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The Mechanism of Clogging of Road Vehicle Combustion Air Filters by Road Dust

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ABSTRACT

Road vehicle combustion air filters utilized for the removal of dust particles from air entering the internal combustion engine for combustion are subjected to clogging. The behavior of the filter medium during blockage by road dust has been studied. We also show the effects of different dust loading rates (0.08 g/s and 0.14 g/s) on the vehicle combustion air filters; this was related to the engine performance. Three filters (two foam filters and one paper filter) of different but comparative parameters were used for the study. Inflated dust from an unpaved road (Dr. Brobbey Junction, Kotei) in Kumasi between 10 February and 17 February, 2011 was collected using four polyethylene sheets and used for the study. It was found that dust particles accumulated near the downstream side of the filter. This shows that filters get clogged first downstream and gradually moves upstream of the filter. Filtration of solid particles causes deposits to remain on the surface of the filter medium resulting in an increase of the filter's resistance or pressure drop. It was found out that with higher dust loading rate, the pressure drop across the filter medium increases significantly and can cause clogging of the filter within a short period. We further found out that filters made of foam with longer length and smaller pore sizes have better performance characteristics. The present study will help transport yards in Ghana and in elsewhere to reconsider their routine maintenance on their vehicles especially during the Harmattan season, as maintenance schedules are only carried out based on the distance covered by their vehicles.

Keywords: *Air filter, engine speed, dust load, pressure drop.*

1. INTRODUCTION

Air filters are used in applications where air quality is important notably in air standard cycle engines, vehicle cabins, air compressors and in building ventilation systems. In the road vehicle engine, combustion air filters are devices which prevent abrasive particulate matter (that can cause mechanical wear) from entering the engine's cylinders, thereby protecting the engine. The removal of airborne particulate from the air stream is called filtration and is accomplished through various means; mechanical and electrostatic means. The mechanical means include interception, inertial impaction, Brownian diffusion and gravitational settling (Hinds, 1999). Collection by interception occurs when a dust particle moves with the airstream and at some point becomes attracted to the media fibres, leaves the airstream and attaches itself to the fibres. Inertial impaction of a dust particle on a fibre occurs when the particle, because of its inertia, is unable to adjust quickly enough to the abruptly changing streamlines near the fibre and crosses those streamlines to hit the fibre and attaches itself. Filtration by Brownian diffusion occurs when small particles collide with the air molecules and move in an erratic path. The path allows for the small particle to come in contact with the media and stay attached.

Particles will settle with a finite velocity in a gravitational force field. When the settling velocity is sufficiently large, the particles may deviate from the streamline (Hinds, 1999). The principle of electrostatic filtration involves passing the air through an ionizer screen where electrons colliding with air molecules generate positive ions which adhere to dust and other small particles present, giving them a positive charge. Vehicle air filters are made of materials such as paper, cotton, foam or gauze. Unclean dusty air limits the amount of clean air needed for combustion hence reducing the performance and efficiency of the vehicle engine.

The engine of the road vehicle depends on power produced from the combustion of fuel (petrol, diesel, etc.) in clean air. The combustion reaction that takes place in the internal combustion engine is: Fuel + Air $\rightarrow$ $CO_2 + H_2O$ + Heat. The air used for the fuel reaction should be a clean air free from deleterious particle including dust. Therefore, dusty ambient air puts heavy stress on the air cleaning system of the vehicle as well as impacts on quality of combustion, heat produced and exhaust into the environment. This study investigates the clogging mechanism of three road vehicle combustion air filters under different dust loads. The study then relates the clogging mechanism to engine performance.

2. MATERIALS AND METHOD

2.1 How the dust was collected by the road.

The first step of the experimental procedure was the collection of dust samples. Inflated road dust from an unpaved road (Dr. Brobbey Junction, Kotei) near Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, was collected using four polyethylene sheets ; area of about 1 m length by 0.8

m width. The sampling period was between 10 February and 17 February, 2011. The clean polyethylene sheets were placed on tables positioned about 10 m from the centre of the road around 11 am each day. The heights of the tables were about 0.9 m above ground. The polyethylene sheets were held to the tables by office pins. The polyethylene sheets were then collected around 4 pm and the dust samples were stored in plastic bottles.

2.2 The method = the experiment.
The schematic diagram of the experimental set-up is in Fig. 1.

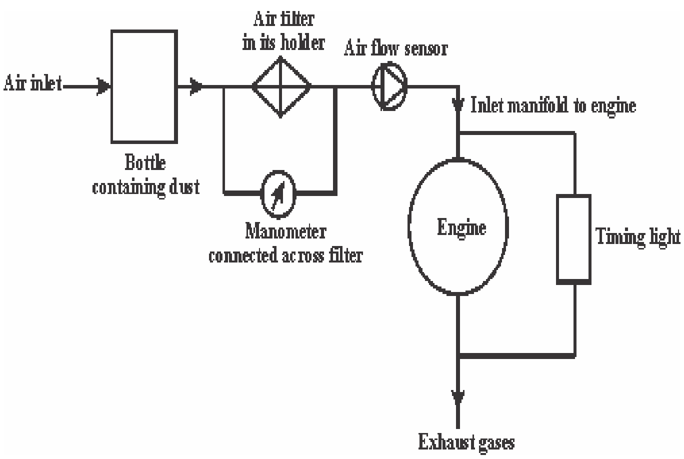

Figure 1. Schematic diagram of the dust experiment

The set-up consists of a big transparent plastic bottle placed on a platform which is about 76 cm high. The platform consists of a table with a plastic container placed on top. A box of paper was then placed on the container and a drawing board on top of the box. This arrangement was made to give the required height to support the plastic gallon. Holes were made with the edge of a screw driver around the base of the plastic bottle. The diameter of the holes was approximately 0.4 cm. The plastic bottle was covered with its lid at the top. This arrangement created air-dust circulation in the gallon. A plane white paper was placed underneath the bottle to collect any dust samples that escaped through the holes.

A hole of approximately 6 cm diameter equal to the diameter of the inlet tube of the filter holder was made on one side of the bottle. The hole on the bottle and the inlet tube cavity were then connected using a plastic hose of slightly larger diameter. To avoid air and dust leakages from the plastic bottle, the plastic hose was sealed with epoxy. Similarly, a metal clip was used to tighten the plastic hose onto the inlet tube of the holder.

The set-up was also equipped with an air flow sensor. The output of the sensor was in volts (V). This gives idea of how much air is entering the engine with time so the volt readings are shown in this study. A digital timing light was used to record the engine speed as dust loading continued. The red wire of the timing light was connected to the positive terminal of the battery while the black wire was connected to the negative terminal. The digital timing light also had a crocodile clip which was connected to the number 1 spark plug cable. Sensors in the clip determine the time current enters spark plug 1 so that the engine speed recorded will be accurate. The fuel level was recorded before and after the various processes. The set-up was also equipped with an inclined manometer with paraffin to measure the pressure drop across the filter assembly.

The dust samples were stored in six different 250 ml plastic bottles. The bottles were grouped into two and each group contained the same mass of dust. The mass of dust in both groups was 529 g. The masses of the three different air filters were measured and recorded. Each filter was placed in its holder and connected to the engine block. In order to obtain a representative comparison, each filter was tested (using the experimental set-up in Fig. 1) two times. In the absence of instrument, the average dust loading rates were calculated theoretically and found to be 0.08 g/s and 0.14 g/s (appendix A) for idling conditions of the engine. To investigate the rate of clogging of each filter, the pressure drop was recorded at 0, 1, 2, 3, 4 and 5 minutes after starting the process. The sampling time of 5 minutes was allowed by the instructor at the site so as not to damage their engine. Each sampling filter was weighed before and after sampling and the dust arrestance/collection efficiency (appendix B) by the filter was then calculated. The engine speed and the air flow rate from the filter into the engine were recorded at the same time interval. The fuel level before and after each test was also recorded. The results obtained from the experimental procedure are presented in graphical form.

Three different filters in Figs. 2 (a) – (c) were used in the investigation.

(a) (b)

(c)

Figure 2: Filters used in the experiment in their clean state; (a) Yellow Foam Filter (YF) (b) Red Foam Filter (RF) (c) Paper Filter (PF)

The main parameters and dimensions of these filters are in Table 1.The yellow foam filter (YF) has a pore size of 2 μm, the red foam filter (RF) has a pore size of 1 μm and the paper filter (PF) has a pore size of 2 μm. These values were provided by the manufacturers. The volume fraction of fibres, called the packing density or solidity, for the filters is shown in appendix B.

Table 1. Parameters of filters

Filter number	Filter material	Fibre distance (cm)	Thickness of fibre (cm)	Breadth of fibre (cm)	Height of fibre (cm)	Number of fibres
1	Foam	0.20	0.1	13.8	2.3	58
2	Foam	0.25	0.15	14.5	1.6	52
3	Paper	0.25	0.1	14.5	1.6	62

3. RESULTS

Graphs showing results of measurements of the three filters used in the study for the dust loading rates of 0.08 g/s and 0.14 g/s are in Figs. 3 to 5.

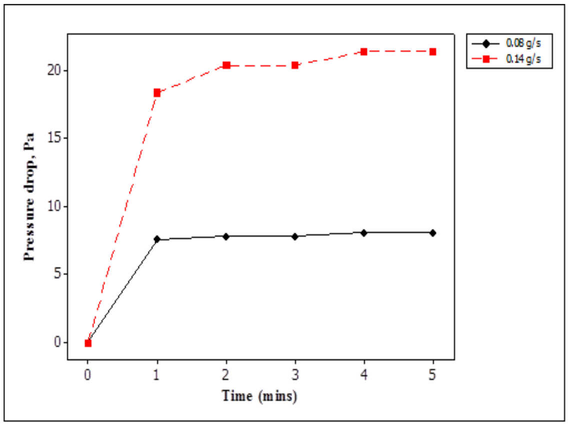

Figure 3(a). Pressure drop against time for YF

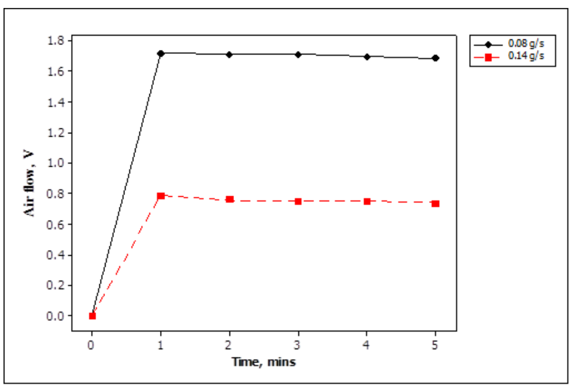

Figure 3(b). Air flow against time for YF

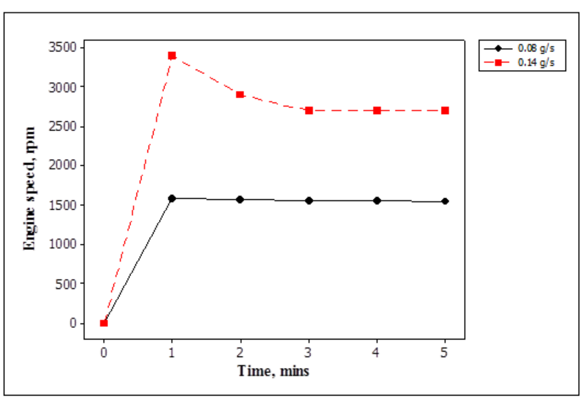

Figure 3(c). Engine speed against time for YF

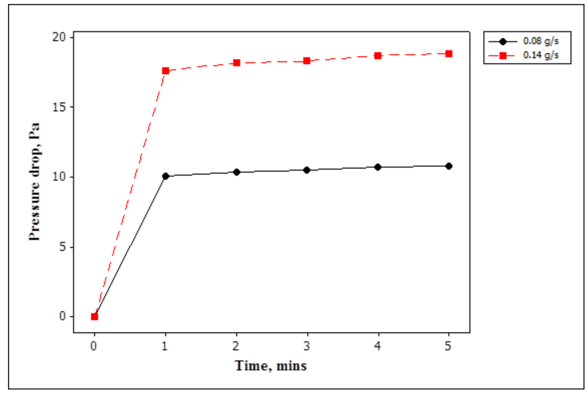

Figure 4(a). Pressure drop against time for PF

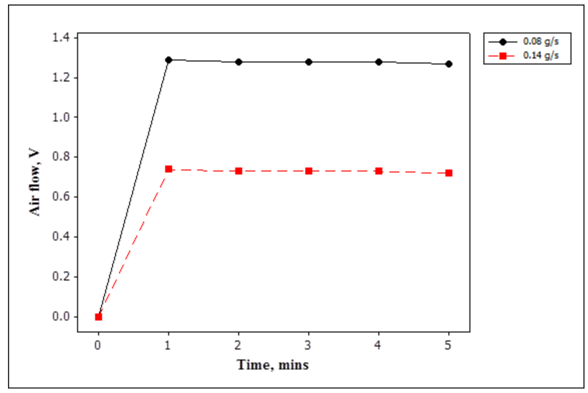

Figure 4(b). Air flow against time for PF

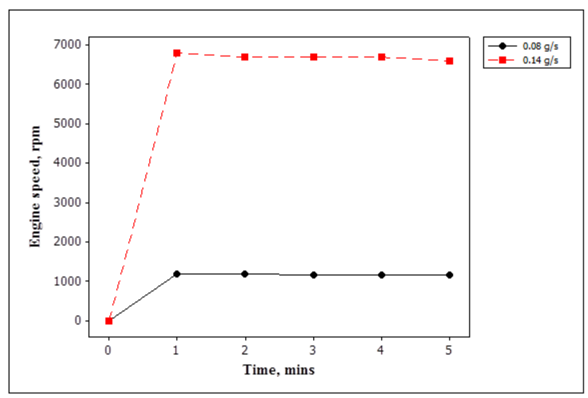

Figure 4(c). Engine speed against time for PF

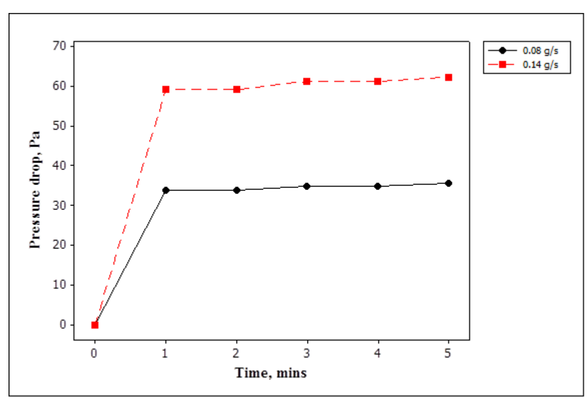

Figure 5(a). Pressure drop against time for RF

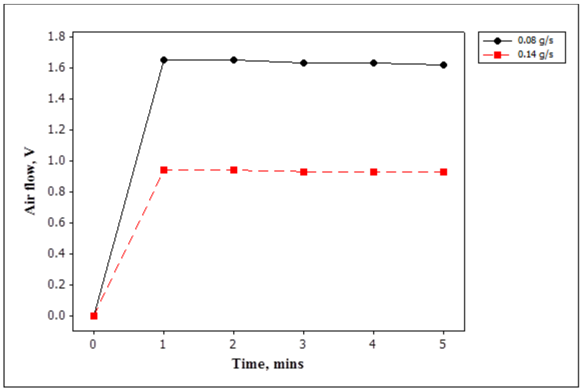

Figure 5(b). Air flow against time for RF

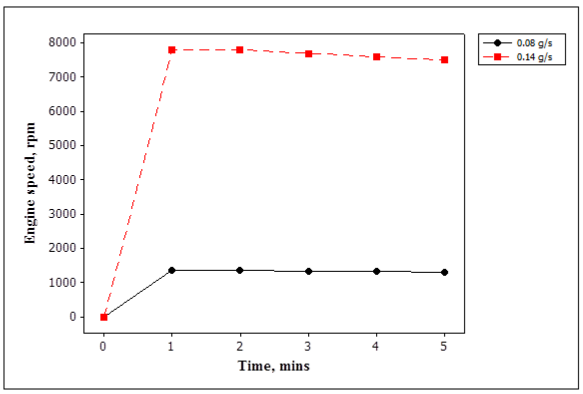

Figure 5(c). Engine speed against time for RF

Results from the measurements of the three different filters clearly show that the pressure drop increased rapidly within one minute after the start of the process. However, for the 0.08 g/s dust loading rate, the resistance (a measure of the pressure drop) for the paper filter was approximately 2 times more compared to the yellow foam filter whilst that of the red foam filter was 26 times more compared to the yellow foam filter, after one minute of the process. For the 0.14 g/s dust loading rate, the resistance of the paper filter was approximately the same compared to the yellow foam filter. The resistance of the red foam filter was 44 times more compared to the yellow foam filter, after one minute of the process. The results also indicate that the air flow after yellow foam filter for the 0.08 g/s dust loading was approximately 0.4 times more and 0.1 times more compared to the paper filter and the red foam filter respectively, within the same interval. For the 0.14 g/s dust loading rate, the air flow after the yellow foam filter was 0.1 times more compared to the paper filter whilst that of the red foam filter was 0.2 times more compared to the yellow foam filter.

Also, the engine speed for the 0.08 g/s dust loading for the yellow foam filter was approximately 0.4 times more and 0.2 times more compared to the paper filter and the red foam filter, after one minute of the start of the process. For the 0.14 g/s dust loading rate, the engine speed was 0.3 times more and 0.4 times more compared to the paper filter and the red foam filter respectively. These results show that as the filter gets blocked with time, the air used for combustion reduces in volume as well as the engine speed.

4. DISCUSSION

4.1 Effect of dust load on pressure drop across the air filters

The experimental results indicate that the resistance to air flow for all three filters increased sharply at the start of the process to a peak value and then increased steadily with time. A similar trend in pressure drop has been observed by Callé *et al*, 2001 and Lee *et al*., 1981. The sharp increase in pressure drop within the first minute is an indication that the pores of the nearest fibres, downstream of the filter, get blocked fast thereby increasing the resistance to air flow through those air passages. With time the resistance to air flow increased slightly because most pores got blocked. These results indicate that as air passes through the filter media, the filter structure causes a resistance that is a measure of air permeability or the pressure drop.

Results of the experiment show that the pressure drop across all filters is directly proportional to the dust loading rate. As the dust loading rate increased from 0.08 g/s to 0.14 g/s, it was found that the pressure drop increased about 2.4 times (from 7.6 Pa for 0.8 g/s to 18.4 Pa for 0.14 g/s) within one minute after the start of the process. Similar trends were seen for the other two filters. The values obtained also indicated that the pressure drop only increased slightly after some time. This means within the time interval, the amount of air passages blocked by the dust was the same or slightly larger. The values obtained show that the pressure drop will continue to grow indicating clogging of the filter. This phenomenon has been observed by Agranovski *et al*, 2001.

The pressure drop across the filters was also found to increase with engine speed within seconds after the start of the process. This is because within this period, more air passes across the length of the filter and enters the engine as resistance to air flow by the filters has not yet been prominent. However, the engine speed reduces with increase in pressure drop just after some time. This is expected because with time the air passage ways get blocked with dust particles increasing the resistance to air flow by the filters and thus reducing the amount of air entering the engine for combustion.

4.2 Effect of dust load on engine speed and fuel level

The relation between pressure drop and engine speed becomes steeper with higher dust loading rates. This indicates that the engine runs at relatively low speeds for higher dust loading rates. The fuel level was also recorded and for the 0.08 g/s dust loading, the drops in fuel level for the yellow foam filter (thickness of 0.1 cm) was 0.6 mm, for the paper filter (thickness of 0.1 cm) it was 0.05 mm and for the red foam filter (thickness of 0.15 cm) it was 0.03 mm. These results also clearly indicate that a filter with a high fibre thickness and small pore sizes with greater number of fibre does not cause an appreciable decrease in fuel level. The average engine speed for filters 1, 2 and 3 (Table 1) for the 0.08 g/s dust loading rate are 1600 rpm, 1200 rpm and 1300 rpm. Values for the 0.14 g/s rate are 300 rpm, 700 rpm and 800 rpm. Comparing these values it is shown that as the dust rate increases, the engine speed reduces.

4.3 Effect of dust load on air flow after the filters

The quantity of air entering the engine after filtration was also found out to be proportional to the pressure drop across the filter within one minute and inversely proportional to the pressure drop after a peak value some seconds after one minute. The results obtained for the three filters show that within one minute, the air flow increases sharply to a peak. The rising increase in air flow during the few seconds indicates that the air passages were not blocked and that the dust particles were not attaching themselves to the filter material. This continued to a peak value that is an indication that dust particles have begun attaching themselves to the filter material downstream. There is a sharp decrease after the peak indicating that more particles were still attaching themselves and blocking the air passages. There is now a gradual decrease in air flow just after two minutes; this clearly indicates that most particles might have now attached themselves to the filter material and blocked most air passages. The times it took for filters 1, 2 and 3 to reach their peak were 72 seconds, 74 seconds and 84 seconds respectively for the two dust loading rates but at different peak values. The values obtained give indication that the time it takes for a filter material to get blocked depends on filter material and area occupied by the fibres on the filter. The greater the fibre area of the filter the more time it takes for the filter material to have its air packages blocked. It can be inferred that as more dust enters the filter, the combined effect of each fibre resisting the flow of air past it increases, thereby reducing the amount of air entering the inlet of the engine for combustion.

The dust arrestance/collection efficiency of the filters was also computed (appendix A) and it was found that, the longer the length of the filter, the better its filtration properties. The reason for calculating this parameter was to know how much of dust particles that were collected by the filters (due to adhesion) and did not penetrate through them.

5. CONCLUSION

The main objective of this research was to study how vehicle combustion air filters get blocked by dust particles and to relate this to the engine performance. It was found that road dust particles take some time to attach themselves to the filter media before causing blockage to air. It was also found that dust particles accumulated near the downstream side of the filter. High concentration of particles located at the downstream part is explained by the fact that, besides the particles collected in this area, the dust washed from the upstream part of the filter also passes through the downstream part. This shows that filters get clogged first downstream and gradually moves upstream of the filter. This has also been observed by Agranovski *et al*., 2001. It was further observed that different filters because of structure and shape affect engine performance. Similar trends in engine performance were obtained for the filters tested. However, results show that the red foam filter performed better in terms of engine performance and clogging time compared to the other two filters. It has also been seen that with higher dust loading rate, the pressure drop across filters increases significantly and can cause clogging of the filters within a short period. Air filters in vehicles that ply on unpaved roads therefore exhibit higher pressure drops than those used in vehicles on paved roads. Air flow measurements also indicated that for vehicle filters used on roads of less dust levels, the air flow values are small compared to filters used on roads of high dust levels. It is estimated that the extreme north of the country is under the influence of the Saharan dust aerosol 80% of the time, compared with only 45% for the city of Kumasi and a tiny 8% for the capital city of Accra (Sunnu, 2006). This clearly indicates that the effectiveness of filters in relation to engine performance of vehicles used in the north will get more affected based on the analysis made in the discussion than filters used in vehicles in Kumasi and Accra. Further works will be carried out to analyse the contents of the exhaust gases.

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Appendix A: Mass Flow Rates of Dust and Collection Efficiency of Filters

Foam filter (Yellow)

Mass of container (before) = 0.125 kg
Mass of container + dust (before) = 0.664 kg
∴Mass of dust (before) = 0.664 – 0.125 = 0.529 kg = 529 g
Mass of filter = 158 g
Mass of filter + dust = 160 g
∴Mass of dust retained by filter = 160 – 158 = 2 g

Mass of container (after) = 0.64 kg
∴Mass of dust entering filter = 0.664 – 0.64 = 0.024 kg = 24 g
Mass of dust entering engine inlet = 24 – 2 = 22 g

$$\Rightarrow \text{Mass flow rate of dust} = \frac{mass \text{ entering filter}}{time \text{ interval}}$$

$$= \frac{24}{5\times 60} = 0.08 \text{ g/s}$$

$$\text{Collection efficiency} = \frac{\text{mass of dust retained}}{\text{mass of dust entering filter}}$$

$$= \frac{2}{24}\times 100 = 8.33\%$$

$$\%\text{ penetration} = \frac{\text{mass of dust entering engine inlet}}{\text{mass of dust entering filter}}$$

$$= \frac{22}{24}\times 100 = 91.7\%$$

Foam filter (Yellow)

Mass of container (before) = 0.125 kg
Mass of container + dust (before) = 0.925 kg
∴Mass of dust (before) = 0.925 – 0.125 = 0.8 kg = 800 g
Mass of filter = 158 g
Mass of filter + dust = 161 g
∴Mass of dust retained by filter = 161 – 158 = 3.0 g
Mass of container (after) = 0.883 kg
∴Mass of dust entering filter = 0.925 – 0.883 = 0.042 kg = 42 g
Mass of dust entering engine inlet = 42 – 3 = 39 g

$$\Rightarrow \text{Mass flow rate of dust} = \frac{mass \text{ entering filter}}{time \text{ interval}}$$

$$= \frac{42}{5\times 60} = 0.14 \text{ g/s}$$

$$\text{Collection efficiency} = \frac{\text{mass of dust retained}}{\text{mass of dust entering filter}}$$

$$= \frac{3}{42}\times 100 = 7.14\%$$

$$\%\text{ penetration} = \frac{\text{mass of dust entering engine inlet}}{\text{mass of dust entering filter}}$$

$$= \frac{39}{42}\times 100 = 92.9\%$$

Paper filter

Mass of container (before) = 0.145 kg
Mass of container + dust (before) = 0.674 kg
∴Mass of dust (before) = 0.674 – 0.145 = 0.529 kg = 529 g
Mass of filter = 195 g
Mass of filter + dust = 198.6 g
∴Mass of dust retained by filter = 198.6 – 195 = 3.6 g
Mass of container (after) = 0.65 kg
∴Mass of dust entering filter = 0.674 – 0.65 = 0.024 kg = 24 g
Mass of dust entering engine inlet = 24 – 3.6 = 20.4 g

$$\Rightarrow \text{Mass flow rate of dust} = \frac{mass \text{ entering filter}}{time \text{ interval}}$$

$$= \frac{24}{5\times 60} = 0.8 \text{ g/s}$$

$$\text{Collection efficiency} = \frac{\text{mass of dust retained}}{\text{mass of dust entering filter}}$$

$$= \frac{3.6}{24}\times 100 = 15\%$$

$$\%\text{ penetration} = \frac{\text{mass of dust entering engine inlet}}{\text{mass of dust entering filter}}$$

$$= \frac{20.4}{24}\times 100 = 85\%$$

Paper filter

Mass of container (before) = 0.145 kg
Mass of container + dust (before) = 0.945 kg
∴Mass of dust (before) = 0.945 – 0.145 = 0.8 kg = 800 g
Mass of filter = 195 g
Mass of filter + dust = 200.4 g
∴Mass of dust retained by filter = 200.4 – 195 = 5.4 g
Mass of container (after) = 0.903 kg
∴Mass of dust entering filter = 0.879 – 0.837 = 0.042 kg = 42 g
Mass of dust entering engine inlet = 42 – 5.4 = 36.6 g

$$\Rightarrow \text{Mass flow rate of dust} = \frac{mass \text{ entering filter}}{time \text{ interval}}$$

$$= \frac{42}{5\times 60} = 0.14 \text{ g/s}$$

$$\text{Collection efficiency} = \frac{\text{mass of dust retained}}{\text{mass of dust entering filter}}$$

$$= \frac{5.4}{42}\times 100 = 12.9\%$$

$$\%\text{ penetration} = \frac{\text{mass of dust entering engine inlet}}{\text{mass of dust entering filter}}$$

$$= \frac{36.6}{42}\times 100 = 87.1\%$$

Foam filter (Red)

Mass of container (before) = 0.128 kg
Mass of container + dust (before) = 0.657 kg
∴Mass of dust (before) = 0.657 – 0.128 = 0.529 kg = 529 g
Mass of filter = 300 g
Mass of filter + dust = 306.5 g
∴Mass of dust retained by filter = 306.5 – 300 = 6.5 g
Mass of container (after) = 0.633 kg
∴Mass of dust entering filter = 0.657 – 0.633= 0.024 kg = 24 g

Mass of dust entering engine inlet = 24 – 6.5 = 17.5 g

$$\Rightarrow \text{ Mass flow rate of dust } = \frac{mass \text{ entering filter}}{time \text{ interval}}$$

$$= \frac{24}{5 \times 60} = 0.08 \text{ g/s}$$

$$\text{Collection efficiency} = \frac{\text{mass of dust retained}}{\text{mass of dust entering filter}}$$

$$= \frac{6.5}{24} \times 100 = 27.1\%$$

$$\text{\% penetration} = \frac{\text{mass of dust entering engine inlet}}{\text{mass of dust entering filter}}$$

$$= \frac{17.5}{24} \times 100 = 72.9\%$$

Foam filter (Red)

Mass of container (before) = 0.128 kg
Mass of container + dust (before) = 0.928 kg
∴Mass of dust (before) = 0.928 – 0.128 = 0.8 kg = 800 g
Mass of filter = 300 g
Mass of filter + dust = 309.8 g
∴Mass of dust retained by filter = 306.5 – 300 = 9.8 g
Mass of container (after) = 0.886 kg
∴Mass of dust entering filter = 0.928 – 0.886= 0.042 kg = 42 g
Mass of dust entering engine inlet = 42 – 9.8 = 32.2 g

$$\Rightarrow \text{ Mass flow rate of dust } = \frac{mass \text{ entering filter}}{time \text{ interval}}$$

$$= \frac{42}{5 \times 60} = 0.14 \text{ g/s}$$

$$\text{Collection efficiency} = \frac{\text{mass of dust retained}}{\text{mass of dust entering filter}}$$

$$= \frac{9.8}{42} \times 100 = 23.3\%$$

$$\text{\% penetration} = \frac{\text{mass of dust entering engine inlet}}{\text{mass of dust entering filter}}$$

$$= \frac{32.2}{42} \times 100 = 76.7\%$$

Appendix B: Solidity/Packing Density of the Filters
Foam Filter (Yellow)

$$Total\ volume = 15 \times 20.3 \times 3.8 = 1157.1\ cm^3$$
$$Volume\ occupied\ by\ one\ fibre = 2.3 \times 0.1 \times 13.8 = 3.174\ cm^3$$
$$\therefore Total\ fibre\ volume = 3.174 \times 58 = 184.09\ cm^3$$
$$Solidity, \alpha = \frac{fibre\ volume}{total\ volume} = \frac{184.09}{1157.1} = \mathbf{0.16}$$

Paper Filter

$$Total\ volume = 16.5 \times 27.7 \times 3.5 = 1599.7\ cm^3$$
$$Volume\ occupied\ by\ one\ fibre = 1.6 \times 0.1 \times 14.5 = 2.32\ cm^3$$
$$\therefore Total\ fibre\ volume = 2.32 \times 62 = 143.84\ cm^3$$
$$Solidity, \alpha = \frac{fibre\ volume}{total\ volume} = \frac{143.84}{1599.7} = \mathbf{0.09}$$

Foam Filter (Red)

$$Total\ volume = 16.9 \times 27.9 \times 3.5 = 1650.3\ cm^3$$
$$Volume\ occupied\ by\ one\ fibre = 1.6 \times 0.15 \times 14.5 = 3.48\ cm^3$$
$$\therefore Total\ fibre\ volume = 3.48 \times 52 = 180.96\ cm^3$$
$$Solidity, \alpha = \frac{fibre\ volume}{total\ volume} = \frac{180.96}{1650.3} = \mathbf{0.11}$$