Original Article https://doi.org/10.4322/2176-1523.20191829

EVALUATION OF DIFFERENT HEPA FILTER MEDIA FOR REMOVING NICKEL OXIDE NANOPARTICLES FROM AIR FILTRATION

Ana Cláudia Canalli Bortolassi [1]
Vádila Giovana Guerra [1]
Mônica Lopes Aguiar [1]

Abstract

Currently, scientific research in the field of nanotechnology has attracted growing interest because of its several applications. The metal oxides have high added value in industrial processes and in addition, human exposure to these nanoparticles can cause respiratory problems. Filtration using fibrous filters is among the various options that can be used to provide efficient elimination of nanoparticles. While it is known that fibrous filters can successfully remove microparticles present in the air, there has been little research concerning the removal of nanoparticles using nickel oxide nanoparticles. The aim of this study was to evaluate the efficiency of three HEPA (High-Efficiency Particulate Air) filter media with glass and micro-quartz fiber for the removal of nickel oxide nanoparticles. Two HEPA filter with glass fibers (H1 and H2) and one HEPA filter with micro-quartz fibers (H3). Nanoparticles were generated using an atomizer generator through a 0.1 g/L nickel oxide water suspension. The efficiency of filter media was measured using an electrical mobility particle analyzer (SMPS) coupled to the filtration line and particles were counted before and after the filter media in the size range between 7.4 and 289 nm. Both filter media had efficiency collection above 99% but H1 filter stand out among the others.
Keywords: HEPA filter; Air filtration; Nanoparticles; Nickel oxide.

1 INTRODUCTION

The term nanoparticle is primarily used to describe nanoscale particles. Nowadays have been increased technological applications involving nanoparticles and diseases caused by these particles. Recent studies show that Asthma, Chronic obstructive pulmonary disorder (COPD), lung cancer and Alzheimer are among the diseases caused by nanoparticles in the air pollution [1]. Cardiovascular problems were associated with acute exposure to inhaled nickel nanoparticles due to the discovery of endothelial damage in a rodent species [2].

In industrial indoor environments where clean air is needed to avoid contamination from fine hazardous dust and polluting action on workers and products, high-efficiency particulate air (HEPA) filters (to control PM < 0.1 with 99.99% efficiency or more) are recommended [3]. Therefore, metallic nanoparticles are clusters of metal atoms which are formed by dimensions below 100 nm and have the following characteristics: high surface area, large plasticity, and little light scattering. Thus, the application of metallic nanoparticles has been important to industries and is becoming more essential the studies of their properties at the nanometer scale [4].

Nickel is a ferromagnetic material that presents cubic structure and has attracted much attention due to applications in magnetic media for recording and as catalysts in a variety of chemical reactions as a nanometric dimension. Besides, nickel oxides are compounds with nonlinear optical properties in uniform and nanometric sizes [5,6].

However, everybody should keep in mind although nickel not released extensively into the environment, may represent a hazard to human health [7]. Nickel is a ubiquitous metal frequently responsible for allergic skin reactions and has been reported to be one of the most common causes of allergic contact dermatitis, as reflected by positive dermal patch tests [8].

Many current types of researches aim to reduce the emission of pollutants that cause serious damage to the ecosystem. Filtration is among these studies and it's one of the most used processes to capture particles from air. It occurs by passing aerosol through the filter medium in which the particles are being deposited on the filter surface. This process is financially viable, easy to operate and highly efficient [9].

There is a wide range of applications using aerosol filters as engine exhaust filters, clean room filters and cigarette filters [10]. Each filter must find out specific requirements when subjected to standard test conditions [11,12]. The operating face velocity of interest is less than 10 cm/s for engine exhaust

[1] *Laboratório de Controle Ambiental, Departamento de Engenharia Química, Universidade Federal de São Carlos – UFSCar, São Carlos, SP, Brasil.*
E-mail: anabortolassi@hotmail.com

filters, clean room, and respirator filters [13,14], 30-60 cm/s for cigarette filters [15], and 2-12 cm/s for inertial filters [16].

A method that has been very used to generate nanoparticles is the atomizers generators, which was used in this work. These generators can be used in liquid suspensions and solutions, which break the liquid into droplets. Liquid droplets evaporate and solid particles of the aerosol are formed when the atomizer is used with a suspension containing solid particles.

Hubbard et al. [17] evaluated sodium chloride and iron oxide particles generation in order to compare the generation of a solution and a suspension. According to the authors' work was used a TSI atomizer generator for generating sodium chloride aerosol of a solution and was also used aerosol generator of the fluidized bed (IST) to atomize iron nanopowder. They could verify that collection efficiencies for Fe were approximately 10-20% higher than for NaCl at equivalent conditions. The increase of Fe particle collection efficiency compared to NaCl particles is caused by an increase in effective density and shape factor.

Boskovic et al. [18] investigated the influence of particle shape on the filtration process using spherical polystyrene latex (PSL) and iron oxide, and perfect cubes of magnesium oxide. It was verified that the filtration efficiency of cubic particles is lower than spherical particles within the range of 50-300nm. So, nanoparticle shape influences the filtration process.

Fibrous filters are among a variety of different equipment potentially able to operate efficiently in remove particles of the environment although there are just a few studies of collecting oxides nanoparticles. So, the aim of this study was to evaluate the efficiency of HEPA (High-Efficiency Particulate Air) filter media composed of glass and micro-quartz fiber for the removal of nickel oxide nanoparticles. Collection efficiency and pressure drop were the parameters used to assess the performance of a filter media.

2 MATERIALS AND METHODS

2.1 Particulate Material

An aqueous slurry of nickel oxide (0.1 g/L) was used to generate nanoparticles using the atomizer generator on filtration tests. The nickel oxide (Sigma-Aldrich) was pure whose density was 4.84 g/cm^3.

2.2 Filter Media

HEPA (High-Efficiency Particulate Air Filter) filter media composed of glass and micro-quartz fibers were the fibrous filters used in the filtration process. There are two HEPA filters with glass fibers (H1 and H2) and one HEPA filter with micro-quartz fibers (H3). H1 (Type H14, 99.995% MPPS efficiency) were obtained from Filtracom Ltda (Brazil). H2 (Type H13, 99,95% MPPS efficiency) and H3 (Type H13, 99,95% MPPS efficiency) fibers were obtained from Energética Ltda (Brazil). All of the filter media had filtration areas of 5.3 cm^2 and can be applied to control the emission of particulates in chimneys, air conditioner, and clean rooms.

2.3 Experimental Unit

Figure 1 shows the experimental unit which consists of an air compressor (Shulz), air purification filters (Model A917A-8104N-000 and 0A0-000), particles generator

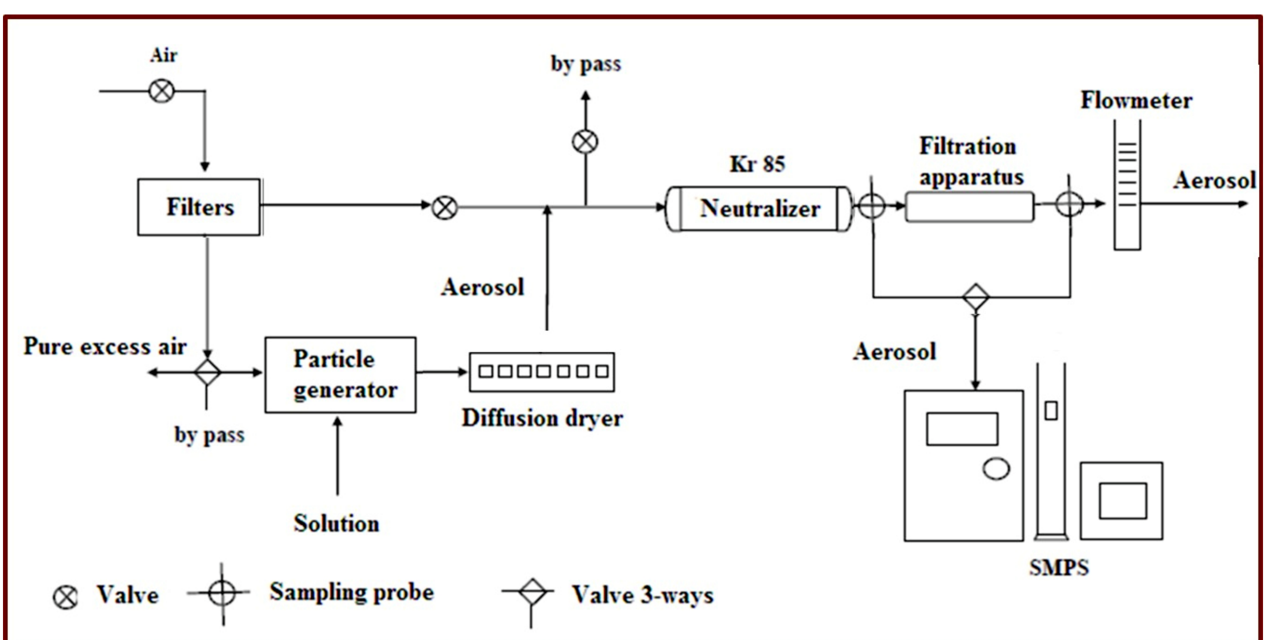

Figure 1. Experimental system [19].

(TSI, model 3079) diffusion dryer (Norgren), Kriptônio and Americium neutralizing source (TSI Model 3054), filter apparatus, flowmeter (Gilmont Number 3) and SMPS device formed by electrostatic classifier (TSI 3080), differential mobility analyzer and ultrafine particles counter (TSI 3776) localized at Environmental Control Laboratory 1.

The collection efficiency is experimentally obtained through the technique of electric mobility in which the amount of particles is calculated before and after passing through the clean filter medium determined by the equation 1 such as used in Barros et al. [19]:

$$E = \frac{C_d - C_u}{C_d} \quad (1)$$

which Cu and Cd represent the concentration of particles upstream and downstream of the filter medium, respectively.

Quality factor was used in previous studies [20-23] to analyze the performance of the filters and is defined as equation 2:

$$Q_F = \frac{-\ln(1-\eta)}{\Delta P} \quad (2)$$

where Q_F represents the ratio between filtration efficiency measure and pressure drop. The pressure drop across the filter is represented by ΔP and efficiency by η. It was obtained the average efficiency after the experiments were repeated three times for each filter. A filter with great filtration efficiency and lower pressure drop will have higher Q_F. Thus, a filter of better performance should have both high efficiency and large Q_F.

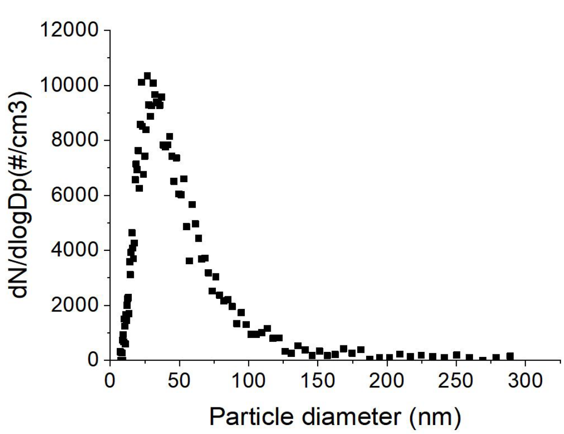

Figure 2. Particle size distribution of nanoparticles.

2.4 Experimental Procedure

Firstly, filter characterization was evaluated such as thickness, grammage, fiber diameter using scanning electron microscopy (SEM) images. It was analyzed the images to obtain the fiber diameter of the filters using Image Pro-Plus v. 7 Program and the same procedure as in Bortolassi et al. [24]. Then, nanoparticles in the size range between 7.4 and 300 nm were generated using particles generator and an aqueous slurry of 0.1 g/L nickel oxide. Filtration tests were conducted during 1 hour and maintained the superficial velocity of 5 cm/s, the flow rate of 1.59 L/min, and the filtration area of 5.3 cm^2 constantly. Then, the number of particles was counted before and after the filter media during the filtration experiments to obtain the average of the filtration efficiency. The experiments lasted one hour for filtration and then a half hour approximately to count particles. Three experiments counting the particles before and after the filter media were performed to reach accurate results.

3 RESULTS AND DISCUSSION

3.1 Characterization

It was possible to measure particles in the size range between 7.4 and 289 nm (Figure 2) related to their particle diameter using a particle analyzer by electric mobility (SMPS) coupled to the filtration line. The method used in this study for particle dispersion was similar to Boskovic et al. [18] but using others oxides. Nickel was used as a simulation of particles in this study because there are a few filtration studies with nickel nanoparticles.

Figure 3 shows the images obtained by scanning electron microscopy (SEM) of H1, H2, and H3 filters and their general characteristics are in Table 1, such as thickness, grammage, fiber diameter and material. Both figures have the same enlargement (5000x). It can be seen that these

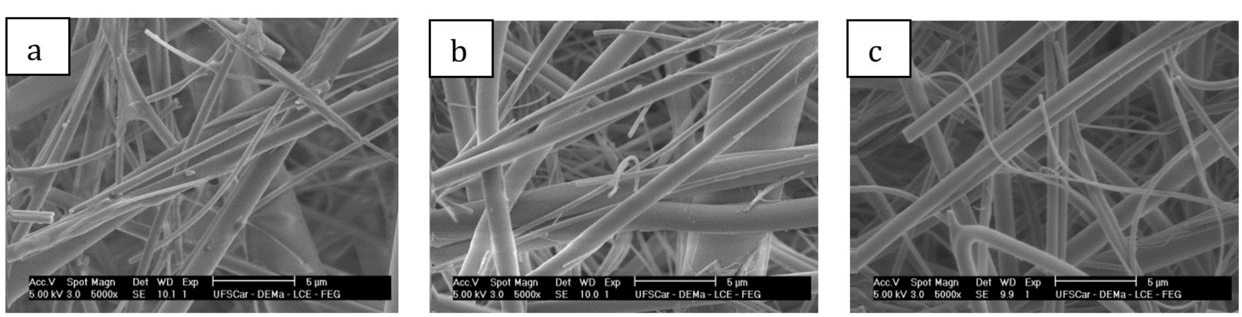

Figure 3. Filter media (a) H1 (b) H2 (c) H3.

Table 1. Filter media general characteristics

Filter media	H1	H2	H3
Thickness(mm)	0.43	0.45	0.45
Grammage(g/m²)	75	82.6	88
Fiber diameter (μm)	0.59	0.37	0.62
Fiber Material	Glass	Glass	Micro-quartz

filter media have heterogeneous fiber diameters, a feature that makes them very effective in removing particles. But it's impossible to see which one has the smaller fiber diameter. So, it was necessary to analyze them with Image Pro-Plus v. 7 Program to obtain more details about the filters.

3.2 Collection Efficiency

Filtration efficiency was evaluated by starting with a clean filter. After one hour of filtration experiments, the number of particles was counted before and after the filter media to obtain the filtration efficiency which is the difference between input and output particles. The experiments were done in triplicate and lasted one hour for filtration plus a half hour approximately to count particles. Figure 4 shows the experimental collection efficiencies obtained with Equation 1 of H1, H2 and H3 filter media. It can be observed the removal efficiency of nanoparticles were above 95% for all experiments. Some penetration occurred within the range of 30-120 nm diameters of nickel oxide nanoparticles. Even with such penetration, these filters were highly efficient in removing particles when evaluated after one hour of filtration and this fact is due to the characteristics of the filters as seen in other studies [24]. Considering that both filters were very efficient to collect nanoparticles, H1 showed less particle penetration in the range aforementioned in this work. Moreover, H1 presented lower pressure drop (269 Pa) when compared to the others (H2=284Pa; H3=402Pa).

Bortolassi et al. [24] studied the same filters and the same range of evaluated the performance of the filter media using different nanoparticles. They reached efficiency above 99.9% and the most penetration particle size (MPPS) range was around 25-150 nm. In addition, it was possible to verify that the efficiency was higher using NaCl particles comparing to nickel oxide particles when analyzed the same filters but it is important to highlight that the number of particles generated was higher using NaCl than NiO.

Hung and Leung [25] analyzed particles in the range of 50-500 nm and showed that the filters of fine nanofibers (94-220nm) gave higher filtration efficiencies for particles 50-200 nm in diameter of NaCl than did filters of coarser nanofibers, mainly because of enhancement in convective diffusion and interception. So, the pressure drop was significantly higher for the filters of thin nanofibers. In this work, the average of the fiber diameter was bigger (520nm) and the range of particles generation was smaller (7-289 nm) comparing to their study. As results, the efficiency in this study was higher for particles bigger than 150 nm in diameter.

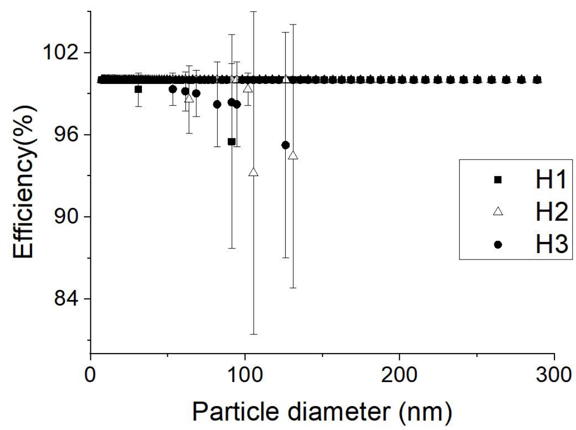

Figure 4. H1, H2, H3 filter efficiency.

3.3 Quality Factor

In the present study, the quality factor among the filters (H1, H2, H3) was very similar (Table 2). It's justified due to the thickness uniformity, small fiber diameter and therefore a high filter quality.

A limited number of studies based on filtration theory have investigated the quality factor effect for nanofibrous filters [21,26-28]. Podgórski et al. [26] confirmed that using nanofibrous filters a significant growth of filtration efficiency for the MPPS range can be achieved and the pressure drop rises moderately. Yun et al. [27] analyzed polyacrylonitrile nanofiber filters and concluded that for given particle size, the filter quality factor and single fiber efficiency for nanofiber filters depended primarily on packing density and fiber diameter. Zhang et al. [11] showed that the filter made up of multiple thin layers of nanofiber mats had a filter quality factor much higher than the single thick layer nanofiber mat. Better thickness uniformity in the multi-layer structure due to stacking compensation and smaller fiber diameters in nanofibers of short-term deposition time are two possible reasons for the improvement of the filter quality.

Comparing the studies of Table 2, it's possible to note that filters composed of PAN material presented the highest quality factor. These filters were also composed with small fiber diameter and it could be one of the reasons of the high-quality factor. It should be noted that the face velocity, particle size, and fiber material composition may be modified in different studies. Therefore, caution should be exercised when comparing the data.

Table 2. Summary of filter quality factor from literature and the present work

Research	Filter	Fiber diameter (μm)	Material	Quality factor	Particles filtered
Podgórski et al. [26]	BL	18	Polymer	~0.003	-
	NL1	0.74	Polymer	~0.004	
	NL4	1.18	Polymer	~0.008	
Yun et al. [27]	ES[a]2	0.27	PAN	0.045	NaCl
Wang et al. [21]	Sample C	~0.15	N/A	0.02	Silver/NaCl/
	Sample A	~0.15	N/A	0.03	PSL
Zhang et al. [11]	PAN 5 x 3	~0.20	PAN	0.063	PSL
	PAN 5	~0.20	PAN	0.037	
Present study	H1	~0.59	Glass fiber	0.013	Nickel oxide
	H2	~0.37	Glass fiber	0.011	
	H3	~0.62	Quartz fiber	0.01	
Other comparisons	Millipore	~0.50	Glass fiber	0.007	-
	LydAir	~0.50	Glass fiber	0.03	

Analyzing HEPA filter media of this study, it was possible to observe that H1 showed the highest filtration efficiency, lowest pressure drop, and the highest quality factor. Differences in the collection of aerosol particles of different type are attributed to the interactions between particles and the fibers of electret filters. This process is influenced by the particles' morphology as well as the charges and surface properties of the particles and fibers [29].

4 CONCLUSIONS

In conclusion, the importance of this work was to evaluate the efficiency and the quality factor of the filters using nickel nanoparticles because there are few filtration studies with these particles and this factor is very important to be analyzed to evaluate the filters that could be used in cleanrooms and air conditioning. It was possible to observe that H1 showed the highest filtration efficiency, the lowest pressure drop, and the highest quality factor when compared to H2 and H3. Even so, the filters in this study are highly efficient in the removal of nanoparticles, although there was penetration within the range of 30-100 nm. Filters quality factors in the present study (0.01) were very similar to those presented in the literature even using different filters and particles. This explains how efficient and useful are these filters to remove nanoparticles from the air.

Acknowledgements

The authors would like to thank the National Council of Technological and Scientific Development (CNPq), Coordination for the Improvement of Higher Education Personnel (CAPES), and PPG-EQ (UFSCar) for their financial support. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001 and São Paulo Research Foundation (FAPESP) grant number (2016/20500-6).

REFERENCES

1 Maher BA, Ahmed IAM, Karloukovski V, MacLaren DA, Foulds PG, Allsop D, et al. Magnetite pollution nanoparticles in the human brain. Proceedings of the National Academy of Sciences of the United States of America. 2016;113(39):10797-10801.

2 Liberda EN, Cuevas AK, Qu Q, Chen LC. The acute exposure effects of inhaled nickel nanoparticles on murine endothelial progenitor cells. Inhalation Toxicology. 2014;26(10):588-597.

3 Dey A, Kayal N, Chakrabarti O, Caldato RF, Andr CM, Guerra VG. Studies on permeability properties and particle capture efficiencies of porous sic ceramics processed by oxide bonding. Journal of Porous Media. 2015;18(9):861-872.

4 Zoccal JVM, Guerra VG, Gonçalves JAS. Avaliação do tempo de filtração no desempenho de filtros de acrílico e fibra de celulose (HEPA) na remoção de nanopartículas de óxido de níquel. In: Anais do XXXVI Congresso Brsileiro de Sistemas Particulados; 2013; Maceió, AL; 2013 Outubro 20-23. Maceió : Universidade Federal de Alagoas; p. 46.

5 Chinnasamy CN, Jeyadevan B, Shinoda K, Tohji K. Synthesis and magnetic properties of face-centered-cubic and hexagonal-close-packed Ni nanoparticles through polyol process. Journal of Applied Physics. 2005;97(10):10J309.

6 Chen DH, Hsieh CH. Synthesis of nickel nanoparticles in aqueous cationic surfactant solutions. Journal of Materials Chemistry. A, Materials for Energy and Sustainability. 2002;12:2412-2415.

7 Cempel M, Nikel G. Nickel: a review of its sources and environmental toxicology. Polish Journal of Environmental Studies; 2006;15(3):375-382.

8 Cavani A. Breaking tolerance to nickel. Toxicology. 2005;209(2):119-121.

9 Donovan RP. Fabric filtration for combustion sources. New York: Marcel Dekker Inc.; 1985. 426 p.

10 Chattopadhyay S, Hatton TA, Rutledge GC. Aerosol filtration using electrospun cellulose acetate fibers. Journal of Materials Science. 2016;51(1):204-217.

11 Zhang S, Shim WS, Kim J. Design of ultra-fine nonwovens via electrospinning of Nylon 6: spinning parameters and filtration efficiency. Materials & Design. 2009;30(9):3659-3666.

12. Wang J, Tronville P. Toward standardized test methods to determine the effectiveness of filtration media against airborne nanoparticles. Journal of Nanoparticle Research. 2014;16:2417.

13 Li LIN, Zuo Z, Japuntich DA, Pui DYH. Evaluation of filter media for particle number, surface area and mass penetrations. The Annals of Occupational Hygiene. 2012;56(5):581-594.

14 Swanson J, Watts W, Kittelson D, Newman R, Ziebarth R. Filtration Efficiency and Pressure Drop of Miniature Diesel Particulate Filters. Aerosol Science and Technology. 2013;47(4):452-461.

15 Hammond D, Fong GT, Cummings KM, O'Connor RJ, Giovino GA, McNeill A. Cigarette yields and human exposure: a comparison of alternative testing regiments. Cancer Epidemiology, Biomarkers & Prevention. 2006;15(1495):501.

16 Hubbard JA, Salazar KC, Crown KK, Servantes BL. High-volume aerosol filtration and mitigation of inertial particle rebound. Aerosol Science and Technology. 2014;48:530.

17 Hubbard JA, Brockmann JE, Dellinger J, Lucero DA, Sanchez AL, Servantes BL. Fibrous filter efficiency and pressure drop in the viscous-inertial transition flow regime. Aerosol Science and Technology. 2012 [cited 24 Sept 2018];46(2):138-147. Available at: http://www.tandfonline.com/doi/abs/10.1080/02786826.2011.616555.

18 Boskovic L, Altman IS, Agranovski IE, Braddock RD, Myojo T, Choi M. Influence of particle shape on filtration processes. Aerosol Science and Technology. 2005;39(12):1184-1190. http://dx.doi.org/10.1080/02786820500442410.

19 Barros PM, Rodrigues Cirqueira SS, Aguiar ML. Evaluation of the deposition of nanoparticles in fibrous filter. Materials Science Forum. 2014 [cited 24 Sept 2018];802:174-179. Available at: http://www.scientific.net/MSF.802.174

20 Kalayci V, Ouyang M, Graham K. Polymeric nanofibres in high efficiency filtration applications. Filtration. 2006;6:286-293.

21 Wang J, Kim SC, Pui DYH. Investigation of the figure of merit for filters with a single nanofiber layer on a substrate. Journal of Aerosol Science. 2008;39:323-334.

22 Sen Wang C, Otani Y. Removal of nanoparticles from gas streams by fibrous filters: a review. Industrial & Engineering Chemistry Research. 2013;52(1):5-17.

23 Wang J, Kim SC, Pui DYH. Figure of merit of composite filters with micrometer and nanometer fibers. Aerosol Science and Technology. 2008;42(9):722-728.

24 Bortolassi ACC, Guerra VG, Aguiar ML. Characterization and evaluate the efficiency of different filter media in removing nanoparticles. Separation and Purification Technology. 2016;175:79-86.

25 Hung CH, Leung WWF. Filtration of nano-aerosol using nanofiber filter under low Peclet number and transitional flow regime. Separation and Purification Technology. 2011;79(1):34-42. http://dx.doi.org/10.1016/j.seppur.2011.03.008.

26 Podgórski A, Balazy A, Gradon L. Application of nanofibers to improve the filtration efficiency of the most penetrating aerosol particles in fibrous filters. Chemical Engineering Science. 2006;61(20):6804-6815.

27 Yun KM, Hogan CJ, Matsubayashi Y, Kawabe M, Iskandar F, Okuyama K. Nanoparticle filtration by electrospun polymer fibers. Chemical Engineering Science. 2007;62(17):4751-4759.

28 Chen Y, Liu HY, Zhang ZJ. Characterization and morphology of composites prepared from polyacrylonitrile and silver nitrate. Applied Mechanics and Materials. 2010;26-28:159-162.

29 Kim J, Gao S, Yermakov M, Elmashae Y, He X, Reponen T, et al. Performance of electret filters for use in a heating, ventilation and air conditioning system and an automotive cabin against combustion and NaCl particles. Aerosol and Air Quality Research. 2016;16:1523-1531.

Received: 24 Sept. 2018
Accepted: 27 Feb. 2019