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Development of granular activated carbon fabric cabin air filter

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Automobile environments are exposed to hundreds of pollutants. In-duct ventilation filters are promising for reducing pollutants in automobile passenger compartments. Cabin air filters remove odours, capture airborne particles, and maintain a clean, fresh environment in the automobile cabin. In this experimental work, the effect of different types of face layer filter fabrics (As pre-filter), varying areal density of face layer fabrics (GSM), and granular activated carbon sizes were studied for the performances of the cabin air filter in terms of pressure drop (ΔP) and adsorption/removal efficiency of polluted gases like hydrocarbon, carbon dioxide, carbon monoxide, and nitrogen oxides. The Spun Bond-Melt Blown-Spun Bond (SMS) fabric shows the highest hydrocarbon (HC) removal efficiency and the lowest pressure drop. In contrast, tissue filament woven fabrics show the lowest removal efficiency for hydrocarbons, carbon dioxide, nitrogen oxides, and pressure drop. The thermal-bonded fabric shows the highest removal efficiency of carbon dioxide (CO_2) and nitrogen oxides (NOx). As the areal density (Layer weight) of face fabrics increases, the removal efficiency of all gases and the differential pressure drop across the cabin air filter both increase. As pressure drops, air filter resistance increases, and hydrocarbon adsorption rises significantly. The removal efficiency of carbon monoxide (CO) gas is 100% across all types of face-layer fabric, layer weight, and granular activated carbon (GAC) sizes. Tissue filament woven face layer fabric (Lowest in price and acts as pre-filter media) provides the same adsorption of carbon monoxide gas (CO) as SMS and thermal bonded nonwoven. As the activated carbon granular size increases, the removal efficiency of the hydrocarbon and the differential pressure drop (ΔP) both decrease.

Keywords: Activated carbon, Cabin air filter, Fabric weight, Gas -adsorption, Pressure drop (ΔP), Pre-filter

1 Introduction

Indoor air pollutants can originate from several sources, including construction materials and human activities such as cooking, smoking, using air sprays, cleaning, and odd jobs. Cabin air not only has particulates but also various pollutants such as toluene, ethylene, formaldehyde, xylene, and benzene molecules. These pollutants can cause a range of effects on health, including allergies, discomfort from odours, skin or throat irritation, headache, nausea, fatigue, and dizziness, as well as asthma and other respiratory diseases, cardiovascular effects, and even some types of cancer. A widely used solution for removing particles is to separate them by fibrous media made of natural, mineral, or synthetic fibres. In contrast, VOCs are generally adsorbed by activated carbon, which is available as either granules, powder, or fibres. So, gas-phase filtration is essential and involves separating one or more constituents of a gaseous mixture. This is usually achieved by adsorption or catalysis through the cabin filter. These applications include agricultural vehicles, heavy trucks, coaches and buses, cars, construction machinery, forestry machinery, cable cars, trains, railroad cars, airports, ICUs, aeroplanes, lifts, automobiles, and air conditioners (A/C). Researchers and manufacturers are interested in and able to provide products for most of the abovementioned applications. However, they mainly focus on classical road transportation, i.e. cars and trucks and closed cabins, depending on the geographical region; this air is conditioned with simple heater radiators, manual A/C units or even more sophisticated automatic air conditioners. In all cases, the air can be pushed or drawn through the A/C unit. New cars often offer the option of recirculating cabin air. The air quality along heavily travelled roads can be polluted and poorly poisoned. Cabin air filters help protect the A/C units in cars. The evaporator or condensers stay clean and dry and are less affected by bacteria and fungi. As seen from the distinction above between particulate and gaseous contaminants, filters can and should be divided into particulate filters, odour (gas-phase) filters, or combination filters. This experimental work explores the design and development of catalytic conversion at room temperature to control both particulate and gaseous separation of cabins using the

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most suitable cabin filters. The automobile cabin air filter has a simple purpose: to filter the air entering your vehicle's cabin[1]. According to the EPA (2018) air toxics assessment[2], diesel exhaust is frequently found in the environment and may harm human health. Diesel exhaust is divided into two phases: gas and particle, increasing the threat. Many urban hazardous air pollutants in the gas phase include formaldehyde, benzene1, 3-butadiene, acetaldehyde, and polycyclic aromatic hydrocarbons. Diesel particulate matter that falls into the fine and ultra-fine particle categories poses the most significant health risk. These tiny and ultra-fine particles may include organic molecules, metals, sulphate, nitrate, other adsorbed substances, and elemental carbon. Fine and ultra-fine particles are highly unsuitable for humans and should be avoided by the respiratory system; they can penetrate deeply into the lungs. Every particle has its shape, chemical composition, volume, weight, etc. UFPs (ultrafine particles) have adverse health effects on the functions of human body organs, including the cardio and lungs[3-5]. Particles in the ultrafine particle (UFP) size range are not captured in the upper nasal tracts due to their size, and they can settle deep down in the lungs[6,7]. Some gases, including, among others, carbon monoxide (CO), volatile organic compounds (VOC) and ozone, are considered pollutants. Exposure to ozone concentrations higher than 120 $\mu g m^{-3}$ has a hazardous effect on living organisms[8,9]. Ozone is a gas whose toxicity has been studied broadly. In addition, ozone reacts with terpene and other unsaturated organic compounds[10]. These reactions will result in the generation of new UFPs called secondary aerosols[11,12]. The Central Pollution Control Board (CPCB) in India discusses the odour index of various chemical compounds. NEERI, Nagpur, developed the compound and their odour index[13]. Strong odours may cause some people to feel a burning sensation, leading to coughing, wheezing or other breathing problems[14].

Fabric Filters

A gas or liquid containing particles is separated physically through a porous fabric material called fabric filtration, which holds onto the solids. Gaseous or liquid streams of environmental contaminants can be efficiently managed using fabric filtering. The efficient application (Optimization) of a cloth filter system would reduce waste disposal issues to a minimum[15,16]. The following factors determine the filter media's performance specifications that are appropriate for indoor air filtration: Process factors, fire resistance, mechanical strength, environmental effect, pressure drop, filtration efficiency, and micro-organism resistance.

Granular Activated Carbon

Granular activated carbon(GAC)as an adsorbent is a unique material, ie a solid and porous substance[17-20]. It is commonly made in a two-step process. Initially, the material is broken down by heating the carbonaceous material until all organic components save carbon are volatilized[21]. After that, the carbon is heated to a high temperature of 700–11000 °C using steam or carbon dioxide. Activated carbon can originate from different sources such as wood, coconut, peat, coal, sawdust and cellulose residues[22,23]. Because of its enormous pore capacity and surface area, activated carbon is a suitable medium for eliminating volatile organic compounds. Activated carbon is often generated in various forms, such as granules, fibres, spherical and cylindrical beads, and powders used in air-cleaning systems[19]. Activated carbon has an organophilic and hydrophobic nature. It mainly comprises neutral carbon atoms that lack an electrical gradient between molecules. Therefore, Carbon adsorbents tend to adsorb non-polar chemicals rather than polar ones because of the non-polarity of the carbon surface. Activated carbon's adsorption capacity and dynamic adsorption rate depend on the pores, total volume, size and shape. Surface area, pore size distribution, and particle size distribution are the main factors that rely on the adsorptive properties of activated carbon. No research work is reported for the study of the control of gaseous emission, filtration efficiency and pressure drop (ΔP) by varying nonwoven fabric types, such as SMS polyester nonwoven, thermal bonded polyester nonwoven and tissue filament woven fabric, their GSM, in combination with different GAC sizes (Granular activated carbon) as cabin air filters. This experimental work, trying to develop the cabin air filters by using various face layer fabrics as a pre-filter, their varying fabric layer weight (GSM) and the sizes of granular activated carbon (GAC) on the performance-differential pressure drop(ΔP) and adsorption behavior (Removal efficiency of gases) of CO, CO_2, NOx and HC. The thermal-bonded polyester nonwoven fabric is used as a base layer for the activated carbons in all cabin air filters. This study will provide an approach for designing and developing efficient and low-cost fabric cabin air filters.

2 Materials and Methods

2.1 Material Specifications

The thermal-bonded polyester nonwoven fabric is used as a base layer in all cabin air filters. In the study, Thermal-bonded nonwoven fabric (GSM, 160 gm) was used as the base layer of the cabin air filter. The thickness and average pore size of thermal-bonded polyester nonwoven fabric were 1.4 mm and 58 microns, respectively. The various parameters of the face layer fabric material (Pre-filter fabrics) are shown in Table 1, and these face layer fabrics have been used as a pre-filter. These face layer fabrics have been mounted over the base layer fabrics as shown in Fig. 1(a), (b) & (c). Three different types of face layer fabric, viz, spun bond- melt Blown-Spun bond (SMS), thermally bonded polyester nonwoven fabric (TBN) and tissue filament woven fabric (TWF), with three different levels of layer weight, viz., 20, 30 and 40 GSM, are used in the filter. Three levels of granular activated carbon (GAC) sizes are also used in this cabin filter's design. Granule activated carbon is sandwiched in between these two layers, i.e. base layer fabric and face layer fabric, by filling GAC particles in both layer gaps (i.e., filling GAC inside the two circular nets, smaller net wrapped by base layer media and bigger net wrapped by face layer media as shown in Fig.1 (a) & (b). Activated carbon is the adsorbent material of the cabin air filter, and the specification of Granular activated carbon used in the experiments is mentioned in Table 2.

2.2 Experimental Plan

A full factorial design of samples (27 combinations) was used in the experimental work to assess pressure drop and various gas adsorption performance of the cabin air filters, as shown in Table 3. Three types of fabric, SMS, thermally bonded nonwoven (TBN) and tissue woven fabric (TWF) of different gram per square meter (GSM) and different granular sizes of activated carbon (GAC), were used in the experiment as discussed above.

2.2.1 Preparations of Granular Activated Carbon Cabin Air Filter

The base layer of filter media was prepared from a polyester thermal-bonded nonwoven fabric, which was wrapped around a perforated drum [Fig. 1 (a),

Table 1 — Face layer fabric materials

Parameters	Tissue filament woven fabric, TWN			Thermal-bonded nonwoven fabric, TBN			SMS nonwoven fabric		
GSM, gm	20.00	30.00	40.00	20.00	30.00	40.00	20.00	30.00	40.00
Thickness, mm	0.07	0.10	0.14	0.02	0.015	0.21	0.26	0.31	0.35
Pore Size, micron	278.86	236.80	158.70	85.93	78.71	68.96	10.22	7.89	5.88
EPI	100	110	160	N/A	N/A	N/A	N/A	N/A	N/A
PPI	82	90	112	N/A	N/A	N/A	N/A	N/A	N/A
Warp (Filament)	Single	Single	Single	N/A	N/A	N/A	N/A	N/A	N/A
Weft (Filament)	Single	Multifilament	Multifilament	N/A	N/A	N/A	N/A	N/A	N/A

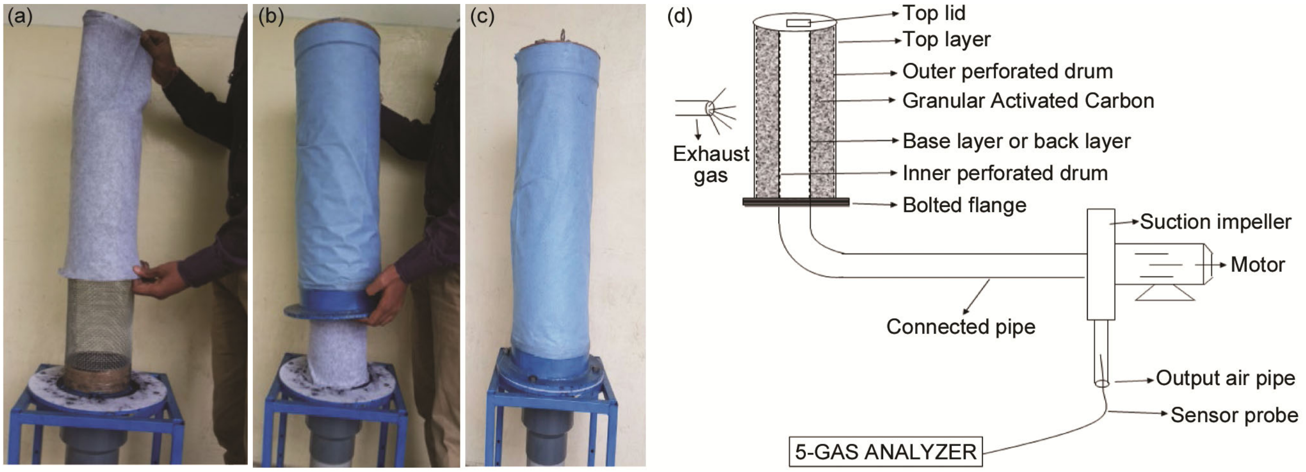

Fig. 1 — (a, b, c) Preparation of cabin air filter, and (d) Schematic diagram for the testing of cabin filters

Table 2 — Granular activated carbon (GAC) specifications

Sr. Number	Sizes, mm	Iodine Number, mg/g
1	3.35 mm	1132
2	6.36 mm	1132
3	11.25 mm	1132

Table 3 — Design of experiment work

Sr number	Sample code	Granular activated carbon (GAC) size	Type of layer fabric	GSM of fabric layer fabrics
1	S1	3.36	SMS	20
2	S2	3.36	SMS	30
3	S3	3.36	SMS	40
4	S4	3.36	TBN	20
5	S5	3.36	TBN	30
6	S6	3.36	TBN	40
7	S7	3.36	TWF	20
8	S8	3.36	TWF	30
9	S9	3.36	TWF	40
10	S10	6.35	SMS	20
11	S11	6.35	SMS	30
12	S12	6.35	SMS	40
13	S13	6.35	TBN	20
14	S14	6.35	TBN	30
15	S15	6.35	TBN	40
16	S16	6.35	TWF	20
17	S17	6.35	TWF	30
18	S18	6.35	TWF	40
19	S19	11.2	SMS	20
20	S20	11.2	SMS	30
21	S21	11.2	SMS	40
22	S22	11.2	TBN	20
23	S23	11.2	TBN	30
24	S24	11.2	TBN	40
25	S25	11.2	TWF	20
26	S26	11.2	TWF	30
27	S27	11.2	TWF	40

(b), and (c)] and it was closed on one side and connected to a pipeline on the other. The inner drum diameter is 5.5 inches, and the outer drum diameter is 8 inches. The outer drum had one side as a top lid, and the other side was connected to a flange. The larger-diameter drum was put on, and the smaller-diameter drum was kept tightened with a bolt and flange. The SMS, thermal-bonded nonwoven, and tissue-woven fabrics wrapped around the outer perforated drum served as a pre-filter in the top layer/outer layer. The empty space between the base layer carrying drum and the face layer carrying perforated drums (The diameter of the face layer drum is higher than the base layer drum) was filled with granular activated carbon, so that both nonwoven layers sandwiched with GAC now act as the cabin air filter. As shown in Fig. 1(d), the cabin air filter rig is sealed by a lid system for granular activated carbon feeding, and the suction impeller or blower is on the other side via a PVC pipeline. Finally, clean, fresh air came out of the test rig's output pipeline. Granular activated carbon was crushed in a grinder to obtain GAC distributions of various sizes. The crushed granular activated carbon was sieved using mesh sizes of 7/6, 1/4, and 6 to obtain the required size distributions of GAC for the cabin filter development, as per the experimental plan.

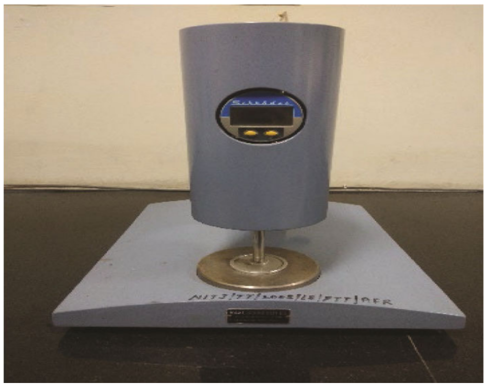

Fig. 2 — Digital thickness testers

Fig. 3 — Capillary flow parameter

2.3 Methods of Testing

2.3.1 Thickness and Mean Pore Diameter

The thickness of the nonwoven/woven samples was measured in mm in accordance with DIN EN ISO 5084 standards. A testing load of 0.5 KPa was used for measurement, and the instrument was a digital thickness tester (Fig. 2). The experimental setup was used to measure the mean pore size diameter of the fabric on the capillary flow parameter instruments (Fig. 3). Using this setup, capillary flow parameters, such as pore size distribution in terms of minimum, maximum, and average pore size in microns, were determined according to the ASTM standard F316 test method. The maximum pore size was calculated at the pressure at which flow was first detected on the wetted sample. Mean flow pore size was obtained at the point where 50 % of the dry curve crossed the wet curve. Minimum pore size was obtained at the point where the dry and wet curves merged. The capillary flow porosimetry test has four options: wet up/dry down, wet up/dry up, dry up/wet up, and wet up/calculated dry, for measuring the mean pore diameter of nonwoven samples in a cabin filter, as either base fabrics or face layer fabrics. Therefore, the mean flow pore size is the pore diameter at a pressure drop at which the flow through a wetted medium is 50 % of the flow through the dry medium. It is not the mean pore size, because the flow through large-diameter pores can be disproportionately larger than that through small-diameter pores.

2.3.2 Adsorption or Removal Efficiency of Gases

The experimental setup for measuring gas removal efficiency consisted of a single-cylinder water-cooled diesel engine used to measure various gaseous exhausts. The fuel supply system consists of a burette flow meter used to calculate volumetric fuel consumption. An AVL DITEST (AVL DIGAS 4000 light gas) gas analyzer was used for oxides of nitrogen (NOx), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2) and hydrocarbon (HC) measurements (Fig. 4). The experimental set-up (Test rig) consisted of all the filters mentioned above (Face fabric types and weights) and devices, which were arranged per the schematic diagram above. Finally, it was attached to five gas analyzer instruments as shown in Fig. 1(d).

Step 01: A 20 min warm-up period was provided for the diesel engine machine to achieve a steady exhaust gas flow.

Step 02: The ten readings were taken at 03 min intervals to determine the performance of the granular activated carbon filter media by measuring diesel-engine exhaust emissions. The detailed specifications of the exhaust gas analyzer[24] are given in Table 4.

2.3.3 Calculation of Cleaning Efficiency of Gases

Before filtration, the gases in air = G1; After filtration, gases in air = G2; Where G1, G2 in PPM unit (Parts per million)

$$\text{Then Gas removal efficiency (\%)} = \frac{(G1-G2)}{G2} \times 100 \qquad \ldots(1)$$

2.3.4 Pressure Drop (∆P)

Pressure drop was calculated using an anemometer, a device that measures wind speed and direction.

Fig. 4 — Exhaust gas analyzer

Table 4 — Gas analyzer specifications[24] (AVL DIGAS 4000 Light gas)

Sr. Number	Object of measurement	CO, HC, CO_2, NOx and O_2
1	Measurement principle	CO, HC, CO_2 = Infrared measurement NOx = Electrochemical measurement
2	Range of measurement	CO = 0-10 % by Volume CO_2 = 0-20 % by Volume O_2 = 0-25 % Volume HC = 0-20000 PPM Volume NOx = 0-4000 PPM Volume
3	Resolution	CO = 0.01 % by Volume CO_2 = 0.1 % by Volume O_2 = 0.1 % by Volume HC = 01 PPM by Volume NOx = 01 PPM by Volume
4	Warm-up time	15 min (self-controlled) at 20°C
5	Speed of response time	Within 15 seconds, 90 % of the response
6	Sampling	Directly sampled from the tailpipe

2.3.5 Calculation of pressure drop (ΔP)

Air flow rate (m/s) to convert into Pascal (Pa)

$p = v^2 \times \frac{d}{2}$; p= Pressure, Pa ; v= Air speed, m/sec; …(2)

d = Density of air = 1.187 kg/m^3 at standard 23^{0}C temperature.

Now, before the filtration process, Air pressure = P_1; after the filtration process, air pressure = P_2; then the differential pressure drop (ΔP) = (P_1-P_2) Pa.

3 Results and Discussion

In this experimental work, three types of face layer fabrics were used: Thermal bonded nonwoven (TBN), Spun bond- melt blown-spun bond nonwoven (SMS) and tissue filament woven fabrics (TWF); three-layer fabric weight and three sizes of granular activated carbon (GAC) have been taken for designing and development of fabric cabin filter. The study of pressure drop (ΔP) and adsorption behavior of the cabin air filter with various polluting gases like hydrocarbons (HC), carbon dioxide (CO_2), carbon monoxide (CO) and oxides of nitrogen (NOx) was done. Test results of different testing parameters of cabin air filters are given in Table 5.

3.1 Study of Differential Pressure Drop (ΔP) of the Cabin Air Filter

3.1.1 Influence of GAC Size, Face Layer and Layer Fabric Weight

It is observed from Fig. 5 (a,b,c) and from Table 6 that as the GAC size of activated carbon decreases from 11.25 to 3.36 mm, the differential pressure drop of cabin air filter increases in all face layer fabric (In SMS fabric layer, ΔP raises from 14.27 to 25.19 Pa, thermal bonded fabric layer from 8.75 to 20.58 Pa and tissue woven fabric layer from 1.84 to 15.26 Pa). It happens because finer GAC particles have more surface area due to a greater number of particles in the same mass of GAC, and offer higher air resistance to the filter during filtration. The finer-sized particles, which were the same weight as coarser-sized GAC

Table 5 — Removal efficiency results (Adsorption) of various gases of cabin air filters

Sr. No.	Granular activated carbon (GAC) Size, mm	Type of fabric layers	Layer weight of fabrics, GSM	HC, %	NOx, %	CO, %	CO_2 , %	Differential Pressure drop, ΔP
S1	3.36	SMS	20	88.70	25.00	100	30	24.25
S2	3.36	SMS	30	89.57	42.50	100	40	24.92
S3	3.36	SMS	40	91.30	53.75	100	50	25.19
S4	3.36	TBN	20	84.35	35.00	100	30	19.47
S5	3.36	TBN	30	86.09	42.50	100	50	20.16
S6	3.36	TBN	40	87.83	50.00	100	50	20.58
S7	3.36	TWF	20	77.39	30.00	100	20	11.38
S8	3.36	TWF	30	80.87	35.00	100	30	13.12
S9	3.36	TWF	40	82.61	37.50	100	40	15.26
S10	6.35	SMS	20	86.09	72.50	100	50	20.99
S11	6.35	SMS	30	87.83	82.50	100	70	21.54
S12	6.35	SMS	40	87.83	86.25	100	70	21.95
S13	6.35	TBN	20	79.13	62.50	100	70	14.7
S14	6.35	TBN	30	84.35	80.00	100	70	15.69
S15	6.35	TBN	40	86.09	85.00	100	80	16.4
S16	6.35	TWF	20	63.48	62.50	100	50	7.27
S17	6.35	TWF	30	75.65	80.00	100	60	10.07
S18	6.35	TWF	40	77.39	82.50	100	70	11.82
S19	11.2	SMS	20	73.91	32.50	100	30	14.27
S20	11.2	SMS	30	73.91	42.50	100	40	14.98
S21	11.2	SMS	40	75.65	45.00	100	40	15.26
S22	11.2	TBN	20	54.78	27.50	100	30	8.75
S23	11.2	TBN	30	58.26	32.50	100	40	9.19
S24	11.2	TBN	40	60.00	38.75	100	50	9.78
S25	11.2	TWF	20	47.83	17.50	100	20	1.84
S26	11.2	TWF	30	51.30	20.00	100	30	3.37
S27	11.2	TWF	40	53.04	32.50	100	40	5.33

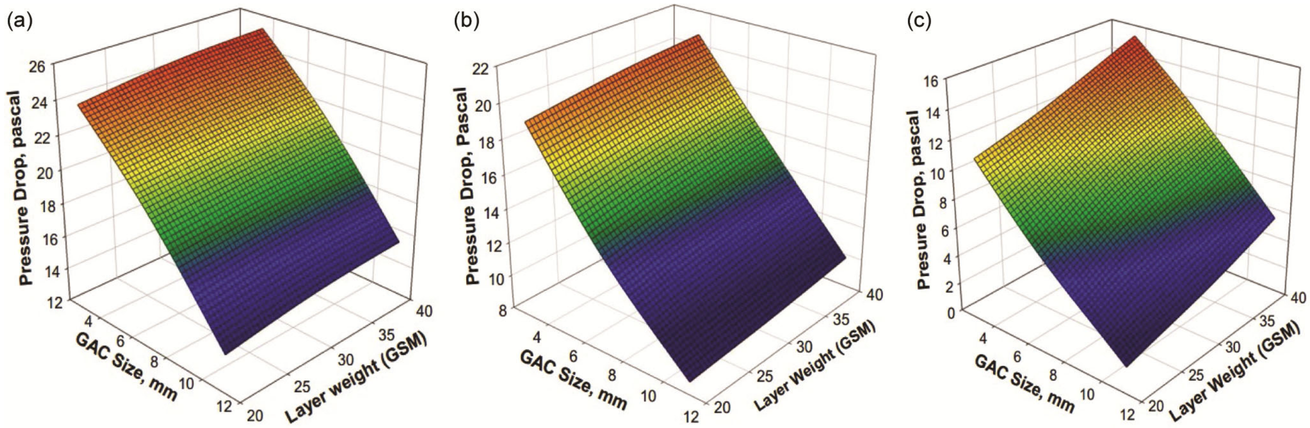

Fig. 5 — (a,b,c) Effects of granular activated carbon size, face layer and layer weight on differential pressure drop (ΔP) (a) SMS fabric Layer, (b) TBN fabric Layer, and (c) TWF fabric layer

Table 6 — ANOVA for pressure drop of cabin air filter

Effect	Sum of square	Degree freedom	ofMean square	F calculated	F Table	% Contribution
GAC Size	476.19	2	238.09	5455.33	4.46	43.04
Fabric Layer	600.43	2	300.22	6878.68	4.46	54.27
Layer Weight	19.37	2	9.69	221.91	4.46	1.75
GAC Size*Fabric Layer	1.55	4	0.39	8.89	3.84	0.14
GAC Size*Layer Weight	0.34	4	0.08	1.95	3.84	0.03
Fabric Layer*Layer Weight	8.22	4	2.06	47.11	3.84	0.74
Error	0.35	8	0.04	-	-	0.03

particles, showed a higher total surface area of particles. For the exact weight of granular activated carbon (GAC), a collection of finer particles will have a higher total surface area than a collection of coarser particles. This is because surface area increases as particle size decreases. Similarly, as the face layer weight increases, the pressure drop increases due to greater compactness, lower porosity, and smaller fabric filter media pore sizes.

It is observed that SMS fabric has the highest pressure drop as compared to thermal bonded and tissue fabric. Also, as the layer weight of SMS fabric increases from 20 to 40, the pressure drop increases from 19.8 to 20.9 Pa. In the case of the layer weight of thermally bonded fabric increasing from 20 to 40 g, the pressure drop increases from 14.2 to 15.8 Pa. The tissue-woven fabric shows the lowest pressure drop compared to thermal-bonded and SMS fabric. Also, as the layer weight of the tissue-woven fabric increases from 20 to 40 g, the pressure drop increases from 7.0 to 9.0 Pa. It is clear from the Figure that the SMS face layer shows a higher pressure drop due to its greater structural compactness. It was also found that the differential pressure drop increases with increasing layer weight. This is due to the lower mean pore diameter of face layer fabrics (which decreases their porosity and increases their layer weight) and the fabric's lower pore size. Lower porosity and smaller pore size in filter fabrics lead to increased differential pressure drop. This is because smaller pores create more resistance to airflow, causing a higher pressure difference between the upstream and downstream sides of the filter as air struggles to pass through. Tissue-woven fabric has a wider pore size, significantly reducing pressure drop. ANOVA results to ascertain the percentage contributions of various parameters are provided in Table 6. The table shows that the percentage contribution for the type of face layer fabric is 54.27%, and the percentage contributions for GAC and Layer weight are 43.04% and 1.75%, respectively.

In designing a cabin filter, the role of the face fabric and the activated carbon's granular size are highly significant and largely influence the differential pressure drop(ΔP). The layer weight does not affect the pressure drop. The interaction of GAC, face layer and layer weight parameters is not significant for the pressure drop of the cabin air filter. Therefore, it is recommended that the selection of filter fabric and the size of GAC be optimized for the cabin filter to minimize the pressure drop, which, in turn, enhances the life of the cabin filter.

3.2 Study of the Removal Efficiency (Adsorption) of Gases

All cabin air filters were treated with diesel engine gas exhaust for adsorption of gases such as hydrocarbons (HC), oxides of nitrogen (NOx), carbon monoxide (CO) and carbon dioxide (CO_2). The removal efficiency of all these gases is measured, and their recitals are discussed below.

3.2.1 Removal Efficiency of Hydrocarbon (HC)

3.2.1.1 Influence of GAC Size, Fabric Layer and Fabric Layer Weight

It is observed from Fig. 6 (a), (b) & (c) and Table 7 that as the GAC size decreases from 11.25 to 3.36 mm, the removal efficiency of hydrocarbon increases in the case of SMS fabric layer from 72 to 91 %, thermally bonded fabric layer from 52 to 87 % and tissue woven fabric layer from 45 to 82 %. This may be due to the reduced size of activated carbon, which increases its total surface area and the total number of pore sites, and to the lower air flow rate, which provides more time for micropore adsorption. It is observed that the total number of pore sites increases in smaller GAC particles, which results in a larger number of pores between the particles; therefore, a higher pore sites is generated between the pre-filter and base filter media layers. The smaller granular activated carbon particles create more pore spaces between them, leading to a higher total number of pore sites and potentially enhancing filtration. This is because the smaller particles pack more tightly, leaving less space between them, but also creating more surface area for adsorption and filtration.

The adsorption efficiency of the activated carbon is enhanced through a longer contact time.

The above graphs show that the SMS fabric has the highest hydrocarbon removal efficiency compared to the thermal-bonded and tissue-woven fabrics. Also, as the layer weight of SMS fabric increases from 20 to 40 g, the removal efficiency increases from 83 to 85 %. This happens because the SMS fabric has a smaller pore-size distribution than other face fabrics, resulting in higher pressure drops (ΔP), lower airflow rates, and increased air adsorption time with activated carbon. Similarly, as layer weight increases from 20 to 40 g in thermally bonded fabric, the removal efficiency increases from 73 to 88 %. Currently, the tissue-woven fabric shows the lowest removal efficiency compared to thermal-bonded and SMS fabrics. Also, as the layer weight of the tissue-woven fabric increases from 20 to

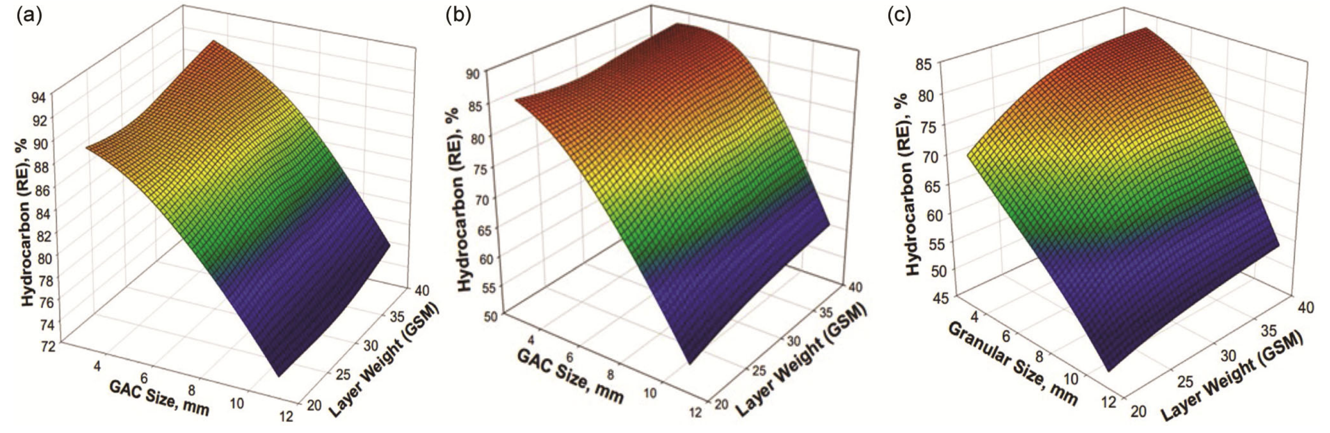

Fig. 6 — (a, b, c) Effects of granular activated carbon size, face layer and layer weight on removal efficiency of hydrocarbon (HC) (a) SMS Fabric Layer, (b) TBN Fabric Layer, and (c) TWF Fabric Layer

Table 7 — ANOVA for removal efficiency of hydrocarbon of cabin air filter

Effect	Sum of square	Degree of freedom	Mean square	Falculated	F Table	% Contribution
GAC Size	3026.10	2	1513.10	593.71	4.46	65.52
Fabric layer	1157.60	2	578.80	227.12	4.46	25.07
Layer weight	129.30	2	64.60	25.36	4.46	2.80
GAC size*Fabric Layer	235.00	4	58.80	23.05	3.84	5.09
GAC size*Layer Weight	19.30	4	4.80	1.89	3.84	0.42
Fabric Layer*Layer Weight	30.70	4	7.70	3.01	3.84	0.66
Error	20.40	8	2.50			0.44

40 g, the removal efficiency augments from 63 to 71 %. In the case of tissue-woven fabric, lower pressure drops, higher air flow rates, and shorter adsorption times result in lower hydrocarbon removal efficiency. A higher GSM of fabric results in greater structural compactness and lower porosity, leading to higher differential pressure drops, lower airflow rates, and longer adsorption times with activated carbon during filtration. Finally, this enhances the removal efficiency of hydrocarbons. ANOVA Table 7 shows that the percentage contribution of GAC size is highest at 65.52 %, and for the fabric layer and layer weight are 25.06 % and 2.79 %, respectively. Hence, the ANOVA results also depicted that the effects of GAC size, fabric layer, and layer weight are significant in the removal efficiency of hydrocarbons. The interaction effect of GAC and fabric layer is also essential for the removal efficiency of HC.

3.3 Removal Efficiency of the Nitrogen Oxides (NOx)

3.3.1 Influence of GAC Size, Fabric Layer and Layer Weight

It is observed from Fig. 7 (a), (b) & (c) and Table 5 that as the GAC size increases from 3.36 to 6.35 mm, the removal efficiency of nitrogen oxides of cabin air filter rises and in the case of SMS fabric from 25 to 85 %, thermal bonded fabric and tissue woven fabric from 25.0 to 86.25 % and 30.0 to 80.5 % respectively. As the GAC size ranges from 6.36 to 3.35 mm, this causes an increase in the differential pressure drop (ΔP). The higher pressure drop can cause uneven airflow through the filter, leading to the desorption of lighter molecular-weight gases such as CO2, NO2, NO, and SO2, thereby decreasing the removal efficiency of NOx. The GAC size increases from 6.35 to 11.25 mm, with the removal efficiency of nitrogen oxides (%) of the cabin filter decreasing in the case of SMS fabric from 85 to 27.5 %, thermally bonded fabric and tissue fabric from 86.25 to 42.5 % and 80.5 to 17.5 %, respectively. It is observed that increasing the GAC size above 6.36 mm decreases the GAC bed surface area and the number of micropores, providing a more open absorbent bed. This ultimately reflected the decreasing trend of NOx removal efficiency. Increasing the size of granular activated carbon (GAC) particles generally decreases the adsorption of various gases. Smaller GAC particles offer a larger surface area for adsorption, resulting in faster, more efficient removal of contaminants. While larger particles may have a longer lifespan, they are less effective at capturing gases because of their reduced surface area and slower diffusion rates.

It is clearly observed from all the above figures that the thermally bonded fabric has the highest removal efficiency of nitrogen oxides as compared to SMS and tissue woven fabric layer, and it also shows that as the layer weight of the thermally bonded fabric increases from 20 to 40 g, the removal efficiency increases from 43 to 62 %. Similarly, the layer weight of SMS fabric rose from 20 to 40 g, and the removal efficiency increased from 42 to 57 %. This is because the SMS fabric has a narrower pore-size distribution than other fabrics, resulting in higher pressure drops and lower air volume per unit time. Firstly, adsorption occurs with higher-molecular-weight gases, while desorption occurs with lower-molecular-weight gases, lowering the efficiency of SMS face-layer fabrics. The tissue-woven fabric shows the lowest removal efficiency compared to the thermal-bonded and SMS fabrics. As the layer weight of the tissue-woven fabric increases from 20 to 40 g, the removal efficiency increases from 36.5% to 50.5%. A small amount of raw gas may pass through the filter because a higher volume of air

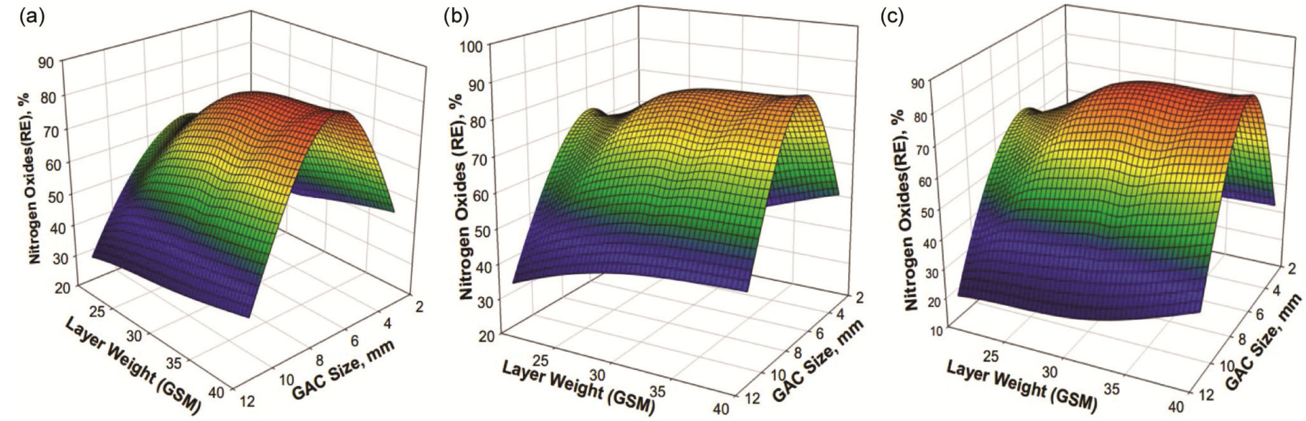

Fig. 7 — (a, b, c) Effects of granular activated carbon size, face layer & layer weight on removal efficiency of nitrogen oxides (NOx) (a) SMS Fabric Layer, (b) TBN Fabric Layer, and (c) TWF Fabric Layer

Table 8 — ANOVA for removal efficiency of nitrogen oxides of cabin air filter

Effect	Sum of square	Degree of freedom.	Mean square	F Calculated	F Table	%, Contribution
GAC Size	9918.52	2	4959.26	109.31	4.46	77.17
Fabric layer type	256.02	2	128.01	2.82	4.46	1.99
Fabric Layer Weight	853.24	2	426.62	9.40	4.46	6.64
GAC Size*Fabric Layer	66.20	4	16.55	0.37	3.84	0.52
GAC Size*Layer Weight	814.81	4	203.70	4.49	3.84	6.34
Fabric Layer*Layer Weight	581.48	4	145.37	3.20	3.84	4.52
Error	362.96	8	45.37			2.82

passes through the unit in a given time, reducing the air contact time with the micro-pores. This ultimately reduces the NOx removal efficiency during filtration.

ANOVA Table 8 shows that the percentage contribution of GAC size is highest (77.17 %), followed by type of fabric layer (1.99 %) and layer weight (6.64 %). The layer weight and its interaction with GAC are also significant for NOx removal efficiency. The interaction of GAC and the fabric layer is not substantial for NOx removal.

3.4 Removal Efficiency of Carbon Monoxide (CO)

3.4.1 Influence of GAC Size, Fabric Layer and Fabric Layer Weight

Figure 8 and Table 5 also show that the carbon monoxide removal efficiency for all combinations of cabin filter samples is 100%. The cleaning efficiency of CO by GAC is 100% across all combinations of face layer and layer weight. This is because the micro-pores of GAC are highly sensitive to CO gas adsorption and consequently fully adsorb CO emissions. This cabin filter is more suitable for CO removal from industries and road traffics.

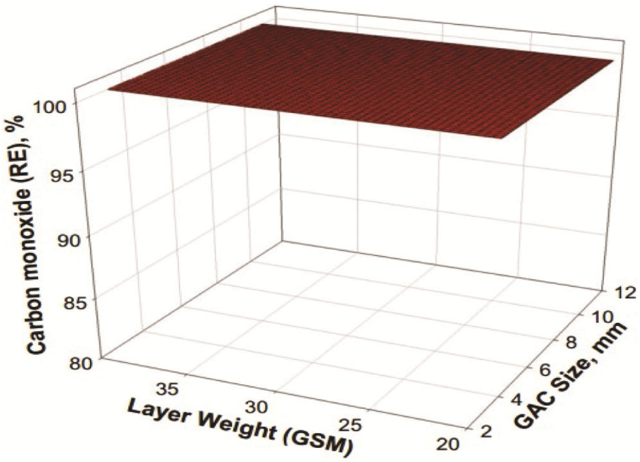

Fig. 8 — Effects of granular activated carbon size, face layer and layer weight on removal efficiency of carbon monoxide (CO)

3.5 Removal Efficiency of Carbon Dioxide (CO_2)

3.5.1 Influence of GAC Size, Fabric Layer and Layer Weight

It is observed from Fig. 9 (a), (b), and (c) and Table 5 as the GAC size increases from 3.36 to 6.35 mm, the removal efficiency of carbon dioxide of cabin filter was increased, in the case of SMS fabric, from 30 to 70 %, thermally bonded fabric 30 to 80 % and tissue woven fabric 20 to 70 %. This is because, as the GAC sizes increase from 3.36 to 6.35 mm, the adsorption of higher-molecular-weight gases decreases, while desorption of lighter gases such as CO2, NO2, NO, and SO2 ceases, thereby increasing the removal efficiency of carbon dioxide.

It is also observed from graphs that as the GAC size increased from 6.35 to 11.25 mm, the removal efficiency of nitrogen oxides of the cabin filter was decreased in the face layer of SMS fabric from 70 to 30 %, thermal bonded fabric and tissue woven fabric from 80 to 30 % and 70 to 20 %, respectively. This is due to the higher open absorbent bed, reduced total surface area of GAC and lower total pore volumes of activated carbon, which reduced the adsorption of CO_2 gas. It is observed from Fig. 16 that as the layer weight of SMS fabric increases from 20 to 40 g, the removal efficiency increases from 36 to 53 %. Thermal-bonded fabric has the highest removal efficiency compared to SMS and tissue-woven fabric. At the same time, as the layer weight of fabrics increases from 20 to 40 g, the removal efficiency increases from 44 to 60 %. Hence, it is found that the lowest removal efficiency of tissue-woven fabric is higher than that of other fabrics, but increasing the layer weight of tissue-woven fabric significantly increases its CO2 removal efficiency. It is clear from the graphs that the layer weight of tissue-woven fabric increases from 20 to 40 g, and the removal efficiency increases from 30 to 50 %. SMS fabric has a smaller pore size and distribution, resulting in higher pressure drops that augment the contact time between air and the GAC bed. These phenomena involve the adsorption of higher-molecular-weight gases, while desorption occurs with lower-molecular-weight gases. The tissue-woven face fabric has a higher pore size

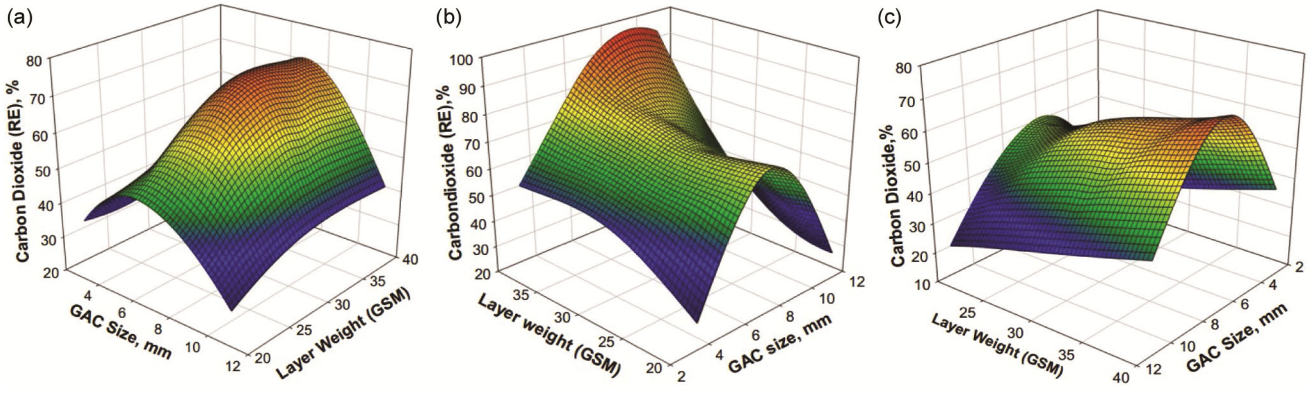

Fig. 9 — (a,b.c) Effects of granular activated carbon (GAC) sizes, fabric layer and layer weight on removal efficiency of carbon dioxide (CO_2) (a) SMS Fabric Layer, (b) TBN Fabric Layer, and (c) TWF fabric layer

Table 9 — ANOVA for removal efficiency of carbon dioxide from the cabin air filter

Effect	Sum of square	Degree of Freedom.	Mean Square	F Calculated	F Table	% Contribution
GAC Size	5029.63	2	2514.81	123.45	4.46	67.70
Fabric Layer Type	674.07	2	337.04	16.55	4.46	9.07
Layer Weight	1451.85	2	725.93	35.64	4.46	19.54
GAC Size*Fabric Layer	59.26	4	14.81	0.73	3.84	0.80
GAC Size*Layer Weight	14.81	4	3.70	0.18	3.84	0.20
Fabric Layer*Layer Weight	37.04	4	9.26	0.45	3.84	0.50
Error	162.96	8	20.37	-	-	2.19

and distribution, so gas adsorption takes less time, decreasing removal efficiency.

ANOVA Table 9 shows that the parentage contribution for GAC size is highest at 67.70 %, 9.07 % for fabric layer type, and 19.54 % for fabric layer weight. The effects of GAC size, fabric layer type, and fabric layer weight on the removal efficiency of carbon dioxide are significant, and no parameter interactions are significant.

4 Conclusion

The Spun Bond - melt Using blown-spun bond (SMS) face fabric as a pre-filter media in cabin filter design results in the highest hydrocarbon (HC) removal efficiency while simultaneously providing the greatest differential pressure drop (ΔP). Thermal-bonded cloth as a pre-filter media demonstrates the highest CO_2 and NOx removal efficiency. As a pre-filter media, the tissue filament woven fabric exhibits the lowest removal efficiency of hydrocarbons, carbon dioxide, and nitrogen oxides while simultaneously causing the lowest differential pressure drop. As the weight of the face fabric layer (pre-filter media) grows, gas removal and pressure efficiency decline. Carbon monoxide gas (CO) adsorption is similar to spun bond, melt-blown spun bond, and thermal-bonded nonwoven. As the granular size of activated carbon rises, hydrocarbon removal efficiency and pressure drop (ΔP) decrease. The size of granular activated carbons ranges from small to medium (i.e., 3.36 to 6.35 mm), thereby increasing the effectiveness of CO_2 and NOx removal. The medium-sized GAC (6.35 mm) effectively removes CO_2 and NOx pollutants. As a result, sizes of granular activated carbons considerably impact CO_2 and NOx removal. It is also concluded that as the pressure drops (ΔP) in the cabin filter increases, the adsorption of hydrocarbons increases. A moderate pressure drop is necessary for increased CO_2 and NOx absorption. Carbon monoxide (CO) gas cleaning efficiency is 100% across all pre-filter media, layer weights, and granular activated carbon sizes. The tissue filament woven face layer fabric (Lowest market price) exhibits the same 100% carbon monoxide (CO) adsorption as the spun bond, melt-blown spun bond, and thermal bonded nonwoven.

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