RESEARCH PAPER

Role of the Electrostatic Mechanism in the Filtration Process of Nanofibers

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Abstract: *The present study aims to investigate the role of the electrostatic mechanism in the filtration process of polyacrylonitrile nanofibers containing single-walled carbon nanotube. The nanofibers were fabricated via electrospinning using 16 wt% polyacrylonitrile polymer (PAN) solution, single-wall carbon nanotubes (SWNT) at a ratio of 99:1 along with N and N-Dimethylformamide solvents. Initial filtration efficiency was tested as per ISO 29463:2011 standard inside a test rig. An electrostatic discharge test was performed via the chemical treatment of the filter media with isopropyl alcohol in accordance to EN779 standard. Mean initial filtration efficiency of the nanofiber media in the capturing of 100 nm and 200 nm particles were 95.92 ±2.74 and 97.26% ±1.11 respectively, while for particles between 80 to 250 nm, this was 96.73% ±2.74. The efficiency of the untreated media was 0.2 to 1.2% higher than the PAN/SWNT media after electron discharge using Isopropyl alcohol with an even bigger difference being observed at lower particle size ranges. After treatment with Isopropyl alcohol, the pressure drop of the filtration media was increased from 164.7 to 185.3 Pa. The reduction in filtration efficiency observed after the electrostatic discharge test indicates that the electrical charge of the electrospun nanofibers is influential in its initial efficiency for removing the submicron particles.*

Keywords: *Nanofibers, Carbon Nanotubes, Filtration, Efficiency, Electrostatic.*

1. INTRODUCTION

Nanofiber networks exhibit high surface to volume ratios, are highly porous and permeable while having a very small pore size. This makes them suitable candidates for purification applications with air filtration being one of the earliest cases of their commercial use [1] [2].
Membrane filtration is generally the most effective physical approach in controlling air pollution [3] [4]. Nanofiber membranes are able to capture the majority of airborne pollutants while also having relatively low pressure drop and basic weight along with a small structure [5]. It is possible to categorize these types of filters as high-efficiency particulate air filters (HEPA). The separation of particles from the air stream during the filtration process is affected by the combination of particles present, their shape and size, as well as the filtration velocity and the type of surface [6].
Fabrication of nanofibers via electrospinning has gained much attention in recent years due to its ability to produce a wide range of nanofibers with controlled structures made from various materials [7]. Electrospun nanofibers have consistent characteristics such as small pore size, high porosity and controllable stacked structures which makes them suitable candidates for air filtration [8]. Polyacrylonitrile polymer (PAN) has been used extensively in the fabrication of nanofibers by electrospinning as they have suitable mechanical resistance and chemical stability [9]. The adding catalyst material to the nanofibers and producing hybrid nanofibers can lead to effectively purification of aerosols and adsorption of chemical or biological materials. In this regard, carbon nanotubes (CNTs) have gained attention due to their unique structure and excellent mechanical/electrical characteristics ever since their conception by Sumio Iijima in 1991 [10]. The adding CNT to the polymer

solution used in the electrospinning process achieves a higher pore count due to the difference in contraction between the polymer and CNT particles during the burn process, while also increasing electrical conductivity creating finer fibers [11]. These aligned hybrid nanofibers have higher surface area, large mean pore diameter and better electrical conductivity due to the dispersion of CNTs during the electrospinning process and activation [12].

Various physical mechanisms are involved in effectively trapping particles of varying size in a high-efficiency air filter. Interception, inertial impaction and diffusion are three of the main physical mechanisms involved in particle attraction and collection [13]. The ability of a filter in using a particular mechanism is dependent on the size of the particles and the air velocity at which the filter is functioning [14]. Other notable mechanisms in particle filtration include gravitational sedimentation, sieving and electrostatic deposition. Electrostatic forces are exerted when the particles or the fibers are themselves electrically charged or when an external electric field is applied. This mechanism involves the Columbic force and the Electrophoretic force and is most effective in the collection of particles ranging in size from 10 nm to 500 nm [15, 16]. The relationship that this mechanism has with other mechanical or physical mechanisms such as direct or inertial impaction is as follows [15, 16]:

Electret filter = mechanical filter + electrostatic charge

There are various types of electrostatic interactions. One such interaction is the Columbic force that exists between a charged particle and a charged monopole or dipole fiber. This is similar to that of an electret filter. Another electrostatic interaction occurs between a charged particle and an electrically neutral fiber. This results in the polarization of the fiber by the charged particle. Similarly, a neutral particle can be polarized by a monopole or dipole fiber that is electrically charged, which results in the activation of dielectrophoretic forces within the particle. Both of these can be achieved using an externally applied electric field. External polarization of the fiber results in a non-uniform field that can steer the particle towards the fiber, while external polarization of the particles activates dielectrophoretic forces within those particles. In particle collection, attraction to the fiber is mostly achieved through diffusion and impaction. Certain conditions may arise where inertial impaction, columbic forces and dielectrophoretic forces become important [15, 16].

The filtration efficiency of neat nanofibers and hybrid nanofibers have already been studied by numerous researchers, but few have focused on the particular mechanisms involved in the separation of particles within the nanofiber layers. The present study attempts to investigate the role of the electrostatic mechanism involved in the submicron particle collection process of PAN nanofibers containing single-wall CNTs. Two tests were used in the present study, namely the "initial efficiency" and "electric discharge" tests. The initial efficiency test determines the efficiency of a clean filter at a specific volumetric flow rate. The electric discharge test determines the efficiency of a filtration media that has been discharged via isopropyl alcohol. This test was actually devised for electret filters which are non-woven fabrics with an electrostatic charge. These filters exhibit excellent initial efficiency in the collection of nano-scale particles and have relatively low pressure drop making them suitable for respirators, cabin air conditioning, clean rooms and HVAC systems. The main drawback of these filters is their loss of electric charge over time, which greatly reduces their efficiency [17].

The filtration performance of nanofiber media has been studied in numerous studies where nanofibers have proven to be as effective as or even better than most high-efficiency particulate air (HEPA) filters in their collection efficiency while also causing less pressure drop. The filtration performance of fibers is associated with different mechanisms: interception effect, inertial impaction, Brownian diffusion, electrostatic interaction, and gravity. Role of the electrostatic mechanism in the filtration process of nanofibers received little attention in previous research, but it is a potentially important parameter especially for electret air filter. The present study aimed to assess the effect of the electrostatic mechanism in the filtration process of Polyacrylonitrile nanofibers containing single-walled carbon nanotube.

2. MATERIALS AND METHODS

2.1. Materials

The Polyacrylonitrile polymer (MW = 80000 g/mol) used in the electrospinning process was obtained from Poly Acryl Isfahan Co. (Iran). The single-wall carbon nanotubes (purity>70%) used in the electrospinning solution was obtained from Aldrich Co. (USA). The N (purity>99%) and N-Dimethylformamide solvents were both obtained from Merck Co. (Germany). The potassium chloride powder (KCl) used to test the efficiency of the filtration media in the collection of particles less than 1000 nm in size was obtained from Merck Co. (Germany). Isopropyl alcohol (MW = 60.10 g/mol, purity>99%) used in the electric discharge test was obtained from Merck Co. (Germany). Spun bond Polypropylene was obtained from Baftineh Co. (Iran).

2.2. Methods

After preparing the polymer solution in accordance with optimized conditions described in previous related studies, non-woven nanofiber media was fabricated via electrospinning [18, 19]. The collection efficiency and pressure drop of the fabricated media was then tested in compliance with filtration test standards.
The initial efficiency test was conducted in order to determine the efficiency of the filter on its initial application while the electric discharge test was performed to determine the influence of the electrostatic mechanism in the filtration process. Both of these will be expanded upon further below.

2.2.1. Filtration Media Fabrication

Polymer-based solution electrospinning was used to create filtration media containing a non-woven nanofiber layer coated on a layer of spun bond Polypropylene.
The nanofibers were made using 16 wt% solution containing Polyacrylonitrile (PAN) polymer, single-wall carbon nanotubes (ratio of 99:1) and N,N-Dimethylformamide solvent (DMF). Electrospinning was done at a voltage of 20 kV, needle-collector distance of 10 cm and an injection rate of 1 mL per hour [20].

2.2.2. Initial Efficiency Test

The initial efficiency test was performed according to the ISO 29463:2011 standard [21] inside a test rig which designed according to the ASHREA 52.2:2007 standard [22] (Fig. 1). This test was performed by injecting KCL particles (10 nm to 300 nm) into the tunnel and measuring the particle count before and after the filtration media using a Scanning Nano Particle Spectrometer (SNPS, HCT, Korea) and an Optical Particle Counter (OPC) (3321, TSI Inc., USA). For this, the prepared media is placed inside a holder while the air stream is monitored at the intended face velocity.

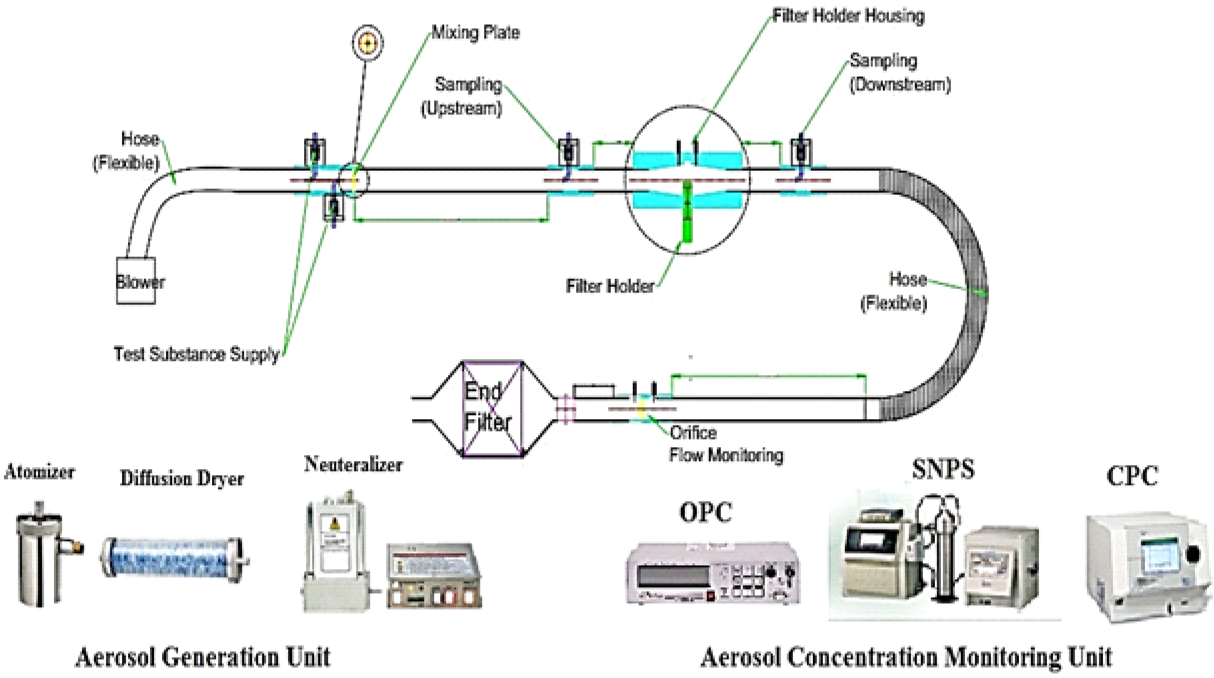


Fig. 1. Schematic diagram of the test rig [24]

KCL particles ranging from 10 nm to 1000 nm were first generated using an aerosol atomizer (4810, HCT, Korea) and then passed through a diffusion dryer (4920, HCT, Korea) and a neutralizer (XRC03, HCT, Korea) in order to remove humidity and electric charge. HEPA filters were used inside the test tunnel for both air purification and particle concentration dilution. The scanning nanoparticle spectrometer used in this test was an impactor containing an electrostatic classifier equipped with a Differential Mobility Analyzer (DMA) (3081A, TSI Inc., USA) column connected to a Condensation Particle Counter (CPC) (3022A, TSI Inc., USA). The inlet air was monitored using the counter system (OPC and SNPS) in order to measure and regulate the influence of the pressure drop created by the filter media at the specific inlet flow rate. Temperature, relative humidity, and the initial pressure drop of the media was also recorded. Then, the flow rate of the atomizer was adjusted based on the desired concentration after which, the counting systems (OPC and SNPS) were turned on. The airstream was constantly monitored before entering the filtration media and in the case of any inconsistency in the generated aerosol concentration, the system would be recalibrated. Collection efficiency was determined by comparing the mean particle count recorded before and after the filtration media. The net effective filtering area in the initial efficiency test was 28.26 cm^2 while the actual face velocity of the test was adjusted to be 10 cm/s (at an airflow volume of 17 L/m) [23]. The collection efficiency of the filtration media at a specific particle size range (E_i) is calculated as per the following:

$$E_i = \left[1 - \frac{n_i}{N_i}\right] \times 100 \qquad \text{(Eq.1)}$$

Here, n_i and N_i represent the number of particles observed before and after the filter media in the size range "i". The mean diameter of the size range di is the geometric mean of the upper (d_u) and lower (d_l) limit diameters of the size range "i" ($d_i=\sqrt{(d_l \times d_u)}$).

2.2.3. *Electric Discharge Test*

The electric discharge test involved the chemical treatment of the media using isopropyl alcohol (IPA) according to the EN779 standard [17]. First, an efficiency test was performed on an untreated sample of the filter media. Then, the filter was submerged in isopropyl alcohol (purity>99.5%) for two minutes ensuring that the entire filter is wet. The filter was then placed on a perforated flat surface (for air transfer) under a fume hood for the alcohol to evaporate. After a 24-hour period, the efficiency test was repeated. The particles generated were passed through a neutralizer as to limit electrostatic mechanism. This test will determine whether the filtration efficiency is dependent on electrostatic mechanism. In order to ensure that the sample is free from IPA, the weight of the untreated (neat) sample was compared with that of the treated sample after drying. The electric discharge test is usually done at 50% and 100% of the nominal face velocity of the filter media. The results obtained at 50% nominal face velocity are used to determine the efficacy of the treatment process while the results obtained at 100% are used for filter classification. The efficiency test performed on the untreated filter was identical to the one performed on the treated filter. The mean efficiency of the two different filters are usually compared with one another for a specific particle size range (such as a mean diameter of 0.4 microns). The mean discharge efficiency is calculated by averaging the discharge efficiency of each sample for the specific size range of "i" [17].

2.3. Structural Properties

Structural properties of the filter media such as its morphology, fiber diameter and surface porosity were determined using a Scanning Electron Microscope (SEM) (SEM, Philips, XL 30; USA). If a ratio smaller than 0.3 is observed between mean fiber diameter and its standard deviation, the fibers are morphologically referred to as uniform (smooth) nanofibers [25]. The thickness of the fabricated media was measured using a caliper (ASIMETO 307-56-3 6", ABS, Hong Kong). The porosity of the filter media was determined using SEM analysis algorithms applied in MATLAB v7 (MathWorks, USA) [26]. Fourier-transform infrared spectroscopy (FTIR) (WQF-510, Rayleigh, China) was used to identify organic compounds and functional groups within the nanofiber layer.

3. RESULTS

3.1. Initial Efficiency Test

All tests were performed at an ambient

temperature of 20°C to 25°C, a relative humidity between 25% to 50% and an atmospheric pressure of around 1005 mill bars. Table 1 showed the results related to initial efficiency, pressure drop, quality factor for particles between 80 nm to 250 nm (as per ISO 29463-3 [21]), overall efficiency for submicron particles, most penetrating particle size (MPPS) and the quality factor for particles between 100 nm and 300 nm. Fig. 2 shows the mean efficiency of the PAN/SWNT filter media based on particle size. The mean efficiency of the filter gradually falls until the 90 nm threshold and then rises after 100 nm. A minimum mean efficiency of 95.71% was obtained at a particle size of 88.2 nm and a maximum mean efficiency of 98.71% was obtained at a particle size of 675 nm, respectively. The PAN/SWNT filter media exhibited higher efficiency in the collection of larger particles (such as 600 nm to 900 nm) than particles in other size ranges.

Table 1. The efficiency results of the PAN/SWNT filter media for submicron particles.

Particle Size (µm)	**Mean (SD) of Initial Efficiency (%) (E_i)**	**Uncertainty (%)**	**Coefficient of Variation**
0.08	95.71±2.89	3	3.01
0.10	95.92±2.74	2.8	2.85
0.125	96.39±2.02	2.1	2.09
0.16	96.88±3.25	3.4	3.35
0.2	97.26±1.11	1.2	1.14
0.25	98.21±1.11	1.2	1.13
Mean Initial Efficiency, 80 nm to 250 nm (%)		96.73±2.47	
Mean Initial Penetration, 80 nm to 250 nm (%)		3.27	
Mean Initial Pressure drop (Pa)		164.71±4.01	
Mean Quality Factor, 80 nm to 250 nm (Pa^{-1})		0.0207	
Mean Initial Efficiency, 300 nm (%)		97.94±1.01	
Mean Quality Factor, 300 nm (Pa^{-1})		0.0235	
Mean Quality Factor, 100 nm (Pa^{-1})		0.0194	
Mean Initial Efficiency, sub 1000 nm		97.16±0.85	
Most Penetrating Particle Size (nm)		88.2	

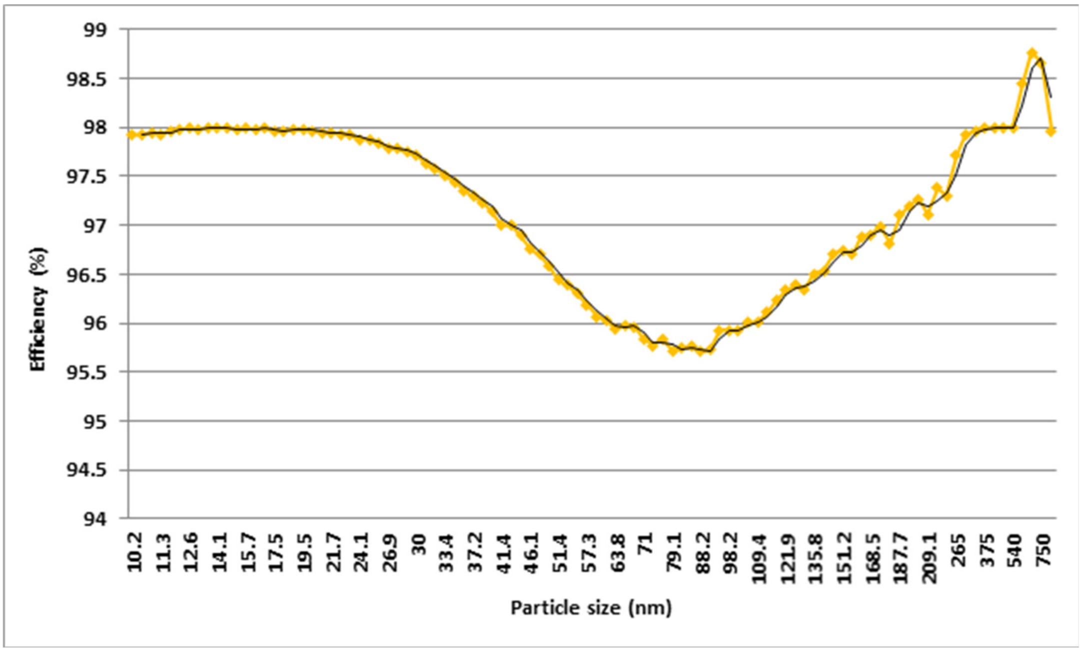


Fig. 2. Mean filtration efficiency of the PAN/SWNT filter media based on particle size.

The properties of the filter media are presented in Table 2 as per ISO 29463 [21]. As can be seen, this filter media meets the requirements needed for classification according to this standard.

3.2. Electric Discharge Test

As was mentioned before, the particles used in this test were passed through a neutralizer in order to remove their electric charge and limit the electrostatic deposition of particles [17, 27]. The use of neutralized KCL particles can also be useful in this regard [28, 29].

The EN779 standard included considerations for the neutralization of the sample filter's electric charge as well. The efficiency obtained in this method is referred to as the "discharged efficiency", while the efficiency obtained from previous methods are referred to as the "untreated efficiency" [17]. Table 3 shows the results of the efficiency tests before and after electric discharge at two different face velocities. The efficiency of the untreated media was 0.2% to 1.2% higher compared to the discharged media. The differences in efficiency observed between the two media types was greater at lower particle sizes (0.2 to 0.25 microns) with the highest reduction in efficiency occurring at 50 nm to 100 nm.

Table 2. Properties of the filtration media and its classification as per ISO 29463.

Media	Efficiency at MPPS (%)	Penetration at MPPS (%)	Classification as per ISO 29463
PAN/ SWNT	95.71	4.29	ISO 15 E

Table 3. The results of the efficiency tests obtained from the PAN/SWNT filter media before and after electric discharge.

Type	**Size Range (μm)**	**Median Size (μm)**	**Face Velocity (cm/s)**	**Mean Efficiency (%)**
Untreated	0.20-0.25	0.22	5	97.76±2.11
			10	97.27±2.12
	0.25-0.35	0.30	5	98.29±3.22
			10	97.87±2.13
	0.35-0.45	0.40	5	98.49±2.03
			10	97.99±2.25
	0.45-0.60	0.52	5	98.50±1.07
			10	98.00±1.32
	0.60-0.75	0.67	5	98.52±1.05
			10	98.63±1.16
	0.75-1.00	0.87	5	98.58±1.00
			10	97.97±1.56
Discharged	0.20-0.25	0.22	5	96.56±2.33
			10	96.07±2.25
	0.25-0.35	0.30	5	97.39±2.83
			10	97.76±2.63
	0.35-0.45	0.40	5	97.69±2.04
			10	97.19±1.80
	0.45-0.60	0.52	5	98.50±2.41
			10	97.30±1.07
	0.60-0.75	0.67	5	98.12±1.15
			10	98.23±0.99
	0.75-1.00	0.87	5	98.38±1.20
			10	97.77±1.15

Fig. 3 shows the comparison between the mean pressure drop of the PAN/SWNT filer media before and after being treated with isopropyl alcohol at three different face velocities. The pressure drop of the filtration media was increased from 164.7 Pa to 185.3 Pa (at tested face velocity) while the quality factor decreased from 0.079 Pa^{-1} to 0.014 Pa^{-1} (for 100 nm particles).

As can be seen from Figs. 4 and 5, the filtration performance of the filter media before and after treatment with isopropyl alcohol was reduced in all particle size ranges with the highest reduction observed in the 50 nm to 100 nm size range.

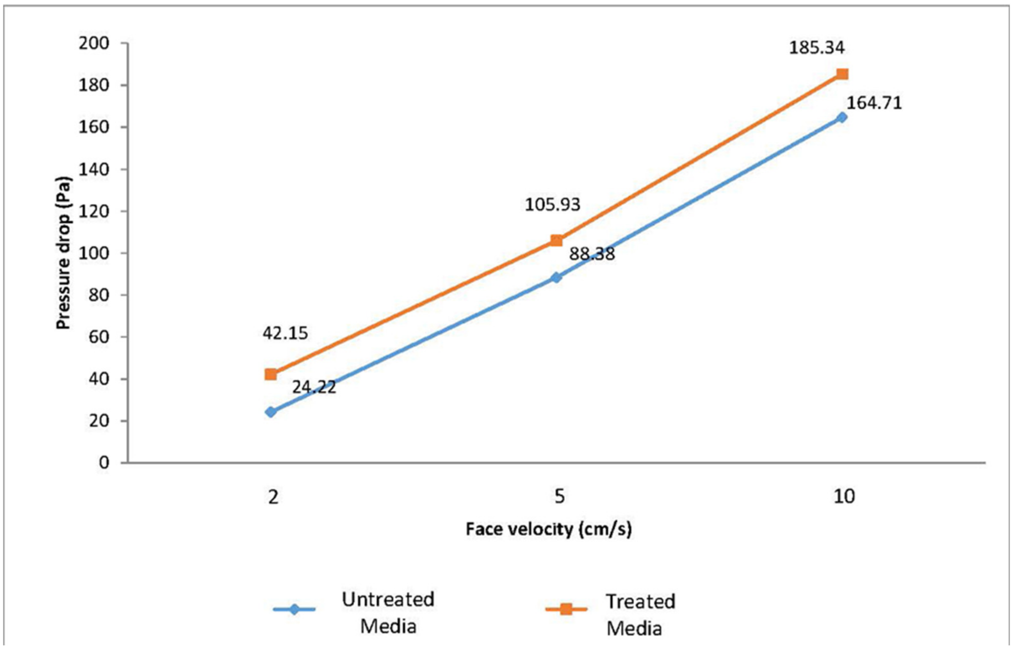


Fig. 3. Mean pressure drop of the filter media before and after treatment with isopropyl alcohol.

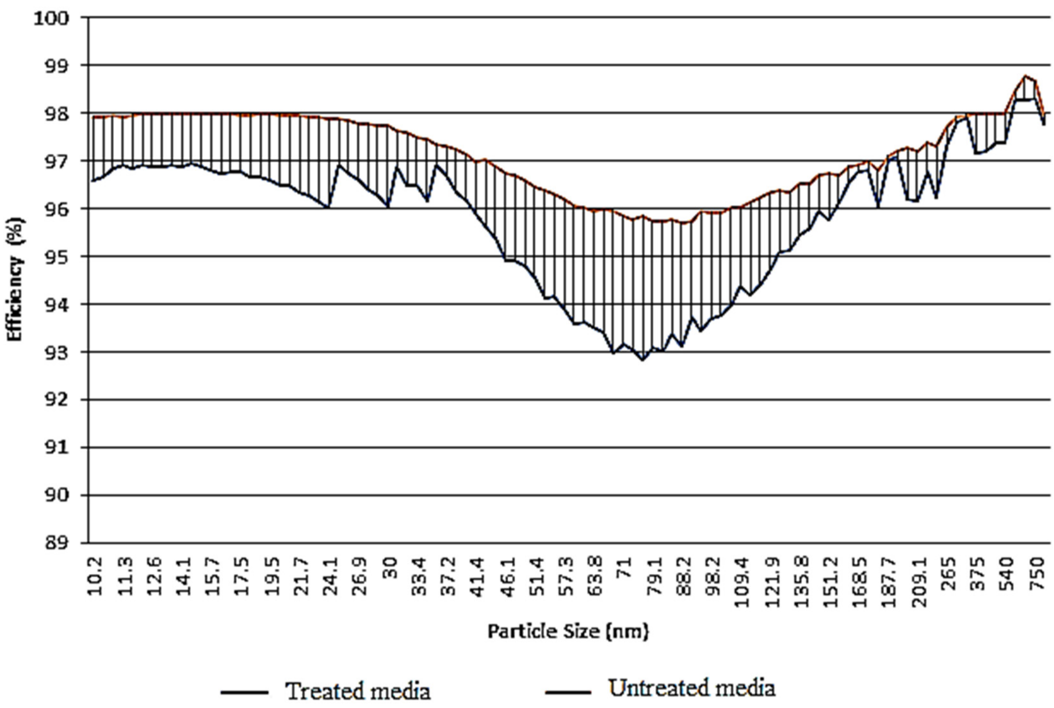


Fig. 4. Mean efficiency before and after treatment with isopropyl alcohol based on particle size.

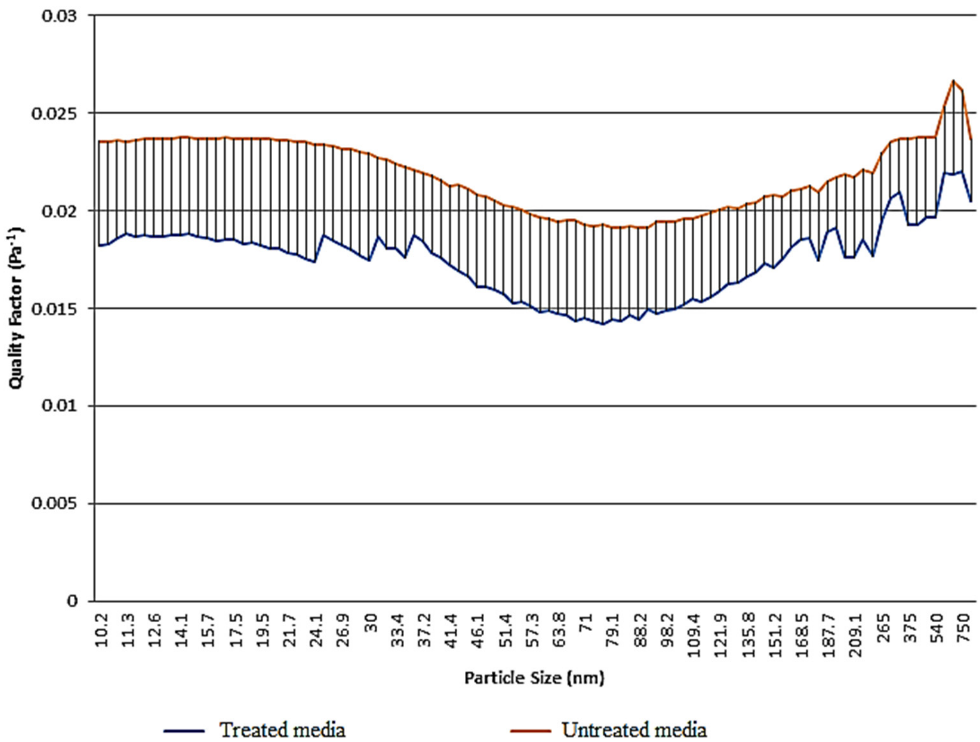


Fig. 5. Quality factor before and after treatment with isopropyl alcohol based on particle size.

3.3. Determining Structural Properties

The SEM images taken from the Polypropylene substrate and the PAN/SWNT nanofiber layer coated on top of it are shown in Fig. 6. The dimensional properties of the PAN/SWNT nanofibers are presented in Tables 4 and 5. The fabricated nanofibers were morphologically beaded, had a mean fiber diameter of 165 nm (CV=1.01) and a surface porosity of 37%.

As can be seen in Fig. 7, the vibrational properties of the −C≡N functional group (the stretching nitrile group associated with the Polyacrylonitrile polymer) is exhibited at 2241 cm-1. The peaks observed at 1224, 1363 and 1451 cm^{-1} are related to the vibrations of the C-H aliphatic group (bending) [30]. The weak stretching vibrations at 1600 cm^{-1} seen in Figure 7 are related to the C-C bond [31]. The peaks present at the 2926 to 2936 cm^{-1} range are related to the aliphatic C-H bonds (stretching) of CH, CH_2 and CH_3. The peaks at 1730 to 1737 cm^{-1} and 1170 cm^{-1} are related to the C=O (stretching carbonyl) or C-O bonds. The peaks at 1628 to 1593 cm^{-1} are related to the C-O resonance bands [32].

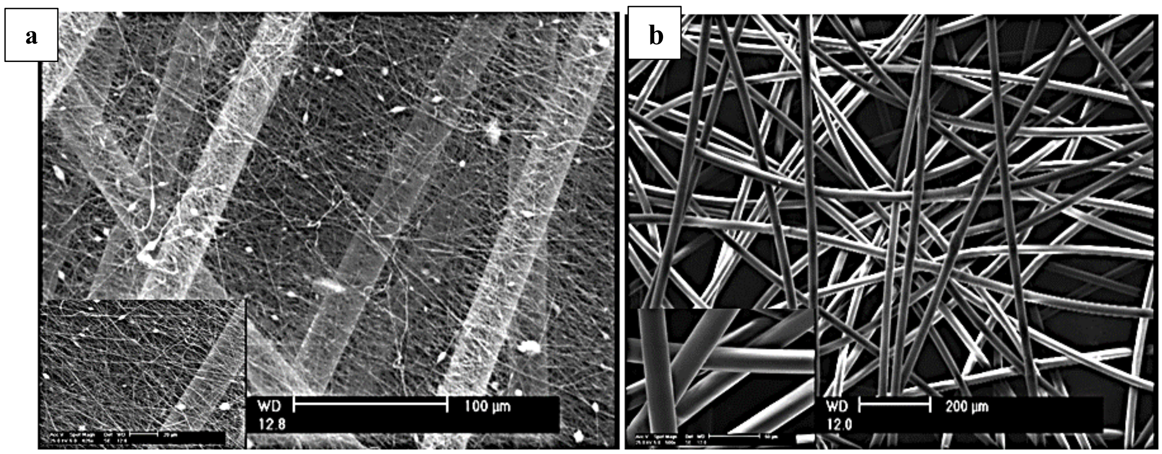


Fig. 6. SEM images taken from the PAN/SWNT nanofiber layer (a) coated on top the Polypropylene substrate (b).

Table 4. Dimensional properties of the PAN/SWNT nanofibers.

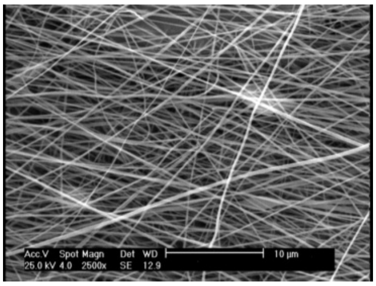
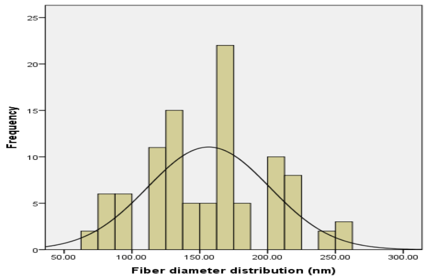
Media	Descriptive Statistics		SEM Image	Histogram Chart
PAN/ SWNT	Mean Fiber Diameter (nm)	165		
	Standard Deviation (nm)	45		
	Variation Coefficient	1.01		

Table 5. Structural properties of the PAN/SWNT nanofibers.

Filter Media	Morphology	Thickness (mm)	Basic Weight (g/m^2)	Porosity (%)
PAN/SWNT	Beaded	0.114	17.62	37

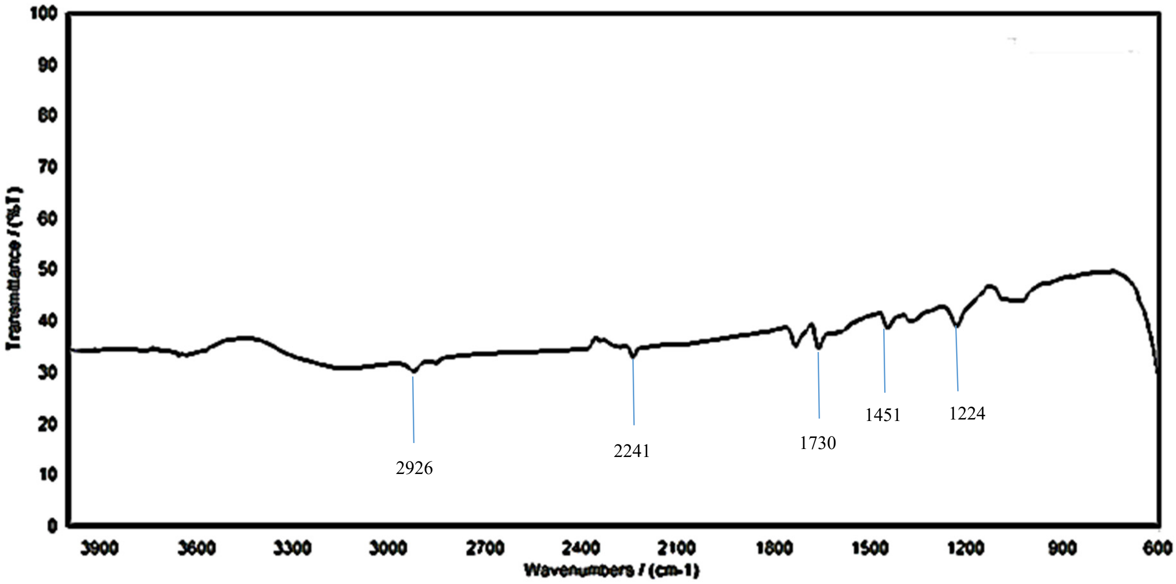


Fig. 7. Results of the FTIR test obtained from the PAN/SWNT filter media.

4. DISCUSSION

4.1. Initial Efficiency

The PAN/SWNT fibers within the filter media were morphologically beaded, non-uniform and bulky (low porosity) which increases the media's air resistance and pressure drop while decreasing it air permeability [33]. The pressure drop of the PAN/SWNT filter media may also be due to its small fiber diameter. According to the classical theory of filtration, pressure drop at a constant flow regime has an inverse relation with the square root of the fiber diameter. Still, the increase in pressure drop caused by the reduction of fiber diameter follows a more moderate slope due to the slip effect [23]. Karwa and Tatarchuk [34] showed that increasing the carbon nanotube content within the filter media increases pressure drop due to the change in surface morphology and smaller effective pore diameter. Pressure drop in a filter media is highly dependent on pore diameter since interstitial velocity in a filter media has an inverse relation with the square root of the pore diameter.

As can be seen from Table 1, increasing the fiber diameter has led to increased collection efficiency for particles between 80 nm to 250 nm. The higher collection efficiency can be attributed to their small diameter, high packing density (low porosity) and beaded morphology. According to the classical theory of filtration, efficiency has a direct relationship with filter thickness and packing density, while having an inverse relationship with fiber diameter and porosity [23]. Fibers with smaller diameters have higher surface area, higher density and smaller pore size which increases the filtration ability of the media. Fibers with a larger diameter however, are usually more bulky, have higher porosity, are more permeable and thus have lower pressure drop [15]. Bortolassi et al. (2019) evaluated the air filtration efficiency of electrospun nanofiber membranes that had been coated with silver (PAN/Ag). Their results showed that the nanofibers were highly efficient (≈100%) in capturing airborne particles with a superior quality factor [35].

Wang et al. (2008) measured the quality factor of filters comprised of a nanofiber layer seated onto a non-woven microfiber substrate. They found that increasing the packing density of the nanofiber increases both efficiency and pressure drop. This is due to the increase in the solid section of the nanofiber layer which reduces porosity and pore volume while increasing the filtration surface [23]. It is clear that efficiency is increased at a lower fiber diameter which corresponds with the theory of slip flow. In a slip flow, airborne particles move closer to the surface of the fiber, increasing the chance of them being attracted via direct impaction. The quality factor is a function of efficiency and pressure drop. It is generally preferable that a filter have high efficiency accompanied by low pressure drop and as such, a higher quality factor indicates better performance. PAN fibers are known to be rigid [36] and are therefore a suitable choice in air filtration applications with numerous studies showing their superior performance [37]. The performance of the PAN fibers can be attributed to their porosity [38, 39] and narrow diameter distribution as well as their uniform and aligned fibers [38, 40].

As was stated, the fabricated PAN/SWNT filter media can be classified within the ISO 29463 standard as it meets their requirements. As the result of this, slip flow forms on the surface of the nanofibers (for nanofibers with a diameter smaller than 500 nm) as the tension force on the fiber is reduced and pressure drop is lowered. Slip flow also causes more pollutant to pass in proximity of the nanofiber surface thus creating more direct impaction and inertial impaction between the fibers and airborne particles. This increases the filtration efficiency of this type of nanofiber at the same pressure drop compared to a conventional fiber that has a consistent and non-slip flow on its surface. In addition to these benefits, the high surface area of the nanofibers facilitates the collection of airborne particles more easily, which is why these nanofiber membranes have gained popularity in air purification applications [41]. The mean distance between free air particles is around 0.066 microns. This means that vibrational flow is present for fibers with a diameter smaller than 0.5 microns and this is why their filtration efficiency improved at a constant pressure [42].

Analysis shows that a smaller fiber diameter corresponds to a lower MPPS. The dominant MPPS for the PAN/SWNT filter media was 101.8 nm. Various studies show that reducing fiber diameter and base weight will shift the MPPS to a lower size range [23, 43, 44]. Conventional microfiber filters have an MPPS in the 100 nm to 500 nm range which can be improved with the aid of nanofibers. Elagib et al. (2019) showed that adding SWNT to a PAN polymer increases efficiency [45], which agrees with our findings. Based on the data presented, the mean filtration efficiency of the fabricated media improved as the particle size was increased from 0.3 to 10 microns. Adding SWNTs to the media increased mean filtration efficiency at this size range.

4.2. Electric Discharge

Applying electrical discharge will remove the electrostatic mechanism between fibers and airborne particles, a mechanism that has a vital role in the performance of electret filters. Without this mechanism, the filtration process is similar to a mechanical filter, which is through direct or inertial impaction as well as diffusion. Considering the nature of electrospinning and also based on the findings of previous studies [46] as well as the finding of the present study, electrospun nanofiber layers will have an electric charge after fabrication. The efficiency values obtained before and after electric discharge suggest that the untreated PAN/SWNT filter media had between 0.2% to 1.2% higher efficiency compared to the discharged media. The pressure drop of the sample media after discharge was also higher. Sun has stated that treating fiberglass media with isopropyl alcohol can change its structure [27]. Kaewsai et al. (2017) used isopropyl alcohol to treat a filter media containing CNTs and reported reduced efficiency [47]. Seeberger reports a slight reduction in the collection efficiency of Di-Ethyl-Hexyl-Sebacat (DEHS) particles after treatment of their sample nanofiber filter media with isopropyl alcohol [48]. The thickness of the media is increased after treatment because certain binders are dissolved and the fibers become looser which reduces their efficiency. Isopropyl alcohol can induce physical changes in polymer materials. Submerging the media in isopropyl alcohol changes the structure of polypropylene and polyethylene due to the solvent swelling effect. These changes are irreversible and have been confirmed via glass transition temperature based thermal analysis [18, 27].

4.3. Structural Properties

Structural analysis of the sample media revealed that the PAN/SWNT filter media had a mean fiber diameter of 165 nm with a CV of 1.01 and was morphologically beaded. Arias-Monje et al. (2020) attempted to fabricate and analyze the properties of PAN nanofibers containing SWNT (15 wt%) [49]. Their results showed that adding carbon nanotubes to the PAN electrospinning solution increases the fiber diameter, which may be due to the increased viscosity of the electrospinning solution after the addition of the carbon nanotubes [49]. Koozekonan et al. (2020) fabricated PAN/CNT, PAN/TiO_2 and PAN/CNT/TiO_2 nanofibers and evaluated their ability to protect against UV radiation [50]. They report that based on their SEM images, the concentration of the nanoparticles can influence fiber diameter and improve collection efficiency [50]. The surface porosity of the PAN/SWNT nanofibers was reported to be 37%. Li et al. (2018) report that the addition of carbon nanotubes to PAN nanofibers can meaningfully increase porosity and thus efficiency [51]. Heo et al. (2019) reached the same conclusion in their research on conductive PAN/SWNT nano-composite fibers [52]. The addition of SWNT can improve the electrical conductivity of the electrospinning solution, which improves membrane arrangement via the efficient arrangement of nanoarrays. Incorporating SWNTs can increase the number of joints and connections thus converting larger pores into smaller ones which reduces the membranes pore size [20].

5. CONCLUSIONS

The high collection efficiency of the PAN/SWNT filter media at the tested particle size range can be attributed to its small pore size, high packing density and beaded morphology. The reduction in filtration efficiency observed after discharge treatment indicates that the electrospun nanofibers have an electric charge that is effective in its initial filtration efficiency and doing chemical treatment of the media using isopropyl alcohol could lead to removing the electrostatic charge between fibers and airborne particles. In conclusion, electrostatic mechanism with lower ratio comparing to interception, inertial impaction and diffusion can be effective on the submicron particle capturing by nanofibers. As our study limitation, zeta potential of the test particle and media were not assessed, so further investigations will explore the detailed mechanism of collection for this media.

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