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USE OF COCONUT FIBER FOR PARTICLE ENLARGEMENT OF PARTICULATE MATTER IN DIESEL EXHAUST

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ABSTRACT

As an alternative system to reduce particulate matter in the exhaust of older diesel engine, a post-muffler device is proposed that initially enlarges the ultra-fine diesel particulate matter in the exhaust so that the formed agglomerates can quantitatively be separated from the exhaust by subsequent cyclone type equipment.

This study focuses on the problem of agglomeration of ultra-fine PM using a renewable fiber matrix. It is a feasibility study to use coir fiber matrix to induce significant particle coagulation to sizes well above 1 μm. A housing was designed and fabricated with an approximate matrix volume of 13 liters which corresponded to 200 – 400 layers of coconut fiber in flow direction. A standardized glass filter was used to capture the particle fraction PM 2.5 out of the exhaust with a custom-made dilution channel. The study shows significant deposition and agglomeration of particulate matter from diesel exhaust.

The obtained results support qualitatively the theoretically derived operating principle of the device. An outline is given for subsequent work to quantitatively evaluate the system and to adapt the equipment design for everyday use in public transport in the Philippines.

I. INTRODUCTION

Particulates, especially those less than 2.5 μm in diameter, characterized internationally as PM2.5, are known to pose a major human health risk because of the high probability for these to deposit deep in the respiratory tract and subsequently cause respiratory diseases such as lung cancer. Unaltered Diesel exhaust particles fall primarily in this size range. A typical particle size distribution of diesel exhaust is shown in Figure 1.

Diesel particulate matter (DPM) consists of solid particles and volatile droplets. Volatile components also cover the particles and function as an agglomerating agent between them (Figure 2). The chemical composition of solid particles includes agglomerated carbon as soot and ash while volatiles can be classified into soluble organic fractions (SOF), volatile organic and sulfur compounds.

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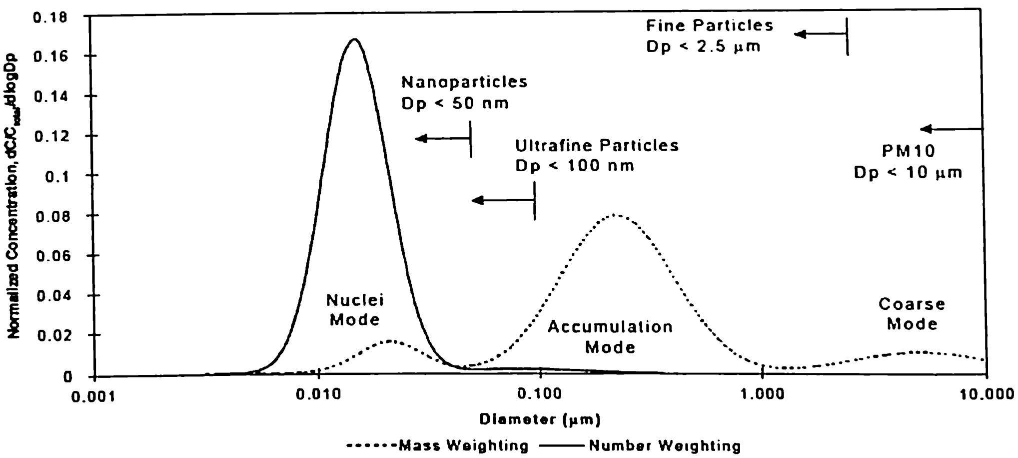

Figure 1. Mass and number distribution of diesel particulate matter (From [10])

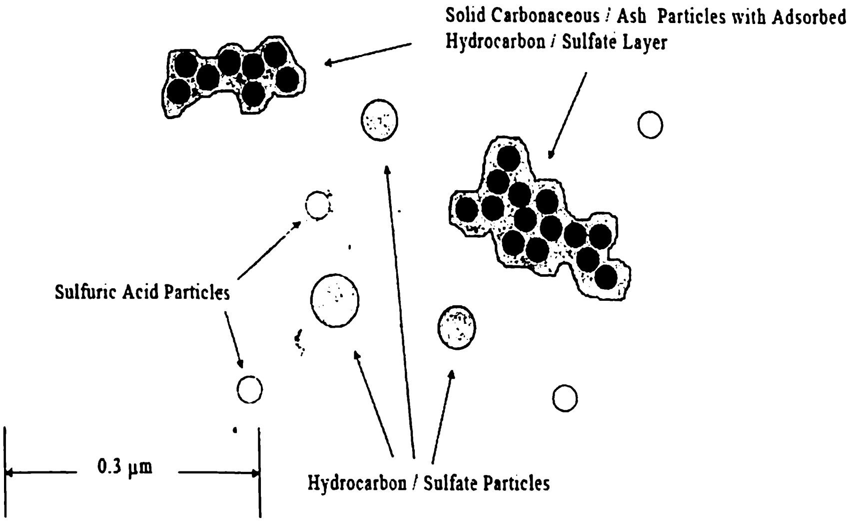

Figure 2. Typical composition of diesel particulate matter (Source: [10])

As a remedy, Diesel particulate filters (DPF) have been established in the EU and the U.S. over the last decade as effective devices in reducing particulate emissions. To warrant the necessary long life time of the catalyst, DPM must be already at low levels when coming from the engine to warrant a reasonable cycle time of the filters. However, due to the economic situation in our country, DPM emissions from most diesel engines exceed far beyond the levels of modern diesel engines. As the vast majority of diesel engines found in trucks, buses and light trucks were imported from abroad as used engines, they do have often life time of 15 to 25 years. Far higher DPM values are therefore a direct consequence of the aged fleet of diesel engines in the Philippines.

More advanced DPF devices also use catalytic converters to clear the filters from soot deposits. To do so, a low sulfur content in the Diesel fuel is, however, mandatory. These conditions are well met by diesel fuel standards in the EU and North America, which require a sulfur content of less than 15 ppm of sulfur. However, in the Philippines national regulations still allow diesel fuel to be sold at sulfur levels up to 500 ppm. Under these conditions, DPFs from Europe or North America cannot be successfully employed in diesel engines in the country. Consequently, until stringent fuel standards are met and the fleet of diesel engines is renewed, a mandatory introduction of DPF in the Philippines cannot be envisioned.

There have been attempts to reduce the current DPM release in the Philippines by the introduction of coconut methyl ester (CME) or bio-diesel. Studies made by the Philippine Coconut Authority have shown a reduction in smoke emissions by 50 percent using 1 percent CME on petroleum diesel fuel. It needs to be pointed out that this finding is very different from those reported in other countries and obviously attributed to the particular fuel quality and diesel engine fleet. In the US, some studies claim that the installation of DPF with diesel engines run by B20 (diesel fuel blended with 20 % by volume of methyl esters of fatty acids such as CME) actually increased NOx emission by 5 % but in terms of an effect on PM, no disadvantages were observed [16].

Concluding from the above, the study will address the particular situation in our country, characterized by high sulfur content in diesel fuel and long life-time of diesel engines, and focus on an intermediate solution for reducing DPM emissions until technical standards can economically be introduced in the country. Our goal is to provide a concept for an innovative solution to significantly reduce DPM by first inducing particle agglomeration and subsequently removing those agglomerates with cyclone type equipment. The particular focus of this work is the design of a coconut fiber matrix and its corresponding housing for particle agglomeration for diesel engines. It is intended to provide proof of concept for using coir matrix to induce significant particle coagulation.

2. CHOIR AS A FILTER MATRIX

Coir is a coarse fiber extracted from the fibrous outer shell of a coconut. Each thread of coir has been shown to contain holes called "pinholes", which are used to contain wax or fatty substances. Coir used in the experiments of this study was bought from Victoria, Laguna at about 1,200 pesos per 100 kilograms (2005).

The ample supply and low cost of coir fiber makes it an economical resource for building filter media for exhaust after-treatment retrofits. As we are envisioning a disposable filter, coir also provides an easy and economical way to incinerate the used filters to ash. Typical physical properties and the chemical composition of coir fiber is shown in Table 1.

Table 1: Typical properties of coir fiber (Source:[9])

Physical properties		Chemical composition	
Diameter / width in micron	16	Water Soluble	5.25%
Length in inches	6 – 8	Pectin and related compounds	3.00%
Density (g/cc)	1.40	Hemi – cellulose	0.25%
Tenacity(g/tex)	10.0	Lignin	45.84%
Breaking elongation %	30	Cellulose	43.44%
Moisture regain at 65 % R. H (%)	10.5	Ash	2.22%
Swelling in water (diameter)	5%	-	-

It should be pointed out that the fibers used in our study had an average diameter of approx. 300 µm, far more than the value reported in [9]. Whereas coir is easily available in our country, there are certain disadvantages connected with using coir, in particular its ability to adsorb water eight times its weight. The good adsorption properties do also extend to oxygen and are due the presence of functional groups on the surface of fiber, such as carboxyl [9], allowing for significant intermolecular forces between water or oxygen molecules and the fiber surface.

In consequence, these properties require that the fibers will have to be kept dry before and during operation, especially during rainy season, to protect the filter matrix from collapsing. Furthermore, to avoid self-ignition which is enhanced by its absorbed oxygen content, the temperatures the coir surface may be exposed have to be carefully controlled.

Whereas in standard filter application particles are trapped predominantly through size exclusion, the separation effect in an open matrix is only based on the deposition of the particulates on the individual fibers. The large fiber-particle interactions of submicron particles like London-Van der Waals forces are subsequently responsible for the agglomeration of the particles on the fiber surface into fractals. Due to the magnitude of those interactions, a particle can confidently be considered trapped once it will have physical contact with the fiber or the agglomerates on it.

To evaluate the motion of a single particle onto the fiber, the following principle mechanisms will have to be taken into account: interception, inertial impaction, diffusion, gravity settling, and electrostatic attraction. All these mechanisms are illustrated in Figure 3. For sub-micron particles, gravitational forces may be neglected. Also, electrostatic forces do not play a role as coir fiber is essentially uncharged. The remaining forces will be considered in determining particle deposition on a single fiber and thus also in a matrix with many layers of fibers.

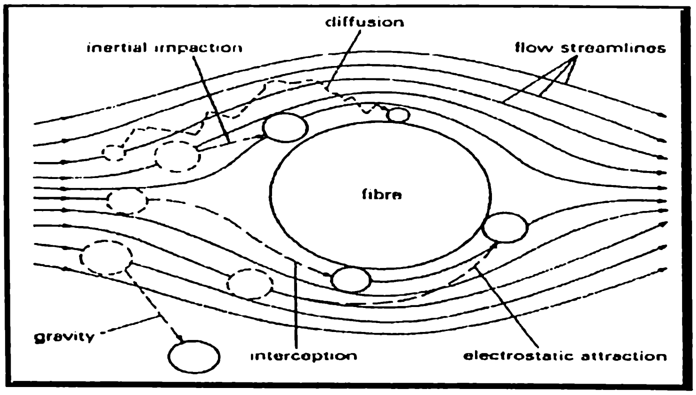

Figure 3. Collection mechanisms (Source: [6])

Particle interception is taking place once the gas streamline on which the particle travels will come so close to the fiber that the particle will touch the fiber surface. With inertial impaction the particle path may deviate from the streamlines of the gas because of the inertia of the particle and bring it into contact with the fiber.

Diffusion is the result of the Brownian motion of particles [6] or the random dancing motion of particles due to fluctuating forces exerted on the particles [3]. As a particle approaches the filter material, diffusion may move the particle to the surface of the fiber, even if its initial position on a streamline in the gas would not lead to a contact. Deposition by diffusion is increasing with decreasing particles size. It is the dominant mechanism for particles smaller than 0.2 µm [2] and is especially important for particles in the 0.01 to 0.1 micrometer size range. As DPM particle sizes range from less than 0.010 µm up to 0.500 µm, all three mechanisms may have to be considered for particle collection in a open fiber matrix.

2.1 Preliminary tests on coir fiber

2.1.1 Self-ignition of coir fiber

Self-ignition tests were conducted in a laboratory-scale furnace. Using untreated, unused samples, self-ignition of coir fibers was observed at temperatures between 280 °C to 320 ° C. Any temperature in the agglomerator will have to be well below that value, so that for design purposes, operating temperatures below 200 °C are recommended. Effects on the self-ignition ability as a function of operation or pre-treatment are, however, beyond the scope of this study.

2.1.2 Fiber Performance in On-Road Tests

Experiments were carried out using 5-10 layers of coir fiber. These fibers were arranged on one side of a 9-inch diameter cylinder fabricated from illustration board as shown in Figure 9. For stability purposes, a board with 3-4 inch holes mounted across the entire diameter to fix the fibers in the center of the cylinder which can be seen. The assembly was put directly on the tailpipe of an "IKOT" jeepney (Figure 10). The vehicle has an ISUZU 4BA1 diesel engine approximately 20 to 30 years old. The test allowed the jeepney to operate for 4 hours its usual route ("IKOT"). Within this time, it made 12 trips back and forth inside UP Diliman, traveling approximately 60 kilometers. Immediately afterwards, fiber samples were examined using a Scanning Electron Microscope (SEM).

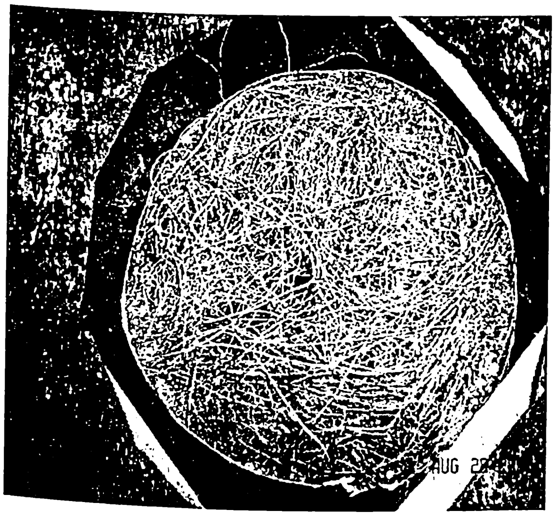
Figure 3. Coir filter set-up


Figure 4. Installation of coir filter set-up

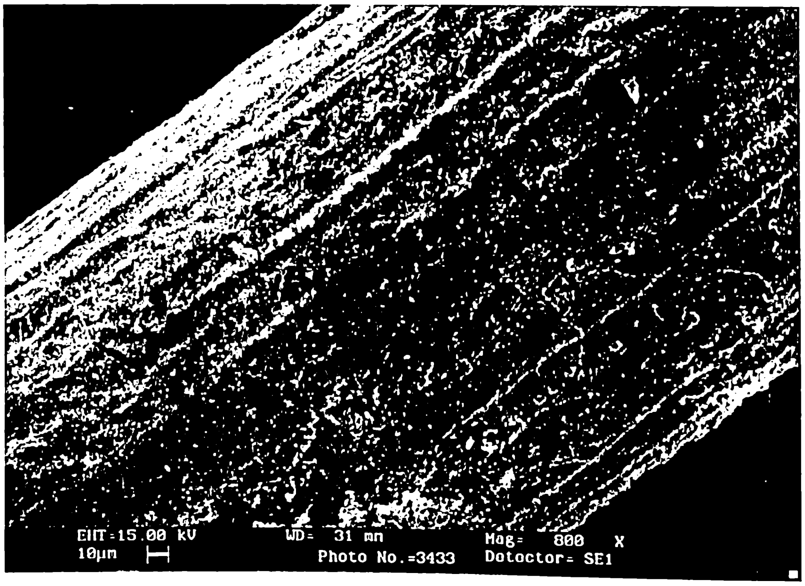

Figure 5. SEM image of surface of coir before on-road test

As seen in Figures 12 and 13, a significant amount of agglomerates have attached to the fiber, when compared with Figure 11, where the original coir is shown. The agglomerates are of the size of up to 160 μm (Point P2 to P2R in Figure 12) on the fiber with 270 μm in diameter (Point P1 to P1R in Figure 12). Furthermore, it becomes evident that the fibers show a distinct side, where agglomerates assemble, although there are also some deposits on the opposite side (Figure 13). A more detailed look (Figure 14) shows further that deposits are indeed agglomerates and do grow from clearly from far below micron diameters to the sizes observed. The results are not surprising, as similar effects have been observed on class fibers [4] as shown in Figure 15.

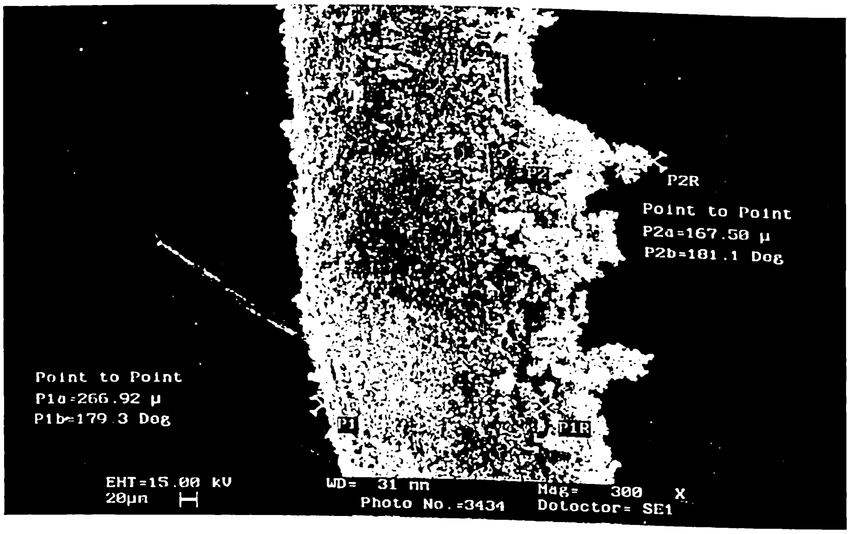

Figure 6. SEM image of DPM agglomeration on surface of coir after on-road test

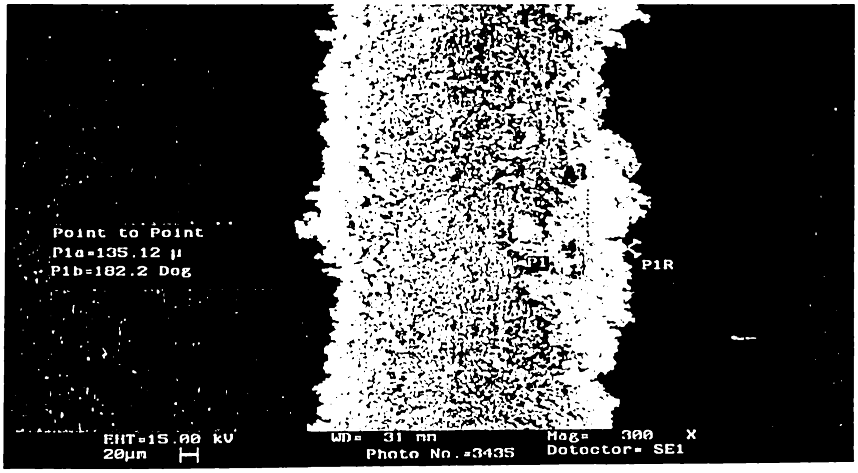

Figure 7. SEM image of DPM agglomeration after on-road test

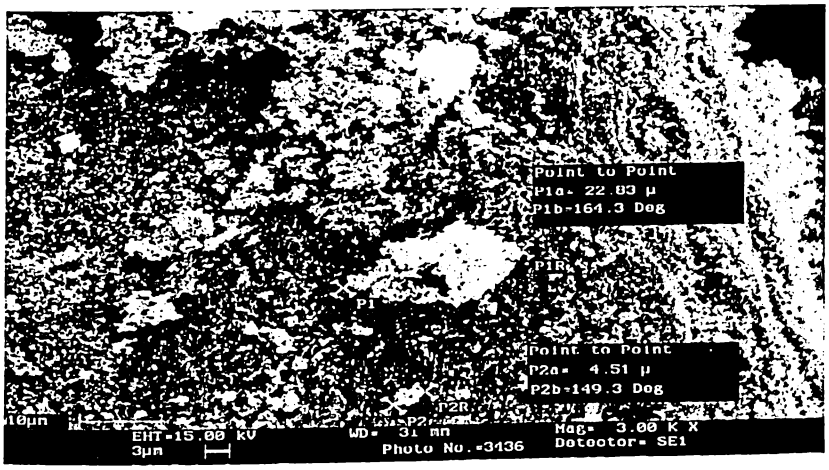

Figure 8. SEM Image size range or deposited particles

Figure 9. Particle agglomeration on 10 μm ceramic fibers (source: [1, 4])

The following calculation will provide support that the deposition is neither primarily from a single particle interception nor from inertia impaction. The regime where these effects take place has been well studied. Using potential flow analysis of inviscid flow around a cylinder the conditions for impaction or interception can be derived as to [3]

$$\mathrm{Stk}_{crt} = 1/8 \qquad \text{eq. (6)}$$

with Stk_{crt} as the critical Stokes Number:

$$\mathrm{Stk}_{crt} = (\rho_p d_m^2 v) / (18\mu\ d_f) \qquad \text{eq. (7)}$$

Applying the average fiber diameter $d_f = 300\ \mu m$, the approximate gas velocity through the fibers $v = 1\ m/s$, the kinematic viscosity of the gas $\mu = 18{,}3\ 10^{-6}$ and the average particle density of a single soot particle of $\rho_p = 800\ kg/m^{3}$, impaction and interception will only be predominant for particle sizes larger than $d_m = 3{,}9\ \mu m$. As shown in Figure 1, there are hardly any particles present in diesel exhaust that are larger than this number. Thus, we can conclude that agglomeration of DPM on the coir fiber happened through other mechanisms other than laminar flow interception and impaction. This is a clear indication that turbulent deposition plays the major role, especially in front of the fiber. A practical life example for such a deposition phenomenon is also the soot collection on regular ceiling fans in homes in metropolitan areas in the country which happens exactly on the sharp front edge of the fan blade.

3. MATERIALS AND METHODS

3.1 Design of agglomerator

The imposed requirements for the equipment design were low cost of hardware, easy manufacturing by any skilled technician, simple exchange of coir matrix and mountable on the outside (back side) of a bus, truck or mini van, especially jeepneys. A 60 liter industrial steel drum was used as outer housing and outfitted with additional pipes and perforated plates as shown in Figure 4. Dimensions can be found in Table 2.

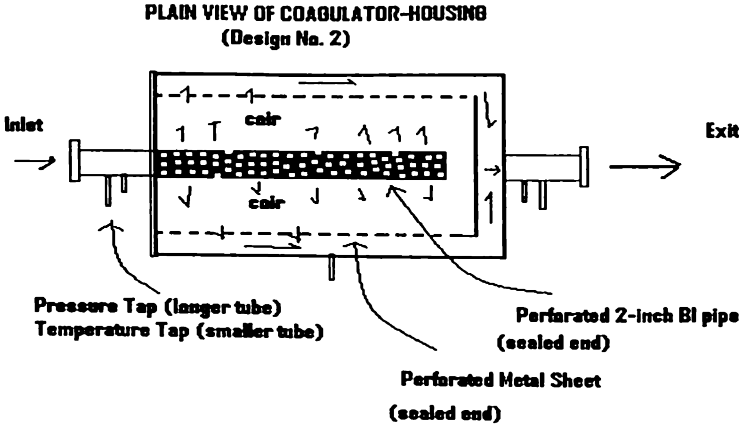

Figure 10. Schematic diagram of agglomerator

Exhaust gas flows through the inner perforated pipe and passes through the coir matrix which is fixed in a cylinder (inner housing) made of perforated metal sheets.

Table 2. Dimensions of Agglomerator

Housing Specification		
Diameter of holes of Inner housing	3/8	Inch
Total Length of housing Diameter of Inner housing	40 21	cm cm
Diameter of holes of the Perforated pipe	0.5	Inch
Length of Perforated pipe	40	Cm
Number of holes - Perforated Pipe - Perforated housing	 260 1852	
Diameter of outer housing	41	Cm
Length of outer housing	50	Cm
specification of Coir matrix		
Number of layers	169	
Porosity	0.966	
Number of fiber layers	169	Layers
Thickness of filter bed	0.0796	M
Volume occupied by coir	0.013	m^3

The end of the perforated pipe as well as the inner housing is closed to prevent any gas bypass. This way, the exhaust is forced to flow in radial direction through the fiber matrix. Applying the dimensions and values for the matrix installed, the average number of fibers N that are in the linear flow path of any given particle can be calculated:

$$N = d_m / d_f * (1/1-\varepsilon) \qquad \text{eq. (1)}$$

whereby the porosity ε is obtained from

$$\varepsilon = 1 - (\rho_b / \rho_f) \qquad \text{eq. (2)}$$

and the bulk density of the matrix

$$\rho_b = (\pi / 4) * L * (d_o^2 - d_i^2) * m_{mx} \qquad \text{eq.(3)}$$

With the density of the fiber $\rho_f = 1{,}400\ kg/m^3$ and the mass of fiber in the design $m_{mx} = 0.614$ kg, a mean porosity of $\varepsilon = 0.966$ is obtained. This results to a number of fibers in the straight flow path of N = 169, i.e. the number of fibers a particle will have to statistically move about before leaving the matrix. Although this value is calculated as a volumetric mean value, it is also referred to as the number for fiber layers, allowing further calculation on the efficiency of the fiber matrix.

3.2 Design of Experimental Setup for Continuous, Steady-state Operation

As a source for a representative DPM exhaust condition, we employed a 6-cylinder, 12-valve Ford diesel engine with a 6.22-liter displacement and maximum engine speed of 1800 RPM. Speed was measured by a bench-dynamometer manufactured in 1970 by Hawker Siddeley Electric Export Ltd. To determine the engine load, a A.C. generator with output of 62.5 KVA, 230 volts, 3 phase, 138 Amperes, and power factor of 0.8 was used. The electric current between the generator and an electrolytic cell was finally measured to determine the actual power release of the engine (Figure 5).

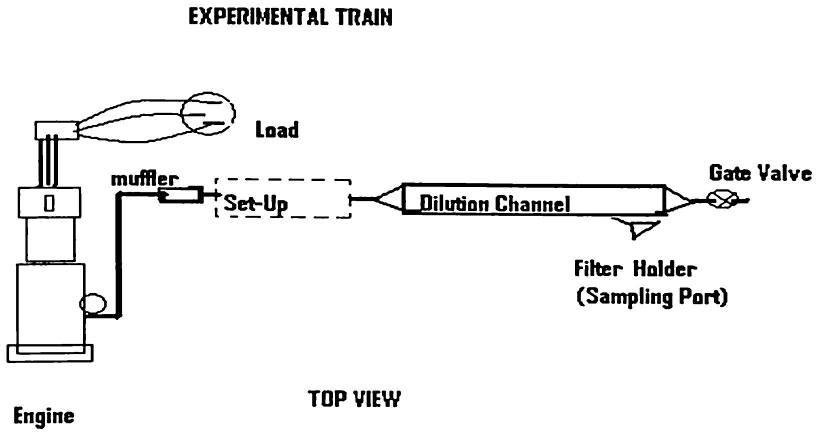

Figure 11. Experimental Train

After the muffler the agglomerator was placed, followed by a dilution channel to allow isokinetic sampling of DPM particles after the agglomerator. Dimensions and the design of the dilution channel can be seen in Figure 6. Exhaust gas flows in laminar flow though the dilution channel with a dilution ratio of 1:20; while the residence time of particles near or at the center of the dilution channel was 0.9 second and 0.7 second at engine speed 900 RPM and 1100 RPM, respectively. Under isokinetic sampling conditions, this also relates to the overall gas velocity in the sampling tube.

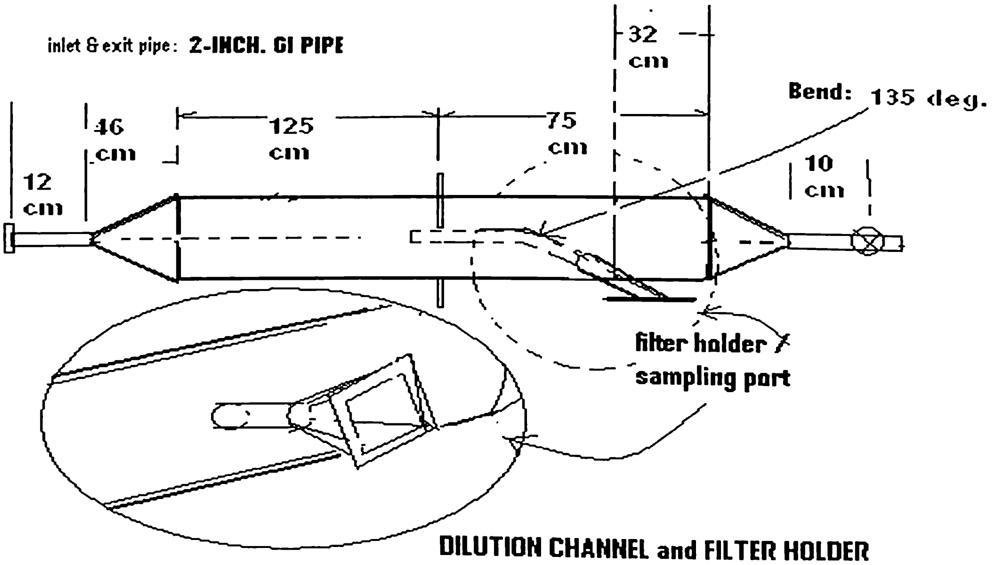

Figure 12. Dimensions of Dilution Channel

To monitor the fluid dynamic conditions, pressure taps were bored along the dilution channel and at a distance equal to twice the diameter of the sampling tube inside the dilution channel. Isokinetic conditions were assumed when the static pressure in the sampling pipe and in the outer dilution channel, measured at the same traveling distance, were identical. To achieve this, a throttle was slightly adjusted at the end of the dilution channel.

At the end of the sampling pipe, a glass filter was mounted on a holder. The type of glass filter used through-out the study was a STAPLEX Type TFAGFS810 Slotted Glass Fiber Filters (8" x 10").

3.3 Agglomerator

Figure 16 shows the three major parts of the agglomerator type used: the outer housing (back), the inner coir cage packed with 400-500 grams of coir (left). Also shown is an secondary cage (right). The latter was not used for tests reported in this paper.

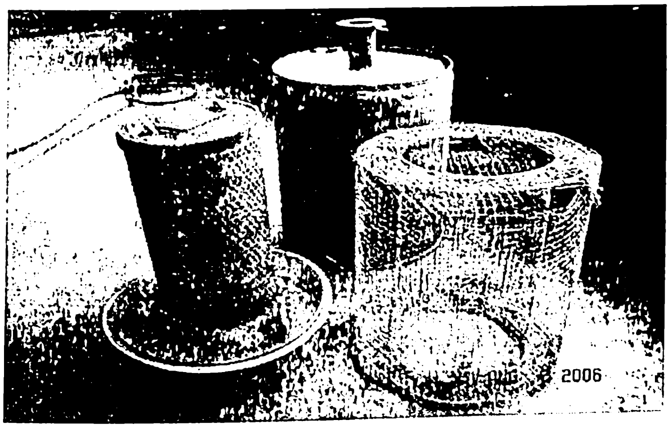

Figure 13. Inner Components of Agglomerator

Figures 15 and 16 illustrate various examples of coir packings used in the tests.

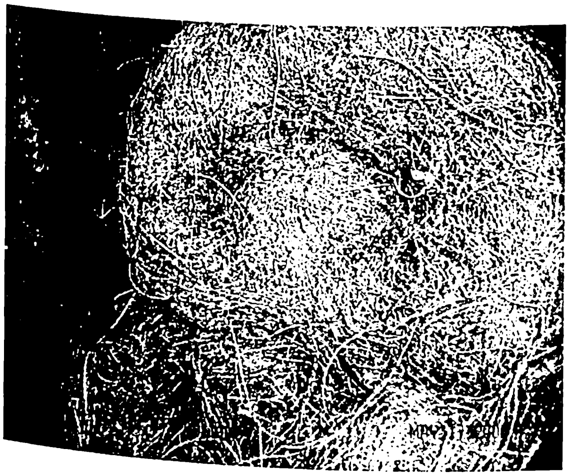

Figure 15. Standard Packing

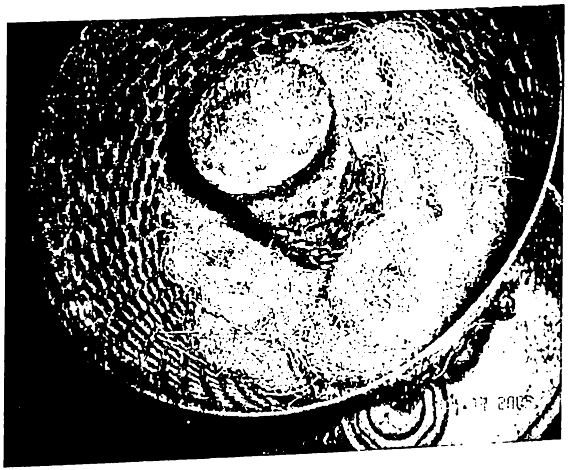

Figure 14. Coilled Coir Packing

Figure 17 shows the test assembly. The agglomerator is positioned directly behind the muffler (left) and immediately before the dilution channel.

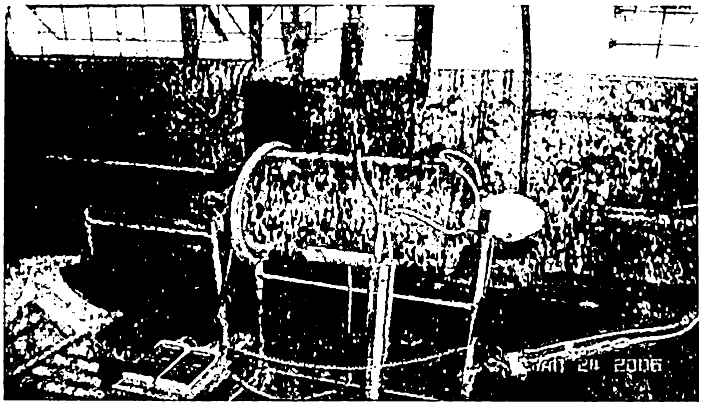

Figure 16. Agglomerator Installed

3.4 Design of Tests

Two engine speeds were considered for the experiments, 900 and 1100 RPM, with varying loads of up to 7.65 kW. The overall run time for 900 RPM was up to 30 minutes while for the 1100 RPM, it was 2 hours.

To determine the efficiency of the agglomerator, three different configurations were employed after the muffler and before the dilution channel:

1. No agglomerator or cyclone is used. The muffler is directly connected to the dilution channel. This relates to the control configuration.
2. The agglomerator was placed between dilution channel and muffler.
3. The agglomerator and a subsequent cyclone assembly is used in the setup

Before each experimental run, the engine was warmed up with the same speed (RPM) for 10 – 15 minutes with load, whereby the load was adjusted during this time to the target value. The current and voltage going through the electrolyte assembly was observed to become stable when the diluted brine solutions started to boil and when the solution level in respect to the electrodes was kept constant by continuously adjusting the height of the electrodes in the brine. Current and voltage readings were taken at constant intervals.

At the end of the warm-up phase, a prepared glass filter was installed at the sampling port and kept until the end of the run. This preparation included placing the glass filter paper in an oven for 1 hour, pre-set at 104 – 110 °C. Thereafter, it was allowed to cool down for 15 – 20 minutes in a desiccator before weighing. For the transport of the glass filter to and from the shop floor the filter was always kept inside an aluminum foil-jacket. After operation, the glass filter was first weighted, then oven dried, cooled down in a desiccator and again weighted. With this, two values were obtained: At first the total sample weight, which would include volatiles, and finally a value for PM2.5, after volatiles have been removed through the oven treatment. Figure 8 shows a photo of a glass filter containing a sample of particulates from one run.

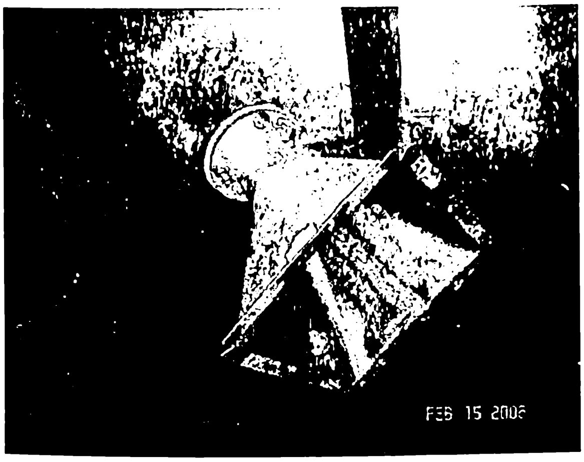

Figure 17. Glass Filter Used

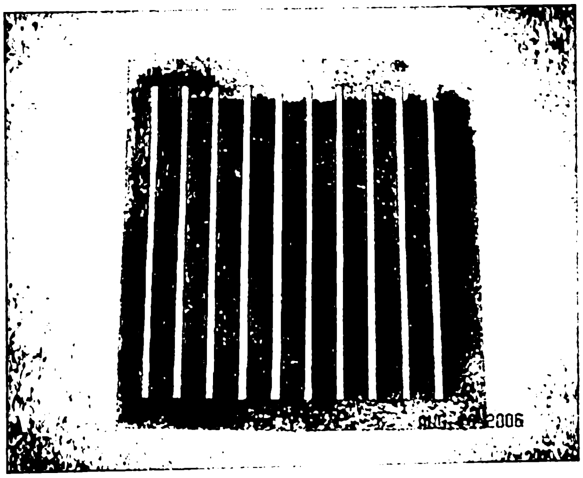

Figure 18. Sampling Filter

4. TEST RESULTS

4.1 Particular Matter vs. Total Deposition

As pointed out earlier, diesel exhaust contains particulates from soot and ash as well as from volatile components. Any deposition will therefore contain both fractions, however, only a non-volatile portion will considered particular matter (PM2.5). To remove the volatiles from the total sample (TS), the filter was oven dried as described above.

In a first step, we studied the fraction of PM2.5 in the sample after going through the agglomerator only. From selected runs, it was observed that this fraction was approx. 95 % and higher at maximum engine loads, whereas for idle and low load runs, it may even be as low as 10 %. As our focus was primarily on the non-volatile particulates, we therefore drew further conclusion on the efficiency of the agglomerator only from runs with maximum engine loads, avoiding misrepresentation of data due to a high content of volatiles in the samples.

4.2 PM Removal through agglomerator

The efficiency of the agglomerator was evaluated based on the portion of PM2.5 that was captured in the first operating hours inside the agglomerator equipped with fresh coir. Although the very idea of the agglomerator is not to function as a filter, but rather release agglomerates after some time to the exit stream for sub-sequential capture in a cyclone, we were able to observe the particle deposition ability of the coir, before agglomerates may be released again into the exhaust.

Results of those runs are given in Table 3 for 900 and 1100 RPM. Since we did not expect agglomerates to be entrained in these experiments, it was not surprising that a subsequent cyclone device did not change the results. It needs to be pointed out that the cyclone's design did not allow particles below 800 nm to be removed from the exhaust stream, therefore excluding the original DPM particles.

Table 3.

Particulate removal in Fresh Agglomerator

Engine Speed	Devices installed	PM	% PM 2.5 Removal
900	Agglomerator + Cyclone	0.0395	76.4
	Agglomerator only	0.0355	78.8
	No device	0.1676	
1100	Agglomerator + Cyclone	0.2456	34.0
	Agglomerator only	0.2799	24.8
	No device	0.3724	

Although it can be seen that PM removal unquestionably takes place, the actual values from representative runs may not been taken as reliable quantitative result. This is particularly the case, when comparing the values for the different engine speeds. It also suggests that at high gas through-put, i.e. higher engine speed, particles may be carried out of the matrix again onto the sampling filter, especially since runs for 1100 RPM were 2 hours instead of 30 min for 900 RPM runs.

4.3 Changes in Fuel consumption

An important aspect for implementing an agglomerator on an operating vehicle is its impact on fuel consumption. Fuel consumption was recorded and compared for runs at 1100 RPM to the value without any additional gadget installed, i.e. direct exit to the dilution channel from the muffler.

Table 4

Changes in fuel consumption for various set-ups

Engine Speed	Devices installed	Engine Load [W]	Fuel [g/min]	Change in Fuel consumption [%]
1100	Agglomerator + Cyclone	7780	64	-1.5
	Agglomerator only	7650	70	7.6
	No device	7440	65	-

With all runs taken at maximum load, no clear changes in fuel consumption can be seen, while also the measured engine power does not change significantly with fuel consumption or changes in the setup. The latter may be very well supported by the fact that the pressure drop of the agglomerator used in these runs is rather low at about 5 mbar and therefore does not pose any significant pressure drop in the exhaust system. However, it is interesting that even the pressure drop in the cyclone, which was around 80 mbar, does not seem to change fuel consumption significantly.

4.4 Temperature within the agglomerator

Another important operational aspect for the agglomerator is its ability to catch fire. As we have pointed out, temperatures should be kept below 200 °C to prevent self-ignition. At low engine speed (900 RPM) the temperature inside the agglomerator did not exceed 80 °C even after 30 min. There are also no significant difference between the two setups, with and without cyclone.

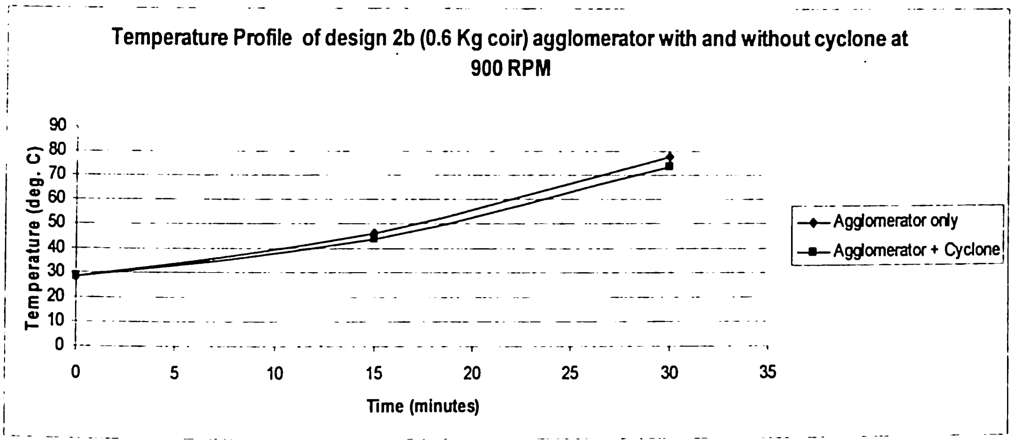

Figure 18. Temperature profile inside the agglomerator for runs at 900 RPM

For higher engine speed (1100 RPM) the temperature profile was very different. Whereas for a run with only the agglomerator the temperature rose to only about 100 °C after 2 hours inside the agglomerator, it reached the design temperature of 200 °C once a cyclone was attached. In this run, the coir matrix finally ignited, as can be seen in the steep slope of the temperature profile at about 38 minutes run-time.

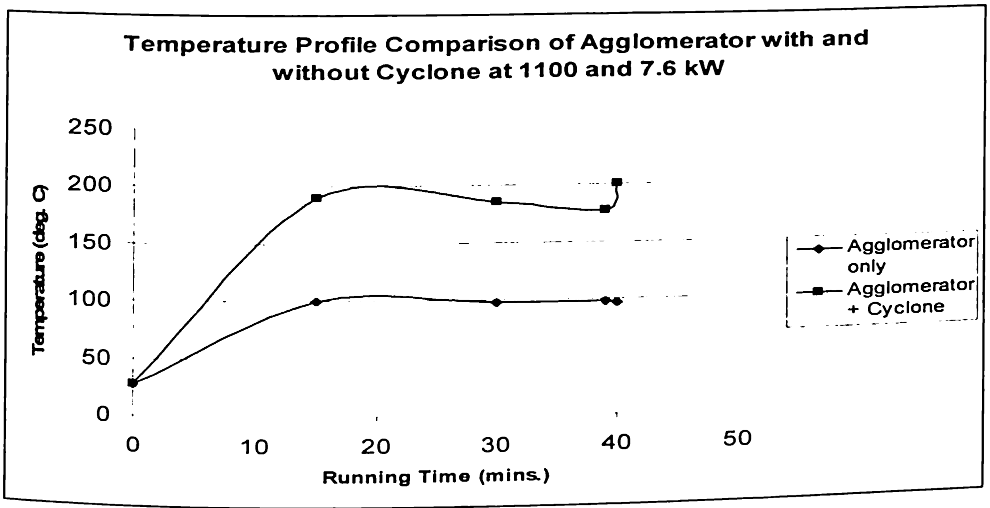

Figure 19. Temperature profile for runs at 1100 RPM

This problem was related to a high pressure drop of the cyclone used, resulting in incomplete exhaust and unburned diesel fuel in the exhaust system. As a consequence, the cyclone setup was changed to a triplex cyclone assembly, which had a much lower pressure drop of about 80 mbar for the 1100 RPM engine speed. With this, temperatures in the agglomerator did not rise above 150 °C allowing safe operation by preventing self-ignition.

5. DISCUSSION OF RESULTS

Due to the difficulty in achieving well reproducible test runs with our setup, our results may be seen primarily as qualitative observations rather than qualitative answers for operational aspects of an coir matrix agglomerator in diesel exhaust.

The first observation is that DPM particle deposition and agglomeration is clearly taking place on the coir fiber. As Figures 7 - 9 point out, DPM deposits on the fiber in particle sizes far below 1 µm. It is also evident by the form of the agglomerates that those must have grown on the fiber rather than being deposited in the size and form shown. However, the extend of particle agglomeration in the exhaust gas before deposition is not entirely clear and also whether this agglomeration in the gas is further supported by the gas flow through the coir matrix. However, the test runs on fresh coir matrix clearly support that PM2.5 particles are being trapped in the agglomerator to a sizable extend.

A significant increase in fuel consumption of the diesel engine due to the additional devices in the exhaust (agglomerator and cyclone) could not be observed. However, as changes for similar setups, i.e. additional muffler, are typically in the range of up to 10 %, our data do not allow a conclusive statements, yet.

Regarding a safe operation we found that self-ignition of the coir can be avoided as long as temperatures in the matrix are kept well below 200 °C. As temperatures relate well with the pressure drop in the cyclone, safe operation can be achieved further by controlling carefully the total pressure drop in the cyclone through proper cyclone design. In our case, this meant keeping the pressure drop below 80 mbar.

6. CONCLUSIONS AND RECOMMENDATIONS

Whereas the principal operation of a DPM agglomerator using coir could be clearly shown, the quantitative effect on using an agglomerator device (possibly with a cyclone) in old diesel engines is still to be carried out. To do so, the following steps need to be taken:

1. DPM measurements should be carried out with certified equipment that would provide an unequivocally conclusion on the performance of the device.
2. For the operation of various diesel engines, a reliable setup should allow reproducible results regarding engine load, engine speed and fuel consumption. Also different operational cycles with varying speeds should be investigated.
3. To allow conclusive results for the very effect of the coir matrix on particle agglomeration, particle size distributions should be carefully measured from both the original diesel exhaust and that after the agglomerator. This will allow to distinguish between larger agglomerated particles that can be trapped easily in a cyclone from those still in the colloidal range (100 – 600 µm). If such measurements are not possible, experiments should be carried out always with a carefully designed cyclone assembly that would ensure that agglomerates are indeed separated from the exhaust stream.

Beyond the actual performance, long term tests should also provide conclusive insights on the operational life span of the coir matrix, as it is expected that the coir will be charred after a certain operating time and possible reducing the stability of the coir matrix. To achieve longer operating time, the stability of the matrix may be possibly extended by treating the coir matrix with silica gel (silicate solution). This effect on operational life and disposition performance should also be studied.

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Nomenclature

Symbol	*Description*	*Units*
N	number of layers of filter	[-]
d_{mx}	matrix thickness	[m]
d_o	diameter of inner housing	[m]
d_i	inner diameter of 2-inch pipe	[m]
ε	porosity of coir fiber matrix	[-]
ρ_f	density of coir fiber	[kg/m3]
ρ_b	bulk density of coir matrix	[kg/m3]
Fv	filter Volume	[m3 or cm3]
d_m	minimum stokes particle diameter	[m]
m_{mx}	mass of coir in agglomerator	[kg]
Stk_{crt}	critical Stokes' Number	[-]
Re	Reynolds Number	[-]
d_f	average diameter of coir based on literature	[m]
ρ_p	particle density	[kg/m^3]
μ	kinematic viscosity of gas at 130 ° C	[Kg/m-s]
v	velocity of gas inside the filter bed	[m/s]
ρ	gas density	[Kg/m^3]

Subscripts, Superscripts and Abbreviations
f =fiber, p=particle, b=bulk, m=minimum, mx=matrix, crt=critical

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