, non-volatile water-based, and oil-based aerosol particles. Therefore, all respirators have to meet both the solid and liquid filter performance requirements [14].

EN 149:2001 was followed by the amended version EN 149:2001+A1:2009 in July 2009. In this amendment two usability classes of disposable respirators: single shift only (non-reusable, marked 'NR') and reusable (marked 'R') were included. The US N95 standard is roughly equivalent to FFP2 or 3 as it is efficient up to 10 x the local occupational exposure limit [6]. The higher the FFP number, the more protection the respirator can provide if it is used properly [14]. EN 149 include filter penetration, extended exposure (loading), flammability, breathing resistance, total inward leakage (TIL), and dolomite dust clogging (optional). For testing filter penetration, EN 13274-7:2008 (Determination of particle filter penetration) is used and it dictates the use of a non-neutralized polydisperse 1% solution of sodium chloride (NaCl) against solid particles and paraffin oil against oil based aerosol at flow rate of 95 L $min^{-1}$. The NaCl aerosol is generated by a Collison atomizer with a particle size range of approximately 40–1200 nm and a mass median diameter (MMD) of ≈ 600 nm. The sodium chloride aerosol is analysed before and after the filtering device under test by flame photometry. Sodium chloride particles are vaporized while they are passing through, and the flame tube gives a characteristic sodium emission at 589 nm. The concentration of sodium in the air flow is calculated from the intensity of this emission [14].

TABLE III
EN 149:2001 PARTICLE FILTER CLASSIFICATIONS [13]

| Filter Class | Efficiency |
|---|---|
| FFP1 | 80% |
| FFP2 | 94% |
| FFP3 | 99% |

Beside EN 149, European standard EN 143 (Respiratory protective devices -Particle filters - Requirements, testing, marking) defines the P1, P2 and P3 classes of particle filters that can be attached to a face mask [16]. Based on their performance level; P1 filters have low filter performance (80% efficiency), P2 filters have medium filter performance (94% efficiency) and P3 filters have high filter performance (99.97% efficiency) [5].

## III. FILTER MATERIALS

A filtering half mask is a face piece that consists entirely or substantially of filter material or comprises a face piece in which the main filter(s) form an inseparable part of the device [6]. Besides, respiratory protection offered by a particulate respirator is a function of the filter efficiency and face seal leakage [17].

The Elsevier Handbook of Filter Media has a precise definition of a filter medium: A filter medium is any material that, under the operating conditions of the filter, is permeable to one or more components of a mixture, solution or suspension, and is impermeable to the remaining components [18]. Fibrous materials are important for filtration. A significant feature of fibrous porous materials is that the fraction of solid material is often much lower than that for a granular material. The main driving force in the filtration industry is the requirements for finer degrees of filtration. In air filtration, the requirement for finer filtration is already being met by media with finer fibers. Typically, in filtration processes, the size of the items to be separated needs to be matched by the size of the fiber so that the removal of particles or microorganisms at diameters of less than 1 micrometer is possible.

More often, fiber blend is used to balance filtration efficiency and pressure drop. High pressure drop across a filter translates to the undesired high energy consumption to drive air flow through the filter. When fiber size is reduced the total filtration efficiency becomes higher. The increase in filtration efficiency is due to the large surface area per volume available for particle capture, especially for small submicron meter particles. This encouraged a wave of small fiber innovation and commercialization that boost the filtration industry starting from early 1980s [19] and leads to the development of nanofibrous filtering media.

## IV. Nanofibers In Filtration

Nanofibers and nanofiber webs, as used in filter media, are an important part of that emerging technology to improve the efficiency of filter media [5]. The filtration and separation of sub-micron sized contaminants is a major concern of modern day nanotechnology. Because of their unique physical and chemical properties, engineered nanoparticles are synthesized for various applications. Nowadays in industrial workplaces the rapid growth of nanotechnology has increased the production of these engineered nanoparticles. Tasks and processes such as cleaning engineered nanomaterials from dust collection systems, spills, and disposal can present a potential for inhalation exposure and a high level of risk [17]. Nanofibrous media have low basis weight, high permeability and small pore size that make them appropriate for a wide range of filtration applications especially for smaller particles. In addition, nanofiber membranes offer unique properties such as high specific surface area (ranging from 1-100 $m^2/g$ depending on the diameter of fibres and intrafiber porosity), good interconnectivity of pores and potential to incorporate active chemistry or functionality on a nanoscale [20]. Nanofibers do not exist independently in filtration, but are produced onto a substrate, typically a nonwoven fabric [5].

There are four main types of relevant filtration mechanism using nanofiber filter media. These are surface straining, depth straining, depth filtration and cake filtration [5]. In practice, the filtration processes often involve a combination of two or more mechanisms. In surface filtering, the surface of filter media plays an active role and the surface pore openings of filter media are precisely controlled in relation to the particulate size to be filtered. Depth straining type of filter media is relatively thick compare to surface filter media and the pores are variable in the flow path length. Depth filtration uses various physical mechanisms for removing a particle from a fluid even though the particle may be smaller than the pore diameter at any point in the pore structure. In cake filtration, the filter medium begins the filtration process; successive layers of particles deposit on the top of preceding layers to form a cake [20].

The technical requirements for filters are a balancing of the three major parameters of filters performance: filter efficiency, pressure drop and filter life time [20] and nanofibers provide a dramatic increase in particle capture efficiency as well as increased pressure drop [21] related to the nanofiber thickness on the base filter substrate.

The market for nanotechnology worldwide was estimated to grow at an annual rate of 19% during the years (2011-2013). Nanofiber-spun webs for nonwoven and filtration purposes are part of the growth [5]. Nanofiber filter media have enabled new levels of filtration performance in several diverse applications within a broad range of environments. Today, more people involved in the air filtration market are looking at nanofiber treated media in order to improve dust holding capacity and filtration efficiency. There are many applications of nanofibrous filters which are already commercialized as well as those still in development [20]. One of them is using nanofibers in facemasks and respirators.

Loesecke et al. indicated that a typical cellulose web with a nanofiber coating could catch particulates down to 0.1 microns, improving filtration efficiency with negligible penalty in permeability or resistance due to the significantly smaller fiber size compared to the substrate itself [22]. The most popular method for creating nanofibers for filtration applications has been electrospinning [5]. Li et al. produced polysulfone based nanofibers for mask filtration by electrospinning. They adjusted the thickness of the electrospun fiber matts with collecting period (15 min < 30min < 60min) and compared three nanofiber masks with disposable non-woven face mask, non-woven mask for operation room, Ito PM2.5, a N95 and a R95 repirator. They demonstrated that, produced nanofiber mask materials could efficiently filter out the PM2.5 particles and simultaneously preserve a good breathability [23]. Skaria et al. incorporate a nanofiber filter media (PT) into the surgical face masks. They observed that, PT with nanofiber filter was able to filter more efficiently than the commercial masks at 65.03% (60.47–69.58%) and when sealed 82.68% (80.57–84.78%). They indicated that, in contrary to the commercial face masks, produced nanofiber prototype retained its low resistance, even when sealed to the face, as well as its filtration performance when unsealed. They also found that this nanofiber media significantly reduced mask airflow resistance and resulted in more of the exhaled air from the manikin passing through the face mask as opposed to by passing the filter and going around the edges [24]. Wang et al. prepared an ultra-light weight (2.94 $g/m^2$) nanofiber-nets binary filter medium by the accumulation of nano-fibers/nets structured PA6-15 and PAN nanofibers via multi-jet spinning, which presented easy-to-use air filters for 300 nm aerosol particles [21]. In the study of Ramaseshan et al., they functionalized a polymer nanofiber membrane to capture chemical warfare agents. They used a catalyst for the detoxification of nerve agents and synthesized from β-cyclodextrin (β-CD) and o-iodosobenzoic acid (IBA). Then they produced PVC nanofiber membranes with β-CD, IBA, a blend of β-CD + IBA, and the synthesized catalyst. They observed that when tested against the decontamination of paraoxon, a nerve agent stimulant, the stimulant gets hydrolyzed. They indicated that, these functionalized membranes are suitable for use in filter media with the properties provided by a filter membrane with increased porosity and hydrophilicity in combination with improved catalytic performance given by catalyst material. Such functionalized nanofibers with different catalysts can also degrade other types of chemical and biological warfare agents and various nanofiber layers can be put together along with a substrate to form protective garments [25].

## V. Conclusion

A filtering half mask or a respirator consists entirely or substantially of filter material to meet high protection. The filtration and separation of sub-micron sized contaminants is a major concern of today. Filter efficiency is known to improve as the size of the fibers decreases. The efficiency curves have a 'V' shape with the apex of the 'V' indicating the MPPS. MPPS for filters is an important factor to be considered in the respirator selection process. As the fiber diameter decreases, the most penetrating particle size decreases and the capture efficiency of the most penetrating particle size increases. In this point nanofibers could be the key elements for filter materials in face masks or respirators. They have very high surface area per unit mass that enhances capture efficiency and other surface area-dependent phenomena that may be engineered into the fiber surfaces (such as catalysis or ion exchange). They could enhance filter performance for capture of naturally occurring nanoparticles such as viruses, as well as micron-sized particles such as bacteria or man-made particles such as soot from diesel exhaust. We believe respiratory protective equipment developments require more research on advanced nanofibers filtration technology to provide necessary protection from airborne threats.

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## References

[1] S. A. Grinshpun, H. Haruta, R. M. Eninger, T. Reponen, R. T. McKay & S. A. Lee, "Performance of an N95 filtering facepiece particulate respirator and a surgical mask during human breathing: two pathways for particle penetration," *J Occup Environ Hyg*, vol. 6 no.10, pp. 593-603, 2009.
[2] FDA, U.S. Food and Drug Administration, Medical Devices, (2017, December 10) [Online]. Available: https://www.fda.gov/MedicalDevices/ucm055977.htm
[3] HAS Health Sciences Authority, Health Products Regulation. (2017, December 10) [Online]. Available: http://www.hsa.gov.sg/content/dam/HSA/HPRG/Consumer_Information/Public%20Advisories/Influenza_A_H1N1_information/consumer_advisories/HSAConsumerGuide-MakingInformedDecisionsWhenBuyingMasks_Respirators-FINAL-Aug09.pdf
[4] S. Rengasamy, R. Shaffer, B. Williams & S. Smit, "A comparison of facemask and respirator filtration test methods," *J Occup Environ Hyg*, vol. 14, no.2, pp. 92-103, 2017.
[5] I. M. Hutten, *Handbook of nonwoven filter media*. Oxford: Elsevier, 2016, ch.8
[6] V. Pathak, (2016 Nov.) "Respirators for protection against PM2.5", 3M Personal Safety Division, [Online]. Available: https://multimedia.3m.com/mws/media/1313143O/respirators-for-protection-agains.pdf
[7] Respiratory protective equipment at work A practical guide, Health and Safety Executive, ISBN 978 0 7176 6454 2, [Online]. Available: http://www.hse.gov.uk/pUbns/priced/hsg53.pdf
[8] ASTM F2100-11 "Standard Specification for Performance of Materials Used in Medical Face Masks"
[9] A. Rengasamy, Z. Zhuang & R. Berry Ann, "Respiratory protection against bioaerosols: Literature review and research needs," *Am J Infect Control,* vol. 32, no.6, pp. 345-354, Oct. 2004
[10] Y.Qian, K.Willeke, S. A. Grinshpun, J. Donnelly & C. C. Coffey, "Performance of N95 respirators: filtration efficiency for airborne microbial and inert particles," *Am Ind Hyg Assoc J*, vol. 59, no.2, pp. 128-132, 1998.
[11] N. Mao, "*Methods for characterisation of nonwoven structure, property, and performance*", *Advances in Technical Nonwovens*, ed G Kellie (Amsterdam: Elsevier) 2016, ch 6.
[12] A. Balazy, M. Toivola, A. Adhikari, S. K. Sivasubramani, T. Reponen, & S. A. Grinshpun, "Do N95 respirators provide 95% protection level against airborne viruses, and how adequate are surgical masks?" Am J Infect Control, vol. 34, no.2, pp. 51-57, 2006.
[13] TS EN 149+A1, "Respiratory protective devices -Filtering half masks to protect against particles-Requirements, testing and marking"
[14] N. Serfozo, J. Ondráček, P. Otáhal, M. Lazaridis and N. Ždímal, "Size-Resolved Penetration of Filtering Materials from CE-Marked Filtering Facepiece Respirators," *J Occup Environ Hyg*, vol. 14, no.12, pp. 965-974, 2017.
[15] TS EN 13274-7: 2008-12," Respiratory protective devices - Methods of test - Part 7: Determination of particle filter penetration"
[16] TS EN 143, "Respiratory protective devices- Particle filters-requirements, testing and marking"
[17] S. Rengasamy, R. BerryAnn, & J. Szalajda, "Nanoparticle filtration performance of filtering facepiece respirators and canister/cartridge filters," *J Occup Environ Hyg*, vol. 10, no.9, pp. 519-525, 2013.
[18] K. Sutherland, "*Filter media*" in *Filters and Filtration Handbook*, 5th ed. K Sutherland Ed. Elsevier, 2008 pp. 41-95.
[19] Y. A. N. G. Chuanfang. "Aerosol filtration application using fibrous media—an industrial perspective" *Chinese J Chem Eng*, 20(1), 1-9.
[20] R S. Barhate, S. Sundarrajan, D. Pliszka and S. Ramakrishna, "Fine chemical processing: The potential of nanofibres in filtration" *Filtr Separat,* 45(4) 32-35, 2008.
[21] N. Wang, Y. Yang, S. S. Al-Deyab, M. El-Newehy, J. Yu & B. Ding, "Ultra-light 3D nanofibre-nets binary structured nylon 6–polyacrylonitrile membranes for efficient filtration of fine particulate matter" *J Mater Chem A*, 3(47) 23946-23954, 2015.
[22] D. Von Loesecke and B. Murphey "Ultra-light 3D nanofibre-nets binary structured nylon 6–polyacrylonitrile membranes for efficient filtration of fine particulate matter" *Filtr Separat*, 45(7) 17-19, 2008
[23] X. Li and Y. Gong "Design of Polymeric Nanofiber Gauze Mask to Prevent Inhaling PM2.5 Particles from Haze Pollution" *J Chem*, 1-5, 2015.
[24] S. D. Skaria & G. C. Smaldone "Respiratory Source Control Using Surgical Masks With Nanofiber Media" *Ann Occup Hyg*, 58(6) 771-7812014
[25] R. Ramaseshan, S. Sundarrajan, Y. Liu, R. S. Barhate, N. L. Lala & S. Ramakrishna, Functionalized polymer nanofibre membranes for protection from chemical warfare stimulants. *Nanotechnology*, 17(12), 2947, 2006.