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Inhibition of particle bounce and re-entrainment using oil-treated filter media for automotive engine intake air filtration

Ajay Kumar Maddineni [a], Dipayan Das [a,*], Ravi Mohan Damodaran [b]

[a] Department of Textile Technology, Indian Institute of Technology Delhi, New Delhi 110016, India
[b] Technology & Strategy, Varroc Group, Aurangabad 431136, India

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ABSTRACT

It is well known that the face velocity is a critical parameter for deciding the capture of airborne dust particles by fibrous filter media. As the face velocity increases, the capture efficiency of relatively large particles increases owing to inertial impaction. This is not true always as found in the current work. Here it was observed that the filtration efficiency of a cellulosic filter media decreased 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. In this work, 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 behaviour 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 behaviour 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.

1. Introduction

Air filtration plays an important role in deciding the performance of automotives in terms of fuel consumption, emission reduction and passenger comfort [1–3]. The air filtration system in automotives includes engine intake air filtration, cabin air filtration, exhaust gas filtration, oil mist separation, etc. The engine intake air filtration removes the airborne contaminants from entering into the engines, which, otherwise, would have caused significant engine wear leading to performance loss, enhanced exhaust emission, high oil consumption, and increased operation cost [4,5]. In engine intake air filtration, the airborne dust particles of 5 μm to 10 μm diameter are known to cause major engine wear [6]. The automotive engine intake air filters are therefore designed to filter out mostly these particles. Further, besides higher filtration efficiency, longer service life and lower pressure drop are also desired for such filters. Of the many filter media available in the market, the cellulosic filter media is mostly used especially in Asian countries due to its low cost, high performance, and good packaging benefits. The particle capture by cellulosic filter media is primarily determined by fiber diameter, packing density, and face velocity. With ever-increasing trend of engine downsizing, the space available for installation of the filter media is reducing, as a result, the face velocity is increasing [7]. With the increase of face velocity for a constant fiber diameter and a constant particle diameter, the stokes number dependant filtration efficiency is known to increase due to dominance of inertial impaction mechanism [8]. However, an increase in face velocity causes an increase of energy associated with the particle depending on its mass-inertia relation that could cause particle to bounce back and re-entrain into the air stream to escape through the media [7–10]. This is also happening in case of dust loaded filter media [11,12]. The non-uniform flow field within the automotive filter system and the associated dust deposition might increase the local velocities within the pore space of the filter media that in turn results in particle penetration through the filter media at higher velocities. This leads to an elevated risk to the engine components, associated with exposure to dust particles.

The problem of particle bounce and re-entrainment is relatively new and there is a scarcity of information available on this topic. Poon and Liu [13] observed the penetration of particles of >2 μm diameter through a foam filter media at a velocity of 6.5 m/s. They also found that the particle re-entrainment due to bounce increased with increasing porosity of the filter media. Maus and Umhauer [14] studied the

* Corresponding author.
E-mail address: dipayan@textile.iitd.ac.in (D. Das).

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particle collection efficiencies for biological and non-biological aerosols in case of automotive cabin air filtration system. They noticed that the particles of >5 μm diameter could bounce from the surface of the filter media at a velocity of 1 m/s. Mueller et al. [15] studied the particle filtration behaviour of cellulosic filter media at different face velocities ranging from 0.1 m/s to 0.3 m/s and observed that the particle penetration through the filter media increased as the face velocity increased. Though the fibrous filter media are typically exposed to face velocities ranging from 0.01 m/s to 0.3 m/s for engine intake air filters for combustion process [13,16], the flow requirements and the terminating conditions vary widely depending on the design of internal combustion engines. Typical terminating pressure drop conditions used for automotive naturally aspirated engines, turbocharged engines, and motorcycle engines were reported to be 25 mbar, 60 mbar and 12.5 mbar, respectively, above the initial pressure drop [16,17]. Also, a few studies indicated that the non-uniform flow distribution across the automotive filter housing and the reduced installation space under the engine bay might cause a remarkable increase of media face velocities that in turn resulted in particle penetration to increase across the filter media [8,18]. These new challenges motivated us to understand the particle penetration behaviour of cellulosic filter media under different velocities ranging from smaller velocity (0.1 m/s and 0.3 m/s), moderate velocity (0.5 m/s) to higher velocity (0.85 m/s and 1.2 m/s).

In order to suppress the particle bounce and thus to counteract the particle penetration behaviour, the adhesion between fiber and particle should be increased. Impregnating the reticulated foam based filter media with viscous oil is often used in Asian countries in order to remove the fine particles at high face velocities [4,13]. This also enhanced the dust holding capacity and so the filter life by several times. Mullins et al. [19] made an attempt to soak the polypropylene fibrous filter media in water and mineral oils and observed that the bounce effect of the particles was inhibited by the liquid film formed onto the filter surface. Hubbard et al. [20] used glycerol as a retention agent to soak the filter media and assessed the filtration behaviour at very high velocities ranging from 2.5 m/s to 11.25 m/s that resulted in Reynolds numbers to vary from 0.24 to 0.72. They found that the filtration efficiency of the treated filter media at the initial stage was improved significantly. Boskovik et al. [21] applied a coating onto the filter media by submerging it into mineral oil to minimize the particle motion upon fiber collision. A similar remedial measure was suggested by Mueller et al. [15] for the fibrous filter media. According to them, a viscous oil film, if available on the filter surface, may suppress particle rebound at high velocities. They found that the filtration efficiency of the oil-treated filter media was less than the untreated filter media at moderate face velocities and also at the terminating pressure drop of 20 mbar. However, what would happen to the filtration efficiency when the oil film is completely loaded with particles and at higher velocities are yet to be known. Also, it is not clear what would happen to the pressure drop across the filter media due to oil treatment at the initial stage as well as during dust loading. It would be therefore interesting to examine the pressure drop and filtration efficiency of oil-treated filter media at different face velocities for different stages of dust loading and compare the same with the untreated media. 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. Materials and methods

2.1. Materials

In the present study, a commercially available cellulosic filter media with phenolic resin was used. The scanning electron microscopic image of this media, taken at 500× magnification, is displayed in Fig. 1a. This image was processed using ImageJ, a java based image processing software, to determine the fiber diameter of the media. The average fiber diameter was found as 23 μm with a coefficient of variation of 34%. The thickness of the media was measured by using a digital fabric thickness tester in accordance with ASTM D5729-97 standard. The average thickness was obtained as 0.75 mm with a coefficient of variation of 9.2%. The basis weight of the media was determined by using a weighing balance as per ASTM D 6242-98 standard. The average basis weight was measured as 181 g/m^2 with a coefficient of variation of 1.73%. Also, in this work, commercially available hydraulic 32 oil with a reported density of 0.86 g/cm^3 and viscosity ranging from 25 cSt to 38 cSt at 40 °C temperature was used to treat the above-mentioned filter media. The scanning electron microscopic image of the oil-treated filter media, taken at 500× magnification, is shown in Fig. 1b. Further, ISO 12103-1 A2 fine dust was used to test the filtration performance of the filter media.

2.2. Method of oil treatment

The dry cellulosic filter media was treated with Hydraulic 32 oil using an in-house fabricated set-up as shown in Fig. 2. In this set-up, the oil was stored in a reservoir tank and supplied to a spray atomizer through a pipe line. Using another pipe line, compressed air was also supplied to the atomizer. The atomizer was used to generate fine droplets of oil at a pressure drop of 6 bar. The oil droplets were deposited onto the dry filter media, which was held by a mounting plate kept at distance of 0.45 m from the atomizer. The mounting plate was allowed to move to and fro by means of a slider and piston mechanism so that the entire width of the filter media was covered by oil droplets. The extra oil was collected in a tray kept below the fixture. In this work, the amount of oil applied onto the upstream of the filter media was kept at two levels viz. 80 g/m^2 and 240 g/m^2. Iterative measurements of weight of filter media were performed after oil treatment to ensure deposition of above-mentioned quantities of oil onto the media.

2.3. Method of testing of filtration performance

The flow and filtration behaviours of oil-treated and untreated filter media were tested at five levels of face velocity viz. 0.1 m/s, 0.3 m/s, 0.5 m/s, 0.85 m/s and 1.2 m/s. The filter media were tested for their filtration performance in accordance with ISO 12103-1 standard by using the experimental set-up as shown in Fig. 3. The test dust was dispersed by a powder dispersion generator with the help of a rotary brush at a pressure of 2 bar. Corona discharge unit for electrical neutralization of dust aerosol was used to ensure reproducible results. Aerosol spectrometer was used to measure the particle distribution by 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. Air flow was controlled by the downstream blower and was precisely measured using a vortex sensed flow sensor. The temperature and the relative humidity were measured at the beginning of the measurement and were maintained throughout the test. During experiments, the ambient conditions such as pressure, temperature and relative humidity were monitored using sensors like PIR (Pressure Indicating Regulator), TIR (Temperature Indicating Regulator) and MIR (Moisture Indicating Regulator), respectively. Before use, the dust was heated in a vessel up to a temperature over 100 °C to eliminate the humidity as recommended in the standard. Test dust (ISO fine dust) of 0.2 g/m^3 concentration was used in the current study. Prior to dust loading of filter under test, dispersed particle concentration of raw gas was determined by gravimetric measurement of absolute filter and monitored by particle size distribution. During dust loading of filter under test, the mass differences due to loading of the filter with dust and the absolute filter were used to check the average concentration during testing. After the measurement of the filter loading, the procedure was repeated to check concentration and particle size distribution of raw gas once again. A small deviation in