Melt-Blown Fibres vs Electrospun Nanofibres as Filtration Media

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Filtration plays an important role in purifying and decontaminating two life necessities: water and air. As awareness of the related health issues has increased, the demand for protection from air-borne pollution and disease has also increased. From this perspective, we explain the unique and enhanced capabilities that electrospun nanofibres provide when used as an active layer in face masks. When compared to common melt-blown filters, electrospun nanofibres provide better protection against air particles, bacteria, and viruses such COVID-19.

1. Introduction

This paper aims to provide a high-level comparison between melt-blown (MB) filters (commonly used for N95 face masks), and electrospun (ES) nanofibre (NF) filters. Nanofibres are widely accepted as particularly effective in stopping submicron and nanometre contaminants with a minimal impact on pressure drop. The filtration mechanisms by which the two filters function will be discussed, as well as the differences in their properties (fibre diameter, surface area, relative strength, filtration mechanism, breathability, and reusability)..

1.1 What is MB fibre?

Melt blowing is a commercially successful and low-cost process for producing filtration microfibres. Melt blowing typically produces fibres with diameters in the range of 1-10 micrometres (µm).[1, 2] The structure of a MB filter is like a non-uniform fishing net. Its pores are $1-3$ µm in diameter - much larger than bacteria, and certainly viruses (0.1 µm).

MB filters are usually made of melted polypropylene (PP) passed through a small nozzle. The resulting filaments are blown out at a high temperature and speed, then cooled in the air. A disadvantage of this process is that only thermoplastic polymers can be used. In addition, it is difficult to control fibre size in the melt blowing process. PP can lead to uneven flow of melt, which can make the fibre thickness uneven, affecting the breathability and filterability. [2, 3]

The filtration mechanisms for MB filters are highly dependent on electrostatic deposition. This means that when the electrostatic charge is lost, the filtration efficiency drops. Such electrostatic charges can be lost due to moisture in the environment. As discussed below at 3.2, the moisture-capturing nature of MB N95 masks have been reported to cause headaches and create a favourable environment for viruses and bacteria.

1.2. What is Electrospun Nanofibre?

Electrospinning is widely considered the most effective method for producing nanofibres. This is due to ES's versatility and ability to use a wide variety of polymers both in lab and mass scale.[4] Historically, nanofibres were not able to be produced in large enough volumes and at low enough cost to be commercially viable. Especially when competing with existing alternatives such as melt-blowing. Worldwide, the nanofibre market is continuing to grow. Recent technology advancements mean that production rates of ES NFs are close to that of the conventional MB process.

Electrospinning uses electrostatic forces to draw charged threads from a polymer solution to create fibres. The diameters of the fibres range from 10 - 300 nanometres (nm).[5] The fibre and pore diameters of the ES NF filters can be easily controlled.

There has been a recent interest in green electrospinning, which involves water-based solutions.[6] Only a few academic groups and Revolution Fibres have investigated aqueous solution electrospinning and other methods of fabricating green electrospun nanofibres.

NF fabrics produced by electrospinning have attracted attention for use in filtration. This is partly because the diameter of nanofibres are 10 - 100 times smaller than that of conventional MB microfibers. The higher surface area in nanofibres induces better filtration efficiency, largely because surface interaction is the dominant driving force in air filtration. ES NF is dependent on multiple filtration mechanisms (discussed below at 2). As such, it is not affected by electrostatic attraction to the same degree as MB filters. In addition, the electrospinning process offers opportunities to fine tune the surface functionality through polymer chemistry, blending and nanofiller incorporation during processing.

Functionality
The electrospinning process can generate functional nanofibres, which provide enhanced properties and lower surface areas compared to MB fibres. The

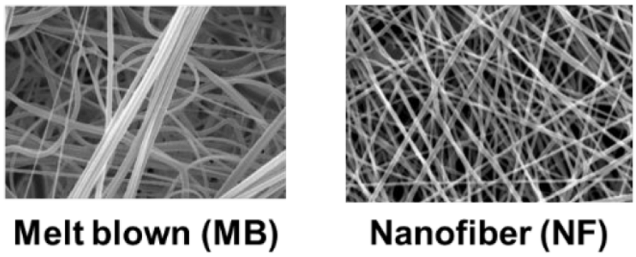

Figure 1: *Scanning electron microscopy images of MB fibre and ES NF.*

high surface area of ES NFs makes it possible to functionalise the nanofibres in a range of different applications. This includes filter media, catalysis, super absorbents, scaffolds for tissue engineering and wound dressings, energy storage, and electronic applications.[5] The ES NFs can be produced from various combinations of natural and synthetic biocompatible polymers at room temperature, potentially lowering energy costs for production. Because electrospinning involves a solution process, it is easier to incorporate antimicrobial, antiviral, biocide and virucide agents compared to MB filters.[5, 7]

Strengths
A recent study reported that ES NF nylon and polyurethane (PU) showed significantly higher strength MB fabrics of the same material.[8] It was found that the strength of ES NF nylon fabric was up to 10 times that of the MB material, and for PU fabric, 2.5 - 3 times that of the MB material.

2. How does mask filtration work?

To understand how ES NFs enhance filtration performance, it is important to understand the particle capturing mechanism. Particles can be blocked by a filter via five different mechanisms: Sieving, Interception, Inertia Impaction, Diffusion, and Electrostatic Attraction (Figure 2). Gravity can aid the filtration process but is often considered negligible for particles smaller than 600 nm. Particles can be classified in different sizes as shown in Figure 2.

Particles larger than the pore size of the filter are captured by the **sieving mechanism**. When the filter is charged, oppositely charged particles are attracted and deposited on the filter by **electrostatic attraction**. Smaller particles not captured by these mechanisms are filtered according to inertial impaction, interception, and diffusion.

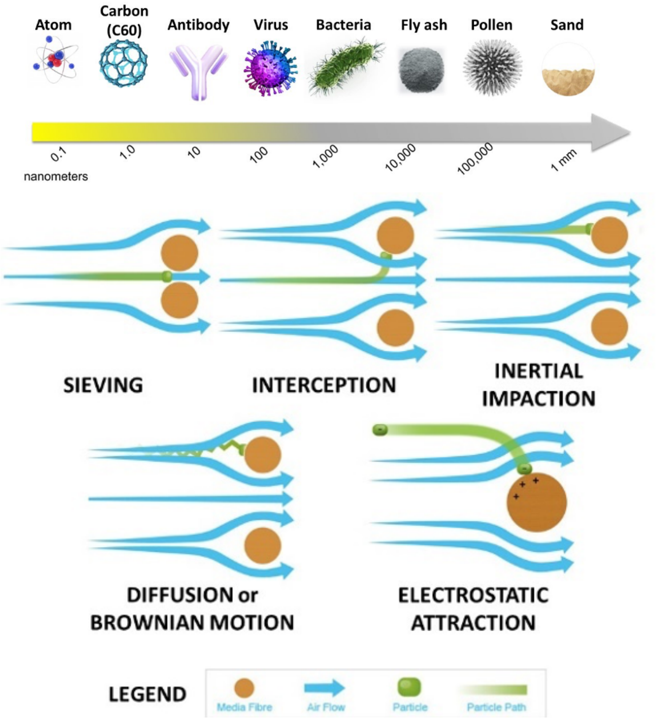

Figure 2: *Concept of size of particles present in nature (top),[9] and the mechanism associated with mask filters (bottom).*

Inertial impaction works on particles between 300 – 600 nm, which follow the airflow. These particles are heavier than the air fluid surrounding them. As the air flow splits in different directions when entering the fibre pore, the particles continue in a straight line and then impact and deposit on the fibre.

Diffusion is very efficient on the smallest particles (< 300 nm). Such particles are not held in place by air fluid and diffuse randomly within the air stream. As the particles traverse the flow stream with random motion, they hit the fibre and deposit.

Direct interception works on particles that are not large enough to have inertia and not small enough to diffuse within the airflow stream. These mid-sized particles follow the air stream as it bends through the fibre spaces. Particles are intercepted when they collide with a fibre.

Because of the various mechanisms by which filtration occurs, the smallest particles are typically not the most difficult to filter. Most filters have a region of lower filtration efficiency somewhere between $0.1 - 0.5$ µm.[10] Particles in this range are large enough to be less effectively captured by diffusion, but small enough to be less effectively captured by interception or impaction. The most penetrating particle size (MPPS) will depend on the filter media, air flow, and electrostatic charge on the particle.

3. Why are electrospun masks better?

Most toxic particulate compounds are smaller than 1 micrometre in diameter. Conventional mechanical fibrous filters (such as MB filters) remove micrometre-sized particles with high efficiency. However, for particles in the submicron range, ES NF are considered better as they offer enhanced filtration performance. This is due to their high surface area and small pore diameter.[11]

Electrospun nanofibres are characterised by a very large surface area, which significantly increases the probability of the particles depositing on the fibre surface - thereby improving the filter efficiency. In addition, ES NFs have low basis weight, high permeability, and tight pore size that make them appropriate for a wide range of filtration applications.[12] ES NF filters have a thinner fibre diameter (10 - 300 nm), and a smaller and more uniform pore size than common MB N95 face masks, which are made of PP fibres with diameters in the range of $\sim$ 500 - 1000 nm. The following sections will discuss why ES NF filters allows for better filtration performance, breathability, and the possibility of reusability.

3.1. Filtration

In general, air filtration is primarily based on depth filtration via the combined effects of sieving, inertial impaction, interception, diffusion, and electrostatic interactions. Figure 3 shows the typical capture efficiency curves for particles captured by fibrous filters as a function of particle diameter.

As discussed above, some particles in the nano range ($\sim$ 100 - 500 nm)are difficult to filter as they do not behave entirely according to one capture mechanism. Filtration of MPPS particles require uniform multiple nanofibre layers, which defer the particles so that they obey one of the mechanisms. Multilayer filters are often hindered by poor breathability and high pressure drop, which is undesirable for filters. However, electrospinning enables control of the porosity, packing density, fibre diameter and surface area of the nanofibres. Modification of these

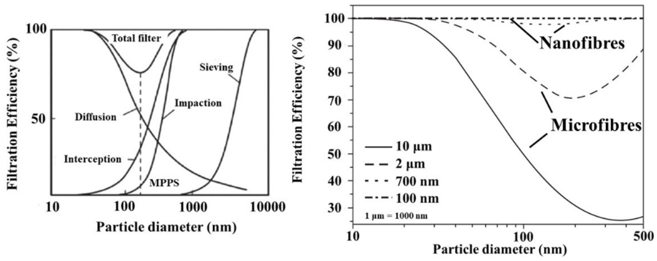

Figure 3: *Filtration efficiency as a function of particle diameter for single-fibre mechanisms and total filtration efficiency (left).[13] Filtration efficiencies of four fibrous filters with different fibre sizes (right). Figure from reference.[14]*

parameters allow them to filter higher amounts and a wider range of particles/contaminants than MB filters. As shown in Figure 3, the smaller the fibre diameter, the higher the overall filtration efficiency for NF filters. Electrospun nanofibres allow optimisation of filtration performance and the possibility of tuning the pressure drop/breathability.

3.2. Breathability

Breathing comfort is commonly associated with pressure drop. However, moisture transportation is another important factor to consider. A recent study conducted breathability tests through N95 MB and ES NF masks to evaluate their water vapour transmission rates (WVTR).[15] It was observed that the WVTR of ES NF filters was superior. MB filters have sponge-like structures which resist moisture. Therefore, moisture takes longer to pass through the filter.

Figure 4 shows the CO_2 emission mechanism for both types of filters. It can be observed that MB filters exhibit poor emission as compared to ES NF filters. Recently, a survey reported on the risk of headaches to healthcare providers from wearing N95 facemasks.[16] They concluded that this is due to higher humidity levels, breath resistance, and accumulation of heat inside the micro-climate of the masks. Other consequences of humidity were discussed in another study. Researchers found that MB N95 masks provide a favourable environment for viruses and bacteria due to its moisture-loving nature.[17] On the other hand, ES NF filters have a finer structure and more uniform morphology and pore diameter. This allows the water vapour to be passed through the filter more consistently and efficiently. This makes ES NF an excellent candidate to replace MB filters.

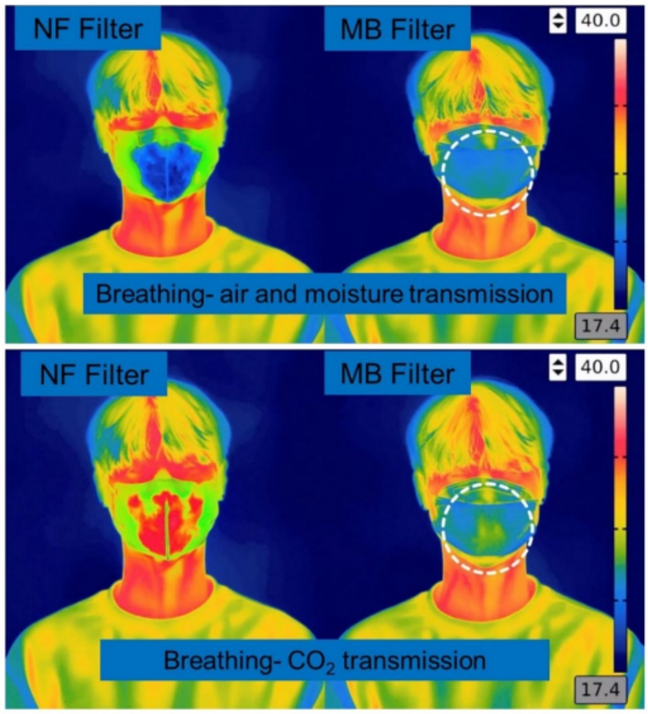

Figure 4: *Evaluation of breathing comfort by infrared thermal camera of ES NF filter and MB filter: (top) air and moisture transmission and (bottom) CO_2 transmission. Figure from reference.[15]*

3.3. Reusability

The current pandemic has amplified the need for masks to be reusable but retain effectiveness. A study was performed on the reusability of MB and ES NF filters when cleaned with ethanol (sprayed and dipped).

The results showed that MB filters are only effective for single use due to the steep reduction of filtration efficiency after ethanol cleaning (to $\sim$ 64%). This is because the electrostatic charge of MB filter is lost when cleaned, leading to a dramatic drop in performance. MB filters lose static electricity when exposed to water and moisture, diminishing their filtering effect to almost half the original performance.

In stark contrast, it was found that ES NF filters can be successfully reused multiple times after cleaning with ethanol as the filtration efficiency remains consistent ($\sim$ 97-99%).[15]

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