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Removal of Combustible volatile organic compounds (VOCs) using Polymetaphenylene isophthalamide Based Nonwoven Fabric (Nomex) Filters with Thin Layer of Activated Carbon

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Abstract

A cost-effective and rapid method has been developed for the removal of volatile organic compounds (VOCs) from gaseous emissions. This involved the use of a sandwich filter made of polymetaphenylene isophthalamide (Nomex) based nonwoven fabrics loaded with a thin layer of activated carbon. The optimum mass of activated carbon per unit area of the fabrics and fabric thickness are 2.89 mg/cm^2, and 4.8 mm, respectively. The air permeability of this filter is 0.5 $cm^3/cm^2/s$. The filter was incorporated in simple equipment provided with solid-state sensors to monitor the concentration levels of VOC before and after removal by the filters. Data transfer on 2G mobile phone networks performed using a General Packet Radio Service (GPRS) link and a Global System for Mobile Communications (GSM) network are used to provide internet access for mobile. Testing of the proposed filtration system design with the exhaust gases emitted from gasoline combustion engines reveals at least 95% removal efficiency of VOCs within 10 min.

*Keywords:*Removal of volatile organic compounds (VOCs), nonwoven fabric filters, filtration efficiency, activated carbon (AC), point source emissions;

1. Introduction

Volatile organic compounds (VOCs) are carbon-based chemicals group of more than 300 harmful compounds [1]. These are gases commonly emitted from variable liquid or solid organic compounds with high vapor pressure and low boiling point [2, 3]. VOCs are produces from both anthropogenic and natural emissions. Natural emissions of VOCs from terrestrial and marine ecosystems (biogenic VOCs) represent the highest proportion of atmospheric VOCs. Industrial activities and vehicular exhaust are the major anthropogenic sources of VOCs in urban areas [6, 7]. Fuels production, storage and transportation are main non-point emission sources of VOCs due to leakage and evaporation related processes. For example, an evaporative emission of 2.9 kg t^{-1} was reported at a liquid fuel service station [1]. Similarly, coal and natural gas production would also result in large VOCsemissions. The natural VOCs emissions were estimated to be about 8 folds as high as VOCs from anthropogenic emissions (1150 Tg C/year vis 142 Tg C/year) [8].

Atmospheric contamination with VOCs could lead to various health hazardous effects. Irritation of eyes, nose and throat, nausea, vomiting, liver damage and

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cancer have been reported [9]. Benzene, toluene, ethylbenzene, xylene (BTEX) and 1,2,4-trimethylbenzene are the major volatile compounds which compose about 60-90% of total VOCs [3, 4]. BTEX are used as an indicator for the evaluation of environmental quality levels and exposure to VOC [5]. The reaction of VOCs with other air pollutants (i.e. nitrogen dioxide and particulates) forms smog, which induce deleterious environmental and health-related problems [10, 11].

With the rapid development of modern technology, varieties of new materials for filtering air and pollutants removal, have been developed. Air filters-fiber materials including natural and synthetic fibers have been suggested. Natural fibers (e.g.,cellulose and cotton) are categorized into plant, animal and mineral-based fibers[12] whereas. synthetic fibers are classified into organic and inorganic fibers[13]. The organic synthetic polymer fibers include polyester, nylon (polyamide), polyaramid (e.g., Kevlar and Nomex), polyphenylene sulfide (PPS), polyethylene, polyacrylic, and polyimide (P84) [14].

In the present study, the filters were made of polyaramid fibers (Nomex) combined with strong adsorbing material (AC) for the removal of VOCs fromsome emission point sources. Polyaramid fibers are a class of heat-resistant and strong synthetic fiber to suit the present task. Nomex and Kevlar are Du Pont trademarks of fibers that belong to the polyaramid classification. Both polymeric fibers resist heat up to 177^{O}C, and can be used in heat resistant air filters [14].

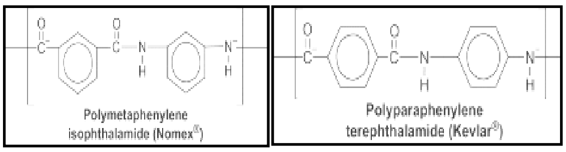


Figure (1): Structure of Nomex and Kevlar (Source: [14]).

Nomex is widely used in needle felt filter media for high temperature baghouse operations. It resists attackes by mild acids, mild alkalis, and most hydrocarbons. It has exceptional dimensional stability and will not stretch or shrink over 2% when exposed to temperatures up to 218^{O}C [14].

Activated carbon is the carbonaceous material which characterized by its large specific surface area, superior porosity, high physicochemical-stability, and good surface reactivity. It is widely utilized as functional materials for various applications [15]. Wood, coal, petroleum residues, peat, lignite and polymers are the traditional expensive and non-renewable materials commonly used for activated carbon production [16]. Considerable efforts have been dedicated to procure activated carbon from cost-effective and easily accessible substitutes, namely agricultural residues (i.e. rice husk, corn straw, bagasse) and solid wastes (i.e. sludge, food waste) [17].

This work aimed to construct a simple and efficient filtration device incorporating a nonwoven filters based on Nomex samples treated with activated charcoal. The influence of the nonwoven fabric material characteristics and the form and concentration of the activated charcoal to Nonwovens filters samples on the physical characteristics and mechanical properties as well as the filtration efficiency were studied and evaluated.

2.Experimental

2.1. Materials

2.1.1. Nonwoven filters

The tested nonwoven fabric samples were examined according to the international standards test methods as follows:

The fabric thickness of fabrics was tested using Standard Test Method for Thickness of Textile Materials (ASTM-D1777-96(2019)) and a thickness gauge, mass per unit area (weight) of fabrics was tested using Standard Test Method (ASTM-D3776 /D3776M-20) and an electronic balance, air permeability test was conducted using method (ASTM-D737), using Toyoseiki (JIKA) instrument. All tests were carried out on the “Nomex” fabric samples before and after applying the activated charcoal. The general characteristics of the used fabrics are shown in Table (1) Scanning electron microscopy-energy dispersive X-ray analysis (SEM-EDX) of the treated fabric was studied using high-resolution scanning electron microscopy (SEMQuanta FEG 250 with field emission gun, FEI Company − Netherlands).

Table 1

Characteristics of the used nonwoven Nomex fabric

Parameter	Fabric specifications
Fibre type	Nomex
Weight	9.26 - 10.83 g
Thickness	4.40 - 4.80 mm
Air permeability	0.498 - 7.68 L/m^2.S

2.1.2. Activated carbon specification

Characteristics of the used activated carbon Table 2.

Table 2

Characteristics of the used activated carbon

Properties	Specification
Particle size 300 mesh	Min. 60%
Acid soluble	2.5%
Water soluble	1.5%
Moisture (105°for 2 hours)	5.0%
Ash	2.5%
pH value	6.0 to 7.5
Methylene blue adsorption	Min. 18 ml/0.1 g

2.2. Methods

2.2.1. Activated carbon

Activated carbon was heated in a drying oven at 60 ^{0}C for 24 hour, and then transferred to a desiccator until testing start.

2.2.2. Preparation of VOC filters

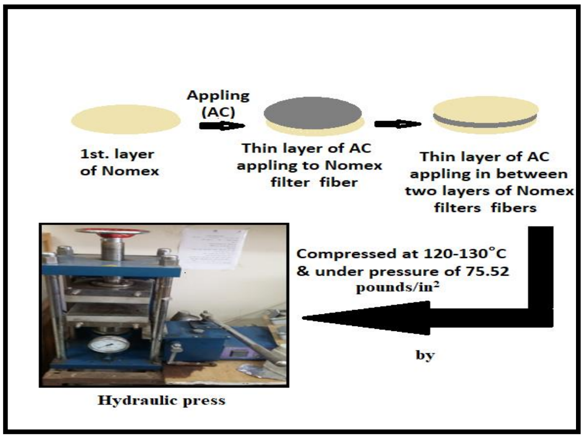


Fig. 2. A diagram showing the preparation steps of the sandwich filters

Characteristics of the filter fabric material before and after inclusion of activated carbon were tested. Fabricsof varied in weights from (9.26 to10.83g), thickness (4.4 to 4.8 mm) and in air permeability from (0.498 to 7.68 cm^3/m^2.s) are depicted in Table2. Also, The activated carbon LR was also in terms of characterized specifications of particle size content (300 mesh), acid solubility, water solubility, moisture content, ash content, pH value and methylene blue adsorption (0.15% solution) are depicted in Table3.

Compression molding technique was used for evaluation of the prepared filters in hydraulic press shown in Fig. (2)

Different four selected weights of activated carbon (250, 500, 750, 1000 mg) was placed between two layers of 10.5 cm nonwoven Nomex fabrics 10.5 cm diameter and 4.40 - 4.80mm thickness and heated at temperatures of 120-130^{O}C and under pressure of 75.52 pounds/in^2. Fig. (4) Shows the filter before and after inclusion of activated carbon.

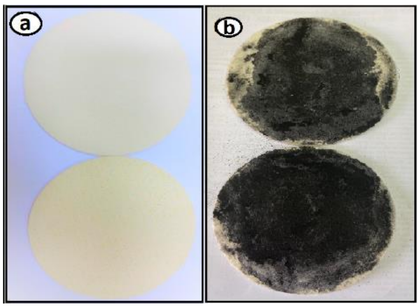


Fig. 3. Nomex filters: (a) before and (b) after addition of activated carbon (inner and outer layers), (b) inner layer of

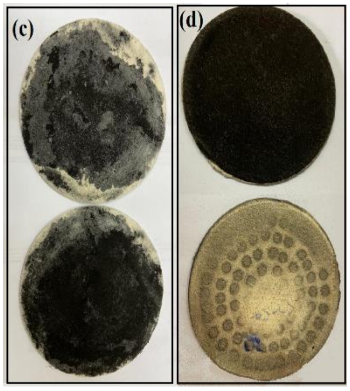


Fig. 4. Nomex filter (10.5 cm diameter) treated with 1000 mg activated carbon after filtration: (c) filter inner layer (d) filter outer layer.

2.4.Efficiency of VOC filtration using a nonwoven Nomex fabric /activated carbon

The efficiency of the prepared sandwich fabrics filter and the reliability of the used device were examined. The flow rate, pressure drop and cleaning efficiency were investigated. A simple homemadelow-cost apparatus with durable fabrics and without any failure was designed for the evaluation of the filtration efficiency.

The apparatus (Figures 5 and 6) consists of:

1- Gas inlet; 2- Converter; 3- Gas ducting sensors; 4- Filter sample holder; 5- Differential pressure gauge;

6- Vacuum pump (low speed); 7- Vacuum pump (high speed); 8- Air compressor; 9- Gas outlet; 10- Dust feed inlet; 11- Gases source; 12- Flexible joint; 13-Δp controller (differential pressure gauge).

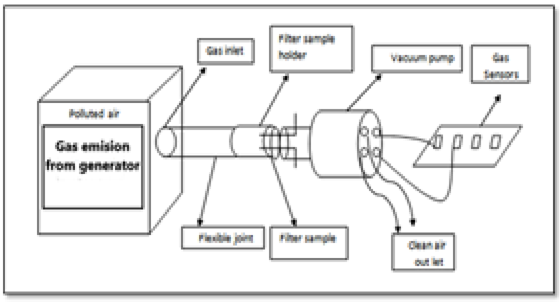


Fig. 5. Schematic diagram of filtration efficiency testing device

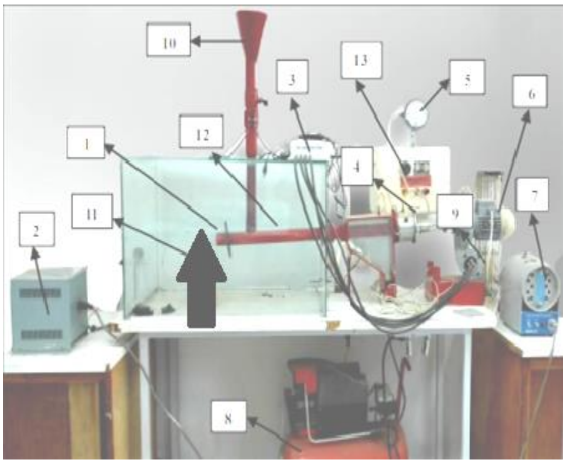


Fig. 6. Filtration efficiency testing device

The device was provided with solid-state gas sensors purchased from Alphasense Ltd, Great Notley, UK to monitor the ppm concentration levels of carbon monoxide (CO), carbon dioxide (CO_2) and volatile organic compounds (VOCs). The sensors convert the adsorbed gases concentrations into an electrical signal by changing resistivity. The Gases Monitoring System (GMS) is an IOT (Internet of Things) based system for monitoring the concentration of gases and odors. CO, CO_2 and ETO (Electrical-Thermal-Optical sensor) were considered as an indication for VOCs odor. Gases and odor concentration used to measure the efficiency of textile filters. Air sampler unit was also attached with a pressure meter to adjust airflow rate through the tested fabric. In the current study, the airflow rate was adjusted to 10 l/min.

2.4.1. Test method

The examined filter sample was placed in the designed holder in the vacuum chamber, which receives the combustion exhaust emitted gases from the generator. The emissions were fed to the filtration apparatus through a tube line at a controlled flow rate. A vacuum pump draws air and the contaminated gas was allowed to pass through the nonwoven filter fabric. To detect the presence of multi gases in the emissions, each type of sensor was used separately for measuring the concentration of concerned gas. The concentration of gas (ppm) passed through the filter was monitored and recorded. Examining the filtration efficiency of the filter can be determined by using the following formula:

Filtration efficiency (E %) = N_1- N_2/N_1 **x** 100

Where, N_1 and N_2 are the concentrations of inlet gas before filtration and outlet gas after filtration, respectively.

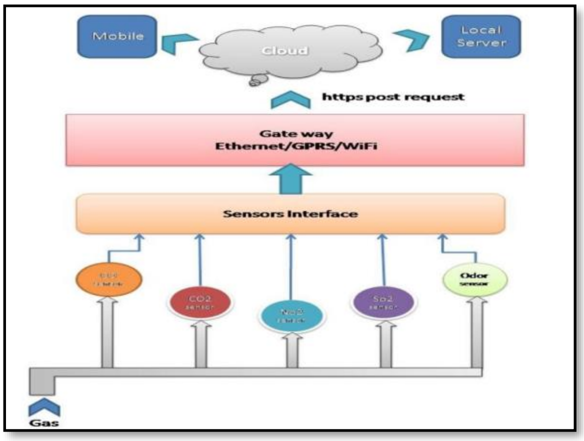


Fig. 7. A diagram of the used gas monitoring system (GMS)

The emissions were passed through the sensors and allowed to interact with an electronic circuit attached to the sensors to read the potential output and converted it from electric signal to ppm concentration values.

A General Packet Radio Service (GPRS) link was also used to allow data transfer on 2G mobile phone networks.

A Global System for Mobile Communications (GSM) network was also used to provide internet access for mobile.

This link can be used to send the results using https post to the server.

The data was validated using security keys and stored in a database application, which was used to retrieve and display data from the database.

Retrieved data can be plotted against time or exported in a comma-separated values file (CSV format), which allows data to be saved in a tabular format and shared using mobile connectivity programs. Figures 7 and 8 displayed the gas sample collection and the data flow

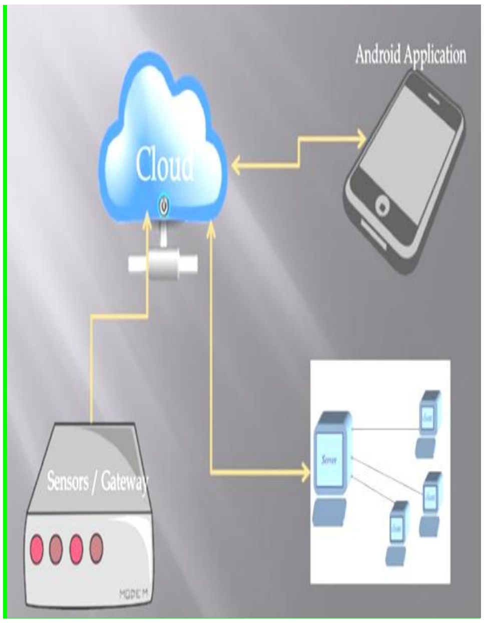


Fig. 8. Data flow.

The concentration range of measurements of the used sensors are range CO 0 to 1000 ppm, **C**O_2 0 to 2000 ppm and VOCs “ETO” 0 to 200 ppm.

3. Results and discussion

The VOC filtering behavior of nonwoven Nomex filters treated with different weights of activated carbon (250, 500, 750 and 1000 mg/filter) were tested.

3.1. Characterization of nonwoven fabrics treated with activated carbon:

3.1.1. Scanning electron microscopy (SEM) and energy dispersive X-Ray (EDX)

Scanning electron microscopy-energy dispersive X-ray analysis (SEM-EDX) technique was used to provide a quick nondestructive determination of the elemental identification and quantitative composition of the sample.

The purpose of EDX in the current study was to confirm the existence of the coated activated carbon (AC’s), as well as the elemental characterization of the test gas emission molecules (VOCs, CO_2, SO_2& NO_2) from benzene generator computation.

The EDX spectra of the Nomex fabric before addition of activated carbon and for filter coated with activated carbon before the filtration process are shown in Figures (9, 10 & 11).

The morphology of nonwoven fabrics before addition of activated carbon has smooth surface with normal structure (Figure 9) for both the inner and outer surfaces.

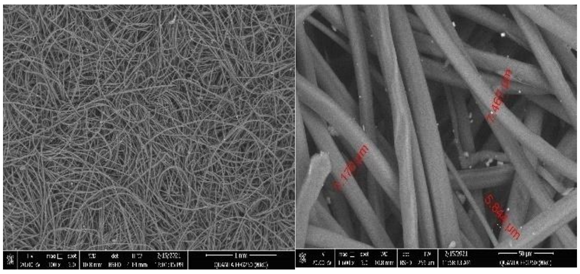
Although the morphological structure after addition of activated carbon on the inner surface of the fabric filter shows a uniform distribution of activated carbon granules within most or all parts of the fabric filter, few irregular shape of activated carbon granules are detected in some other parts (Figure 10).

After the filtration process, few irregular activated carbon granules were detected on the inner and outer filter surfaces. These irregular granules were agglomerated and attached to the fibers during the filtration process (Figure 11).

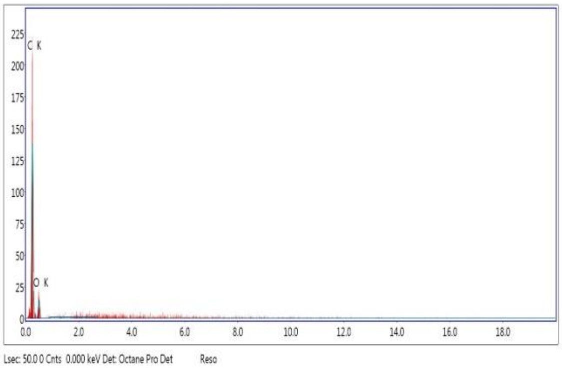
EDX elemental examination reveals that the dominant elements composition of inner and outer surfaces of the blank filter before addition of activated carbon are carbon and oxygen.

Similarly, carbon and oxygen elements were the main contents of filters after addition of activated carbon.

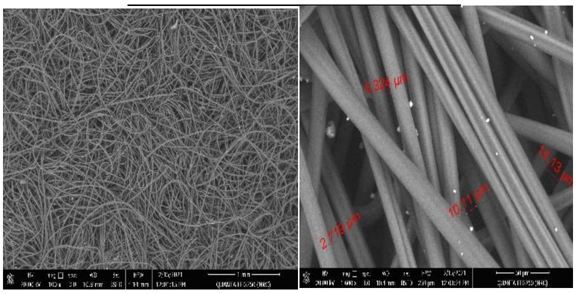
After VOC filtration process, EDX shows other elemental composition assigned to nitrogen, silicon, calcium and sulphur elements in minor contents compared to the dominant carbon and oxygen elements.



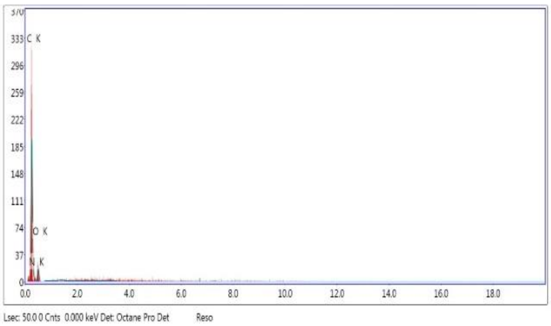
Inner



Element	Weight %	Atomic %
C K	77.5	82.1
O K	22.5	17.9

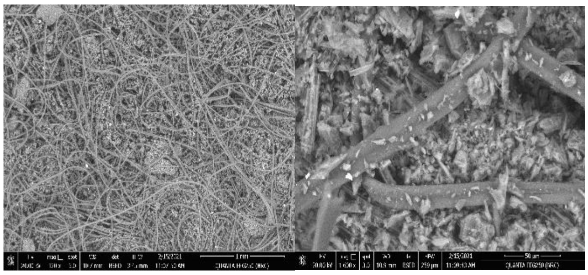


Outer

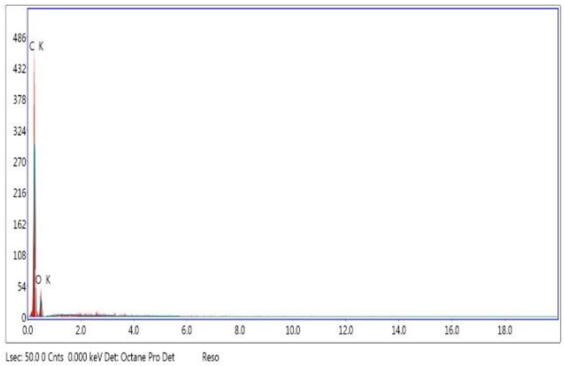


Element	Weight %	Atomic %
C K	65.85	70.81
N K	14.11	13.01
O K	20.04	16.18

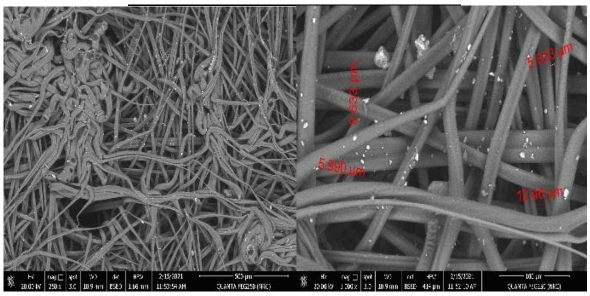
Fig. 9. SEM and EDX of blank Nomex filter before treatment with activated carbon



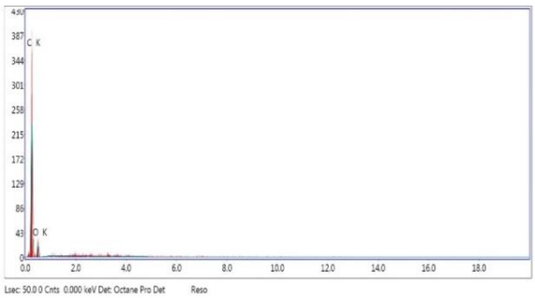
Inner



Element	Weight %	Atomic %
C K	78.96	83.33
O K	21.04	16.67

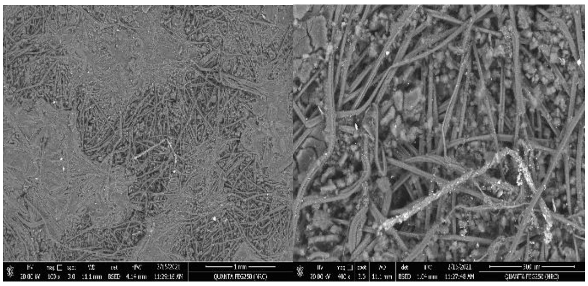


Outer

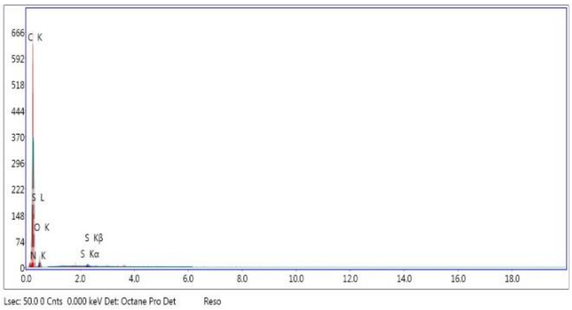


Element	Weight %	Atomic %
C K	77.77	82.33
O K	22.23	17.67

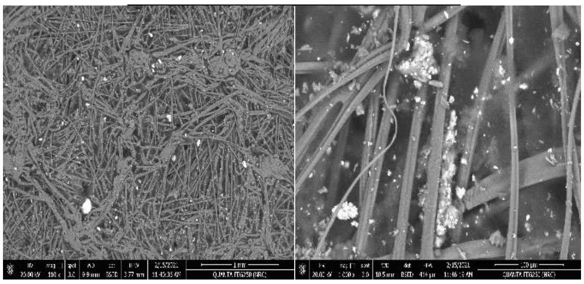
Fig. 10. SEM and EDX of Nomex filters coated with activated carbon before VOC filtration



Inner



Element	Weight %	Atomic %
C K	82.94	86.49
N K	3.03	2.71
O K	13.55	10.61
S K	0.48	0.19



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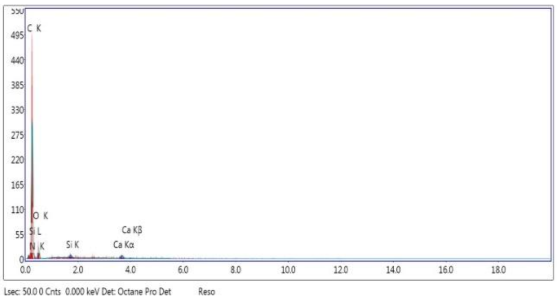

Element	Weight %	Atomic %
C K	74.59	79.53
N K	6.48	5.93
O K	17.54	14.04
Si K	0.42	0.19
CaK	0.97	0.31

Fig. 11. SEM and EDX of Nomex filters coated with activated carbon after VOC filtration

3.2. Mass of activated carbon per filter unit area:

Mass of activated carbon (mg) per filter unit area (cm^2) and weight of activated carbon (mg)/area of filter (cm^2) were shown in Table (3). Nomex filters of 10.5 cm diameter were treated with 250, 500, 750 and 1000 mg of activated carbon and used for VOC filtration. Masses of carbon per unit area are 0.72, 1.44, 2017 and 2.89 (mg/cm^2), respectively.

Filter area = 3.14 r^2 (where r = 10.5)

Table 3

Mass and mass per unit area of activated carbon on the filter

Mass of activated carbon (mg)	Mass of activated carbon per unit area (mg/cm2)
0	0
250	0.72
500	1.44
750	2.17
1000	2.89

3.3. Filter fabric thickness

The thickness of each Nomex filters treated with 250, 500, 750 and 1000 mg of activated carbon were measured and found to be 4.47, 4.60, 4.68 and 4.80 mm, respectively. Thickness of the blank filter (0.0 mg carbon) was 4.4 mm. Figure 12 shows a linear increase of filter thickness with the increase of activated carbon mass in filter, with good positive correlation ($R^2 = 0.9923$). This indicate the formation of a uniform and homogeneous distributed of activated carbon on the surface of fabric filter under the applied temperature and pressure used for filter preparation.

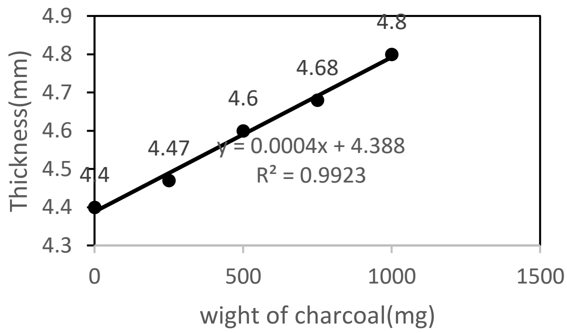

Fig. 12. Filter thickness as a function of applied activated carbon mass

3.4. Filter air permeability

The measured permeability of Nomex filters treated with 0, 250, 500, 750 and 1000 mg of activated carbon were 7.62, 6.61, 2.57, 0.93 and 0.5 $cm^3/cm^2/s$, respectively. Figure (13) shows a decrease of the filter air permeability with the increase of the mass of activated carbon. The negative correlation was high (R^2=0.9226) probably due to the high density of carbon, which reduces the airflow across the filter fabric.

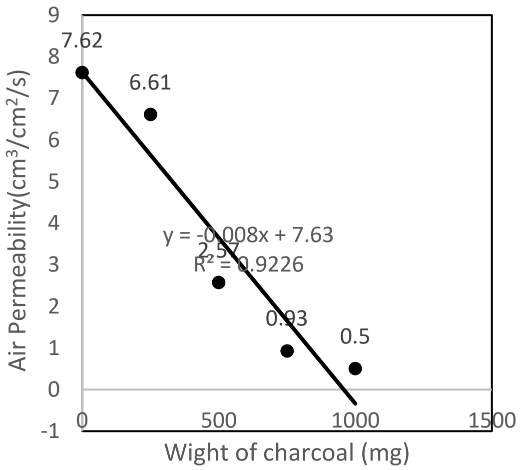

Fig. 13. Effect of activated carbon mass on filter air permeability

3.5. Filtration efficiency measurement

The filter efficiency was tested by measuring VOC concentration (ppm) passing in and out of the filtration system incorporating nonwoven Nomex fabrics. Under optimized conditions, more than 95% of VOC was removed from an airflow.

3.5.1. Effect of time on the rate of VOCs filtration

Figure (14) shows the VOC removal as a function of time over 15 minutes. The VOC emissions were allowed to pass through the designed filter and the average concentration of VOC in ppm was monitored and recorded. The results showed that VOC concentrations passed out from the filter were gradually decreased with time until reaching a steady state after 10 minutes upon using filters loaded with activated carbon compared with the control filters. This indicated that the filtration efficiency of the used filters increased with the increase of the activated carbon dose on the filter during the first 10 minutes and became stable after that.

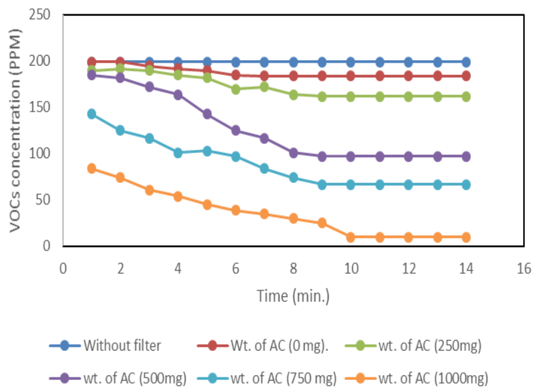

Fig. 14. Change of VOCs concentration with time during the filtration process

3.5.2. Effect of activated carbon (AC) mass on VOCs removal

It can be seen that VOCs concentration was decreased with the increase of the loaded activated carbon mass of the filters. The percentage reduction in VOCs concentration at the end of the test compared to the started concentration for different filter types was in the order of:

(1000 mg > 750 mg > 500 mg > 250 mg activated carbon per filters, with a percentage of 12%, 46%, 52% and 85%, respectively (Figure 15).

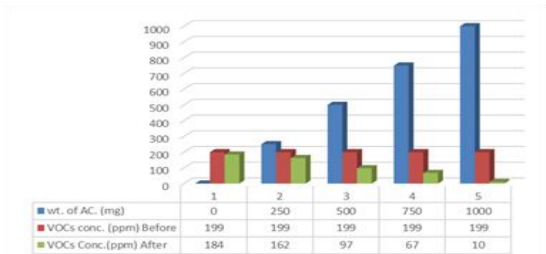

Fig. 15. Change of VOCs concentration with increase the mass of activated carbon.

Compared to control filter, VOCs concentration was decreased with approximately 9%, 51%, 66% and 95% by using 250, 500, 750 and 1000 mg/filter of activated carbon, respectively. This is probably due to the increase of the specific filtration surface area (SFSA), as well as the increase of filtration efficiency (Figure 16).

Table 4 One-way ANOVA for the effect of activated carbon mass on VOCs filtration.

Outlet emissions	Activated carbon, weight (mg)/Filter					Main effects	
VOCs concentration	0	250	500	750	1000	F-ratio	p-level
	1.8433E2	1.6200E2	97.00	69.00	10.00	4.575E3	0.00*

Table 5 Performance of some types of VOCs filters

Filter type	Conditions of prepared filter and comments	VOCs removal efficiency	Reference
Two layers (sandwich) of Nomex fabrics (diameter 10 cm) treated with 1.0 g activated carbon	temperatures of 120-130^{O}C and under pressure of 75.52 pounds/in^2	95%	Current study
Self-supporting bifunctional conjugated microporous polymers membrane	20 ◦C, RH: 23.7%, membrane pressure difference: 0.1–1.0 kPa	95%	[12]
Metal-organic framework coated electret filter media	the MOF particles (MIL-125-NH2, UiO-66-NH2 and ZIF67) coating, 5, 10 and 25 wt% of the mass of the MERV 13 and HEPA media	74% - 85%	[18]
Combining air pollution control devices and modified Fly ash	to achieve the maximum removal condition,the operating tempreture should be as low as possible(≥105◦C)	40% - 80%	[19]

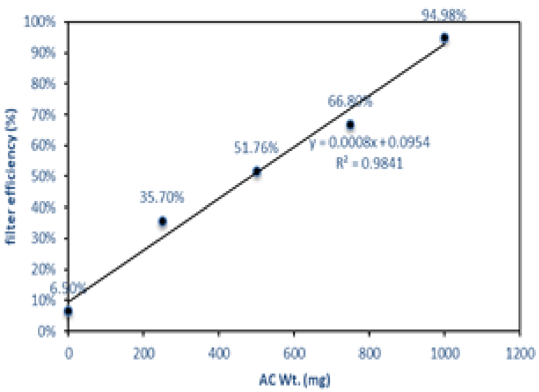

Fig. 16. Effect of activated carbon mass on the filter efficiency

3.6. Statistical analysis

Functional performance of the nonwoven Nomex filter samples related to their properties and gas filtration effectiveness was statistically analysed using post-hoc Duncan test (P=0.05). Concerning the properties of the nonwoven filters, it was found that the increase of the loaded activated carbon mass had better filtration enhancement. This may be related to the increase of the surface area of the filter and consequently more VOCs adsorption. One-way ANOVA statistical analysis (Table 4) shows high significant effects of activated carbon mass on the filtration efficiency, which was confirmed by the decrease of VOCs concentrations in filter effluent upon using higher activated carbon mass.

4. Conclusion

For decades, the importance of air filtration has increased to eliminate the increased levels of air pollutants and avoid deleterious effects on human health and environment.. Nonwoven filters are widely used in air filtration applications due to their distinctive advantages characteristics. The present work aimed to investigate the effectiveness of polymetaphenylene isophthalamide (Nomex) based nonwoven fabrics loaded with thin layer of activated carbon for VOC removal. The influences of various experimental parameters were examined. Under optimized conditions, the present proposed system offer many advantages in terms of simplicity and efficiency compared with many of those previously described. (Table 5)

5. Conflicts of interest

There are no conflicts to declare.

6. References

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