OIL-TREATED FIBROUS AIR FILTERS FOR AUTOMOTIVE ENGINE INTAKE APPLICATION

Ajay Kumar Maddineni and Dipayan Das

Department of Textile Technology, Indian Institute of Technology Delhi, Hauz Khas, New Delhi-110016

Abstract: *This work deals with development, characterization and performance evaluation of oil-treated fibrous air filters for automotive engine intake application. According to the classical theory of air filtration, an air filter would exhibit higher filtration efficiency when tested at higher face velocity. This is however not found true in the current research work. Here, the filtration efficiency of a cellulosic filter media was found to decrease at higher face velocities for relatively large particles. This happened apparently due to particle bounce and re-entrainment phenomenon. Nevertheless, it poses a major challenge to achieve the futuristic target of filtration efficiency with ever-increasing trend of engine downsizing and less availability of installation space for automotive engine intake air filter media. Here it was demonstrated that the particle bounce could be suppressed by oil treatment to the filter media, as a result, the filtration efficiency of the oil-treated filter media increased at higher face velocities for large particles, unlike the untreated ones. This behavior was explained in the light of theoretical and empirical models of air filtration. In case of less oil loading, the initial pressure drop across the oil-treated filter media was found to be almost the same as that across the untreated one. But, when the oil loading was high, the initial pressure drop increased tremendously. This behavior was discussed with the help of Davies equation by taking into account of the changes in diameter of oil-coated fiber and packing density due to oil treatment. Further, at lower dust loading, the oil-treated filter media exhibited lower pressure drop and lower filtration efficiency at lower face velocities, but, at higher face velocities, the same media displayed higher filtration efficiency but with a similar pressure drop. However, at higher dust loading, the same media exhibited higher filtration efficiency.*

Keywords: *Automotive engine intake air filtration, particle bounce and re-entrainment, oil-treated filter media, filtration efficiency, pressure drop, dust loading.*

1 INTRODUCTION

Engine intake air filters in automotive application were primarily used to remove the air borne dust particles to reduce the wear of moving components. Dust particles of 5-10 µm particles causes the major increase in wear over engine life time followed by 10 -20 µm [1]. Therefore, the automotive engine air filters are designed to reliably filter out those fractions of particles. Increasing emission regulations and the evolving requirements associated with engine durability, packaging environment, sophisticated engine technology, etc., are challenging the design of automotive air filter to efficiently capture the dust particles [2]. Wide variety of filter media such as polyurethane based reticulated foam, cellulose based wet laid paper, polymer based nonwoven were popularly used in automotive industry. Among the said filter media technologies, standard cellulose-based paper filter media is well known in Asia due to its performance, cost and packaging benefits. Particle penetration of such filter media is influenced by various factors such as fiber diameter, packing parameters of the fibers that result in wide pore sizes, operating conditions. A lot of efforts have been put in the past to optimize these filter media to reduce particle penetration. However, the velocity of the particles to which the media is exposed greatly affects the particle penetration. Reducing installation space in the vehicle for air filters now-a-days increases the flow velocities. It is known that with increasing flow velocity, filtration efficiency increases due to dominance of inertial impaction mechanism [3]. However the same is not true always. Increase in flow velocity increases the energy associated with the particle depending on mas-inertia relation that cause particle to bounce back and re-entrain into the fluid stream to escape through the media. This leads to an elevated risk to the engine components, associated with exposure to dust particles. These limitations are posing a challenge for the futuristic target of filtration efficiency and the air filter system design for automotive engine intake application. These new challenges motivated us to understand the particle penetration behavior of cellulosic filter media. Recently, limited studies showed the improvement of the filtration efficiency by treating the fibrous filter media with oil [4]. The present work made an attempt to investigate the impact of oil treatment on the filtration efficiency and pressure drop of automotive engine intake air filter media for different face velocities at the initial stage of filtration as well as during dust loading.

2 EXPERIMENTAL

2.1 Materials

In this study, a commercially available cellulose based filter media was used. The average fiber diameter of such filter media observed under SEM was found as 23 µm with coefficient of variation of 34%. The thickness of the fabric was measured by a digital fabric thickness tester in accordance with ASTM D5729-97 standard. The average thickness of the fabric was obtained as 0.75 mm. The basis weight of the fabric was measured by using a weighing balance as per ASTM D 6242-98 standard. The average basis weight of the fabric was determined as 181 g/m^2 with a coefficient of variation of 1.73%. Hydraulic oil with density of 0.86 g/cm^3 and viscosity ranging from 25 to 38 cSt at 40°C temperature was used to treat the cellulose filter media.

2.2 Methods

The cellulosic filter media was treated with Hydraulic oil 32 using the in-house fabricated test setup as shown in Figure 1. The oil will be sprayed in the form of fine droplets onto the filter media, using an oil atomizer. Hydraulic oil is stored in the reservoir tank and is supplied to the spraying gun. The dry filter element is hold by a mounting plate at a distance of 0.45 m from the spray gun. The mounting plate moves in lateral direction of spray gun by means of slider and piston mechanism so as to spray oil onto the filter surface as uniformly as possible. The extra oil is collected in the tray below the fixture. Defined oil quantity on 100 cm^2 of filter area is applied on the raw gas side of the pleated filter media. Iterative measurement of weighing oil element after oil treatment is performed using a weighing balance to maintain proper quantity of oil. SEM image of oil distribution on the fibers of the filter media is shown in Figure 3.

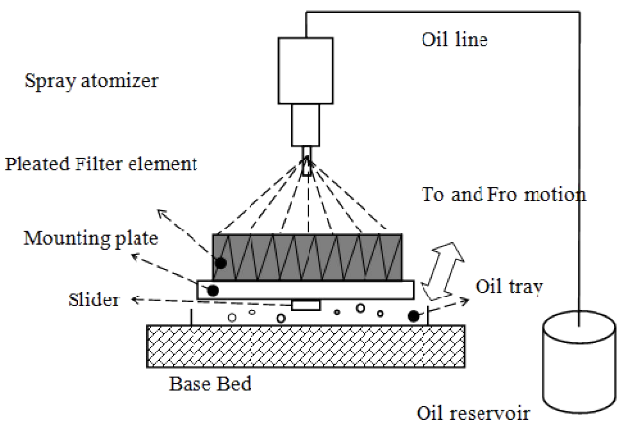

Figure 1 Chemical treatment setup

The oil treated as well as the non-treated filter media is challenged with ISO fine dust aerosol according to ISO 12103-1 was used for filtration efficiency measurements. The experimental setup for measurement of filtration efficiency is displayed in Figure 2. Test dust was dispersed by the powder dispersion generator with brush at a pressure of 2 bar. Aerosol spectrometer of Welas was used to measure particle distribution using light scattering technique. Test dust samples were attached to the particle analyzer using the iso-kinetic probe. Pressure drop was measured using the pressure taps placed across the filter media. Test dust of 0.2 g/m3 concentration was used in the current study. Particle measurements at higher concentration lead to false results. Continuous loading of the circular blank test samples using test dust and simultaneous measurement of pressure drop and particle size downstream was done.

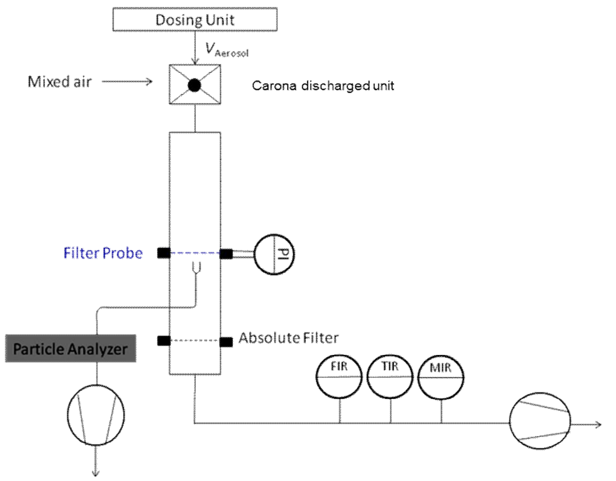

Figure 2 Experimental setup for filtration test

3 RESULTS AND DISCUSSION

The effect of face velocity on the initial pressure drop of oil-treated and untreated filter media is displayed in Figure 3. It can be observed that the untreated and the filter media treated with oil of 80 g/m^2 exhibited almost similar at all velocities tested. In contrary to this, the filter media treated with 240 g/m^2 oil displayed an increase of 5 to 9 times pressure drop as compared to the untreated filter media. This might be due to the fact that a higher quantity of oil deposited onto the filter media caused an increase of diameter of oil-coated fiber and a reduction in porosity that in turn resulted in increase of pressure drop across the media. In the following, an attempt was made to explain this scientifically using following expression [3, 5]:

$$d_{f,o} = d_f \sqrt{\left(1 + \frac{W_o}{W_f}\frac{\rho_f}{\rho_0}\right)} \quad (1)$$

$$\mu_{f,o} = \frac{W_f + W_o}{Z\left(\frac{g_f \rho_f + g_o \rho_0}{g_f + g_o}\right)} \quad (2)$$

$$\Delta P = \frac{64\mu_{f,o}^{1.5}\left(1+56\mu_{f,o}\right)^3 \nu U Z}{d_{f,o}^2} \quad (3)$$

where $d_{f,o}$ and d_f stand for the diameters of oil-coated and untreated fibers, respectively; W_o and W_f denote the weight of oil per unit area of the filter and weight per unit area of dry filter media, respectively; and ρ_f and ρ_o indicate the densities of fiber and oil, respectively. g_f and g_o are the mass proportions of fiber and oil, respectively, in the filter media and Z is the thickness of filter media. The diameter of oil-coated fiber and the packing density of oil-treated filter media could be substituted in the following Davies equation to determine the pressure-drop across the filter media. where ΔP denotes the pressure drop, ν indicates the viscosity of air, and Urefers to the face velocity.

It can be seen that the Davies equation using the diameter of oil-coated fiber and the packing density of the oil-treated filter media corresponded satisfactorily with the pressure drop data obtained experimentally.

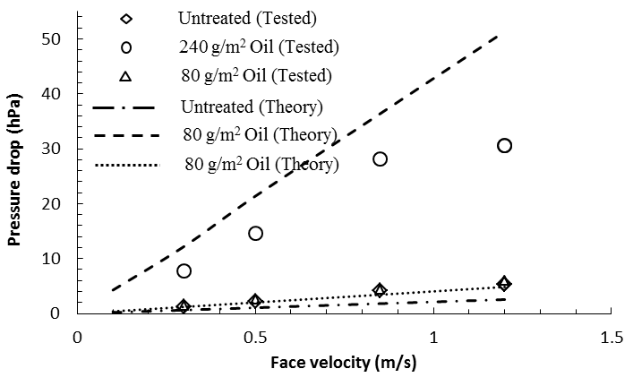

Figure 3 Initial pressure drop as a function of face velocity

Initial filtration efficiency of the untreated and oil-treated filter media at different velocities 0.1, 0.3, 0.5, 0.85 and 1.2 m/s respectively were shown in Figure 4. Particles beyond 0.5 µm particle size, the filtration efficiency increased with the increase of particle diameter as the interception and impaction mechanisms of particle capture were predominating. Filtration efficiency rose to higher than 99% for larger particles and at the face velocity of 0.1 m/s. A similar trend was observed at a face velocity of 0.3 m/s. However, the efficiency of filtering large particles at a face velocity of 0.3 m/s was less than that at 0.1 m/s. At a face velocity of 0.5 m/s, the filtration efficiency rose to 97% when the particle size was 4 µm, but decreased afterwards, however. A similar observation was found at a face velocity of 0.85 m/s velocity with significant decrease in filtration efficiency from 95 to 89% beyond the particle size of 2 µm. A further reduction in filtration efficiency was observed at 1.2 m/s when the particle size was 2 µm and beyond. It was therefore observed that the filtration efficiency decreased for larger particles at higher velocity. This finding contradicted the classical theory of air filtration. Probably, this unusual behavior was attributed to rebound of particles after colliding the filter surface and followed by subsequent re-entrainment of particles in the air streams at higher velocity. Figure 4b displays the initial filtration efficiency of the oil-treated filter media with oil loading of 80 g/m^2. The oil-treated filter media with 80 g/m^2 oil loading did not show any particle bounce for all particle sizes, regardless of the face velocities chosen. As the oil droplets present on the surface of the filter media caused the particles to adhere to the oil-coated fiber, the oil-treated filter media did not show any reduction in filtration efficiency, especially at higher face velocities and at larger particle sizes. The measured filtration efficiency of the untreated and oil treated filter media was calculated using the theoretical relations of collection efficiency.

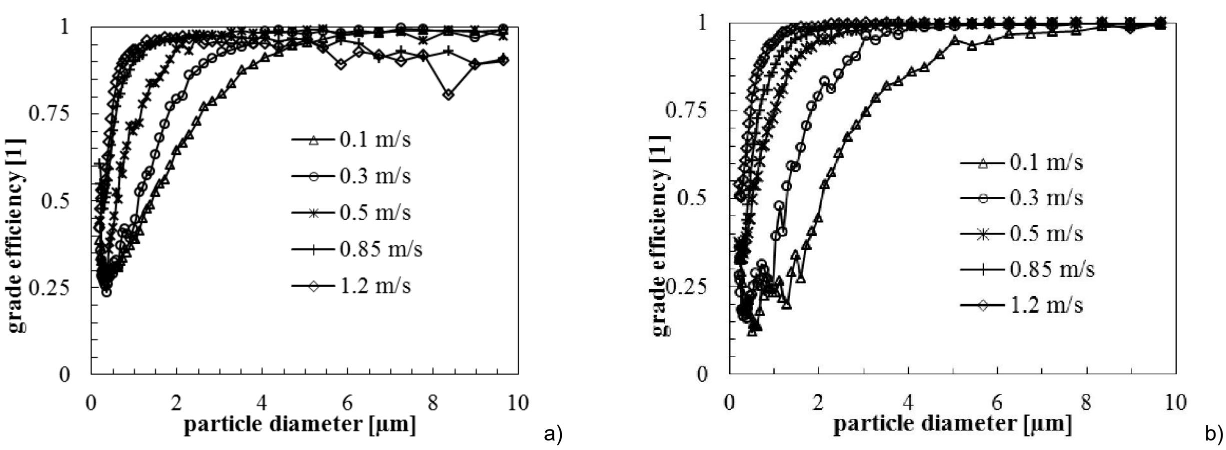

Figure 4 Measured grade efficiency at initial stage for untreated filter media (a) and oil-treated filter media with oil loading of 80 g/m^2 (b)

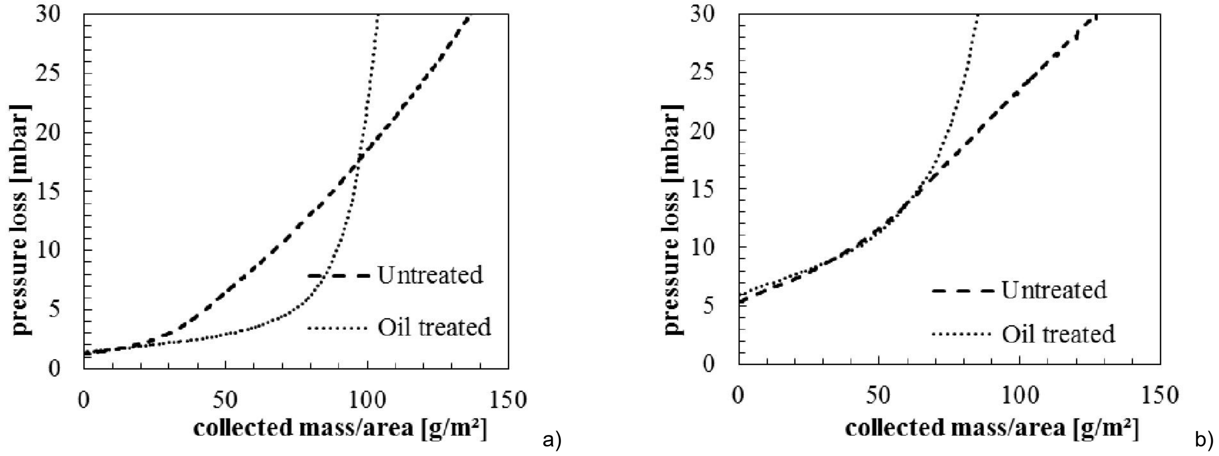

Figure 5 Evolution of pressure drop during dust loading at face velocities of 0.3 m/s (a) and 1.2 m/s (b)

The pressure drop curves of untreated and oil-treated filter media during dust loading at face velocities of 0.3 m/s, and 1.2 m/s was shown in Figure 5. At a low level of face velocity, i.e., 0.3 m/s, the untreated media exhibited slow increase of pressure drop till 30 g/m^2 of dust collection and at the end it accumulated 145 g/m^2 of dust to reach a pressure drop of 30 mbar. At the same velocity, the oil-treated filter media displayed slow increase of pressure drop till 60 g/m^2 of dust accumulation, but at the end it accumulated 100 g/m^2 of dust to reach the pressure drop of 30 mbar. The initial slow increase of pressure drop across the oil-treated filter media was due to the combined effect of depth loading and oil loading. In this stage of dust loading, the pressure curve of oil-treated filter media lay at a significantly lower position than that of the untreated one. In case of oil-treated filter media, the dust particles adhered to the oil and formed dust islands that mobilized around the fiber with the oil, creating more pore space than the untreated one. But, as the oil droplets were saturated with dust particles, surface filtration started that increased the pressure drop suddenly with very little addition of dust particles. At a very high level of face velocity, i.e., 1.2 m/s, the oil-treated and the untreated filter media exhibited similar pressure drop characteristics till the surface filtration started. At higher velocities the aerodynamic drag was dominant due to the fact that the oil droplets were saturated with the dust particles at a faster rate due to dominant inertial deposition and thus rate of pressure loss increased with dust loading.

The evolution of gravimetric filtration efficiency of untreated and oil-treated filter media at three different stages of dust loading was displayed at Figure 6. The untreated filter media showed filtration efficiency greater than 99% at a dust loaded pressure drop of 10 hPa and the same was increased with increasing pressure drop from 10 to 20 hPa at a velocity of 0.3 m/s (Figure 6a). This indicated that a dendritic growth of particles took place at the upstream side [6] and thus the increasing trend of particle capture is observed. The oil-treated filter media also exhibited increasing trend of filtration efficiency with increasing pressure drop from 10 to 20 hPa. However, the oil-treated filter media displayed lower filtration efficiency than the untreated one at pressure drops of 10 hPa and 20 hPa. This behaviour was probably due to the fact that some of the dust particles were captured by the fibres and the rest were adhered to the oil-droplets; hence the dendritic growth was not significant at this stage of filtration. At a further higher level of dust loading (equivalent to 30 hPa pressure loss), the untreated media exhibited a drop in filtration efficiency due to increased local velocities within the filter that caused the particles getting more energy and were able to penetrate the filter media. While the oil-treated media displayed an increase in filtration efficiency with increasing dust loading. Interestingly, the oil-treated filter media showed higher filtration efficiency than the untreated media at a pressure drop of 30 hPa. This might be due to increased adhesion between particles and fibers. At 1.2 m/s face velocity, the oil-treated filter media exhibited an increasing trend of filtration efficiency as the pressure drop increased. The untreated filter media showed a drop in filtration efficiency as dust loading and face velocity increased, whereas the oil-treated media displayed an increase of filtration efficiency with the increase of dust loading and face velocity. The filtration efficiency of the oil-treated filter media was related to the loading of oil by dust particles. As the oil loading was higher the increase of filtration efficiency was lower. Interestingly, the filtration efficiency of the untreated media was higher than the oil-treated media at low levels of dust loading and at lower face velocity.

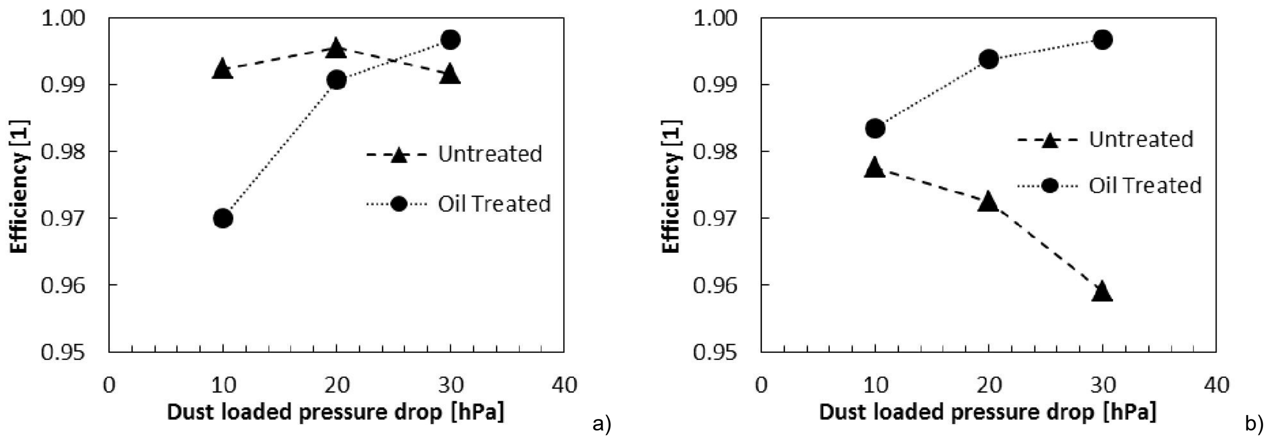

Figure 6 Evolution of filtration efficiency during dust loading at face velocities of 0.3 m/s (a) and 1.2 m/s (b)

4 CONCLUSIONS

Oil-treated and untreated cellulosic filter media were examined for pressure drop and particle filtration behaviors at the initial stage of filtration as well as during dust loading. The initial pressure drop across the oil-treated filter media was found to be almost the same as that of untreated media at a low level (80 g/m^2) of oil loading. But, when the oil loading was increased to as high as 240 g/m^2, the pressure drop was 5 to 9 times higher, depending on the face velocity, than that of the untreated media. This behavior was explained in the light of Davies equation by taking into account of the change in diameter of oil-coated fiber as well as in packing density due to oil treatment. During initial stage of filtration, the untreated filter media displayed higher filtration efficiency at higher velocity for lower particle size, but the filtration efficiency decreased for large particle size as the face velocity increased. This was attributed to particle bounce and re-entrainment phenomenon and its effect was more at higher face velocity. This behavior was explained in the light of theoretical and empirical relations. Inhibition of particle bounce using oil spraying was found to be a suitable technique, as a result, the filtration efficiency of the oil-treated filter media increased at higher face velocities for large particles, unlike the untreated ones. At lower dust loading and lower face velocities, the oil-treated filter media exhibited lower pressure drop and lower filtration efficiency. However, at higher face velocities, the oil-treated filter media displayed higher filtration efficiency but with a similar pressure drop at lower dust loading. Nevertheless, the same media exhibited higher filtration efficiency at higher dust loading.

Acknowledgements: *The financial support received from Science and Engineering Research Board of Department of Science and Technology, Govt. of India under project number SB/S3/ME/063/2015 for carrying out this work is gratefully acknowledged.*

5 REFERENCES

1. Mollenhauer K., Tschoeke H. (Eds.): Handbook of Diesel Engines, Springer, 2010, DOI 10.1007/978-3-540-89083-6
2. Maddineni A.K., Das D., Damodaran R.: Experimental and numerical study on automotive pleated air filters, SAE Technical Paper 2016-28-0100, 2016, https://doi.org/10.4271/2016-28-0100
3. Brown R.C.: Air filtration: an integrated approach to the theory and applications of fibrous filters, Pergoman press, Oxford, 1993, eBook ISBN 9780080912608
4. Müller T.K., Meyer J., Thebault E., Kasper G.: Impact of an oil coating on particle deposition and dust holding capacity of fibrous filters, Powder Technol. 253, 2014, pp. 247-255, https://doi.org/10.1016/j.powtec.2013.11.036
5. Agranovski I., (Ed.): Aerosol- Science and Technology, Wiley (Germany), 2010, ISBN: 978-3-527-32660-0
6. Oh Y.W., Jeon K.J., Jung A.I., Jung Y.W.: A simulation study on the collection of submicron particles in a unipolar charged fibre, Aerosol Sci. and Technol. 36(5), 2002, pp. 573-582, https://doi.org/10.1080/02786820252883810