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Development of activated carbon fabric filter for controlling particles and gaseous emissions of indoor carbonaceous aerosols

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A fabric filter media has been developed using polyester thermal bonded nonwoven fabric with activated carbon to battle indoor pollution. The effect of fabric weight (g/m^2) and type and sizes of activated carbon on the performance of filter media has been studied. The fly ash dust (1 µ-10 µ) and gaseous emissions from the diesel engine are separately passed through the filter media, and their capturing ability is measured. The concentration of particulate matter decreases with the increase in fabric weight (GSM) and the reduction in granular activated carbon size. The adsorption of gases increases as the size of granular activated carbon decreases.

Keywords: Carbonaceous aerosols, Granular activated carbon, Indoor air pollution, Particulate matter, Polyester thermal bonded fabric filter

Introduction

Building occupants are exposed to several hundreds of pollutants in indoor environments. In rural areas, wood, plant leaves, and agricultural and cattle livestock by-products are used for cooking, heating, mosquito control, religious worship, etc. All these are the sources of carbonaceous aerosol. Due to its detrimental effects on human health and its possible influence on the atmosphere, the burning of household fuels is a significant issue[1]. Combustion of household fuel releases smoke, an essential contributor to air pollution that impacts various aspects of the surrounding environment[2-3], atmospheric chemistry[5], human health[6,7], and climate change. A significant amount of the worldwide disease burden and death in rural and undeveloped countries are caused by burning smoke from domestic fuels[8,9] . Carbonaceous aerosol (BC and OC) is a component of smoke from burning household fuel. These compounds are known carcinogens and mutagens, such as polycyclic aromatic hydrocarbons (PAHs) and their alkylated homologues[10]. Moreover, it affects the balance of atmospheric radiation, which may change local rainfall patterns.

A gas or liquid containing solids is separated physically through porous fabrics called fabric filters, which hold the solids. The fabric filter system would efficiently reduce waste disposal issues. The performance of a filter medium suitable for indoor air is assessed by considering the following: filtration efficiency, microorganism resistance, pressure drop, mechanical strength, environmental impact, and fire resistance.

Activated carbon is a solid and porous material, and it is the most common adsorbent in HVAC systems[11,12]. It is commonly made in a two-step process. First, the carbonaceous material is decomposed by heating until all organic compounds except carbon are volatilized. Then, the carbon is activated with steam or carbon dioxide at a high temperature of (700-1100°C). Activated carbon can originate from different sources, such as wood, coconut, peat, coal, sawdust and cellulose residues[13]. Activated carbon has a large surface area and pore volume, making it a suitable medium for removing volatile organic compounds (VOC)[14]. Generally, activated carbon is produced in different forms, including powders, cylindrical, spherical beads, fibres and granules that can be used in air-cleaning systems[12,15]. Activated carbon is hydrophobic and organophilic. It comprises primarily neutral carbon atoms with no electrical gradient between molecules.

Therefore, due to the non-polarity of the carbon surface, carbon adsorbents tend to adsorb nonpolar compounds rather than polar[16]. The porous structure is the most important property of activated carbon. The adsorption capacity and dynamic adsorption rate of activated carbon depend on the pores' total volume,

size and shape. The pore structure parameter can be better defined in two ways. Firstly, the surface area increases the number of adsorption centres, increasing the probability of gas molecule absorption. Secondly, pore and micropore volume benefit the adsorption of gas molecules[13]. Two major activated carbons are used in indoor air control: (i) activated carbon from coconut shells and (ii) activated carbon from coal.

An in-duct ventilation filter is a promising technology for reducing the level of indoors pollutants. In this study, an attempt has been made to reduce and manage the carbonaceous aerosols in the indoor environment by using fabric filters with activated carbon. The air filter media was developed using polyester thermal bonded non-woven fabric with granular activated carbon. The effect of fabric weight (g/m^2), types and sizes of activated carbon on filtration performance was studied.

Experimental Section

Specification of materials

The main objective of this experimental work was to develop a filter media using polyester thermal bonded nonwoven fabric with granular activated carbon to study the performance of activated carbon filters on the removal of particulate matter from carbonaceous aerosols. Thermal bonded polyester non-woven fabric with three different fabric weights ie GSM (g/m^2), two types of activated carbons (coconut shell and coal based), mixtures composition of 50:50 percentages (i.e., coconut shell and coal based) and their sizes (300, 355, and 425 µ) are used for sample preparation as shown in Table 1.

Research methodology

A total of 15 samples were prepared as per the Box-Behnken experimental design as shown in Table 2 and all samples were tested for various particulate and gaseous adsorption and filtration properties.

Preparation of granular activated carbon fabric filter media

The filter media, composed of polyester thermal bonded non-woven, granular coal-based, coconut shell-based activated carbon, and a mixtures (50:50) of the above two types, were prepared. The coconut shell-based and the carbon-based activated carbon with a mesh size of 8/30 were crushed in a grinder to obtain various size distributions used in the experiments. The crushed granular activated carbon was sieved with BS mesh of 36, 44, and 52 to get the required size distributions used in the experiments. The non-woven sample and granular activated carbon with known proportion (60% of the fabric weight) were combined with an acrylic binder (Ethyl methacrylate) in low quantities to guarantee the activated carbon and non-woven fabric sample cohesion.

Table 1 — Specifications of thermal bonded non-woven fabrics

Materials Parameters	Thermal-bonded polyester non-woven fabric		
Fabric weight (g/m^2)	20	35	50
Fabric thickness (mm)	0.157	0.293	0.325
Pore size (µ)	85.938	78.711	68.962

Table 2 — The Box-Behnken experimental design

Sample No.	Fabric weight (g/m^2)	Granular activated carbon size (µ)	Granular activated carbon types and their mixtures
S1	20	300	Coconut shell
S2	20	425	Coconut shell
S3	20	355	Coal based
S4	20	355	Mixture (Composition of 50:50 %, Coconut shell and coal based
S5	35	300	Coal based
S6	35	425	Coal based
S7	35	300	Mixture (Composition of 50:50 %, Coconut shell and coal based
S8	35	425	Mixture (Composition of 50:50 %, Coconut shell and coal based
S9	35	355	Coconut shell
S10	35	355	Coconut shell
S11	35	355	Coconut shell
S12	50	300	Coconut shell
S13	50	425	Coconut shell
S14	50	355	Coal based
S15	50	355	Mixture (Composition of 50:50 %, Coconut shell and coal based

Measurement of fabric thickness

The thickness of the non-woven sample was measured by DIN EN ISO 5084 standards. A testing load of 0.5 KPa was used for the measurement.

Measurement of pore size in the non-woven fabric

The ASTM standard test method F316 was followed to measure the pore size distribution, minimum, maximum, and average pore sizes in microns using a capillary flow parameter. The wetted sample's maximum pore size was determined at the pressure at which the flow was first noticed. The

mean flow pore size was found when 50% of the dry curve crossed the wet curve. The point at which the wet and dry curves combined yielded the minimum pore size. Wet-up/dry-up testing was done.

Testing of filter media performance

The filtration instrument shown in Fig. 1 consists of the following parts: dust feeder assembly, upstream chamber, downstream chamber, humidity and temperature sensing probe, differential pressure tapings, pulsing nozzle and temporary storage tank, specimen window, specimen frame, HEPA filter, etc.

The whole set-up is divided into two parts by the test specimen. The test specimen is placed on the specimen frame and clamped on the specimen window. Two pressure sensors (placed symmetrically) are provided on either side of the test specimen to measure its pressure differences. The humidity and temperature sensing probe senses the temperature and pressure of the air and gives the data to the computer. The ongoing process can be observed through a fixed transparent window and a weatherproof light provided on the upstream side. On the clean side, the window is openable to mount the test specimen. The clean air from the downstream chamber is drawn through a HEPA (High-efficiency particulate air) arresting filter assembly by a blower. The valve provided can be used to manually adjust the flow rate in case the blower cannot provide the required flow. Before the HEPA filter assembly, a tube connection is given from the outlet of the downstream chamber to the dust analyzer "Promo 2000" (Light-scattering aerosol spectrometer system) for measuring the particle sizes. The operational conditions used for the experimental work are given in Table 3.

Testing of adsorption of exhaust gases by using a gas analyser

The experimental setup consists of a single-cylinder water-cooled diesel engine, which was used to generate various gaseous exhausts. The fuel supply system consists of a burette flow meter, which was used to measure the volumetric fuel consumption. For NOx, CO, CO_2, O_2, and HC measurements, model AVL DIGAS 4000 Light gas analyzer (M/s AVL India Pvt. Ltd., Gurgaon, India) was used. The experimental set-up consisting of all the above-mentioned devices was arranged as shown in Fig. 2. The sample was fixed on the sample holder, which is made of cast iron, as shown in Fig. 3 and lastly, the gas was passed through the gas analyzer machine for gaseous emission testing.

Table 3 — Operational conditions of flat media filtration equipment

S. No.	Test conditions		Test dust	Duration of test
1.	Face velocity	1 m/min	Indoor carbonaceous aerosols like fly ash (1µ-10µ)	60 min per sample
2.	Dust concentration	0.12 g/m³		
3.	Dust feed	1.2 g/min		
4.	Pulse-jet tank pressure	2 bar		
5.	Filter Area	900 cm^2		

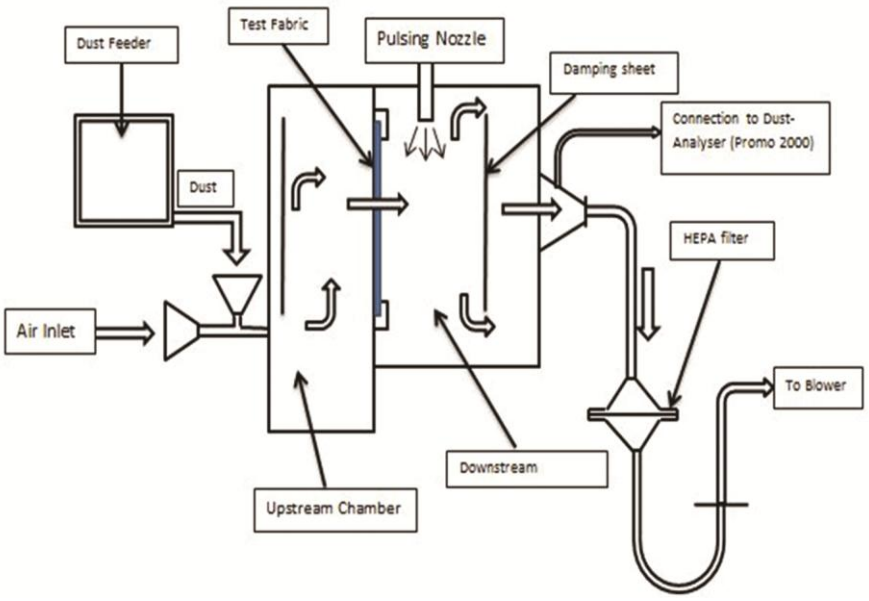

Fig. 1 — Schematic diagram of the filtration instrument setup

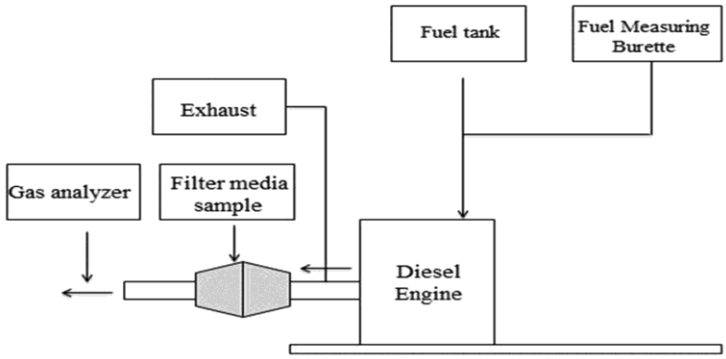

Fig. 2 — Schematic diagram of experimental set-up for gas testing

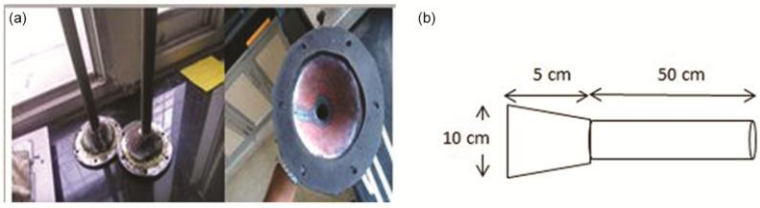

Fig. 3 — (a) Photograph and (b) diagram of the sample holder

Table 4 — Specifications of AVL DIGAS 4000 LIGHT gas analyser[17]

Types of gas	Measurement Range	Resolution
CO	0-10 % vol.	0.01% vol.
CO_2	0-20% vol.	0.1%
HC	0-20,000 ppm	1 ppm
NOx	0-5000 ppm	1 ppm

The first reading was recorded after 15 min and then the remaining four readings at an interval of 2 min were taken to determine the performance of granular activated carbon filter media against engine exhaust emission using a diesel engine. The engine was first run on diesel under no load conditions. A time of 20 min was given to warm up the machine. The detailed specifications of the exhaust gas analyzer are shown in Table 4.

Results and Discussion

Effect of filter media fabric weight, activated carbon types and sizes on the characteristics of particulate matter at the downstream side/clean side

Fig. 4 shows the influence of thermal bonded non-woven fabric weight (GSM), granular activated carbon type, and granular activated carbon size on the number and mass concentration of particulate matter, $PM_{2.5}$, and PM_{10} emissions from filter media. It is observed from Fig. 4 that on the clean side/downstream side, the particle concentration steadily decreases with an increase in fabric weight (g/m^2). It is also observed that the concentration of particulate matter also increases with an increase in the granular size of activated carbon. However, the concentration of particulate matter in the filtrate is not significantly influenced by the type of activated carbon. An analysis of variance (ANOVA) was carried out to find the effect and contribution % of different parameters on particle emission and is given in Table 5.

It is observed from Fig. 4 that as the fabric weight increases, the number and mass concentration of particles, $PM_{2.5}$, and PM_{10} emissions decrease significantly. This may be due to the more extended torturous pathway for the particles to follow because of the higher weight and thickness of the fabric. It is also evident from the ANOVA (Table 5) that the fabric weight is the primary parameter of the filter that significantly influences the concentration of particulate matter in the filtrate. The concentration of particulate matter and $PM_{2.5}$ increases with increasing the size of activated carbon granules. However, PM_{10} is not significantly influenced by the size of activated carbon. It envisages that reducing the size of activated carbon granules influences only the capture of small particles, while the capture of larger particles remains unaffected. As the granule size of activated carbon decreases, the total surface area increases and the pore size of the filter media decreases, thereby increasing the capture of minor particulate matter. However, the

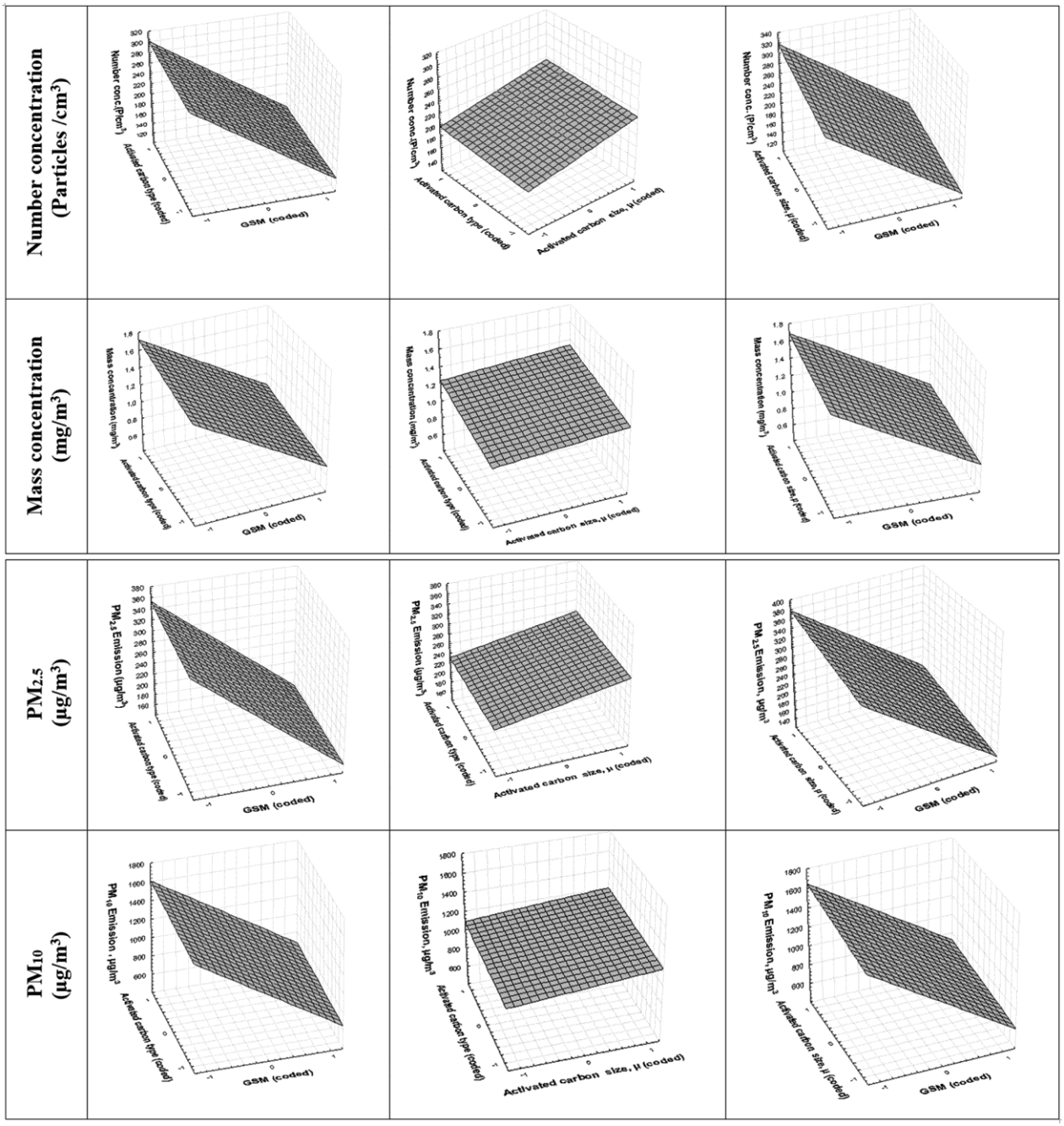

Fig. 4 — Effect of fabric weight, activated carbon types, and sizes of the filter on particulate matter emission characteristics

Table 5 — ANOVA for particulate matter characteristics

Effect	Sum of square	Degree of freedom.	Mean square	F Calculated	F Table	% Contribution
			For number concentration			
GSM	40548.72	2	20274.36	123.9629	4.46	91.84 %
Activated carbon size	2060.20	2	1030.10	6.2983	4.46	4.66 %
Activated carbon type	32.50	2	16.25	0.0994	4.46	0.073 %
Error	1506.9	8	163.55			3.41 %

(*Contd*.)

Table 5 — ANOVA for particulate matter characteristics (*Contd*.)

Effect	Sum of square	Degree of freedom.	Mean square	F Calculated	F Table	% Contribution
		For mass concentration				
Fabric weight, GSM	1.024931	2	0.512465	9.821183	4.46	63.82 %
Activated carbon size	0.076849	2	0.038425	0.736392	4.46	4.78 %
Activated carbon type	0.086655	2	0.043327	0.830353	4.46	5.39 %
Error	0.417437	8	0.052180			25.99%
		For $PM_{2.5}$ emission				
GSM	56413.59	2	28206.80	259.7804	4.46	93.15 %
Activated carbon size	2829.72	2	1414.86	13.0306	4.46	4.67 %
Activated carbon type	445.12	2	222.56	2.0498	4.46	0.73 %
Error	868.64	8	108.58			1.43%
		For PM_{10} emission				
GSM	1179320	2	589660.1	16.85274	4.46	77.22 %
Activated carbon size	56810	2	28404.9	0.81182	4.46	3.72 %
Activated carbon type	11097	2	5548.3	0.15857	4.46	0.73 %
Error	279912	8	34989.0	-	-	18.3%

Table 6 — ANOVA for gas adsorption of filter media

Gas	Effect	Sum of square	Degree of freedom	Mean square	F calculated	Ftable	% Contribution
CO	GSM	0.000010	2	0.000005	11.22028	4.46	15.87 %
	AC size	0.000041	2	0.000020	44.18881	4.46	65.07 %
	AC type	0.000008	2	0.000004	8.70280	4.46	12.69 %
	Error	0.000004	8	0.000000			6.34%
CO_2	GSM	0.048523	2	0.024261	10.52459	4.46	25.19 %
	AC size	0.094606	2	0.047303	20.52014	4.46	49.11 %
	AC type	0.031038	2	0.015519	6.73218	4.46	16.11 %
	Error	0.018442	8	0.002305			9.57 %
HC	GSM	0.230042	2	0.115021	1.00348	4.46	5.26 %
	AC size	2.827189	2	1.413595	12.33268	4.46	64.66 %
	AC type	0.397720	2	0.198860	1.73492	4.46	9.09 %
	Error	0.916975	8	0.114622			20.97 %
NOx	GSM	10.18269	2	5.09135	10.18269	4.46	15.98 %
	AC size	40.55769	2	20.27885	40.55769	4.46	63.67 %
	AC type	8.95192	2	4.47596	8.95192	4.46	14.05 %
	Error	4.00000	8	0.50000			6.28 %

size of the activated carbon shows a more negligible impact on the concentration of particulate matter in the cleaned air. The type of activated carbon does not significantly influence the capturing of particulate matter. It is observed that among all the samples, S12-S15 show a relatively lower concentration of particulate matter in the cleaned air because of higher GSM, i.e. fabric media weight.

Adsorption characteristics of the activated carbon fabric filter media against gaseous emissions of carbonaceous indoor aerosols

The adsorption characteristics of granular activated carbon filters against various carbonaceous indoor aerosols are studied. Fig. 5 gives the effect of various filter media parameters, such as fabric weight (GSM), granular activated carbon type, and granular activated carbon size, on the treatment of diesel gas exhaust, such as CO, CO_2, HC, and NOx. It is observed from the figures that, irrespective of the gases, the adsorption of gas increases linearly as the size of granular activated carbon decreases. The size of activated carbon greatly influences the adsorption of gases. Decreasing the size of activated carbon will increase the total surface area available for gas adsorption; hence, it absorbs more carbonized aerosols. The number of pores and pore volumes are essential parameters for the adsorption of gas particles.

It is also observed from the figure that the adsorption of gases increases a little as the GSM of the filter increases. The type of activated carbon also slightly influences the adsorption of gas. The contributions of GSM and type of activated carbon are 5–15%. and 9–16%, respectively. ANOVA was conducted to find the effects and contributions of the different parameters (Table 6). It is also observed that among all the samples, S2, S6 and S13 show the

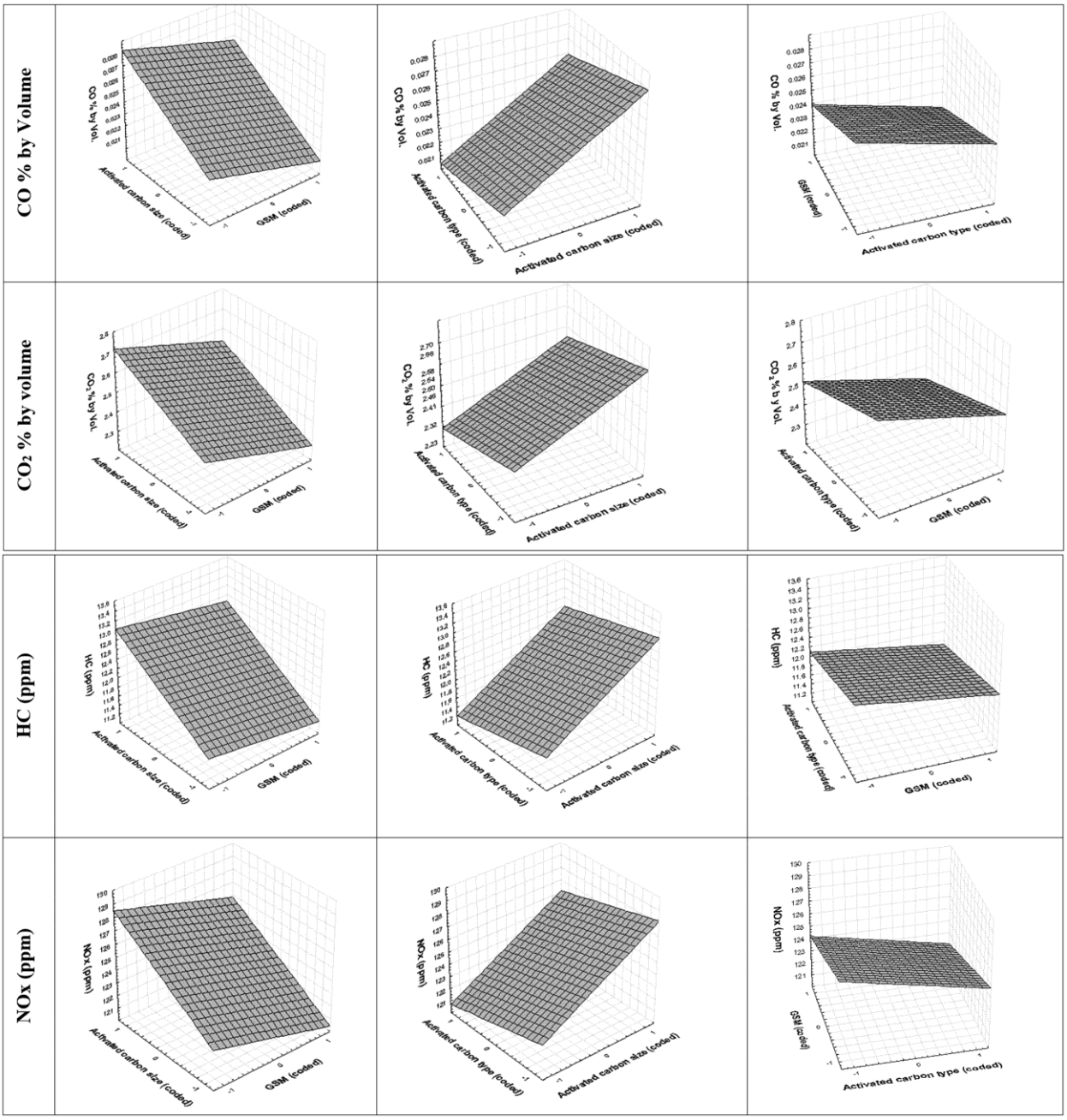

Fig. 5 — Effect of fabric weight, activated carbon sizes, and its types on adsorption of gases

lowest adsorption of gases because of the bigger size of activated carbon. S12 shows the highest gas adsorptions due to the smaller size of activated carbon and higher GSM. The activated carbon type influences the adsorption of gases. The coconut shell type shows average adsorption while the mixture shows the highest adsorption, and the type shows the least adsorption behaviour; this may be due to its available active sites. As mixture gas was introduced to the filter media, gaseous adsorption was initially completed for the smaller micro-pores with higher adsorption potential. It is observed from the table that carbon monoxide shows the lowest attraction to the adsorption sites. The initial efficiency for the adsorption of CO is not as high as expected, and the possible reason for this may be the negative influence of the high-pressure drop values arising due to the competing of other gases from the mixture in the filter media.

Conclusion

In this study, the influence of thermal bonded non-woven fabric weight, granular activated carbon type, and their sizes on the performance of non-woven filter media was studied. Based on the investigations and results of filter media, the following conclusions have been drawn: The number and mass concentration of particles and $PM_{2.5}$, in clean gas decreases with the increase in filter media fabric weight (ie GSM) of thermal bonded non-woven fabrics and with the reduction in granular activated carbon size. PM_{10} is not significantly influenced by the size of activated carbon. It envisages that reducing the size of activated carbon granules influences only the capture of small particles, while the capture of larger particles remains unaffected. The type of activated carbon does not significantly influence the capturing of particulate matter. The adsorption of gases increases as the size of granular activated carbon decreases. Mixture of granular activated carbon (coal and coconut shell) shows better adsorption behaviour than activated carbon based on only coal or coconut shell.

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