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Composite nonwoven filter media with hierarchically arranged fibres of different geometries for automotive engine intake air filtration

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This paper reports the development, characterization, and performance assessment of a series of promisingly designed nonwoven air filter media for automotive engine intake application. Commercially available fibres are processed through a laboratory-based needle-punched nonwoven line to prepare a plurality of composite nonwoven filter media with hierarchically arranged fibres of different sizes or shapes. The filter media are then assessed for their dynamic filtration performance both at cleaned and clogging states by employing testing devices based on gravimetric measurement and particle counting technologies. The composite nonwoven filter media with hierarchically arranged fibres of different geometries display excellent filtration performance and are found to be very promising for commercial engine application. As compared to their homogeneously-mixed counterparts, the composite nonwoven filter media offer higher gravimetric as well as fractional filtration efficiency, higher dust holding capacity, and more delayed rise of pressure drop.

Keywords: Air filtration, Automotive engine, Composite filter, Fibrous filter media, IC engines, Nonwoven technology

1 Introduction

The internal combustion engines of automotive vehicles need clean air for the supply of oxygen required for fuel combustion. The air is sourced from the atmosphere, but the atmospheric air is highly polluted due to presence of various contaminants. The contaminants include particulate matter, atmospheric dust, coal dust, beach sand, pollens, carbon black, diesel soot, to name a few. These contaminants must be removed from the air, otherwise, they would cause significant wear and tear to the engines, leading to remarkable performance loss, enhanced exhaust emission, high oil consumption, and increased operational cost [1-3].

The removal of these contaminants from the air is usually achieved by means of particle filtration technology using filter media. The filter media suitable for engine intake application are required to exhibit high filtration efficiency, low pressure drop, and high dust holding capacity. As these requirements are contradictory, it possesses a great challenge for the filter manufacturers to design appropriate filter media for engine intake air filtration.

There are different kinds of filter media available for engine intake application. They are foam filter media, paper filter media, and nonwoven filter media. The foam filter media are known to offer high dust holding capacity and low pressure drop but low filtration efficiency. On the other hand, the paper filter media exhibit moderate filtration efficiency but high pressure drop and low dust holding capacity. The nonwoven filter media display high filtration efficiency but moderate pressure drop and moderate dust holding capacity. Over the years, the foam filter media are found in limited usage, however, the paper filter media are mostly used nowadays, and the nonwoven filter media are considred to be relatively "young" for engine intake application [4]. Nevertheless, the nonwoven filter media manifest remarkable depth filtration and are expected to evolve significantly for engine intake air filtration within the next decade. Worldwide, research is going on for creating innovative nonwoven structures for enhancement of filtration performance in engine intake application.

In the past, a few attempts were made to develop composite nonwoven filter media by combining two or more layers of different filtration efficiencies [5]. This kind of filter media exists in many embodiments. In one embodiment, the upstream layer was used as a prefilter and the downstream layer was used as a main filter. In the other embodiment, a gradient density depth filtration was achieved by arranging two layers of increasing densities from the upstream to the

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downstream sides of the filter media. The outer layers served as a containment zone to inhibit particle migration from the inner layers. In another embodiment, a nanofibre layer was kept at the downstream of a microfibre layer to create a gradient of fibre size [6]. The microfibre layer contributed more to filtration of coarser particles, while the nanofibre layer contributed more to filtration of finer particles. Though this kind of filter media was reported to offer excellent filtration efficiency at an initial stage of filtration, however, there was hardly any assessment made on the filtration performance of such filter media at the clogging state. Whether the creation of more than one layer with different fibre sizes along the depth could offer any advantage in the filtration performance still remains as an open question. Also, there may be several other possibilities to create innovative filter media combining two or more layers of different filtration efficiencies. There is, therefore, a need to explore such possibilities for development of innovative and improved nonwoven filter media for engine intake air filtration. This paper reports on development, characterization, and performance assessment of a series of promisingly designed nonwoven air filter media for automotive engine intake application.

2 Materials and Methods

Polypropylene fibres of three different cross-sectional areas and polyester fibres of three different cross-sectional shapes were used. The specifications of the fibres are given in Table 1. It can be seen that all the fibres have same length (51 mm). The three categories of polypropylene fibres have same cross-sectional shape (round), but varied mean diameters (19.13 µm, 30.17 µm and 48.24 µm). On the other hand, the three categories of polyester fibres have same cross-sectional size (24.97 µm), but different cross-sectional shapes (round, trilobal and deep-grooved).

2.1 Development of Filter Media

A laboratory-based nonwoven production line consisting of a fibre opening machine, a fibreweb forming machine, a fibre web stacking machine, and a needle-punching machine was employed for development of nonwoven filter media. The fibre opening machine was used to open the fibre tufts by increasing the volumes of the tufts or by breaking the bigger tufts into smaller ones. The fibreweb forming machine was a double cylinder roller carding machine that was employed to open the fibre tufts, individualize them into almost single fibre stage, and consolidate them in the form of a two-dimensional fibreweb. The fibreweb was then fed to a stacking machine, which was essentially a cross-lapping machine that folded the fibreweb and stacked the same till the desired basis weight was obtained. Finally, a needle-punching machine imparted final integrity to the stacked fibreweb by the action of a series of barbed needles and formed a nonwoven filter medium.

Table 1 — Specifications of fibres

Fibre	Length mm	Fineness denier	Diameter µm	Cross-sectional shape
Polypropylene	51	2.5	19.13	Round
	51	6	30.17	Round
	51	15	48.24	Round
Polyester	51	6	24.97	Round
	51	6	24.97	Trilobal
	51	6	24.97	Deep-grooved

In accordance with the method described above, two sets of nonwoven filter media were developed. In the first set, the fibrewebs made up of polypropylene fibres of different diameters were stacked in such a manner that the larger fibres faced the upstream side of the filter media and the smaller fibres faced the downstream side of the same filter media. This is schematically shown in Fig. 1(a). As the size of fibres was known to decide the filtration efficiency, pressure drop, and dust holding capacity, it was expected that nonwoven filter media would exhibit a multilevel filtration performance along the depth of the filter media. In order to compare the filtration performance of such composite filter media, the same fibres were mixed homogeneously to prepare a set of hybrid filter media.

The second set of nonwoven filter media was prepared by judiciously structuring fibrewebs made up of polyester fibres of different cross-sectional shapes such that the round fibres faced the upstream side of the filter media and the non-round fibres faced the downstream side of the same filter media. This is schematically shown in Fig. 1(b). As it was known that the fibres of different cross-sectional shapes would offer defferent levels of filtration efficiency, pressure drop, and dust holding capacity, it was very likely that the nonwoven filter media would exhibit a multilevel filtration performance along the depth of the filter media. Here also, in order to compare the filtration performance of such filter media, the same fibres were mixed homogeneously to prepare a set of hybrid filter media.

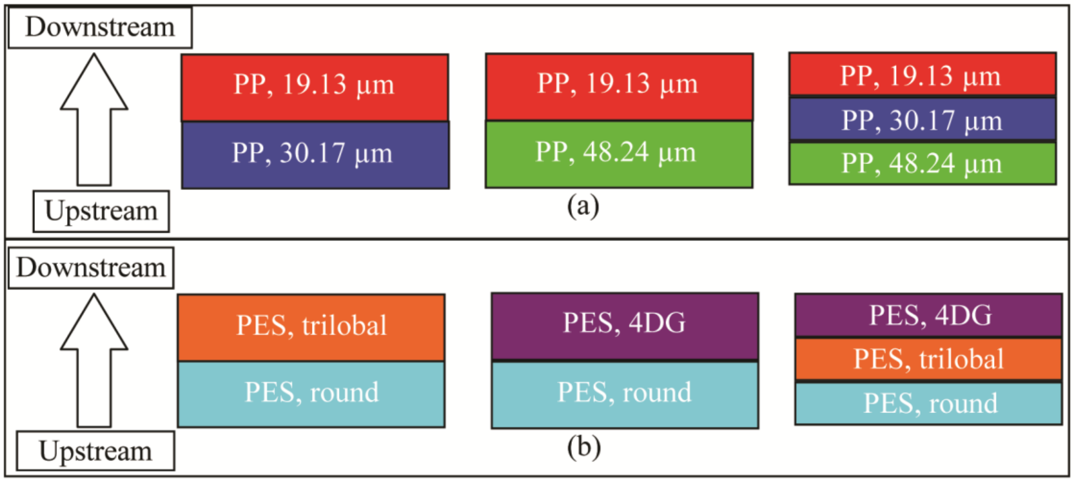

Fig. 1 — Schematic diagram of nonwoven filter media with hierarchically arranged fibres of different sizes (a), and shapes (b)

2.2 Characterization of Filter Media

The filter media were tested for basis weight, thickness, and filtration properties. The basis weight was determined in accordance with ASTM D 6242-98 standard. For this, the filter specimens of 10 cm × 10 cm size were cut by using a cutting machine. The cut samples were then weighted by using an electronic weighing balance. The thickness was determined in accordance with ASTM D 5729-97 standard. A digital thickness tester was used to measure the thickness of the filter media.

The filter media were also tested for gravimetric filtration efficiency, pressure drop, and dust holding capacity in accordance with ISO 5011 standard. The air filter test rig, as also reported by Maddineni *et al.*[7], was employed for this purpose. ISO 12103-1 A2 fine test dust was used to challenge the test media. The test dust was dispersed by a powder dispersion generator with a brush at a pressure drop of 1 bar. An air flow rate of 0.5 m^3/min was controlled by a blower placed at downstream and the flow rate was precisely measured by using a vortex shedding flow sensor. The dust penetrated through the test media was collected on an absolute filter media placed at the downstream of the test media. The absolute filter media had a minimum efficiency of 99.58 % at 8.5 m^3/min flow rate as per the ISO 5011 standard. Gravimetric measurements on the test filter media and the absolute filter media were carried out at certain intervals to estimate the dust holding capacity of the test filter media and the filtration efficiency was determined from the following expression:

$$E = \frac{\Delta MU}{\Delta MU + \Delta MABS} \qquad \ldots (1)$$

where E refers to filtration efficiency, ΔMU indicates the increase in mass of the test filter media, and $\Delta MABS$ denotes the increase in mass of the absolute filter media. The pressure drop across the test media was measured by using static pressure taps placed at the inlet duct and the outlet duct, connected each to a pressure sensor by a ring line. The test was carried out by injecting test dust at a feed rate of 0.5 g/min. The terminating pressure drops for the initial filtration efficiency (clean media) and the final filtration efficiency (clogging media) were maintained respectively at 200 Pa and 1000 Pa above the initial pressure drop. The experimental data were analyzed to examine the evolutions of filtration efficiency, pressure loss, and dust holding capacity during dust loading of the tested filter media.

The nonwoven filter media were also tested for determination of fractional filtration efficiency by employing a filter test setup reported elsewhere [8]. The setup comprised an aerosol generator for generation of submicrometer-sized particles, a pair of particle counters to mesure the upstream and downstream concentrations of particles, a pressure transducer for measurement of pressure drop and a flow transducer for measurement of velocity. Latex was used in the atomizer to generate particles in the sizes of 1 µm, 3 µm, 5 µm, 7 µm, and 10 µm. The solvent in the atomized droplets was dried in the dryer with silica gel as a dissicant. Electrical charges present on the dried particles were conditioned in a neutralizer. The test setup was equipped with two laser based particle counters in order to count the number of particles in the upstream and downstream of the test filter media. The filtration efficiency at each particle size was calculated from the measured particle concentrations at upstream and downstream of test filter media, as shown below

$$E\left(d_p\right)=1-\frac{C_{down}\left(d_p\right)}{C_{up}\left(d_p\right)} \quad \ldots (2)$$

where $E\left(d_p\right)$ refers to the filtration efficiency for a test particle size, C_{up} (d_p) denotes the concentration of particles of a specific size at the upstream of filter media, and C_{down} (d_p) indicates the concentration of particles of same size at the downstream of filter media. The test face velocity was chosen as 0.3 m/s. The pressure drop across the test filter media was measured by using a pressure tranducer. A flow transducer was used to determine the velocity of air flowing through the test specimen. A HEPA filter medium was mounted perpendicular to the air flow to ensure no particle in the exhaust.

3 Results and Discussion

3.1 Filtration Performance of Nonwoven Filter Media with Fibres of Different Sizes

It is of interest to examine whether the nonwoven filter media prepared with one or more layers of different fibre sizes would possess same filtration performance as those prepared from homogeneously-mixed fibres. The gravimetric filtration efficiency, pressure drop, and dust holding capacity of the composite nonwoven filter media as well as the hybrid filter media are reported in Table 2. As shown in Fig. 1(a), the composite filter media have fibres of different cross-sectional areas arranged in specific pattern along the upstream to the downstream sides of the media. It can be seen that the basis weight and the thickness of the comparable filter media are practically constants. Considering the filtration performance, the composite filter media register higher initial as well as final filtration efficiency, lower initial pressure drop, and higher dust holding capacity than the corresponding hybrid filter media. Of all the three composite filter media, the one comprising one-third of 19.13 μm fibres in the downstream side, one-third of 30.17 μm fibres in the middle and one-third of 48.24 μm fibres in the upstream side displays higher filtration performance. The composite filter media consisting of one-half of 19.13 μm fibres in the downstream side and one-half of 30.17 μm fibres in the upstream side registers lower pressure drop and higher dust holding capacity than that comprising one-half of 19.13 μm fibres in the downstream side and one-half of 30.17 μm fibres in the upstream side. However, the former displays lower filtration efficiency than the latter. This is due to the effect of fibre size of the fibrous layers. The upstream fibrous layer in this case consists of the largest fibres, i.e. 48.24 μm diameter and thus offers lower fibre surface area per unit volume as compared to the fibrous layer comprising of fibres of 30.17 μm diameter. This results in less probability of particle capture on the fibre surface across the filter depth.

Table 2 — Filtration performance of nonwoven filter media with fibres of different sizes

Nonwoven filter media	Weight proportions of fibres of different sizes			Mean basis weight g/m^2	Mean thickness mm	Mean initial filtration efficiency %	Mean final filtration efficiency %	Mean initial pressure drop Pa	Mean dust holding capacity g/m^2
	19.13 μm	30.17 μm	48.24 μm						
Composite filter media	1/2 (Downstream)	1/2 (Upstream)	-	306	3.61	98.51	99.47	79.36	810.53
Hybrid filter media	1/2	1/2	-	301	3.52	98.08	98.89	87.80	747.37
Composite filter media	1/2 (Downstream)	-	1/2 (Upstream)	308	3.69	98.15	99.42	68.96	905.26
Hybrid filter media	1/2	-	1/2	304	3.49	97.74	98.83	83.48	789.47
Composite filter media	1/3 (Downstream)	1/3	1/3 (upstream)	304	3.53	98.52	99.74	67.59	1368.42
Hybrid filter media	1/3	1/3	1/3	297	3.45	97.22	98.48	74.75	1042.11

Nevertheless, the composite filter media consisting of one-third of 19.13 μm fibres in the downstream side, one-third of 30.17 μm fibres in the middle and one-third of 48.24 μm fibres in the upstream side exhibit higher initial as well as final filtration efficiency due to progressive filtration of particles by multiple layers consisting of fibres of different sizes. Of all the hybrid filter media, the one prepared with equal proportion of 19.13 μm, 30.17 μm, and 48.24 μm fibres registers the lowest pressure drop and highest dust holding capacity. But, the hybrid filter media prepared with equal proportion of 19.13 μm and 30.17 μm fibres registers the highest initial filtration efficiency as well as final filtration efficiency. But, the same media show a higher pressure drop and a lower dust holding capacity than that prepared by homogeneous mixing of equal proportion of 19.13 μm and 48.24 μm fibres. Clearly, the hybrid filter media work like a typical filter media which remove more dust particles with the increase of smaller fibres, enabling high efficiency but associated with inherent disadvantage of low dust holding capacity and higher resistance to air flow. On the other hand, the composite filter media is configured to overcome the disadvantages of high pressure drop and low dust holding capacity, besides offering high filtration efficiency. As shown in Table 2, the difference in thickness between composite and hybrid filter media is found very small.

In the field of air filtration, it is widely known that the smaller particles are difficult to capture than the larger ones. The four mechanisms responsible for particle capture by the kinds of filter media studied in this work are Brownian diffusion, direct interception, inertial impact, and gravitational setting. Of them, Brownian diffusion predominantly works in the regime of capturing smaller particles. The other three mechanisms are more important for capturing larger particles. In order to examine if the composite filter media is able to filter out more smaller particles than the hybrid filter media, the filter media are tested for filtration efficiency by particle counting method. Figure 2 displays the experimental results of filtration efficiency corresponding to a set of particle sizes (0.3 μm, 0.5 μm, 1 μm, 3 μm, 5 μm, and 10 μm) for the composite filter media as well as the hybrid filter media made up of fibres of different sizes. It can be seen that the filtration efficiency of the composite filter media is about 20 - 45 % higher than the corresponding hybrid filter media for smaller particles (0.3 μm, 0.5 μm, and 1 μm). But, for the larger particles (3 μm, 5 μm, and 10 μm), the composite filter media exhibit around 2 - 15 % higher filtration efficiency than the hybrid filter media. This is an indicative of the fact that Brownian diffusuion is more predominating in the case of composite filter media, while direct interception, inertial impact, and gravitational setting are more important in the case of hybrid filter media. Further, it can be seen that the composite filter media consisting of one-third of 19.13 μm fibres in the downstream side, one-third of 30.17 μm fibres in the middle and one-third of 48.24 μm fibres in the upstream side exhibit higher

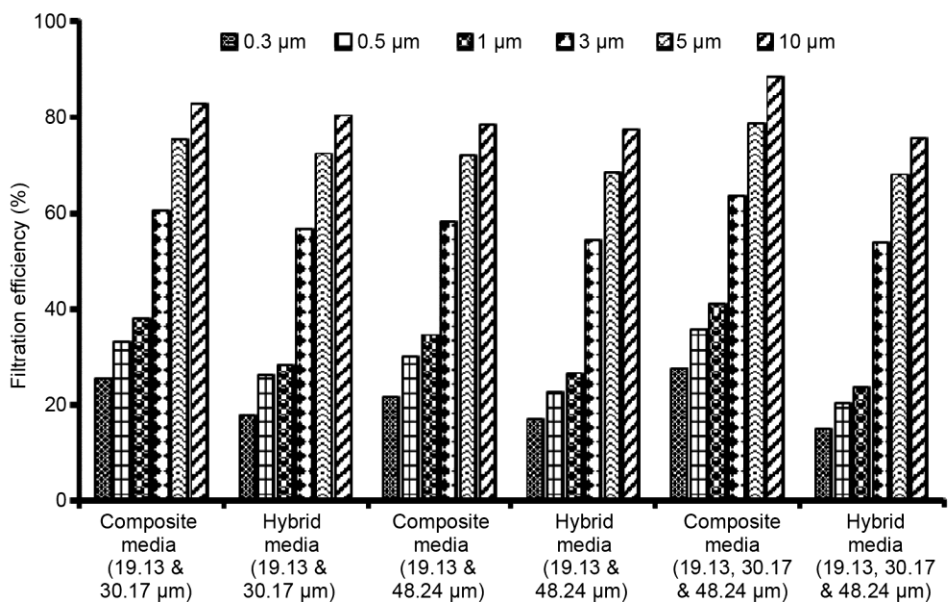

Fig. 2 — Comparison of filtration efficiency of composite filter media and hybrid filter media made up of fibres of different sizes

filtration efficiency than the other two composite filter media for particles of all sizes. Similarly, for all particle sizes, the composite filter media with 19.13 μm fibres in the downstream side and 30.17 μm fibres in the upstream side show higher filtration efficiency than the composite filter media with 19.13 μm fibres in the downstream side and 48.24 μm fibres in the upstream side. But, this is not the case with the hybrid filter media. Of the three hybrid filter media, the bi-component filter media prepared with equal proportion of 19.13 μm and 30.17 μm fibres show the highest filtration efficiency, followed by another bi-component filter media prepared with equal proportion of 19.13 μm and 48.24 μm fibres and the tri-component filter media prepared with equal proportion of 19.13 μm, 30.17 μm, and 48.24 μm fibres.

Figure 3(a) displays the evolution of pressure drop with dust holding capacity in case of composite as well as hybrid filter media made up of equal proportion of 19.13 μm and 30.17 μm fibres. It can be observed that the composite filter media show a little delay in increase of pressure drop as compared to its hybrid counterpart, though depth filtration behavior is quite significant in both cases. The intial pressure drops of the two media are practically same till 0.8 mm aqua but then the pressure drop of hybrid filter media is increased a little more than that of composite filter media. In case of composite filter media, the pressure drop increases at a slower rate than in hybrid filter media. When the terminal pressure drop is reached approximately 10 mbar, the weight of dust held up by the composite filter media is 7.7 g and that by the hybrid filter media is 7.1 g. This shows that the dust holding cacapcity of the composite filter media is around 8.4 % higher than that of the hybrid filter media. Figure 3(b) shows the evolution of pressure drop of the composite filter media and hybrid filter media constituted with equal proportion of 19.13 μm and 48.24 μm fibres. The dust loading results show that the intial pressure drops in case of both media are approximately same till 0.3 mm aqua but the difference in pressure drops starts afterwards. Overall, the composite filter media exhibit a higher delay in increase of pressure drop as compared to the hybrid filter media. After reaching the terminal pressure drop (10 mbar), the amount of dust accumulated onto the gradient filter media is 8.6 g and the same onto the mixed filter media is 7.5 g. This infers that the dust holding cacapcity of the composite filter media is almost 14 % higher than that of the hybrid filter media. Figure 3(c) shows the evolution of pressure drop of the composite filter media and hybrid filter media comprising an equal proportion of 19.13 μm and 30.17 μm and 48.24 μm fibres. The dust loading results show that the intial pressure drops of both the media are approximately the same till 0.24 mm aqua but afterward, the delay in pressure drop is increased with the composite filter media. The filter media made up of equal proportion of 19.13 μm and 30.17 μm and 48.24 μm fibres show higher pressure delay than those prepared with 50 % 19.13 μm & 50 % 30.17 μm fibres and 50 % 19.13 μm & 50 % 48.24 μm fibres. Clearly, in the case of composite filter media, the pressure drop increases at a slower rate than in the case of hybrid filter media. When the terminal pressure drop is

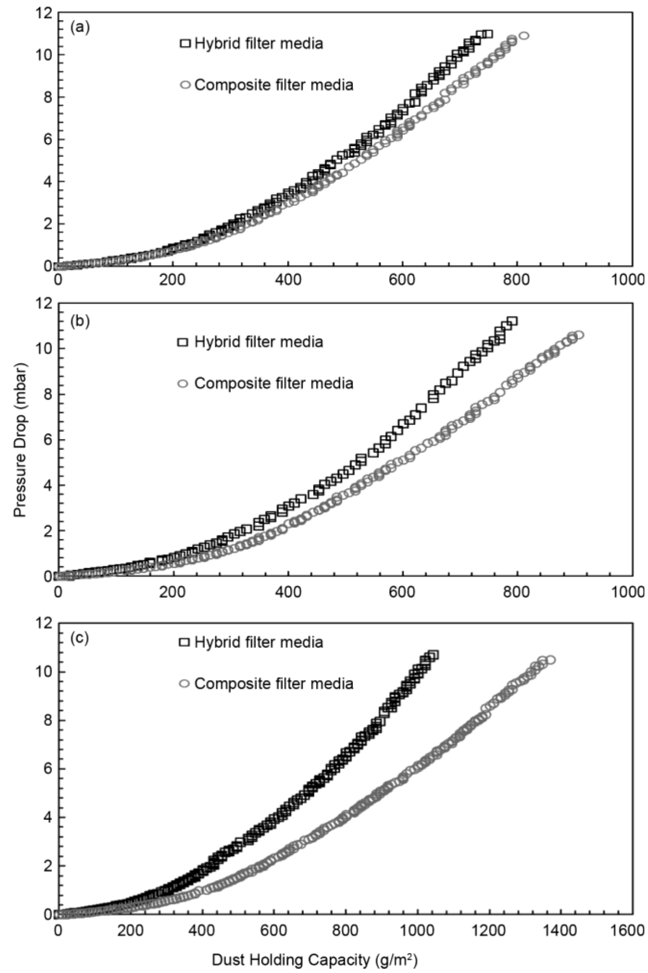

Fig. 3 — Evolution of pressure drop with dynamic loading of dust in case of composite filter media and hybrid filter media: (a) equal proportion of 19.13 μm and 30.17 μm fibres, (b) equal proportion of 19.13 μm and 48.24 μm fibres and (c) equal proportion of 19.13 μm, 30.17 μm, and 48.24 μm fibres

reached approximately 10 mbar, the dust mass deposit on the composite filter media is 13 g and the same on the hybrid filter media is 9.9 g. This means that the dust holding capacity of the composite filter media is 31.3 % higher than that of the hybrid filter media. This indicates that the composite filter media would have a longer service life and exhibit lower energy consumption than the hybrid filter media.

Looking at the evolution of pressure drop curves, it is clear that the composite filter media as well as the hybrid filter media behave as a depth loading filter in contrary to a surface loading filter such as cellulosic paper filter media. The extent of filter clogging can be visualized from the images of a representative filter media before and after dust loading, as shown in Fig. 4. As shown in Fig. 4, the surface of the filter media is full of dust particles. This is true to all media. Therefore, it is not possible to distinguish between the composite and the hybrid filter media in the clogged state. Figure 4 shows the reproducible image to indicate extent of clogging in nonwoven filter media.

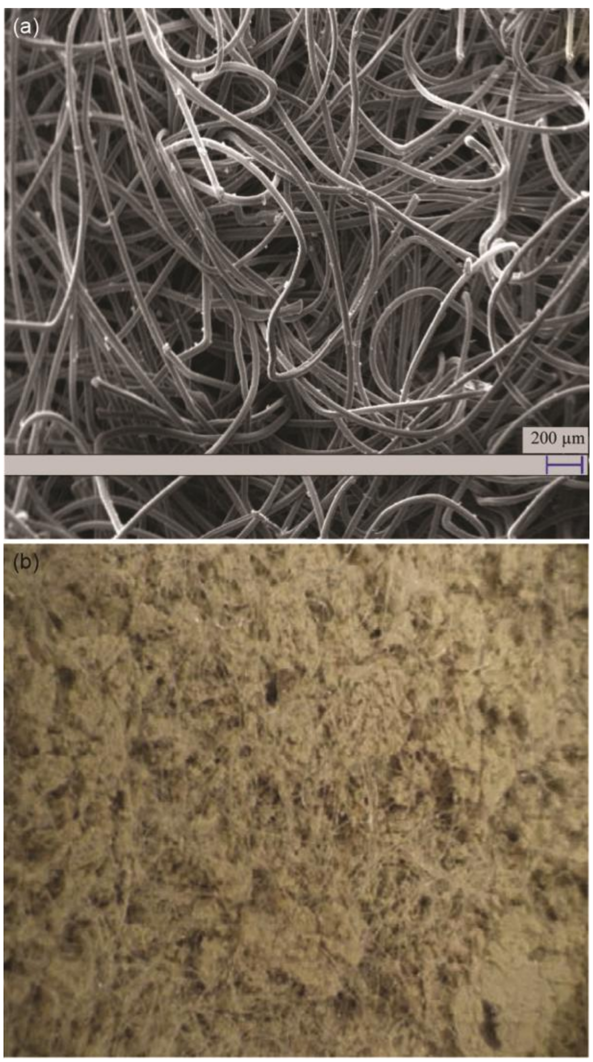

Fig. 4 — Composite filter media prepared from 19.13 μm and 30.17 μm polypropylene fibres, (a) before dust loading and (b) after dust loading

The composite filter media display a remarkable delay in filter clogging as all the fibrous layers are effectively utilized to capture the particles uniformly across the filter depth. The sequence of the fibrous layers is such (the higher permeable layer at the upstream followed by the less permeable layer at the downstream) that the majority of dust is trapped in the depth of the media, the smaller particles are penetrated deeper into the media and the bigger particles are collected closer to the upstream side. This selective distribution of dust particles in the media could maintain an acceptable level of pressure drop till the filter media is clogged with dust particles. On the contrary, the hybrid filter media collect dust particles on the upstream side with less penetration into the media. As the dust loading is increased, the growth of the dust layer occurred on the upstream side of the filter media at a faster rate and eventually results in clogging of the filter media.

3.2 Filtration Performance of Nonwoven Filter Media with Fibres of Different Shapes

Experiments are conducted to examine whether the hybrid nonwoven filter media prepared with homogeneous mixing of fibres of different cross-sectional shapes results in different filtration performance than that registered by the corresponding composite nonwoven filter media prepared with one or more layers of fibres of different shapes. Table 3 reports structural characteristics and filtration performance of composite and hybrid filter media prepared with fibres of different cross-sectional shapes (round, trilobal deep-grooved). The filtration performance includes initial filtration efficiency, final filtration efficiency, initial pressure drop, and dust holding capacity. It can be seen that the basis weight and thickness of the comparable filter media are practically same. Considering the filtration performance, the composite filter media prepared with fibres of different cross-sectional shapes register higher initial as well as final filtration efficiency, lower initial pressure drop, and higher dust holding capacity than the hybrid filter media prepared. In case of pressure drop without dust loading, the composite filter media prepared with equal proportion of trilobal

Table 3 — Filtration performance of nonwoven filter media with fibres of different shapes

Filter media	Weight proportions of fibres of different shapes			Basis weight g/m^2	Thickness mm	Initial filtration efficiency %	Final filtration efficiency %	Initial pressure drop Pa	Dust holding capacity g/m^2
	Round	Trilobal	Deep grooved						
Composite filter media	1/2 (Upstream)	1/2 (Downstream)	-	300	3.67	97.39	98.85	56.51	1052.63
Hybrid filter media				303	3.39	95.50	97.83	60.92	968.42
Composite filter media	1/2 (Upstream)	-	1/2 (Downstream)	297	3.52	97.48	98.97	60.92	968.42
Hybrid filter media				295	3.44	97.31	98.43	71.42	915.79
Composite filter media	1/3 (Upstream)	1/3 (Middle)	1/3 (Downstream)	294	3.43	98.04	98.99	57.09	1105.26
Hybrid filter media				297	3.51	96.94	98.34	69.95	936.84

(downstream) and round (upstream) fibres exhibit lowest pressure drop followed by the one prepared with equal proportion of deep-grooved (downstream), trilobal (middle), and round (upstream) fibres and the one prepared with equal proportion of deep-grooved (downstream) and round (upstream) fibres. Such trend is true for the hybrid filter media as well. The effect of fibre shape, deviated from circularity, is more understood in this case. As expected, the hybrid filter media made up of equal proportion of round, trilobal and deep grooved fibres exhibit lower filtration efficiency than the hybrid filter media made up of equal proportion of round, and deep grooved fibres and higher filtration efficiency than the filter media made up of equal proportion of round and trilobal fibres. A similar trend is observed in the case of dust holding capacity and initial pressure drop as well. Similar to hybrid filter media, the composite filter media with equal proportion of deep-grooved (downstream) and round (upstream) fibres exhibit higher initial filtration efficiency, higher final filtration efficiency and lesser dust holding capacity than the one with equal proportion of trilobal (downstream) and round (upstream) fibres. The above-mentioned behavior can be explained in terms of the cross-sectional shape of the fibres comprising the filter media. Interestingly, the composite filter media with equal proportion of deep-grooved (downstream) trilobal (middle) and round (upstream) fibres exhibit highest initial filtration efficiency, final filtration efficiency, and dust holding capacity, too. This can be ascribed due to the effect of multiple gradients of fiber shape along the depth of the filter media

It is of interest to know if the composite filter media made up of fibres of different cross-sectional shapes are able to filter out more smaller particles than the corresponding hybrid filter media. Figure 5 displays the experimental results of filtration efficiency corresponding to a set of particle diameters (0.3 μm, 0.5 μm, 1 μm, 3 μm, 5 μm, and 10 μm) for the composite filter media as well as the hybrid filter media made up of fibres of different shapes. It can be seen that the filtration efficiency of the composite filter media is about 18 - 27 % higher than the corresponding hybrid filter media for smaller particles (0.3 μm, 0.5 μm, and 1 μm). But, for larger particles (3 μm, 5 μm and, 10 μm), the composite filter media exhibit around 5 - 15 % higher filtration efficiency than the hybrid filter media. This is an indicative of the fact that Brownian diffussion is more predominating in the case of composite filter media, while direct interception, inertial impact, and gravitational settling are more important in the case of hybrid filter media. Further, it can be seen that the composite filter media consisting of equal proportion of deep-grooved (downstream) and round (upstream) fibres exhibit higher filtration efficiency than the other two composite filter media for particles of all sizes. Similarly, for all particle sizes, the composite filter media prepared with equal proportion of deep-grooved (downstream), trilobal (middle), and round

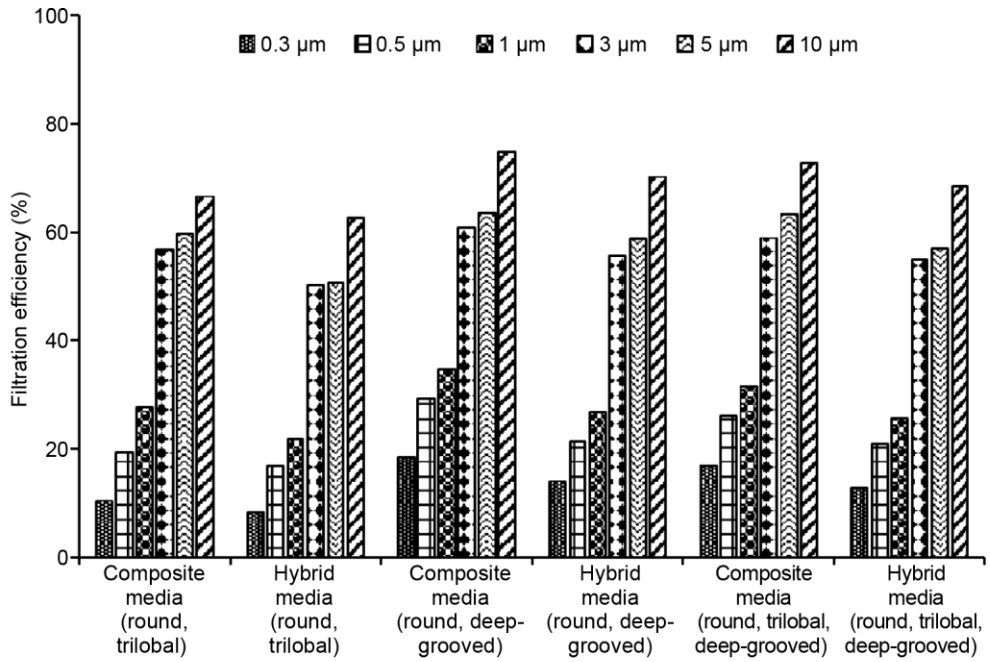

Fig. 5 — Comparison of filtration efficiency of composite filter media and hybrid filter media made up of fibres of different shapes

(upstream) fibres show a higher filtration efficiency than the composite filter media made up of equal proportion of trilobal fibres in the downstream and round fibres at the upstream. A similar observation is made in case of hybrid filter media prepared with fibres of different cross-sectional shapes. Of the three hybrid filter media, the bi-component filter media prepared with equal proportion of round and deep-grooved fibres display the highest filtration efficiency, followed by the tri-component filter media prepared with equal proportion of round, trilobal, and deep-grooved fibres and the bi-component filter media prepared with equal proportion of round and trilobal fibres respectively.

Figure 6(a) displays the evolution of pressure drop of the composite and hybrid filter media made up of equal proportion of round and trilobal fibres. As shown, the composite filter media exhibit remarkably lower pressure drop than the hybrid filter media. When the terminal pressure drop (10.5 mbar) is reached, the amount of dust held by the composite filter media is 10 g and the same held by the hybrid filter media is 8.9 g. This infers that the dust holding capacity of the composite filter media is around 12.35 % higher than that of the hybrid filter media. Figure 6(b) shows the evolution of pressure drop of the composite and hybrid filter media made up of equal proportion of round and deep-grooved fibres. As shown, both filter media register approximately same pressure drop of 2.1 mbar till a dust holding capacity of around 4 g. Afterwards, the hybrid filter media exhibit a slightly higher pressure drop as compared to the composite filter media. When the terminal pressure drop is reached at 10 mbar, the amount of dust held by the composite filter media is 9.2 g and the same held by the hybrid filter media is 8.7 g. This infers that the dust holding capacity of the composite filter media is 5.7 % higher than that of the hybrid filter media. It is clearly evident that the fibre shape, deviated more from the circularity, displays early clogging, although fibre surface area is higher. This is true for both composite and hybrid filter media. Nevertheless, the composite filter media exhibit the increase in dust loading capacity. Figure 6(c) displays the evolution of pressure drop of the composite and hybrid filter media made up of equal proportion of round, trilobal and deep-grooved fibres. As shown, both filter media registered approximately same pressure drop of 1.76 mbar till a dust holding capacity of around 4.5 g. Afterwards, the hybrid filter media exhbited a slightly higher pressure drop as compared to the composite filter media. When the terminal pressure drop (10 mbar) is reached, the amount of dust held by the composite filter media is 10.5 g and the same held by the hybrid filter media is 9.7 g. This infers that the dust holding capacity of the composite filter media is approximately 7.21 % higher than that of the hybrid filter media. The composite filter media

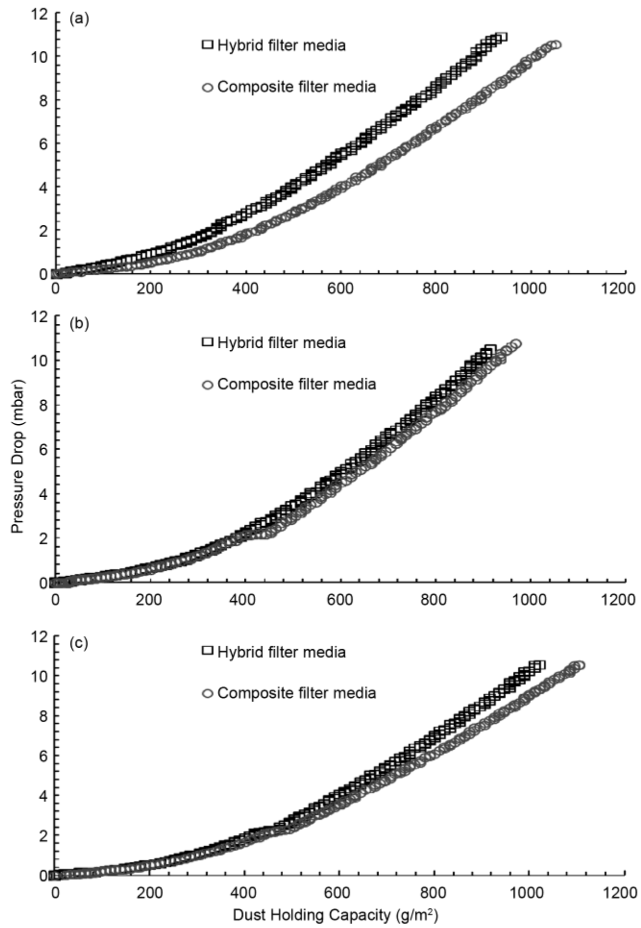

Fig. 6 — Evolution of pressure drop with dynamic loading of dust in case of composite and hybrid filter media, (a) equal proportion of round and trilobal fibres, (b) equal proportion of round and deep-grooved fibres and (c) equal proportion of round, trilobal and deep-grooved fibres

is designed by placing the fibres whose cross-sectional shapes are more deviating from circularity on the layer of the downstream side. Dust particles entrained in intake airflow are trapped such that larger filtered particles are trapped at or near the upstream fibrous layer and progressively smaller filtered particles are trapped at positions in the filter media progressively closer to the downstream fibrous layer. This results in more uniform and selective deposition of particle across the filter depth and thus the resulting air filter exhibit favorable depth loading, filtering efficiency, and air flow characteristics.

4 Conclusion

This work shows a set of promisingly-designed nonwoven air filter media for automotive engine intake application. The composite nonwoven filter media with hierarchically arranged fibres of different sizes or shapes display excellent filtration performance in the cleaned state as well as in the clogging state. As compared to the homogeneously-mixed fibre filter media, the composite filter media offer higher initial as well as final filtration efficiency, lower initial pressure drop, and higher dust holding capacity. The composite filter media are found to filter out a higher number of smaller particles than the hybrid filter media. As far as the evolution of pressure drop is concerned, the composite filter media exhibit slower rise of pressure drop over accumulation of dust particles than their hybrid counterparts.

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