Use of Nano Fibers in Filtration - A Review

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Abstract— Filtration is an effective separation process and textile materials are being used since ages as the media for this separation. Conventional textile filter media consist of natural as well as man-made fibres with fibre diameters usually in the range 1– 50 µm. Fibres with finer fibre diameter are supposed to provide higher surface are finer degree of filtration i.e. better filter efficiency. From this consideration, filter media made of nano-fibre enable new levels of filtration performance for several applications ranging from industrial, medical and consumer as well as filtration processes required in defence application. Nano fibres are defined as fibres having diameter of 500nm or less and are readily accessible by the electrospinning process

Key words: Nano-fiber, Electrospinning, Filtration

I. INTRODUCTION

Textile materials are used for a variety of dry and wet filtration processes allowing either the increase of the purity of the material filtered or the recovery of solid particles. Typical examples for textile-based filtration processes are air filtration, process filtration (e.g. solid liquid separation), industrial effluent treatment or dehydration of sewage sludge. Conventional textile filter media consist of natural or man-made fibres with diameters ranging from a few single to a few ten microns. Filter media made of fibres of finer diameter are well known to provide better filter efficiency which is related to the increase in surface area-to-weight ratio. With the development of nano fibre, it is possible to make filters made of nano fibre based filter media and such filter media enable new levels of filtration performance for several applications in different environments. Nano-fibres with diameters between 50 nm and 500 nm can be made by the electrospinning process. A broad range of polymers ranging from natural and synthetic organic to inorganic polymers can be electrospun from the polymer solution allowing the generation of tailored nano-fibre webs (a nonwoven like textile structure [Fig. 1]) for various applications.

Furthermore, the nano-fibre webs may be used as active reaction sites at the nano scale for subsequent fixation of various substances to fibre surfaces. This increases the possibilities for production of, e.g. hygienic functionalised filters or of temperature stable filters with catalytic activity. Hygienic filters produced from cationic polymers or with incorporated silver which can reduce the contamination of air or water filters with bacteria while temperature stable filters, which can be obtained from SiO2-precursor or silica hybrid materials and which are loaded with metal/metal oxide nano-particles, destined for air pollution control.

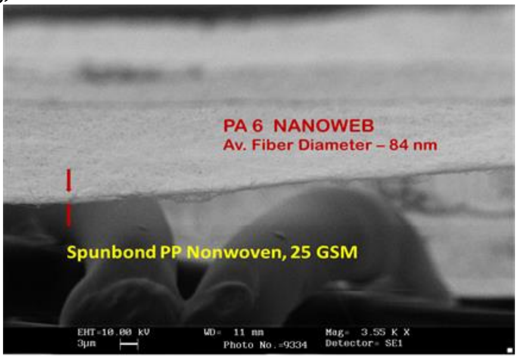

Fig. 1: Cross Sectional View of Electrospun Nanoweb Coated on Polypropylene Nonwoven (Adapted from [5]).

II. APPLICATION OF NANO FIBRES FOR DEVELOPMENT OF FILTER MEDIA

The large surface area of nano-fibre webs allows rapid adsorption of dust and other particles from air such as micro-organisms or pollen as well as hazardous molecules. The latter necessitates reactive sites in the polymer or catalytically active additives allowing chemical binding or decomposition of hazardous substances, respectively. Besides fineness and resulting large specific surface area of nano-fibre webs, their high porosity and small pore size contribute further to their high adsorption and filtration efficiency. Pore size and porosity of filter media are determined by the diameter of fibres used for production of filter media. Filter media of nano webs consisting of nano-fibre and of ultrathin thickness are effective. The thickness of the nano-web can be less than 1–5 µm. While the thinness of the nano-web provides high permeability to flow, the nano-web has limited mechanical properties that preclude the use of conventional web handling and filter pleating equipment. This calls for necessity of a porous substrate as a support to the nano web. The small fibre diameter of nano-fibres and the thin nano-web layer result in high filter efficiency with minimal increases of pressure drop. Furthermore, nano-fibre filter media have demonstrated longer filter lifetimes than conventional filtering materials.

The technical requirements for filters are a balancing of the three major parameters of filter performance:

- Filter efficiency
- Pressure drop, and
- Filter life

An improvement in one category generally means a corresponding sacrifice in another category. It was shown that the proper use of nano-fibres can provide marked improvements in both filtration efficiency and lifetime, while having a minimal impact on pressure drop [1]. Nano-fibre webs can be applied onto various substrates, e.g. onto conventional non-woven, too. These substrates can be selected to provide appropriate mechanical properties to allow pleating, filter fabrication, durability in use, and in some cases, filter cleaning. Apart from using synthetic polymers bearing special functionalities or specific add-ons to the spinning solution, chemical and biological functionality can also be achieved from natural polymers accessible from waste materials. For example the chitin-derivative chitosan is known to provide antimicrobial effectiveness or keratin fibres are known for their propensity in binding air polluting substances. Chitosan bearing nano-fibres can reduce microbial growth and are potentially interesting for air and water filtration uses[2].

III. Application Areas in Filtration Using Nano Materials

There are many areas in filtration where nano materials can be used for filtration applications. Some of them discussed here are as follows:

- Air Filtration
- Water Filtration
- Gas Filtration
- Aerosol Filtration

A. *Air Filtration:*

Currently charcoal and glass fibres are the two most important materials widely used in air filtration applications. Their usages in different areas of applications are summarized in the forthcoming sections separately.

1) Protective Clothing Applications [3]:

Conventional Technologies:

Conventionally, charcoal impregnated with metal oxides such as Ag, Cu, Zn, and Mo in the presence of triethylene diamine (TEDA) has been used in the existing protective clothing applications. Two types of protective suits, i.e. impermeable and permeable protective suits, were widely used by soldiers to protect against chemical and biological contaminants. Low vapour pressure contaminants were removed by physical adsorption, whereas high vapour pressure contaminants were removed by chemical reaction. Some drawbacks of the existing protective clothing are: heavy, moisture adsorption, and the problem of disposal after use. Hence, in order to overcome the drawbacks in the existing technology, nano materials are used.

Modern Technologies Using Nano Materials:

The incorporation of nano particles such as MgO, TiO2, Al2O3 and other oxides into nano fibres was recently explored for air filtration applications. This is because of the unique ability of nano particles to decontaminate wide varieties of toxic gases, such as chemical contaminants, biological contaminants (viruses, bacteria), pesticides, and many more. Recently, the nano particles were incorporated into nano fibers by using various methods and protective clothing applications were developed.

2) Clean Air Applications In Hospitals And Other Domains:

One of the breakthrough domains to use nano material as filter media is in clean air applications in hospitals. This idea is based on the fact that the filtration efficiency of nylon-6 nano fibrous membrane is better than the commercialized high-efficiency particulate air filter (HEPA) [4]. One of the drawbacks is high pressure drop across the membrane. However, they can be potentially employed as HEPA filter with high efficiency in clean air applications such as in hospitals (and other applications) wherein the contaminated air (bacteria and other pathogens) in a room can be filtered before entering into other rooms due to centralized air conditioning systems.

Another application of nano material as filter media is industrial filter. Dust production under several industrial set up is very common. Filtration of fine dust is one aspect. But energy efficiently filtration and maintenance of filtration device is also equally important. At the packaging stage of powdered paint, dusting occurs in the working area. Such dust is harmful to the workers and the environment; hence it needs to be handled carefully. In order to take care of the problem, the plant is usually equipped with efficient air filtration devices, which reduces the in-plant dusting as well as emissions in the environment. Following figure shows the comparative working performance data using conventional filter media module and the Nanofiber based filter media module. The results show that with utilization of the nanofiber based filter media, the emission has been reduced at the lower working pressure and hence lower energy consumption [5].

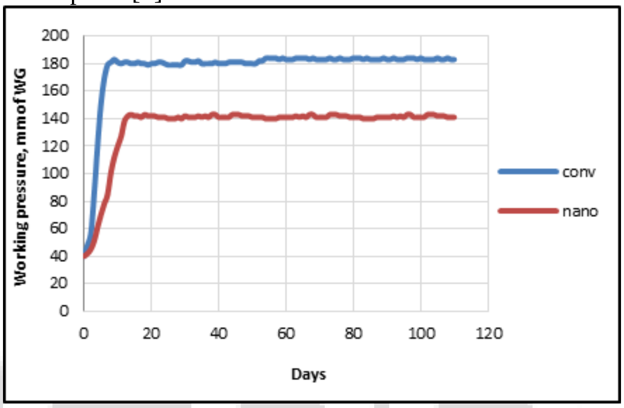

Fig. 2: Result of field trial in a paint industry with filter module made using nanofiber based media for dust filtration (Adapted from [5]).

Efficient face mask is another application area where probably finest degree of filtration of particles is of utmost important. Face masks are usually produced using spun bond as well as melt blown nonwoven media and are of limited protection capability specifically when it is used for protection against viruses, e.g. swine flu or avian flu viruses. Nanofiber based media is an ideal filter media for such very fine degree of filtration. Not only filtration, if such nano fibres are so designed that it contain material like nano silver incorporated in it, specifically distributed on the nanofiber surface, microorganisms can be killed once it comes under the contact of silver nano particle during the course of filtration. The face mask prepared by using composite filter media having nano silver filled nanofiber layer deposited on the surface of nonwoven substrate has been found to be having VFE(Virus Filtration Efficiency) of 99.9 % when tested adapting ASTM F2101 procedure. Because of very good porosity possible with the nanofiber mat, breathing through such mask is also normal [6].

B. *Water Filtration:*

Conventional water filtration media are all based on multi-layer composite structures, containing an asymmetric porous membrane to provide filtration functions and a non woven fibrous support with large fibre diameters of the order of several microns to provide mechanical strength or structure integrity.

Recently, pre-filters gained more attention due to their high versatile applications over filtration of micro-particles from waste water. Polysulfone nanofibers were used as pre filters prior to ultra/nano filtration for micro particle separation, which enhance the life of ultra/nano filtration membranes. Due to its high porosity with high surface area; they can be widely used as pre-filters. The particle size plays an important role in determining the efficiency of the membranes and it is directly related to the flux and separation factor [3].

After pre-filtration, Ultra-filtration (UF) is the important stage in water filtration system. Conventional UF systems are based on porous membranes which are typically manufactured by the phase immersion method. The flux rates obtained in such UF systems are usually low due to the torturous porosity in these membranes. Using electrospun Polyacrylonitrile (PAN) nano fibre based filter media; a high flux UF system has been developed [7]. The developed composite UF system contains a thin layer of hydrophilic but water-resistant chitosan coating, an asymmetric electrospun PAN nano fibrous mid-layer supported on a non-woven PET substrate. By nature, the electrospun nano fibrous support possesses a highly interconnected pore structure throughout the entire mid-layer scaffold thickness (the porosity can be larger than 70%), which is very different from that of conventional asymmetric porous membranes with a porosity only in the range of 34%. To support the thin layer of chitosan coating, an asymmetric electrospun support with finer fibre diameter for the coating surface was produced by sequential electrospinning of two different polymer concentrations. Three-tier composite membranes exhibited flux rates that could be over an order of magnitude higher than the commercial nano filtration filter (e.g. NF 270 from Dow) after 24 h operation, while they maintained good filtration efficiency with rejection ratios better than 99.9%.

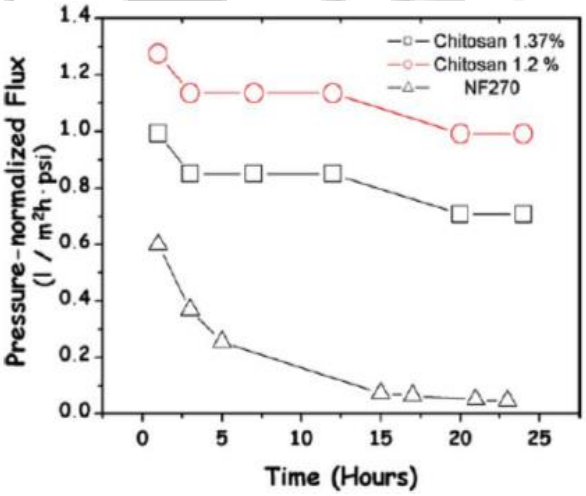

Fig. 3: Result of filtration performance of a three-tier Chitosan based nano filter against commercially available nano filter (Adapted from [7]).

The natural polymer, chitosan is water insoluble but has hydrophilic surface. For this unique property, this biodegradable polymer has been used for electrospinning either alone or in combination with other polymers intending to use it in various applications including water filtration and effective removal of hazardous contaminants [8]. Chitosan has been used successfully for electrospinning by blending it with low percentage of polyethylene oxide [9]. The formation of the blended nanofiber has been confirmed by thermo gravimetric analysis. The application of this developed nano fibre based filter media has been studied for heavy metal ion binding, antimicrobial as well as physical separations. They have observed that the filtration efficiency largely depends upon the fineness of the electrospun fibre. Binding of hexavalent chromium ion has been demonstrated using the developed filter media [10].

Chitosan has also been used for electrospinning in combination with polyvinyl alcohol and zero valent iron to produce nano fibrous mat. This composite mat has been demonstrated to be useful for removal of both forms of inorganic arsenic from arsenic-contaminated aquifers at near-neutral pH [11]. The developed nanofibers mat was found capable to remove 200.0 ± 10.0 mg g−1 of As(V) and 142.9 ± 7.2 mg g−1 of As(III) from aqueous solution of pH 7.0 at ambient condition. Addition of ethylenediaminetetraacetic acid (EDTA) enabled the stability of iron in zero valent state. Also, PP spun bond supported nano web produced from only PVA containing zero valent iron was found to be effective in removing arsenic from the contaminated water [12].

In another study, Acetyl cellulose and Chlorhexidine were electrospun on cellulose substrate to form nanofiberous filter media. To check the biocidal properties of the modifier used, the microbiological tests of: acetyl cellulose nanofibres without chlorhexidine added, electrospun acetyl cellulose nanofibres with chlorhexidine and the chlorhexidine digluconate modified acetyl cellulose nanofibres were performed. In addition, research was performed to assess the virus barrier properties of filters prepared. First, gene-based structures were prepared (expression vector – pCMV Fut plasmid) containing characteristic marker sequences. The tests were aimed at assessing the efficiency of binding the genetic material by acetyl cellulose nanofibres. The tests showed a demonstrably higher DNA binding efficiency by the chlorhexidine containing discs. The microbiological tests of chlorhexidine modified nanofibres performed show a high inhibition of bacterial growth for all modification methods. Initial tests for assessing the barrier properties of nanofibres as antiviral filters showed that they considerably inhibit plasmid penetration into the filtrate at the designed testing unit [13].

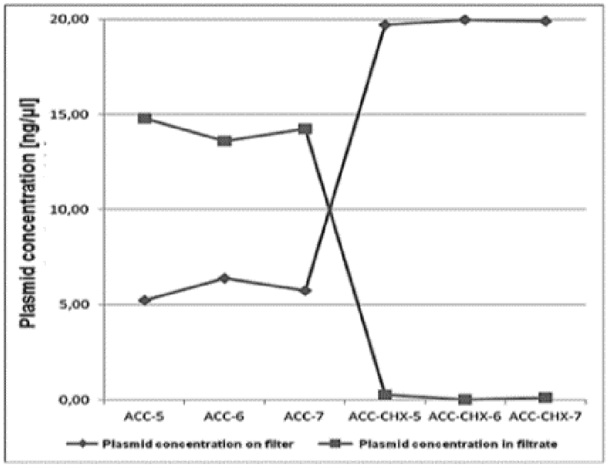

Fig. 4: Result of measuring plasmid on filter and in filtrate (Adapted from [13]).

ACC – acetyl cellulose filter without chlorhexidine; ACC-CHX – chlorhexidine modified acetyl cellulose filter

Silver nano particle is established bactericidal agent. Control release of nano silver particles has been established by its incorporation in polyacrylonitrile(PAN) nano fibre [14]. A durable antibacterial Ag/ PAN hybrid nanofiber has been prepared by electrospinning technique and it has exhibited slow and long lasting release of silver ion. The developed mat was then tested for their ability to destroy bacteria in water. The test result show high degree of bactericidal effect.

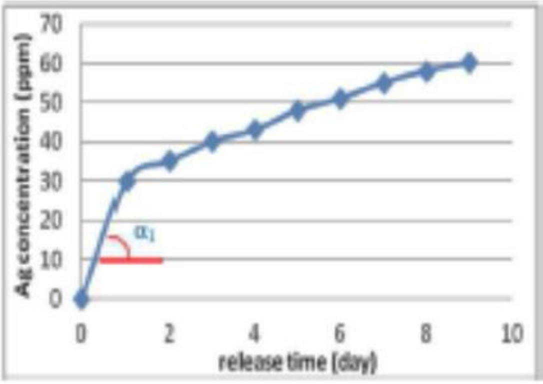

Fig. 5: Silver release profile (Adapted from [14]).

Recently a filter media has been developed consisting of one dimensional nano structures for water filtration [15]. The structure consists of fibers spanning three length scales, each providing a different functionality. The substrate used is cotton which is chemically and mechanically robust. The pores between fibers in cotton are in the range of tens to hundreds of micrometers, much larger than the length scale of bacteria, which prevents the device from mechanically clogging during use. The next component of the structure is silver nano-wire (AgNW) with diameters from 40 to 100nm and lengths up to 10µm. These provide a secondary mesh. Silver is chosen since it is a very well-known bactericidal agent, and recently a large amount of interest has been spurred by the discovery that silver nanoparticles work extremely well at killing bacteria and can be attached to various surfaces with chemical techniques. AgNWs afford various advantages over Ag nanoparticles. First, a nano-wire can have multiple binding points with cotton fibers for strong physical adhesion. Second, AgNWs can form an efficient electrical transport network in filters since they reduce significantly the number of electron hopping times as compared to nanoparticles. This is an important advantage. Noble metal electrodes are known to exhibit antibacterial action under moderate currents, and the enhancement of a sheet of silver nano-rods' antibacterial action when placed in an electric field has recently been observed. The final component of the device is carbon nano tube (CNT). This component of the system ensures good electrical conductivity over the entire active area of the device so it can be placed at a controlled electric potential and used in solution as a porous electrode. The results with the AgNW/CNT cotton are compared to that of CNT-only cotton. The CNT-only cotton shows much less activity at all voltages tested, indicating the importance of the AgNWs for effective bacterial inactivation. Over the scale of volumes studied, the performance of the device remains robust. In addition to enabling electrical inactivation of bacteria, Ag NWs also impart a passive resistance to bio-fouling, and they can be easily integrated into a variety of filters without the need for chemical strategies to attach them to interior surfaces.

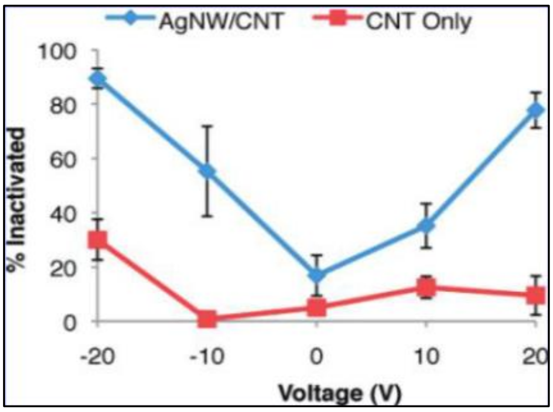

Fig. 6: Inactivation efficiency for AgNW/CNT cotton as well as CNT-only cotton (Adapted from [15]).

C. *Gas Filtration [16]:*

One of the most important filtration area in gas filtration is cigarette smoke. Cigarettes contain numerous compo¬nents: tobacco, paper material and ad¬ditives. Therefore, after burning, a very complex mixture is generated. Ciga¬rette smoke comprises a highly complex chemical mixture of non-specific prod¬ucts of organic material combustion and chemicals specific to the combustion of tobacco and other components of the cigarette. For most of the compounds and substances added to tobacco, little is known of their combustion chemistry, which creates difficulties in determin¬ing the relationship between chemicals in tobacco and those actually inhaled in the smoke. Nano fibres can be used either alone or in conjunction with other filtering me¬dia, such as larger fibres, paper, activat¬ed charcoal, etc. for effective filtration of harmful components of the smoke at the time of smoking. Filters with nano fibres need not be dense as the molecules of the smoke become attracted to the nano fibres due to quantum mechanics instead of be¬ing sieved out. A PVA aqueous solution was chosen to form the nano fibres by electrospinning. The nano fibre spun from the polymer solution has significant applications in the area of filtration because a nano fibre membrane has a highly porous structure of high surface area. The low basic weight and small diameter of the filaments are ideally suited for filtering submicron par¬ticles from smoke.

The pictures of nano fibre membranes be¬fore and after cigarette smoke filtration are shown in figure 7. PVA nano fibres membranes as a filter for cigarette smoke have the advan¬tage of average diameter nano fibre filaments, which is obvious for qual¬ity parameters. A higher diameter of nano fibre filaments makes the filter more effective. The PVA nano fibre membrane as a filter for cigarette smoke is effective for holding organ¬ic compounds with polar O-H or N-H groups, carbonyl group (>C=O) con¬taining compounds, ethers C-O and compounds with C-N bonds.

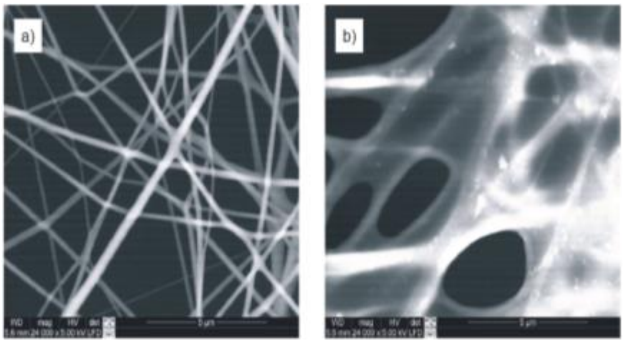

Fig. 7: Nano fiber membrane before (a) and after (b) filtering (Adapted from [16]).

D. *Aerosol Filtration [17]:*

In the course of studying micro porous membranes for protective clothing systems, the U.S. Army Natick Soldier Center has developed a new elastomeric membrane comprised of nonwoven of nano fibres. By using the method of electrospinning and the process of melt blowing, highly deformable nonwoven membrane structures have been made that can be uniaxially strained to over 200% with full elastic recovery. These membranes are soft, flexible, and possess average pore diameters ranging from 0.5 to 50 microns. These membranes can be laminated to knit fabrics to impart wind, water and aerosol resistance to knits for sport and protective clothing. Electrospun samples, melt blown fabrics, and electrospun-coated melt blown samples were characterized and then stretched in two directions to various strain levels, and measured to determine the effect of biaxial deformation on pore structure and transport properties.

In this study, three types of filter media were developed. First, filter media with thin layer (0.04mg/m2) of electrospun Estane® on melt blown Estane®, second, filter media with thick layer (0.05mg/m2) of electrospun Elastane® on melt blown Elastane® and third, nylon-6 nano fibers coated onto carbon loaded foam. Aerosol penetration results shown in figure 8 indicate that very little aerosol penetrates through electrospun-layered melt blowns. Very thin top coatings of electrospun material, even a deformable elastic electrospun layer no thicker than a fraction of a micron, can decrease aerosol penetration by more than two orders of magnitude. In terms of relative change, aerosol penetration increased to 100% penetration when the melt blown was strained to 45%; penetration increased to 0.2% when the melt blown/thin electrospun specimen was strained; and there was an imperceptible increase in penetration to only 0.03% when a melt blown with a thick electrospun layer was strained to the 45% strain level.

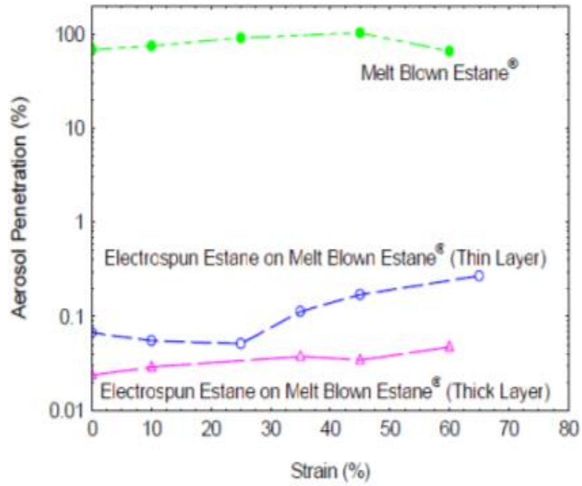

Fig. 8: Effect of deformation on aerosol penetration for melt blown Estane®, a thin layer of electrospun Estane®, and a thicker layer of electrospun Estane® on the melt blown substrate (Adapted from [17]).

In this study, it has been found that, there is a relationship between aerosol filtration and air flow resistance through nanofibers coated onto carbon-loaded foam and the same is shown in figure 7. Here, it was shown that it was possible to increase aerosol filtration from 76% to 99.9% while increasing air flow resistance from 107 to 1010 m-1. It was possible to achieve high levels of aerosol protection with very thin coatings of nanofibers while minimizing the air flow resistance that the nanofiber layer produced. A very light fiber layer of only 0.5 g/m2 was required to filter 99.9% aerosol particles with a flow rate of about 1m/min .

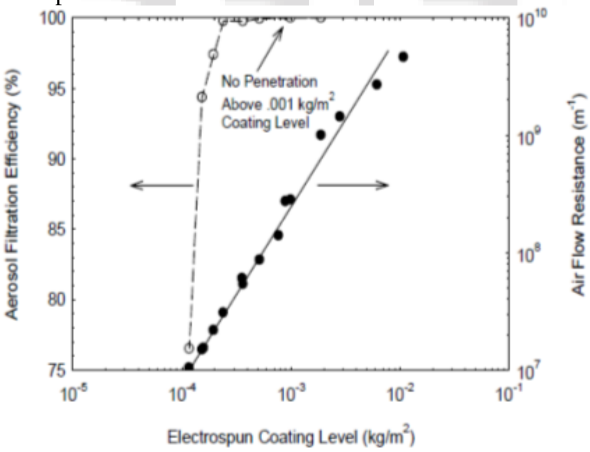

Fig. 9: Aerosol filtration efficiency and air flow resistance of open cell carbon-loaded foam as a function of electrospun fibre mass (Adapted from [17]).

IV. CONCLUSION

There are many filters available in the market for filtration of polluted air, polluted water and harmful gases. But these filters cannot filter out sub-micron size particles. To overcome these limitations, new types of filters are being developed, namely nano fiber filters, which can filter out sub-micron as well as nano sized harmful particles. These nano fiber filters have a very unique advantage over the conventional filters, that, active chemistry or functionality, e.g. chitosan, can be incorporated in the fibers at nano scale, thereby increasing the overall filtration efficiency of the filters.

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