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ORIGINAL ARTICLE

Development of a Novel Spiral Duct Particulate Matter Separator for Internal Combustion Engines

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ABSTRACT – In compliance with the stringent BS-VI emission norms, control of particulate matter in diesel engine exhaust emission is currently achieved through diesel particulate filters, catalytic convertors, and baffle filters of various designs. In the present study a device comprised of a spiral duct with an increasing cross-sectional area over the length is designed and developed. The duct has a lining of heat-resistant and porous material fixed along the inside walls. The inlet of the devices is connected to the outlet of the tailpipe of the exhaust system. The device will collect the particulate matter in the heat-resistant porous lining along the walls of the spiral. The developed device is simple, economical and easily serviceable. The developed spiral duct particulate matter separator was tested on diesel vehicles, and the smoke density of tailpipe emission was measured in terms of the light absorption coefficient. During the analysis it was found that there is a reduction in light absorption coefficient by 25.37%. The developed design also overcomes the clogging problem of the exhaust system, which is a cause of backpressure in the case of conventional particulate filters. The design of the device is such that it can be easily retrofitted in the existing fleet of vehicles, making them compliant with stringent statuary emission norms.

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INTRODUCTION

Tailpipe emissions from an internal combustion engine comprise mainly carbon dioxide (CO2), unburnt total hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x) and particulate matter (PM). In a typical petrol engine vehicle, the major components of harmful tailpipe emissions are CO2, CO and HC, whereas a diesel engine vehicle produces significant quantities of CO2, NO_x and PM [1]. With the increased density of vehicles, high levels of health-hazardous release of NO_x and PM (mainly carbon) as tailpipe emissions have caused health concerns for respiratory and cardiovascular problems [2] [3]. Diesel engines suffer from the disadvantages of harmful pollution causing exhaust, namely NOx and PM which are facing increasingly stringent emission regulations.

Exhaust gases of internal combustion engines normally contain small amounts of particulate materials comprising mostly soot (over 50%) and unburnt or partially burnt fuel/ lubricating oil, fuel-derived sulphates, metal from wear and tear and bound water. Since conventional automotive exhaust systems are not designed to remove particulate matter, most of the particulates are released into the atmosphere [4]. The Bharat VI emission regulations have been implemented since the year 2020, leapfrogging from BS-IV, for the Indian automotive industry. These new emission standards are stringent about the emission of particulate matter from vehicular exhaust. To comply with the BS-VI norms, vehicles will require PM reduction devices like DPF (Diesel particulate filter), catalytic converters, baffle and mesh filters, which have intricate designs. Fitting these devices in new or existing vehicles will increase their cost. [5]. The present state of filters being used for the reduction of particulate matter from the tailpipe emissions of internal combustion engines has severe limitations of creation of engine back pressure due to clogging of filters and entails a cumbersome system of filter regeneration / burn out process, and these drawbacks are recurring in nature thereby increasing the operating costs.

The most commonly used catalytic converter technique for compression ignition engines is the use of the oxidation process. The oxidation catalyst reduces particulates by oxidizing the HC portion of the PM, and the wall maze or a mesh traps the soot and ash constituents. Various experiments on such filters of different designs were researched in the past with varying results. It was found that the effectiveness of these PM filters increased with the increasing size of particles [6]-[9]. Also, it was found that the life of such catalysts is limited by several factors, one of which is that the catalyst bed tends to become plugged or deactivated by the particulate matter contained in the exhaust gas leading to decreased catalytic activity. This also increases backpressure in the exhaust system due to the clogging of such filters. Although the current available catalytic diesel particulate filters claim particulate reduction efficiency of more than 90%, at the same time, experimental studies show problems of reduction in output power by 10 to 15 % at different loads due to backpressure created by accumulated soot in the filter [10]. To overcome the clogging problem of particulate filters, the process of regeneration (oxidation of accumulated soot) has been developed [11],[12]. Various techniques to de-clog through a burnout process are inefficient and make the system quite cumbersome and expensive. Mahadevan et al. [13] conducted experiments mapping the time taken by the regeneration process of a catalytic diesel particulate filter and reported a time taken of 10 minutes for 50% regeneration and de-clogging of the filter. Also, the process of regeneration

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of filters is periodic, requiring extra time and resources and always has the drawback of causing undue back pressure in the vehicle's exhaust till the time of the regeneration process. The cost of catalytic elements and regeneration of filters add substantially to the operating costs of such systems.

The upcoming concept of PM separators using the principle of centrifugal forces is very promising as it eliminates the problem of generation of backpressure in the engine and is mostly maintenance-free. In this kind of PM separators, exhaust gases are made to flow in a circular path inside the separator bringing into play centrifugal forces acting on the gaseous medium along with the particles contained therein. Due to the action of differential inertial forces, the particles follow a different trajectory and get separated from the gaseous flow. The literature shows various experiments and research work in developing such centrifugal particulate separators for vehicular exhaust emission control [14],[15]. It was found that this process was not very useful in the separation of smaller particles. To make the process more effective, different designs were experimented with by increasing the velocity of the gaseous medium, doubling the separation chambers, using refractory alumina to create larger conglomerates, etc. The acceleration of gaseous flow causes a drop in static pressure resulting in the condensation of condensable elements in the gaseous flow. These condensates trap fine particles creating large-sized aggregates which then get separated through centrifugal action [16][17].

All the above-mentioned techniques need a complex design to be fitted at the tailpipe of the vehicle. This not only increases the cost of acquisition but also increases the running cost of vehicles. The present proposed design is simple, with a negligible running cost involved.

DESIGN OF SPIRAL DUCT PARTICULATE MATTER SEPARATOR

The primary objective of the proposed device is to simplify the process of particulate matter control of diesel engine vehicle emission, thereby reducing the operating costs. The device is simple, economical and easily serviceable and is used to control the particulate matter component of diesel engine exhaust emission. Based on the principle of centrifugal forces, the device is capable of removing particulate matter from exhaust gases. Due to the inherent design of the device, the problem of clogging is also eliminated.

Description of Device

The device is fitted in the exhaust system of a diesel engine vehicle through an inlet pipe adapted to be connected between the engine exhaust and inlet (1) of the device. An outlet pipe from the device is connected to the tailpipe of the vehicle's exhaust system (in Figure 1).

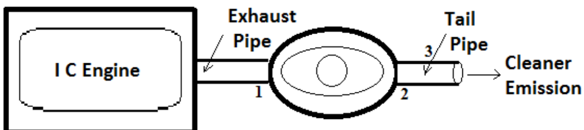

Figure 1. Schematic diagram of the device.

The device design, as shown in Figure 2, comprises a spiral duct. The cross-sectional area of the spiral duct progressively increases over the length from the center to the outlet bend.There is a lining of heat-resistant and porous material fixed along the inside walls of the ducting. Referring to Figure 2, the gaseous flow after entering the spiral duct moves in a circular motion. Because of the circular motion, the paths of the flow of gases and the solid and liquid particulates carried therein are influenced by the centrifugal force. Due to different inertial forces on gas and the particles, the particles flow tangentially to the circular flow of the gaseous medium. The particles, thus separated from the gas, get stuck/collected in the porous linings on the duct walls.

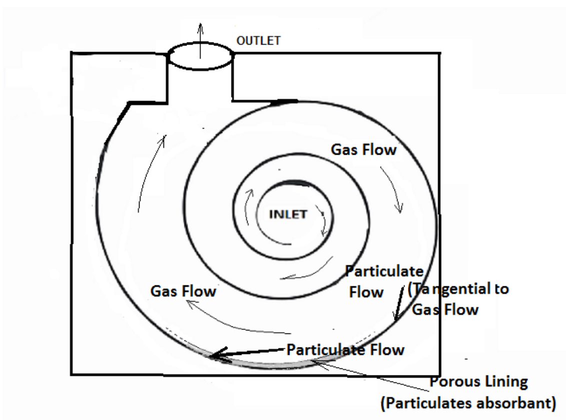

Figure 2. Diagram of spiral duct PM separator.

Principle of Operation of the Device

The above-mentioned behavior of particulate matter under the influence of centrifugal forces has been well defined by two-phase fluid mechanics theory, incorporating particle size, densities and drag coefficients. Assuming a laminar flow, an expression is derived [18] that relates the collection efficiency to the different cyclone parameters and operating conditions shown in Eq. (1).

$$\eta = \frac{\pi N_e \, \rho_P d_P^2 V_g}{9\mu W} \tag{1}$$

where, η - collection efficiency, Ne - effective number of revolutions, ρ_p - particle density, d_p - particle diameter, V_g - gas velocity, W - width of the rectangular inlet.

This model indicates that the particulate collection efficiency is directly proportional to the particle diameter (squared) and particle density, the number of effective vortex turns and the inlet velocity, whereas it is inversely proportional to the inlet diameter. Also, the increasing cross-sectional area of the spiral ducting causes a drop in pressure and temperature of the gaseous medium, causing subcooling and condensation of the condensable components of exhaust gases. The particles carried in the gases act as nucleation sites for condensation. The solid-liquid particle droplets are further segregated from the gaseous flow path. The desired tangential divergence of the flow path of the particulate matter droplets relative to the flow path of gas composition thus removed the same from the gaseous flow and captured effectively at the porous lining of the duct. This expansion of the flow medium is achieved using the concept of a logarithmic spiral as its path. An equiangular spiral, also known as a logarithmic spiral, is a curve with the property that the angle between the tangent and the radius at any point of the spiral is constant. The logarithmic spiral has the following parametrization [19].

$$x(\theta) = ae^{b\theta}cos(\theta) \tag{2}$$

$$y(\theta)=ae^{b\theta}sin(\theta) \tag{3}$$

The distance *r* of a point on this spiral to the origin is therefore: *r(θ)=aebθ*, where *a* and *b* are constants. To achieve the increase in cross-sectional area to double in each rotation, after one full rotation,

i.e.: θ *to* $\theta+2\pi$

i.e.: $r(\theta+2\pi)=2r(\theta)$, and by substituting we get $2=e^{2b\pi} or b=ln(2)/2\pi \approx 0.1103178$. The value of constant a is taken as 0.05 and dimensions of the ascending equiangular spiral for 4 effective turns are calculated in Table 1, and drawn as in Figure 3.

Table 1. Logarithmic spiral (Ascending Equiangular spiral) dimensions calculations (b=0.11, a=0.05).

angle (in deg)	θ (in rad)	$r(\theta)=ae^{b\theta}$	r (mm)	angle (in deg)	θ (in rad)	$r(\theta)=ae^{b\theta}$	r (mm)
0	0	0.05	00.05	750	13.10	0.21	79.72
30	0.52	0.05	20.00	780	13.62	0.22	84.45
60	1.05	0.06	21.19	810	14.14	0.24	89.46
90	1.57	0.06	22.44	840	14.67	0.25	94.77
120	2.10	0.06	23.77	870	15.19	0.27	100.39
150	2.62	0.07	25.18	900	15.71	0.28	106.34
180	3.14	0.07	26.68	930	16.24	0.30	112.65
210	3.67	0.07	28.26	960	16.76	0.32	119.33
240	4.19	0.08	29.93	990	17.29	0.33	126.41
270	4.71	0.08	31.71	1020	17.81	0.35	133.90
300	5.24	0.09	33.59	1050	18.33	0.38	141.85
330	5.76	0.09	35.58	1080	18.86	0.40	150.26
360	6.29	0.10	37.69	1110	19.38	0.42	159.17
390	6.81	0.11	39.93	1140	19.90	0.45	168.61
420	7.33	0.11	42.30	1170	20.43	0.47	178.61
450	7.86	0.12	44.81	1200	20.95	0.50	189.20
480	8.38	0.13	47.46	1230	21.48	0.53	200.43
510	8.90	0.13	50.28	1260	22.00	0.56	212.31
540	9.43	0.14	53.26	1290	22.52	0.60	224.91
570	9.95	0.15	56.42	1320	23.05	0.63	238.25
600	10.48	0.16	59.77	1350	23.57	0.67	252.38
630	11.00	0.17	63.31	1380	24.10	0.71	267.35
660	11.52	0.18	67.07	1410	24.62	0.75	283.20
690	12.05	0.19	71.04	1440	25.14	0.79	300.00
720	12.57	0.20	75.26				

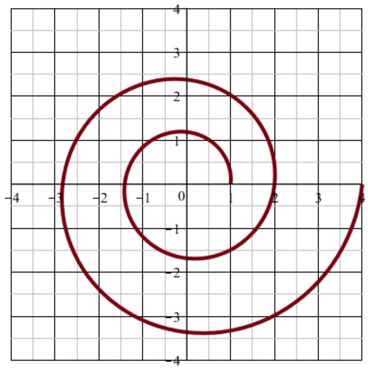

Figure 3. Construction of spiral.

Dimensions of the Device

The dimensions of the device are listed in Table 2. The outermost width of the device is limited to a maximum of 600 mm to make it suitable for retro fitment in the vehicle. The spiral dimensions for four effective turns are calculated by taking the outer diameter of the spiral as 600 mm as shown in Table 1 above. The dimensions of the device are shown in Figure 4.

Table 2. Device dimensions.

Dimension	Units (mm)
Outer diameter	600
Inlet diameter	40
Outlet diameter	40
Height of spiral	50

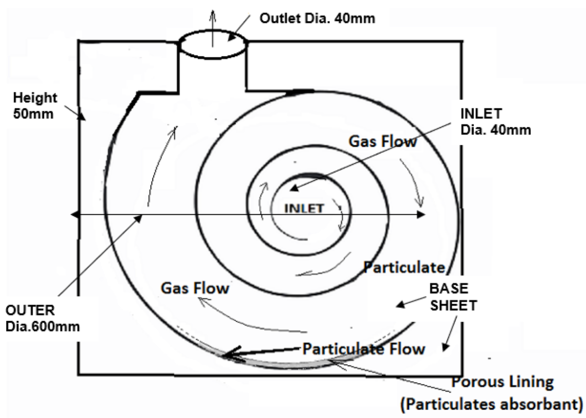

Figure 4. Dimensions of the device.

FABRICATION OF THE SPIRAL DUCT DEVICE

Commercial exhaust pipes are usually made of mild carbon steel with a dip coating of aluminum. The material used for the fabrication of the prototype for testing purposes is mild steel. A 50 mm wide MS strip of 1 mm thickness is arc welded on a 1.6 mm thick sheet in an expanding spiral. The maximum outer diameter of the spiral is 600 mm (Figure 5). A glass wool fiber lining, 50 mm wide, is fixed vertically to the outer walls of this spiral path as shown in Figure 6. The density of the fabric used is 0.3 kg/m^2. The spiral ducting of the device is sealed with another MS sheet of 1.6 mm using packing gasket, as shown in Figure 7. This cover sheet is securely tightened using a set of 5 sets of nut-bolts arrangements. Inlet and outlet round pipes of 40mm diameter each are also arc welded at the designated places as per design. Figure 8 shows the final assembled spiral duct particulate separator device.

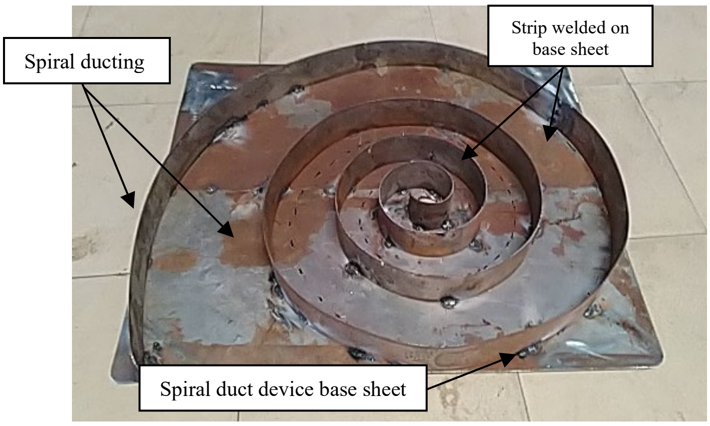

Figure 5. Fabrication of the spiral duct.

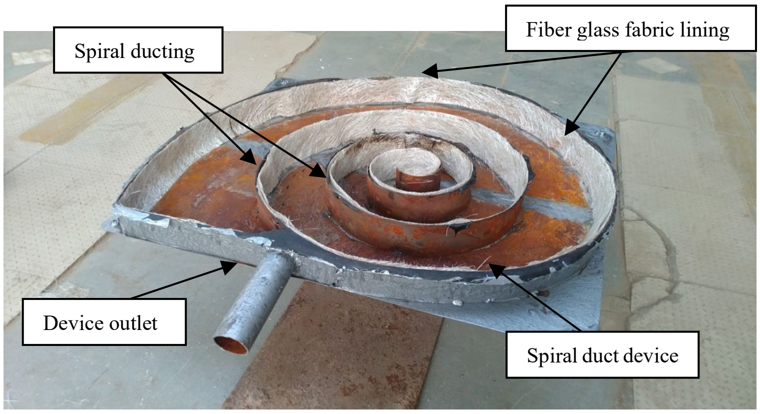

Figure 6. Fiber glass lining fitted in the spiral duct.

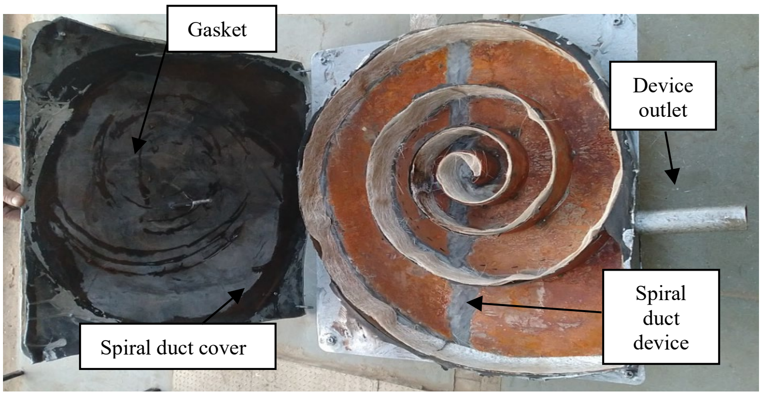

Figure 7. Device cover with gasket.

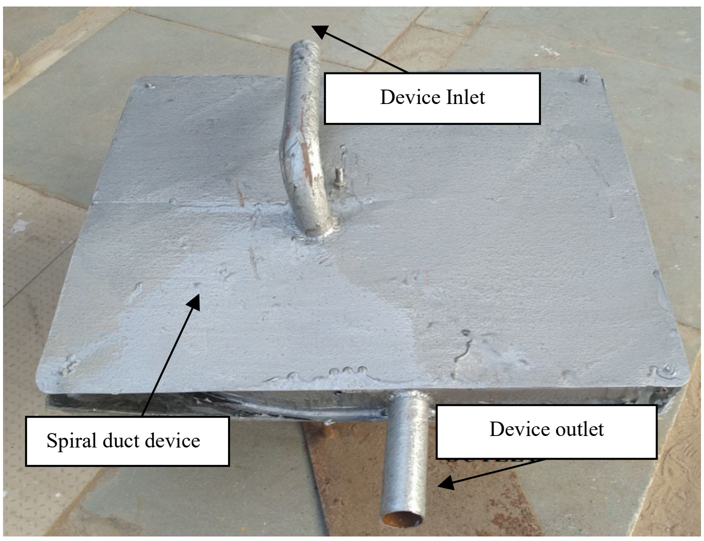

Figure 8. Assembled spiral duct device.

EXPERIMENT SETUP AND METHODOLOGY

The spiral duct device is tested at a government-authorized pollution checking center for diesel vehicles using a smoke meter. The smoke meter essentially measures the reduction in the intensity of light detected by a receptor when light travels through a gaseous medium and determines the opacity N (%) and the light absorption coefficient k (m^{-1}) of the medium. The light absorption coefficient is measured as per ARAI regulations using Govt. of India Ministry of Road Transport and Highways portal online PUC application [20]. The online PUC portal is available at the website www.vahan.parivahan.gov.in for the use of authorized personnel. The device is tested on five different Maruti Suzuki Ertiga cars with specifications detailed in Table 3. The smoke meter specification are detailed in Table 4 and the temperature measuring device specification is provided in Table 5.

Table 3. Test vehicle specification.

Engine type	D13A (DOHC)
Fuel type	diesel
Number of cylinders	4
Bore	69.6mm
Stroke	82.0mm
Piston displacement	1248 cm^3
Compression ratio	17.6 ($\pm$0.4) :1

Table 4. Specifications of smoke meter.

Model number	AVL437
Display	Digital
Heating time	5 min
Measuring range	0 – 100 HSU (Hatridge smoke unit)
Smoke temperature	250 0C maximum
Ambient temperature range	0 – 50 0C
Humidity	90% at 500C
Principle	Light absorption
Power supply	AC 240V

Table 5. Temperature measuring instrument specification.

Temperature range	-58°F to 572°F (-50°C to 300°C)
Temperature accuracy	±0.5°C from 0 to 100°C
Probe length	3.8" stainless steel probe
Display	digital

METHODOLOGY

The subject vehicles are tested before and after the fitment of the spiral duct device by the smoke meter. The inlet pipe of the developed spiral duct device is connected to the exhaust tailpipe of a test vehicle using a flexible metal pipe and the probe of smoke meter is led into the outlet of the spiral duct device for taking the measurements as shown in Figure 9.

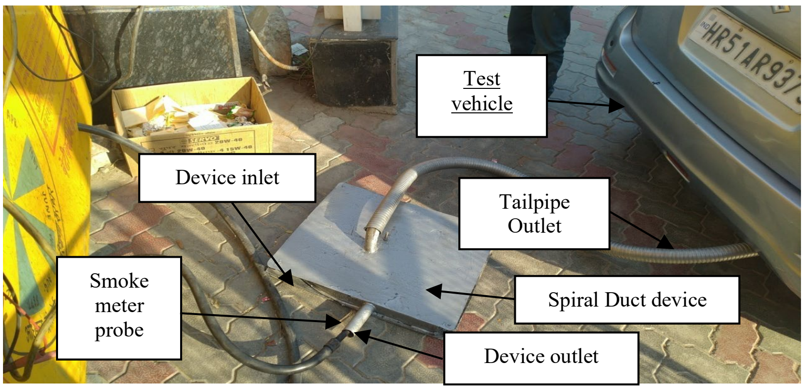

Figure 9. Exhaust emission measurement with device.

The measurement of exhaust emission of a diesel vehicle with the smoke meter is done by connecting the tailpipe to the inlet probe of the testing equipment. A sensor device to record the RPM of the engine is fitted to the vehicle. Using the MORTH online PUC application, the registration number of the subject vehicle is recorded, and the online software self-populates all the registration details of the vehicle like engine number, chassis number, and year of manufacturing. The measurements are taken under free acceleration test conditions on a warmed-up engine. The reading is taken three times by accelerating the engine to 2000-3000 rpm each time. The online system, based on the inputs, calculates the light absorption coefficient measurement of the exhaust emission of the test vehicle. The maximum permissible limit under the emission norms is 1.62 [20].

RESULTS AND DISCUSSION

The sample vehicles were tested for tailpipe emission, and the measured light absorption coefficient was recorded. A total of 25 sets of measurements were taken, five each for every vehicle. Each vehicle was first measured without fitting the device and then the device was fitted in the tailpipe of the vehicle and retested by putting the smoke meter probe in the outlet of the device. This procedure was repeated for five sets of measurements for each of the five vehicles. The measured values before and after the fitment of the spiral duct device are tabulated in Table 6 and Table 7 for each vehicle.

Table 6. Light absorption coefficient measured values without device (in m^{-1}).

Vehicle	Sample1	Sample2	Sample3	Sample4	Sample5	Avg.
V1	1.01098	0.77566	1.01368	1.23929	0.83479	0.97489
V2	1.34014	1.05118	1.39499	0.93689	1.19984	1.18460
V3	1.32858	1.28958	1.34934	1.51881	1.39710	1.37667
V4	1.24357	1.48594	1.48182	1.29102	1.25045	1.35056
V5	1.38399	1.33536	1.29589	1.35125	1.37453	1.34820

Table 7. Light absorption coefficient measured values with device (in m^{-1}).

Vehicle	Sample1	Sample2	Sample3	Sample4	Sample5	Avg.
V1	0.74821	0.56903	0.80526	0.90970	0.61781	0.73000
V2	0.99211	0.78254	1.03865	0.66951	0.78388	0.85334
V3	0.98286	1.03166	0.91947	1.21505	1.11768	1.05334
V4	0.99486	1.28635	1.23466	0.92048	0.88036	1.06334
V5	1.01335	0.82685	0.87351	0.97000	1.09962	0.95667

The average of measured values as shown in Table 6 and Table 7 are tabulated in Table 8. It also highlights the reduction in smoke density as measured in terms of the light absorption coefficient achieved with the use of the developed spiral duct particulate matter separator device.

Table 8. Average LAC values (m^{-1}) and reduction achieved with device.

Vehicle	Avg. w/o	Avg. with	Reduction%
V1	0.97489	0.73000	25.11978
V2	1.18460	0.85334	27.96406
V3	1.37667	1.05334	23.48606
V4	1.35056	1.06334	21.26667
V5	1.34820	0.95667	29.04139
Average	1.24699	0.93134	25.37559

The reduction of smoke density of various test vehicles varied from appx. 21% to 29 %, with an overall average of 25.37 %. The average light absorption coefficient is calculated as 0.93134, which shows a reduction of 25.37% in the smoke density of the exhaust emission with the use of the novel spiral duct particulate matter separator. Table 5 reflects the consistency of the operation of the developed device showing average values of measured values for each vehicle without and with the device. It was observed that the novel spiral duct particulate matter separator device was able to reduce the temperature of the exhaust gaseous medium by about 30.92% on average due to its characteristic design causing expansion of the medium.

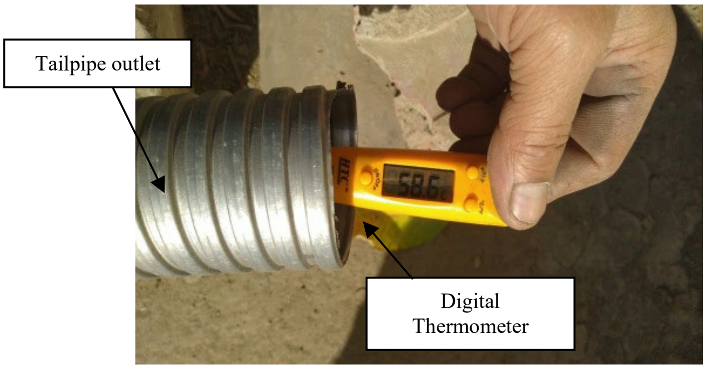

Figure 10. Temperature measurementat outlet of tailpipe.

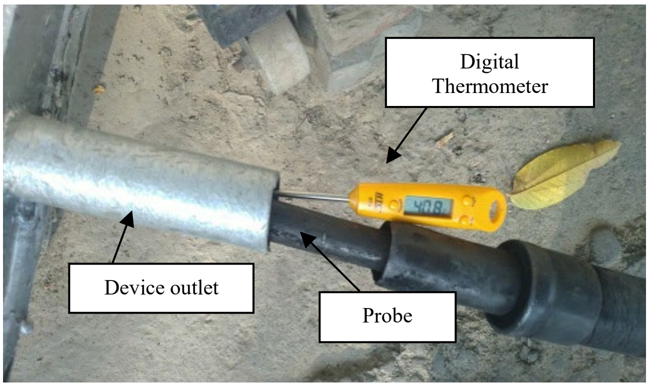

Figure 11. Temperature measurement at outlet of spiral duct device.

The temperature of the exhaust gases at the vehicle's tailpipe outlet/inlet of the spiral duct device when fitted to the tailpipe is measured as well as at the device outlet as shown in Figure 10 and Figure 11. The results are tabulated in Table 9 and drawn in Figure 12 for each vehicle.

Table 9. Temperature measurement results.

Vehicle	Inlet temperature (°C)	Outlet temperature (°C)	Reduction (%)
V1	58.6	40.8	30.37
V2	54.7	40.3	26.32
V3	56.6	37.6	33.56
V4	55.3	38.9	29.65
V5	66.0	43.1	34.70
Average	58.24	40.14	30.92

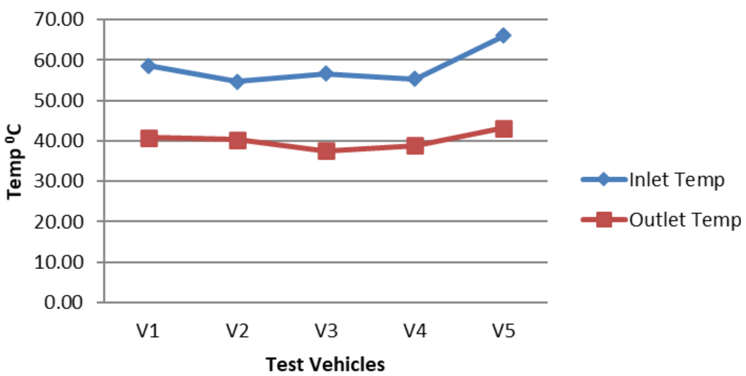

Figure 12. Vehicle-wise temperature measured values.

This 30.92% reduction of temperature in exhaust emission gaseous medium has been achieved due to a drop in pressure in the device, which further facilitates in condensation of water vapors present in the exhaust gas. The nucleation of the liquefiable substance occurs in the form of drops having a relatively large diameter and the aggregates from the carrier flow are separated by the effect of inertial forces exerted. Such systems are capable of removing micron and submicron size particles without causing an undue pressure loss in the overall gas flow. These condensates form heavier conglomerates increasing the collection efficiency of the device.

CONCLUSION

In the present research, a novel device, the spiral duct particulate matter separator, is designed and a prototype is developed. The problem of clogging and back pressure creation in the tailpipe during the particulate filtration as reported in conventional filters is also inherently eliminated due to its unique design. This device is capable of removing PM from an internal combustion engine exhaust in a simple, economical and easily serviceable manner. The developed design was tested on five vehicles having 4-cylinders 1248 cc diesel engine, and the experiment result indicates a reduction in smoke density of their exhaust emission by 25.37%. Due to its compact and sleek size, this device can also be easily retrofitted in the existing fleet of vehicles, making them compliant with stringent statuary emission norms.

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