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Microstructure and particle filtration behavior of multimodal fibrous filter media made of fibres of different sizes for engine intake air filtration

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This paper reports a set of theoretical expressions for describing the microstructure of multimodal fibrous filter media comprising fibres of different cross-sectional sizes along with the application of such expressions to predict the filtration performance of clean and clogging media for engine intake air filtration. It is found that the overall filtration efficiency corresponds very well with the classical theory of air filtration after suitably modifying the single fibre efficiency and mean fibre diameter. The square of mean fibre diameter is found to be a weighted harmonic mean of the square of fibre diameter of individual component. The single fibre efficiency of multimodal filter media, when expressed as a summation of single fibre efficiencies of individual component of fibres weighted by the corresponding surface area fraction, correlates very well with the experimental results. The evolution of pressure drop is explained satisfactorily based on Berman's approach after suitably modifying the Davies equation.

Keywords: Dynamic filtration behavior, Engine intake air filtration, Fibrous filter media, Multimodal fibre size distribution, Polypropylene fibre

1 Introduction

Air filtration plays an important role in deciding the performance of automotives with regard to engine life, fuel economy, emission control, and passenger safety[1-3]. The engines require clean air for fuel combustion, but the atmospheric air contains a lot of dust particles of different sizes. If the dust particles enter into the engines, they cause significant engine wear, create inadequate air-to-fuel stoichiometric ratio, give rise to malfunctioning of air flow sensors, and emit pollutants from the engines as exhaust. This leads to poor engine life, remarkable performance loss, high oil consumption, increased operational cost, enhanced air pollution, and greater CO_2 emission[4-7]. The dust particles are separated from the atmospheric air by means of engine intake air filtration. A modern engine intake air filtration system is expected to comply with stringent filtration performance as laid down in the following relevant specifications under all operating conditions. The filtration efficiency should be greater than or equal to a minimum specified efficiency for a greater engine protection. The pressure drop should be less than or equal to a terminal pressure drop in order to attain a targeted level of fuel efficiency. The dust holding capacity should be extremely high in order to offer a greater service life. A high-quality engine intake air filtration system would have these parameters optimized to deliver a desired level of performance.

Nowadays, fibrous filter media are mostly used for engine intake air filtration. The fibres are the building block of such filter media. Their geometries, geometrical arrangements, and mutual interactions describe the microstructure of the filter media. The microstructural features and the fluid characteristics ultimately decide the filtration performance of the filter media. With a view to engine intake air filtration, it is always desirable for filter media to exhibit high filtration efficiency, low pressure drop and high dust holding capacity. In general, the fibres with small cross-sectional size lead to higher filtration efficiency, but at the cost of higher pressure drop and lower dust holding capacity. On the other hand, the fibres with large cross-sectional size result in lower pressure drop and higher dust holding capacity, but at the cost of lower filtration efficiency [8-10]. Therefore, fibrous filter media consisting of either small fibres or large fibres showing unimodal fibre size distribution cannot offer enhanced filtration performance [11].

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To derive the best of filtration efficiency, pressure drop, and dust holding capacity, a fibrous filter medium should have a combination of small and large fibres, showing multimodal fibre size distribution.

In literature, a significant amount of theoretical, numerical, and experimental research findings is available on unimodal fibrous filter media. But the same on multimodal fibrous filter media is found to be limited. The mean fibre diameter of multimodal fibrous filter media was always expressed empirically as a weighted arithmetic mean of fibre diameter of individual component [12-22]. The weights were obtained from mass fraction or number fraction or surface area fraction or volume fraction of fibre components comprising the entire filter media. The classical theory of air filtration [23] in conjunction with this expression was used to explain the filtration behavior of multimodal fibrous filter media in the clean state. A set of empirical formulas was utilized to compute the filtration efficiency of a single fibre due to diffusion, interception, impaction, and gravitational settling [24-27]. However, there was no such attempt made to describe the particle filtration behavior of multimodal fibrous filter media in the clogging state. This paper reports a set of theoretical expressions for describing the microstructure of multimodal fibrous filter media and reports on application of such expressions to predict the filtration performance of the filter media in the clean state as well as in the clogging state.

2 Materials and Methods

2.1 Fibre Materials

In this work, circular polypropylene fibres of same cut length (51 mm) but three levels of linear density (mass per unit length), viz. 2.5 denier, 6 denier, and 15 denier were used.

2.2 Preparation of Fibrous Filter Media

The polypropylene fibres of different levels of linear density were blended homogeneously in different mass fractions to prepare a set of fibrous filter media by employing a laboratory-based nonwoven production line. As the fibres were of three levels of linear density, a three-component augmented simplex lattice design was followed for preparation of fibrous filter media. According to this design, ten different blends of fibres were prepared. The fibre blends were processed through a nonwoven production line comprising a fibre opening machine, a fibre web-forming machine, a fibre web-stacking machine, and a needle-punching machine. The fibre opening machine was known to open the fibre tufts by increasing the volumes of the tufts or by breaking the bigger tufts into smaller ones. The fibre web-forming machine was a double cylinder roller carding machine that supposedly opened the fibre tufts, individualized them into almost single fibre stage, and consolidated 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 form a mechanically-bonded fibrous filter medium. While needle punching, the punch density was kept constant at 250 punches/cm^2 and the depth of needle penetration was also maintained constant at 10 mm. The nominal basis weight and thickness of the fibrous filter media was kept at 300 g/m^2 and 3 mm respectively.

2.3 Characterization of Fibrous Filter Media

The fibrous filter media were tested for fibre diameter, basis weight, thickness, filtration efficiency, pressure drop, and dust holding capacity.

The diameter of polypropylene fibres was measured by using an image analysis system comprising of a scanning electron microscope (Zeiss Model EVO50) and an image analysis programme (Image-J). The images of the three filter media comprising polypropylene fibres of pure blends were taken by using the scanning electron microscope. The images were then employed to determine fibre diameter by using the image analysis programme. On each of three filter media, fibre diameter was measured from 450 different places. Based on measurements, a set of statistical parameters was calculated.

The basis weight was determined in accordance with ASTM D 6242-98 standard. For this, the filter samples 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 basis weight and the thickness were used to determine the fibre packing density of the filter media. For this, the density of polypropylene fibres was taken as 910 kg/m^3.

The fibrous filter media were tested for gravimetric filtration efficiency, pressure drop, and dust holding capacity in accordance with ISO 5011 standard. The air filter test rig, reported by Maddineni *et al.*[28], was employed for this purpose. ISO 12103-1 A2 fine test dust was used to challenge the filter media under test. Before use, the test dust was heated in a vessel up to temperatures >100°C to eliminate any humidity as recommended in the standard. The test dust was dispersed by a powder dispersion generator to achieve a dust concentration of 1 g/m^3 as specified in ISO 5011 standard. The temperature and relative humidity were measured at the beginning of the measurement and were maintained throughout the test. The test filter media were mounted in the measuring duct. 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 medium placed at the downstream of the test media. The absolute filter medium 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 :

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

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 (clogged media) were maintained at respectively 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.

Also, in this work, the fibrous filter media were tested for determination of fractional filtration efficiency by employing a standard filter test setup reported elsewhere [29]. The setup comprising an aerosol generator for preparing of submicrometer-sized particles, a pair of particle counters to measure 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 desiccant. 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 :

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

where $E\left(d_{\mathrm{p}}\right)$ refers to the filtration efficiency for a test particle size; $C_{\mathrm{up}}\left(d_{\mathrm{p}}\right)$ denotes the concentration of particles of a specific size at the upstream of filter media; and $C_{\mathrm{down}}\left(d_{\mathrm{p}}\right)$ 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 transducer. 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.

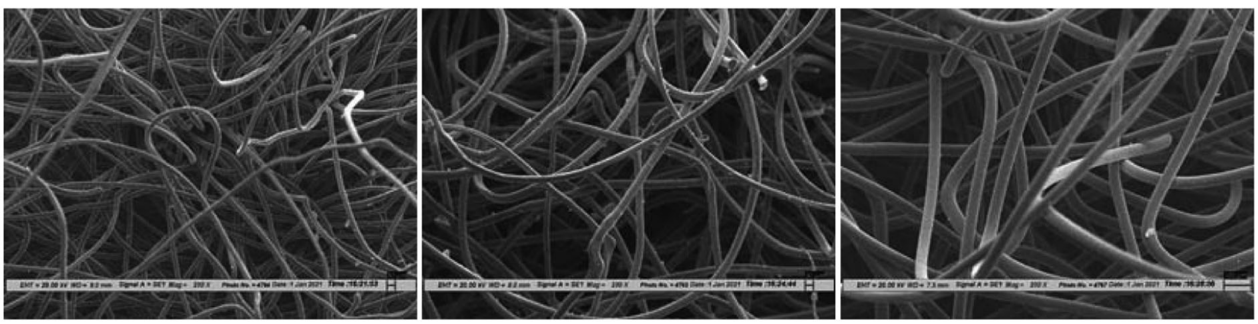
3 Results and Discussion

3.1 Microstructure of Fibrous Filter Media

In this work, regular polypropylene fibres of three different levels of linear density were used in different mass fractions to prepare a set of ten carded and needle-punched nonwoven filter media. The basis weight and thickness of the filter media are shown in Table 1. It can be noticed that the basis weight and the thickness of all the ten filter media remain practically constants. The composition of polypropylene fibres in the filter media is also shown in Table 1. The diameter of polypropylene fibres of

Table 1 ─Structural characteristics of fibrous filter media

Filter media	Mass fractions of fibres of different fineness			Mean fibre diameter µm	Basis weight g/m^2	Thickness mm
	2.5 denier	6 denier	15 denier			
F1	1	0	0	19.13	294.29	3.43
F2	0	1	0	30.17	298.33	3.47
F3	0	0	1	48.24	305.27	3.64
F4	1/2	1/2	0	22.85	294.34	3.44
F5	1/2	0	1/2	25.15	296.04	3.45
F6	0	1/2	1/2	36.17	303.00	3.57
F7	2/3	1/6	1/6	21.95	294.17	3.44
F8	1/6	2/3	1/6	28.12	297.67	3.47
F9	1/6	1/6	2/3	32.76	301.47	3.55
F10	1/3	1/3	1/3	26.53	296.86	3.45



F1 **F2** **F3**

Fig. 1 — SEM images of fibrous filter media

three levels of linear density is determined from the scanning electron microscopic images of the three filter media (F1, F2, F3) (Fig. 1). The mean diameter of 2.5 denier polypropylene fibre is determined as 19.13 µm with a standard error of 0.03 µm. The 6 denier polypropylene fibre is found to exhibit an average diameter of 30.17 µm with a standard error of 0.02 µm. And the mean diameter of 15 denier polypropylene fibre is determined as 48.24 µm with a standard error of 0.04 µm. The aforesaid numerical values of mean diameter of 2.5 denier, 6 denier, and 15 denier fibres were substituted in an analytical expression, which is derived hereunder, to determine the mean fibre diameters of the remaining seven filter media (F4-F10).

Let us consider a multimodal fibrous filter medium that consists of n components of fibres. Here, the numerical value of n can be 2 or 3. The filter medium has a total mass m. The mass of i-th component is m_i, where $i = 1, 2, \ldots, n$. The mass fraction of i-th component is w_i, where $w_i = m_i / m$. Evidently, $\sum_{i=1}^{n} w_i = 1$. The average fibre characteristics of i-th component are as follows: length $\bar{l}_i$, cross-sectional area $\bar{a}_i$, fineness $\bar{t}_i$, and density $\bar{\rho}_i$. Let us assume that the mean cross-sectional area ($\bar{a}_i$) of the fibre is equal to the area of a circle of mean diameter ($\bar{d}_i$) such that $\bar{d}_i = \sqrt{4\bar{a}_i/\pi}$, then $\bar{d}_i$ is called mean equivalent diameter of the fibre. The total length of fibres in the i-th component is $L_i = m_i/t_i = m\,w_i/t_i$. And the total length of all fibres in the filter medium is $L = \sum_{i=1}^{n} L_i = m \sum_{i=1}^{n} (w_i/t_i)$. Then, the mean fineness of fibres in the filter medium is $\bar{t} = m/L = 1\Big/\left(\sum_{i=1}^{n} w_i/t_i\right)$. The mean cross-sectional area of fibres in the filter medium is $\bar{a} = 1\Big/\left(\sum_{i=1}^{n} w_i/\bar{a}_i\right)$. Hence, the mean diameter of fibres in the filter medium can be stated as follows :

$$\bar{d} = 1\Bigg/\left(\sqrt{\sum_{i=1}^{n} \frac{w_i}{\bar{d}_i^{\,2}}}\right) \qquad \ldots (3)$$

As shown, the mean fibre diameter is neither an arithmetic mean nor a geometric mean and nor a harmonic mean of fibre diameter of individual component, but the square of mean fibre diameter is a weighted harmonic mean of the square of fibre diameter of individual component. A more generalized form of this expression can be found from the work of Neckář and Das [30].

The calculated mean diameters of the fibres comprising the seven filter media (F4-F10) are reported in Table 1. It can be seen that the mean diameters of the fibres in these filter media vary considerably. From fibre blending point of view, three (F1, F2, F3) of the ten filter media comprised of fibres with unimodal diameter distribution and the remaining seven (F4-F10) media are composed of fibres with multimodal diameter distribution.

3.2 Filtration Efficiency of Fibrous Filter Media

The filtration efficiency of clean filter media is termed as initial filtration efficiency. The initial filtration efficiency is always critical as the filter media show their lowest efficiency at the clean state, and this can have an adverse effect on the engine life. The initial filtration efficiency of the ten filter media obtained from gravimetric measurement is displayed in Fig. 2. The highest initial filtration efficiency (98.84 %) is registered by the unimodal filter medium (F1) made up of fibres of 19.13 μm mean diameter. The lowest initial filtration efficiency (93.55 %) is recorded by the unimodal filter medium (F3) made up of fibres of 48.24 μm mean diameter. The unimodal filter medium (F2) comprising fibres of 30.17 μm mean diameter exhibits 96.76 % initial filtration efficiency. The multimodal filter media (F4-F10) display initial filtration efficiency between 95.54 % and 98.09 %. Interestingly, all the multimodal filter media display a synergistic effect in a sense that their initial filtration efficiency is higher than the weighted arithmetic mean of the initial filtration efficiencies of the constituent individual components. This difference is more with more number of fibre components in the filter media. It can be observed that the initial filtration efficiency increases as the mean fibre diameter of the filter media decreases. This is expected as a filter media comprising smaller fibres offers higher specific surface area than a filter media consisting of larger fibres.

According to the theory of air filtration, a fibrous filter medium captures particles of different sizes with different levels of efficiency. The four mechanisms responsible for particle capture by the kinds of filter media studied in this work are Brownian diffusion, direct interception, inertial impaction, and gravitational setting. Of them, Brownian diffusion predominantly works in the regime of capturing smaller particles, while direct interception, inertial impaction, and gravitational setting are more important for capturing larger particles. However, there could be particles that do not adhere to fibre

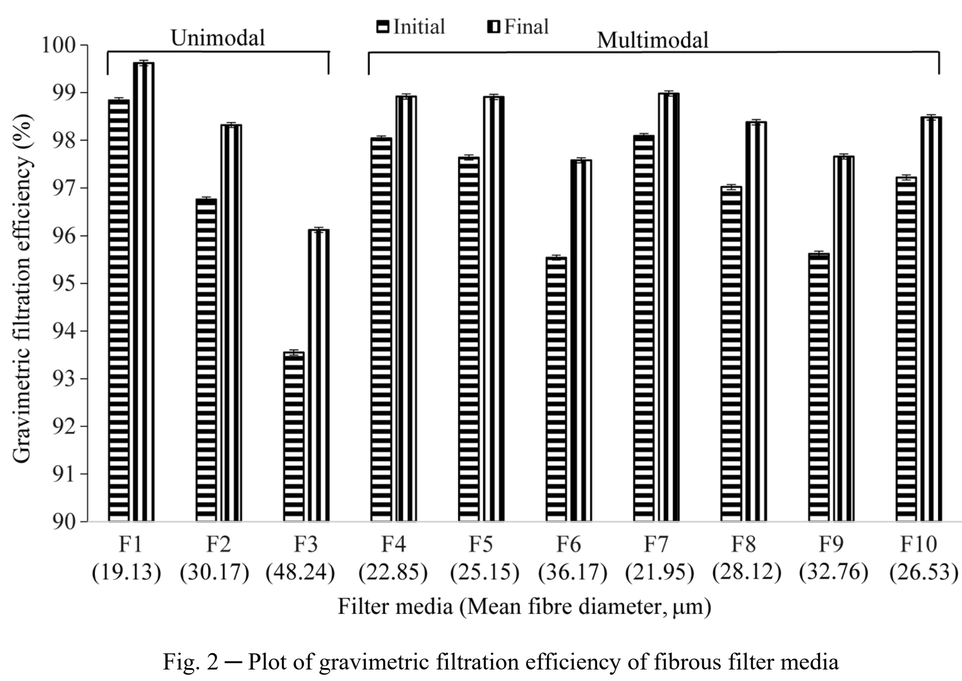


Fig. 2 — Plot of gravimetric filtration efficiency of fibrous filter media

surfaces upon contact, but rebound and reentrain into the airstream before penetrating through the filter media. To examine the particle filtration behavior of unimodal and multimodal fibrous filter media, the filter media were tested for filtration efficiency by particle counting method. Figure 3displays the experimentalresults of fractional filtration efficiency of the clean filter media corresponding to particles of different sizes viz. 1 μm, 3 μm, 5 μm, 7 μm, 10 μm. As expected, all the filter media capture larger particles with higher efficiency and smaller particles with smaller efficiency. But, the overall fractional filtration efficiency of the clean filter media increases with the decrease in mean fibre diameter.

It is of an interest to predict the fractional filtration efficiency of multimodal fibrous filter media, if the single fibre efficiencies of the constituent fibres are known. The single fibre efficiencies of the fibres of three levels of linear density are determined by substituting the overall filtration efficiency of the three filter media (F1, F2 and F3) in the following equation :

$$E = 1 - \exp\left[-\frac{4\alpha E_{\Sigma} Z}{\pi(1-\alpha)} \sqrt{\sum_{i=1}^{n} \frac{w_i}{d_i^2}} \right] \quad \ldots (4)$$

where E stands for overall filtration efficiency, E_{Σ} refers to single fibre filtration efficiency, α denotes packing density, and Z represents thickness. Thus obtained single fibre efficiencies are used in the following expressions to compute the single fibre efficiency of the multimodal fibrous filter media

$$E_{\Sigma} = \sum_{i=1}^{n} w_i E_{\Sigma,i} \quad \ldots (5)$$

$$E_{\Sigma} = \sum_{i=1}^{n} \beta_i E_{\Sigma,i} \quad \ldots (6)$$

$$E_{\Sigma} = \sum_{i=1}^{n} \gamma_i E_{\Sigma,i} \quad \ldots (7)$$

$$E_{\Sigma} = \sum_{i=1}^{n} \kappa_i E_{\Sigma,i} \quad \ldots (8)$$

where $E_{\Sigma,i}$ denotes the single fibre efficiency of the *i*-th component fibres; E_{Σ} indicates the single fibre efficiency of multimodal fibrous filter media; w_i, β_i, γ_i and κ_i denote the mass fraction, volume fraction, surface area fraction, and number fraction of *i*-th component respectively. While the mass fraction (w_i) of *i*-th component of fibres is an easily measurable quantity, the other fractions are not. In fact, they can be expressed in terms of mass fraction in the following manner :

$$\beta_i = \frac{(w_i/\bar{\rho}_i)}{\sum_{i=1}^{n}(w_i/\bar{\rho}_i)} \quad \ldots (9)$$

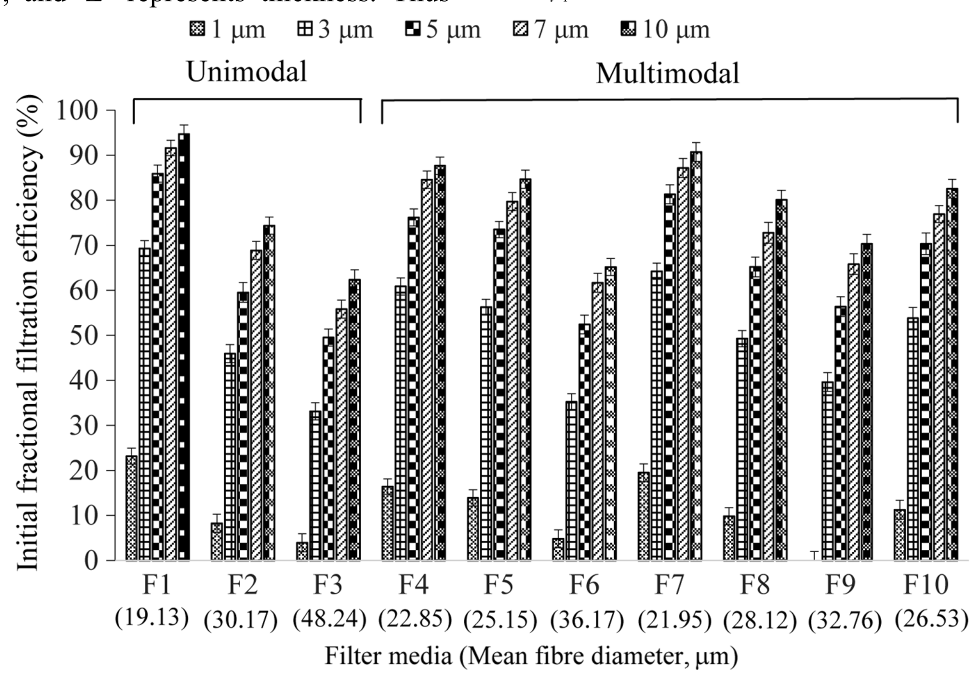


Fig. 3 ─ Plot of fractional filtration efficiency of fibrous filter media

$$\gamma_i = \frac{\left(w_i \sqrt{\overline{\rho}_i} / \sqrt{\overline{t}_i} \right)}{\sum_{i=1}^{n} \left(w_i \sqrt{\overline{\rho}_i} / \sqrt{\overline{t}_i} \right)} \quad \ldots (10)$$

$$\kappa_i = \frac{\left[w_i / \left(\overline{l}_i \overline{t}_i \right) \right]}{\sum_{i=1}^{n} \left[w_i / \left(\overline{l}_i \overline{t}_i \right) \right]} \quad \ldots (11)$$

where $\overline{l}_i$, $\overline{\rho}_i$, and $\overline{t}_i$ denote the mean length, mean density, and mean linear density of fibres of *i*-th component respectively. It can be noted that in this case the mass fraction of fibres is same as the volume fraction of fibres as all fibres possess same density. The other two fractions are determined from Eqs (10) and (11). The single fibre efficiencies based on mass, area, and number fractions of fibres in the multimodal fibrous filter media computed from Eqs (5) – (11) are substituted in Eq. (9) to calculate the overall filtration efficiencies of the filter media. A comparison between the calculated results and the experimental ones is shown in Fig. 4. The coefficient of determination is found to be 0.99 for area fraction, 0.97 for mass fraction and 0.96 for number fraction. This confirms

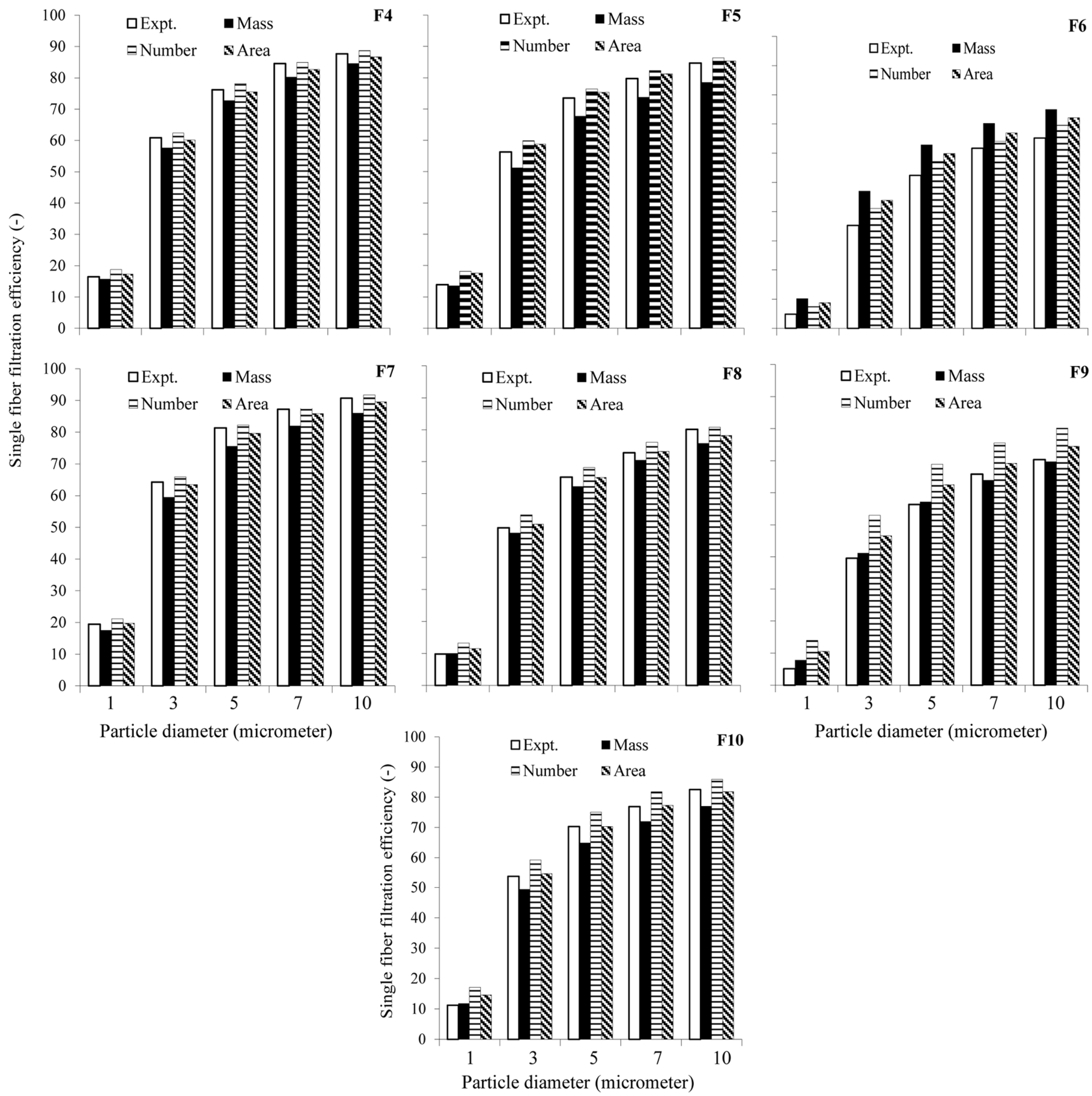


Fig. 4 ─ Comparison of fractional filtration efficiency of different filter media that the single fibre efficiency of the multimodal fibrous filter media is best represented by the addition of the single fibre efficiency of individual components weighted by the corresponding surface area fraction, not by the mass fraction or the volume fraction or the number fraction.

3.3 Evolution of Pressure Drop Across Fibrous Filter Media

Pressure drop is a very important measure of filtration performance of air filter media. If it exceeds a certain specific value, then there would be a significant impact on the performance of air filter media. Figure 5 displays the pressure drop of the ten fibrous filter media at the clean state. It can be seen that the initial pressure drop of the filter media decreases with the increase in mean fibre diameter. Here, an attempt has been made to explain this behavior in the light of Davies' equation after suitably modifying it with the expression of mean fibre diameter, as shown below :

$$\Delta P = 64\eta \frac{Q}{A} Z\alpha^{1.5}\left(1+56\alpha^3\right)\left(\sum_{i=1}^{n}\frac{w_i}{\bar{d}_i^2}\right) \quad \ldots (12)$$

where ΔP refers to the pressure drop across clean filter media; w_i and $\bar{d}_i$ denote the mass fraction and mean fibre diameter respectively of *i*-th component; η stands for dynamic viscosity of air; Q indicates air flow rate; and A, Z, and α are cross-sectional area, thickness, and packing density respectively, of the filter media. A comparison between the calculated results and the experimental data is shown in Fig. 5. Evidently, Davies equation in conjunction with the analytical expression of mean fibre diameter predicted the experimental results of pressure drop very well.

Pressure drop is also known as a key descriptor that decides the costefficiency of air filter media. As filtration proceeds the pressure drop increases due to accumulation of dust particles. A slow rise of pressure drop would demand less energy for the air to flow through and add more life to the filter media. Fig. 6 displays how the pressure drop is developed in response to accumulation of dust particles in the filter media. Two phases can be distinguished in the evolution of pressure drop during clogging of the filter media. In the first phase, the evolution is gradual, whereas in the second phase, the evolution is abrupt and markedly linear. The first phase is definitely a slow evolution process, but the second phase of evolution is surely a fast process. While the gradual rise is associated with dust loading in the depth of the filter media, the abrupt rise is connected to dust cake formation on the surface of the filter media. It can be noticed that the coarser fibre filter media display a slower rise of pressure drop than the finer fibre filter media. This leads to significantly higher dust holding capacity of the former as compared to the latter (Fig. 7a). The entire evolution of pressure drop across the unimodal fibrous filter media is first conceptualized by Bergman *et al.*[31]. It is

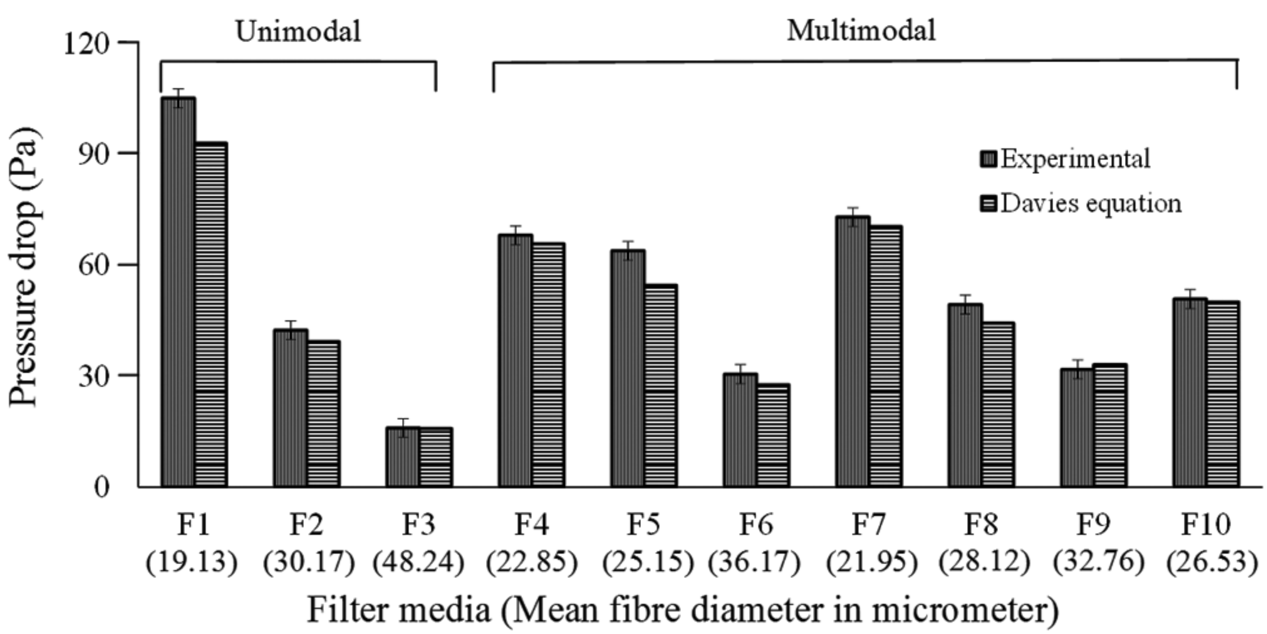


Fig. 5 — Plot of pressure drop across fibrous filter media in clean state

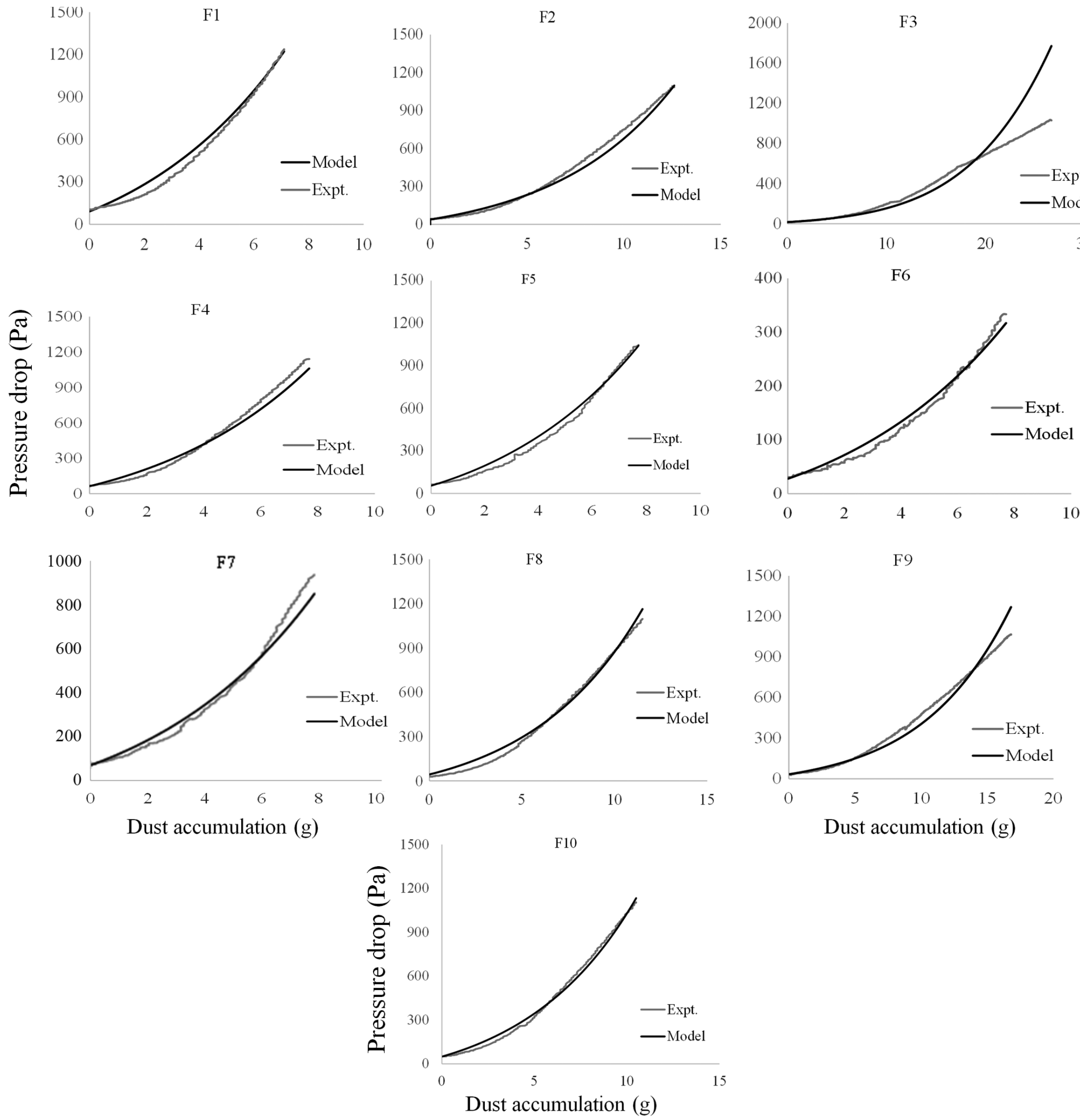


Fig. 6 — Evolution of pressure drop with accumulation of dust

thought that the particles are collected by two kinds of fibres over the entire depth of the filter medium. At the beginning, the particles are collected by the clean fibres. Later on, the accumulated dust particles forming dendrites on the surface of the filter medium act as fibres to collect incoming dust particles. Based on this idea, the Davies' equation was modified for predicting the pressure drop of dust-loaded filter media consisting of fibres of same size. However, there is no such study carried out on the multi-component filter media. As there is no simple expression available for predicting the evolution of pressure drop across the multimodal filter media, an accurate assessment of operating cost of the filter media still remains uncertain. In this work, Bergan and his coworkers' approach is suitably modified in the following manner to explain the dynamic pressure drop across the multimodal fibrous filter media :

$$\Delta P* = 64\eta\frac{Q}{A}Z\left(\frac{\alpha}{\overline{d}^2}+\frac{\alpha_p}{\overline{d}_p^{\,2}}\right)^{\frac{1}{2}}\left(\frac{\alpha}{\overline{d}}+\frac{\alpha_p}{\overline{d}_p}\right)\left[1+56\left(\alpha+\alpha_p\right)^3\right] \quad \ldots (13)$$

where ΔP^* denotes the pressure drop across dust-loaded filter media; $\overline{d}_p$ refers to the mean diameter of collected particles; and α_p stands for the packing density of collected particles. Clearly, this model is difficult to apply in practice as it demands knowledge

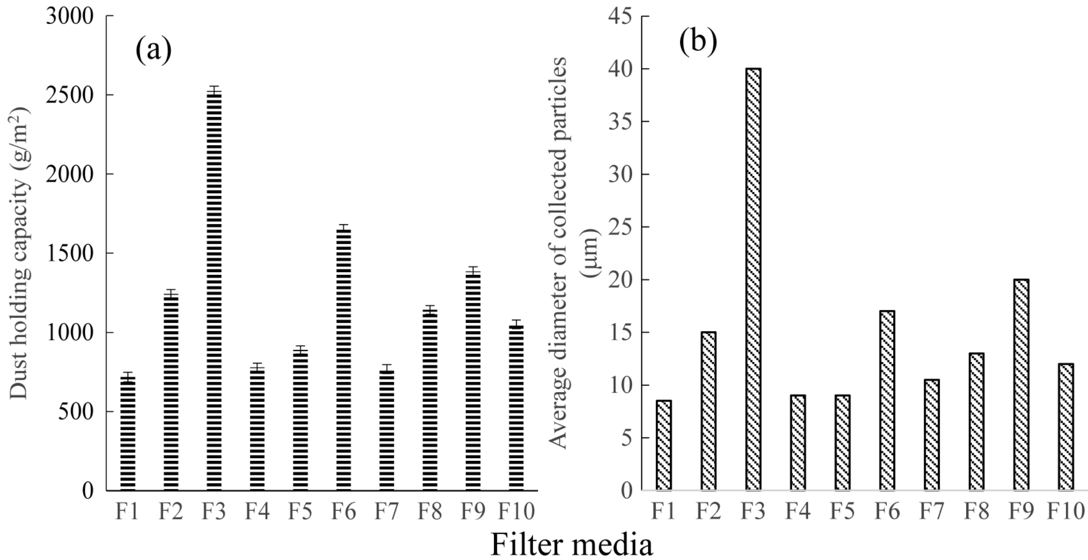


Fig. 7 — Dust holding capacity (a) and average particle diameter (b) of various filter media

on the diameter and the packing density of the collected particles. As, in practice, the particles collected by a filter media are different in terms of their sizes, it is difficult to measure the average diameter of the collected particles. Nevertheless, it is possible to estimate it by means of statistical regression of experimental data. Nevertheless, the packing density of the collected particles can be calculated from the following expression :

$$\alpha_p = \frac{m_p}{\rho_p V} \qquad \ldots (14)$$

where m_p is the mass of dust particles deposited onto the filter media and V is the volume of the filter media[32]. Statistical regression analysis has been carried out on the experimental data to compare with Eq. (14) and best-fit curves are obtained as displayed in Fig. 6. The estimated average diameter of the particles collected in the filter media is shown in Fig. 7b. Clearly, the particles collected by the coarser fibre filter media are on an average larger than those collected by the finer fibre filter media. This is associated with more particle collection by the coarser fibre filter media, leading to higher dust holding capacity than the finer fibre filter media. It is also known that the larger particles entail smaller pressure drop, owing to smaller specific surface area. This observation is found to be in line with that reported by Thomas *et al*.[13]. Through experiments they observed that the pressure drop during aerosol filtration is smaller as particle size is higher.

4 Conclusion

This paper reports a comprehensive methodology for characterization of microstructure of multimodal fibrous filter media made up of fibres of different cross-sectional sizes. It is observed that the blending of fibres of different sizes results in a synergistic effect on gravimetric filtration efficiency, and this effect is more with a greater number of fibre components in the filter media. The difference between final and initial gravimetric filtration efficiencies increases with the increase in mean fibre diameter. The overall fractional filtration efficiency of the multimodal fibrous filter media corresponds very well with the classical theory of air filtration after suitably modifying the mean fibre diameter and single fibre efficiency. The mean fibre diameter is neither an arithmetic mean nor a geometric mean nor a harmonic mean of fibre diameter of individual component, but the square of mean fibre diameter is a weighted harmonic mean of the square of fibre diameter of individual component. The single fibre efficiency of multimodal filter media is expressed by a summation of single fibre efficiencies of individual component of fibres weighted by the corresponding surface area fraction. The Davies equation, when used in conjunction with the theoretical expression of mean fibre diameter, correlates very well with the pressure drop of clean filter media. The evolution of pressure drop in multimodal fibrous filter media is explained satisfactorily based on Berman's approach after suitably modifying the Davies equation.

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