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Performance Analysis of Diesel Particulate Filter using Glass Fibers

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ABSTRACT:

To limit the adverse health effects to human beings due to the sub-micrometer particles emitted from the diesel engine exhaust, various after treatment devices have been developed. Number of researches have been done to improve the efficiency and to reduce the cost of the filters used to trap these diesel particulate matters. In this paper glass fiber filters have been used to trap the particulate matters. This attempt to use glass fiber as a filter is mainly to reduce the cost of the filter and to find a better alternative for trapping diesel particulates.

KEYWORDS:

Particulate matter; Wide open throttle; Smoke opacity; Total particle mass concentration; Light extinction coefficient

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1. Introduction

The automobile density in the world is increasing day-by-day, so the emission standards have become more stringent than the past. The importance and usage of diesel engine also in turn made the emission limits more stringent. Emissions formed during burning of the heterogeneous diesel air/fuel mixture depend on the conditions during combustion, during the expansion stroke, and especially prior to the exhaust valve opening. The major emissions in diesel engine are unburnt hydrocarbons (HC), oxides of carbon, (CO and CO_2), oxides of nitrogen, (NO and NO_2), oxides of sulphur, (SO_2 and SO_3), particulates, soot and smoke. The particulate matter emission doesn't have any relation with oxides of Nitrogen and HC, but it has influence on these emissions during their control. Diesel particulate emission poses a great impact on human health. So control of diesel particulate emission is very important. Diesel particulates are the individual particles present in diesel exhaust gas.

Particulate matter (PM) represents compounds with high carbon content (e.g. aromatics) that have not completely burnt when the combustion chamber is exhausted. These combine with sulphur and water to form particulate matter (soot). PM is generated in diesels primarily during the diffusion flame. Maximum density of particulate emissions occurs when the engine is under load at wide open throttle (WOT). At this condition maximum fuel is injected to supply maximum power, resulting in a rich mixture and poor fuel economy. Soot particles are clusters of solid carbon spheres of diameter from 9nm to 90 nm. But most of them are within the range of 15-30nm. The spheres are solid carbon with HC and traces of other components absorbed on the surface. A single soot particle may contain up to 5000 carbon spheres. Diesel soot or Diesel Particulate Matter (DPM) is not entirely comprised of combustible carbon but also contains non-combustible ash resulting primarily from the additives used in crankcase lubrication oils, fuel or intake air additives, and from the fuel itself. The composition of DPM [6] is given by,

$$DPM = soot + SOF + IF \tag{1}$$

The term SOF (Soluble Organic Fraction) refers to the organic material that can be extracted using a Soxhlet apparatus. IF (Inorganic Fraction) contains volatile and semi-volatile compounds like sulphates and nitrates, ash and water. By convention, SOF is combined with sulphates and nitrates to a single component termed as Volatile Fraction (VF) which can be determined by heating particles in an inert atmosphere. The size of particles is directly linked to their potential for causing health problems. Small particles less than 10 μm in diameter pose the greatest problems, because they can get deep into human lungs, and some may even get into your bloodstream. Exposure to such particles can affect both human lungs and heart. Larger particles are of less concern, although they can irritate human eyes, nose and throat. Small particles of concern include "fine particles" (such as those found in smoke and haze), which are 2.5 micrometers in diameter or less, and "coarse particles" (such as those found in wind-blown dust), which have diameters between 2.5 and 10 μm.

The air that was breathed by human being contains numerous particles. The human body has protective measures against larger particles, but it cannot protect itself against particles roughly smaller than 10 μm, also known as PM-10. To reduce the health problems to humans due to particulate matter emission, the control of these particles becomes essential. Filters have been used to physically capture the particulate matter in the diesel exhaust and prevent their discharge from the exhaust pipe, while allowing exhaust gases to escape. These filters are named as Diesel Particulate Filter (DPF). These filters are usually referred as after-treatment devices because the particulate matter emissions are controlled after combustion. A number of filter materials exist or have been evaluated, including ceramic monoliths, woven silica fiber coils, ceramic foam, wire mesh and sintered metal filters-many other forms. Three different materials for DPF are on the market today: SiC, Aluminium Titanate and Cordierite [1].

In this paper to trap the DPM glass fiber filter has been employed. As the glass fiber is having excellent thermal resistance, it is at great extent accepted in the production of high-performance composite materials, including protective materials, various filters, protective clothing and packing [4]. Ceramic material is widely used for filtering diesel particles. But the disadvantage of using ceramic material is that it causes cancer due to their fiber diameter from 1 to 20 μm, they are breathable. And also ceramic fiber cannot resist vibration. So, in this paper the glass fibers have been employed for trapping diesel particulates.

2. Materials

The glass fiber used is S-glass fiber whose properties are given in Table 1. The selection of the glass fiber for filtering the particulate matter was done by comparing the properties of S-glass fiber with the properties of Silicon Carbide, Aluminium Titanate and Corderite [8]. The important properties taken into consideration are maximum use temperature, density and ultimate strength. The property comparison is shown in Table 2. The properties of S-glass fiber are more or less equal to the materials that have been already used for collecting the diesel particulates. As an alternative for these materials that have been in use, glass fibers are selected and tested as a filter to collect particulate matter. For any filter air permeability test is important. The air permeability of a fabric is defined as the amount of air passed over a surface under a certain pressure difference in a unit time. The unit of air permeability is $cm^3/cm^2/s$. The air permeability test for this plain weave glass fiber was done using FX 3300 TEXTEST machine for a total area of $20cm^2$ with a total pressure of about 125Pa. The air permeability value for the glass fiber filter used in this paper is $14.6cm^3/cm^2/s$.

Table 1: Material property comparison

Properties	S-Glass fiber	Carbon fiber
Strength to weight (kN.m/kg)	1906	2475
Ultimate strength (MPa)	4710	4137
Density (g/cm^3)	2.47	1.75
Decomposition temperature (°C)	850	1300

Table 2: Property comparison

Properties	S-Glass fiber	SiC	Aluminium Titanate	Corderite
Maximum use temperature	1200	1650	1371	1300
Density	2.47	3.1	2.6	2
Ultimate strength	1906	1088	-	-

3. Experimentation

The experiment of the filter was done on a single cylinder diesel engine. The engine was connected to a dynamometer which helps to vary the torque by keeping the speed constant. To know the exhaust gas temperature a thermometer is connected to the exhaust pipe. A chamber similar to the size of Diesel Oxidation Catalyst (DOC) is attached to the exhaust pipe at a distance of 1ft from the exhaust manifold. To measure the opacity of smoke AVL 437 smoke meter was used. Opacity is a measure of light reduction/loss over a smoke column path usually expressed as %. The smoke sample to be measured is fed into a chamber with non-reflective inner surface. The light is transmitted from one end of this chamber containing smoke sample. The light received in the receiver after extinction indicates the opacity. The effective length of the light absorption track is determined by taking into consideration possible influences of devices used to protect the light source and photocell. The effective length is 0.430 ± 0.005m.

First the test is carried out without placing any filter. The load i.e., torque is varied by keeping the speed constant. The corresponding smoke opacity, temperature and fuel consumption was noted. Next the filter is placed in the chamber which is placed at 1ft from exhaust manifold. Then the test was carried out by varying the torque and corresponding smoke opacity, temperature and fuel consumption was noted. After the load test a free acceleration test was carried out without placing a filter and by placing a filter. The free acceleration test was carried out by giving sudden acceleration. First the speed was reduced to 1300 rpm then the accelerator pedal is left suddenly. By leaving the accelerator suddenly, the speed increases from 1300 to 1500 rpm. At this time AVL 437 smoke meter calculates the opacity reading. The test was done for 3 to 4 times continuously and finally the smoke meter gives the mean smoke opacity value and absorption co-efficient. The image of the filter material after testing is shown in Fig. 1.

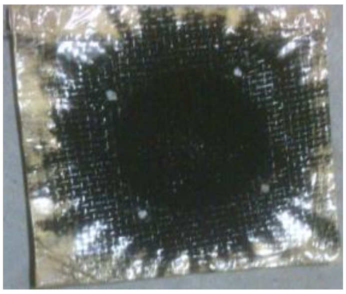

Fig. 1: Filter after testing

For emission testing of a vehicle usually this free acceleration test were carried out. This test will give us the mean smoke opacity value and the absorption or extinction co-efficient value. From the smoke opacity value obtained during the test, the following parameters are determined. That is the value of transmittance (T), total particle mass concentration, light extinction co-efficient. Transmittance of a sample is the ratio of the intensity of the light that has passed through the sample to the intensity of the light when it entered the sample. It is just the opposite of opacity. The relationship between the smoke opacity and the transmittance is [7],

$$\%Opacity = (1 - T) * 100 \quad (2)$$

$$T = 1n(I/I_0) \quad (3)$$

Where, I is the intensity of transmitted light and I_0 is the intensity of incident light. Relationships between plume opacity and particulate mass concentration have been reported for specific emissions. Hawksley et al [2] estimated the relationship of the particulate mass concentration to the plume opacity for two sizes of light absorbing particles of $2gcm^{-3}$ density. The relationship for particles much smaller than the light wavelength is

$$1n(I/I_0) = -4.0WL \quad (4)$$

Where, L is the Illumination path length in meters (usually stack diameter), and W is the total particle mass concentration in gm^{-3}. The diesel particulate size is much smaller than light wavelength. The transmission of light through a volume containing an aerosol is described by the Lambert-Beer Law [3],

$$I/I_0 = \exp(-B_E L) \quad (5)$$

Where L is the illumination path length and B_E is the extinction coefficient. Extinction coefficient is a measure of the rate of diminution of transmitted light via scattering & absorption for a medium.

4. Results and discussions

The result obtained by placing filter is compared with the results obtained without placing filter. Calculations have been done to obtain the values of transmittance, Total mass particle concentration, light extinction co-efficient depending on the relationships obtained above. The SEM image of the particles trapped in the filter is shown in Fig. 3. Compared to the results without filter the results by placing a filter should be: the smoke opacity value should be less, transmittance should be more, total mass particle concentration should be less, light extinction co-efficient should be less. The reason for this is understood from the definition of all these terms. The results are shown in Figs. 4 to 7. The material which was newly tried for filter withstands a temperature more than 850°C without any degradation. During this testing the temperature range reached for various loads is shown in Fig. 8. The performance of the engine is not that much affected by placing a filter. The fuel consumption by placing a filter is of very minimum quantity. This variation is shown in Fig. 9.

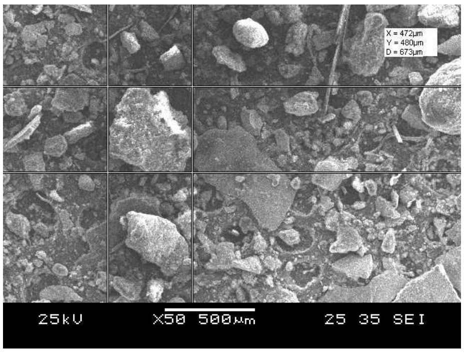

Fig. 3: SEM image of the particles collected in the filter

Any hindrance to the flow of gases surely results in some back pressure. The effect of back pressure is very important while using any filter. The filter implemented here results in very negligible amount of back pressure because the filter thickness used here is 0.49mm thick which is less compared to the thickness of the current diesel particulate filter. So the back pressure effect is very less. Variation in opacity with respect to torque is given in Fig. 4. It can be observed that the opacity increases with the torque irrespective of filters used. However, opacity tends to reduce when the filter is employed. Fig. 6 shows the variation of total particle mass concentration with respect to torque. It can be seen that the filter reduces the particle mass concentration drastically.

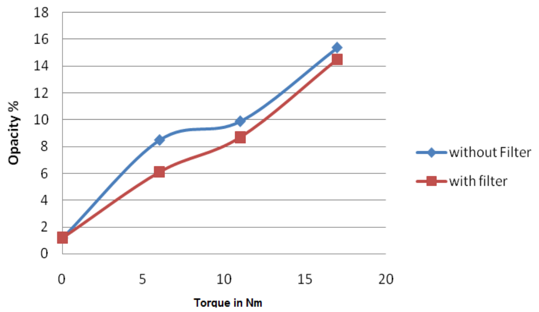

Fig. 4: Variation of the opacity with respect to torque

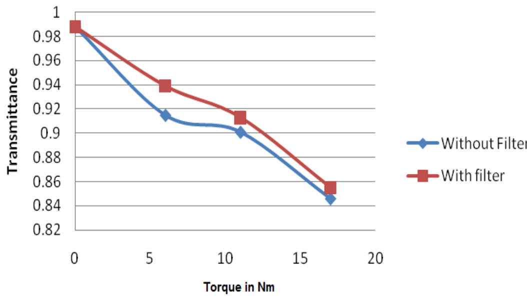

Fig. 5: Variation of transmittance with respect to torque

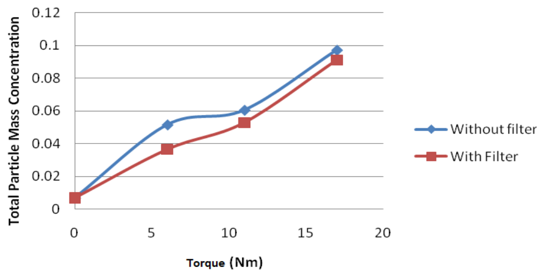

Fig. 6: Variation of total particle mass concentration (gm^{-3}) with respect to torque

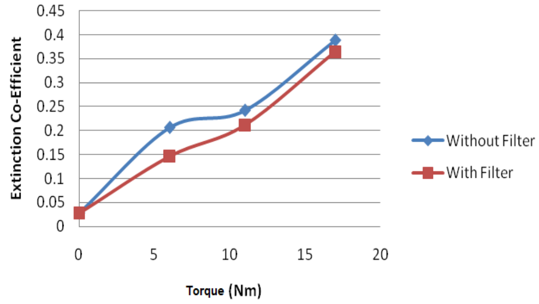

Fig. 7: Variation of total light extinction co-efficient with respect to torque

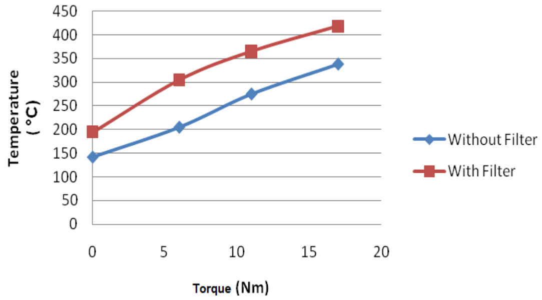

Fig. 8: Variation of temperature with respect to torque

It can be seen that the light extinction co-efficient and temperature increases with load. The usage of filter also increases the light extinction co-efficient and temperature. Fuel consumption with respect to time is presented in Fig. 9. It can be seen that there was a slight increase in fuel consumption when we use the filter. Even though there was a slight increase in certain factors the particulate matter in the filter is greatly reduced. The free acceleration test was done with and without filter. The mean smoke opacity and the absorption coefficient value without placing a filter is 74.1% and 3.215 m^{-1}. And by placing a filter the mean smoke value and absorption coefficient obtained is 53.8 and 1.79 m^{-1}. This clearly shows that the particulate matter is effectively trapped by the filter.

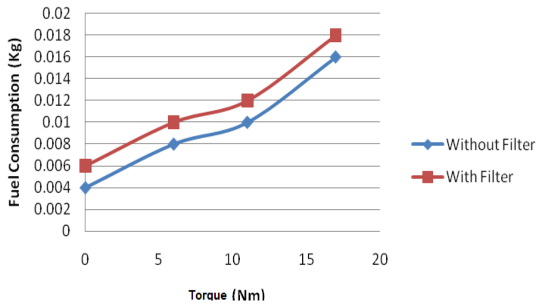

Fig. 9: Fuel consumption with respect to torque

5. Conclusion

In this paper, it has been demonstrated that the glass fibers can be used as a filter for trapping particulate matters from the diesel engine exhaust. The glass fiber is of low cost and high strength fiber which can withstand high temperature without any degradation. So glass fibers can be used as a filter to collect DPM. The performance of glass fiber filter can be improved by changing the weaving pattern of the filter, porosity of the filter, the glass fiber with the matrix.

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