New Air Filter Materials to Capture Particulate Matter

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Air pollution is a severe health issue in many parts of the world. In 2019, 99% of the world's population lived in places where the World Health Organization's air quality guideline levels were not met, and air pollution is estimated to cause around 6.7 million premature deaths each year[1]. One of the leading causes of air pollution is particulate matter (PM), which are solid particles and liquid droplets suspended in air with size of around 0.1 to 10 micrometers. These particles can enter lungs and even bloodstreams, causing respiratory diseases, heart attacks, and other long-term health effects. Given the widespread occurrence of air pollution, it is crucial to develop technology to efficiently remove particulate matter in the atmosphere. Currently, the most common method to remove PM is through using High-Efficiency Particulate Air (HEPA) filters in ventilation systems or as standalone devices[2]. HEPA filters are defined as air filters that remove 99.97% of particles that are 0.3 μm in size, and even higher efficiency for particles both larger than or smaller than 0.3 μm. Despite their effectiveness in removing both PM_{10} and $PM_{2.5}$, particulate matter smaller than or equal to 10 and 2.5 μm respectively, HEPA filters can be easily clogged by dust particles and have a limited lifetime of around 6 months, which leads to unnecessary waste when they are replaced. Therefore, new filter materials with improved lifetime while maintaining high efficiency and low pressure drop are needed.

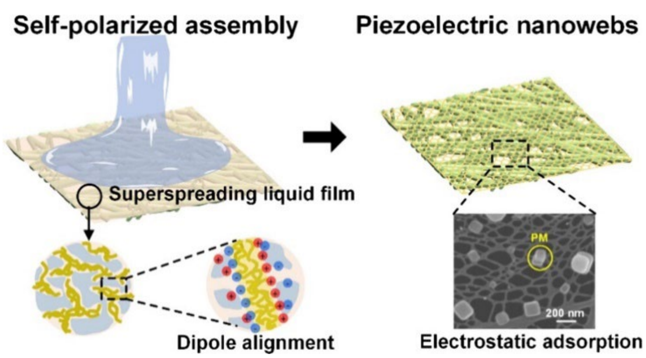

Figure 1. PVDF nanoweb fabrication mechanism

Searching for the next generation of fiber-based air filters, Yang et al. developed a piezoelectric nanoweb material from a superspreading liquid film[3]. The authors were motivated to create thinner fibers with strong electrostatic properties to improve the filter efficiency, and selected polyvinylidene fluoride (PVDF) for its sensitive phase separation characteristic and strong piezoelectric properties. The PVDF solution is dropped onto an electrospun polyamide (PA) membrane and transformed into solid PVDF nanoweb through phase inversion upon submerging in water, as shown in Figure 1. The authors were able to obtain continuous PVDF nanoweb structures with diameters of around 20 nm, compared to that of around 0.2 to 30 μm wide polypropylene or borosilicate glass fibers in commercial HEPA filters. The decrease in fiber diameter leads to larger surface area, which should improve the filter efficiency. However, the PVDF nanowebs falls just short in matching the HEPA filter standard, with a measured efficiency of 99.84 % for particles smaller than or equal to 0.3 μm ($PM_{0.3}$). This is likely due to the thin depth of the fabricated PVDF nanowebs, compared to the pleated sheets used in commercial HEPA filters. As a result, the PVDF nanoweb filter uses significantly less material, has a smaller pressure drop, and uses less energy compared to commercial HEPA filters. The author shows that the PVDF nanoweb has high stability in high moisture environments, unlike HEPA filters.

The authors also claim that the PVDF nanowebs has a significant increase in lifetime to other fiber-based air filters, but only compared their results with their previous work and not with commercial HEPA filters. The reported lifetime of the PVDF nanoweb is 30 days, with no clear indication of the metric as they reported the efficiency to be maintained at 99.44 % after 30 days. It is therefore unclear how does the lifetime of PVDF nanowebs compare to commercial HEPA filters. It is also worth noting that the 99.84% efficiency and 34 Pa pressure drop of the PVDF nanowebs is obtained at the airflow velocity of 5.3 cm/s, and increasing the airflow to 16.6 cm/s caused the efficiency to decrease to 95% and pressure drop to increase to 140 Pa. The limitation of high efficiency only at slow air flow makes it challenging for this material to filter through large volume of air. The author also did not provide filtration efficiency of PM_{10} and $PM_{2.5}$, making it difficult to compare to other filter materials. Nonetheless, this work introduced a novel technique of fabricating fiber-based air filter material through superspreading liquid and showed its promising material efficiency in particulate matter removal.

With the goal of developing a long lifetime air filter in mind, Kwon et al. developed a washable ceramic filter that is claimed to have a lifetime of 20 years[4]. Unlike the fiber-based air filters used in commercial HEPA filters, ceramic filters are designed with a rectangular honeycomb structure with alternating channels for the inlet and outlets to increase surface area, as shown in Figure 2. Ceramic filters have a different mechanism compared to fiber-based filters, as the particles are trapped by the porous ceramic through either deep-bed or cake filtrations. Ceramic filters have been commercially used for filtering diesel exhausts, but their efficiency against PM is limited to around 50%. In their work, the authors deposited an additional inorganic membrane layer onto commercial cordierite ceramic, significantly improving its filtering efficiency to 98.0% for $PM_{2.5}$ and 97.7% for PM $PM_{2.5}$ with a pressure drop of 136 Pa at the flow rate of 1 m/s.

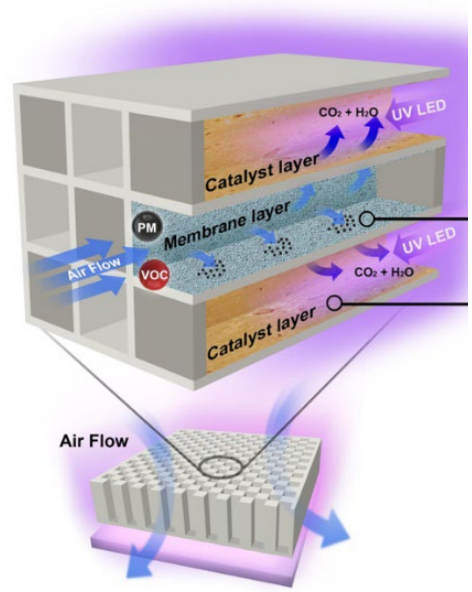

Figure 2. Ceramic filter mechanism

The authors did not specify the identity of the crucial membrane, only saying that a "metal oxide nanoparticles" was used to coat the commercial ceramic filter in the Methods section. Perhaps the authors did so intentionally as an attempt to protect their intellectual property. Nevertheless, the modified ceramic filter is reported to have a high dust loading capacity of 20 g/L, around four times that of HEPA filters, and can operate at high temperature and humidities. Additionally, the ceramic filter can also be easily regenerated by washing with deionized water, which is not feasible for typical HEPA filters. The authors claim that the ceramic filter "may possibly indicate a usage of 2 years without regeneration… [and] implies that we can use the [ceramic filter] for 20 years through ten regenerations of simple water washing". Despite this promising long lifetime claim, it is worth noting that authors reported the efficiency of PM_{10} filtration dropped to 88.7% after 10 cycles of filter usage and regeneration, and it is unclear how stable the ceramic filter will be with 20 years of actual usage.

Unlike any conventional air filter, Zhang et al. explored particulate matter removal through the air-liquid interface by creating microbubbles with a doped conjugated polymer matrix[5]. The authors found that controlling the size of particle-containing microbubbles and pairing with a compatible functional liquid are crucial in finding the ideal balance of PM filtration efficiency and air flow rate. The authors synthesized the doped conjugated polymer matrix (DPM) with dodecyl benzene sulfonate doped polypyrrole on a stainless-steel mesh, creating different pore size by varying the deposition time. The surface property of the deposited DPM can be reversibly modified electrochemically through holding oxidizing or reducing potentials, altering the hydrophobicity of the surface, and controlling the bubble size.

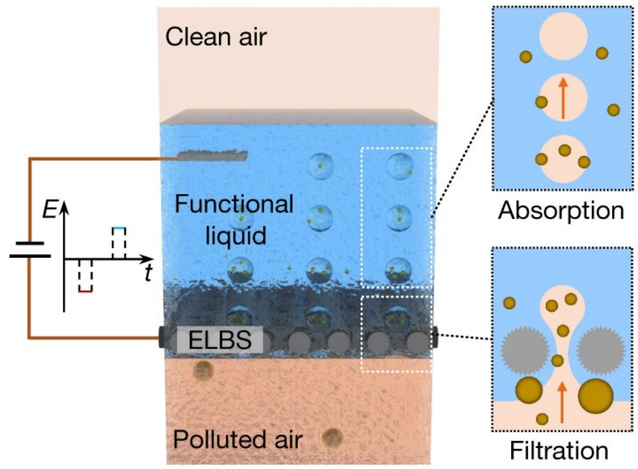

Figure 3. Air-liquid interface filter mechanism

The idea of removing PM through bubbling the polluted air in solution may appear to be straightforward, but the authors demonstrate that millimeter-scale bubbles cannot remove PM efficiently and studied the mechanics of microbubbles. In this work, larger PM are filtered by the polymer matrix, while smaller PM is trapped in the microbubbles created by the matrix. As the air bubble floats to the surface, the pressure differential created by the bubble formation causes the particles in the bubble to travel to the air-liquid interface of the bubble, where the capillary pressure and buoyancy forces transports the particle into the liquid phase. The properties of the liquid phase and its interaction with the polymer matrix is crucial for the optimal filter efficiency, and the authors has demonstrated that decreasing the bubble size led to an efficiency of 99.6% for PM_{10}, which is maintained at 98.2% after 100 hours of operation. Unfortunately, the authors did not provide longer lifetime studies or analyze filtration efficiency for particles sizes below 10 µm. It would be interesting to see whether the polymer matrix will be stable long term, and how effective this filtration method would be against smaller particles that are greater threats to human health.

As the world continues its battle against air pollution, new promising materials with drastically different approaches have emerged in search of long-lifetime high-efficiency air filters. As further research is conducted to improve upon these ideas or search for new ones, it would be beneficial to have a more consistent metric to measure the efficiency of these filters to allow for more direct comparisons, given the large variations of efficiency measurement techniques at various particle sizes and at different flow rates that currently exist in the literature. Furthermore, future research on air filter material should also strive to use sustainable or biodegradable materials to further minimize any negative impacts of these air filters on the environment.

References:

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