Feasibility Studies on Two Different Analytical Techniques of Measuring Soot Emissions from a Power Generating Set

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Abstract: ***This research focused on developing simple, reliable and cost-effective methods for the determination of the amount of soot being emitted daily in to the atmosphere from the combustion of fossil fuels. This was with the view of monitoring the level of environmental pollution or the impact assessment of soot emission on the environment. Two novel methods, A and B; based on the principle of adsorption on paper and liquid, both from a timed-running diesel and petrol-powered generating sets were used respectively. The difference in the weight of the adsorbed paper was expressed as the weight of the emitted soot. The results obtained showed that between 1-5 hours, the amount of soot ranged from 1.7587± 0.1425 to 3.2260 $\pm$ 0.1231g for method A and from 0.1342$\pm$0.0606 to 0.5822$\pm$0.0322g for method B respectively. Though the mass of soot in method B was generally found to be much lower than that in method A, method B may not be said to be ineffective because gasoline, the fuel on which method B generator was run, produces less black carbon or soot as compared to a diesel engine of method A obviously because of the lesser number of hydrocarbon chains in premium motor spirit as compared to automotive gas oil. On the whole, the results obtained from both methods were not only highly significant but were also cheap, simple and would encourage further method development.***

Keywords: Soot, Adsorption, Environment, Pollution, Fuel

1. Introduction

Soot, also called lampblack or carbon black, is a slightly sticky, fine black to brown powder formed through incomplete burning of fossil fuels and is found clinging to things like chimneys and exhaust pipes, walls and even in the back of cooking pots for those using wood as their source of fuel. For soot to be formed or generated, an object most relatively be burnt at a low temperature with a reduced supply of oxygen.

The continuous emission of soot in to the atmosphere on daily basis and across the globe is now a cause of serious concern to environmental scientists. This is no thanks to the harmful effects of soot emissions which include; greenhouse effect (CO_2 and CH_4), primary and secondary air pollutants, production of nitrogen oxides (NOx) through high-temperature combustion processes, impurities of heavy metals and sulphur in the fuel resulting in by-product combustion and other products of incomplete combustion, including carbon monoxide (CO), particulate matter (PM) and hydrocarbons (HCs)

Though soot has some important applications like its use in the vulcanization process to treat rubber, it is also used in a wide range of pigment, paint, and dye products, ranging from crayons to fine ink for fountain pens, in cosmetics, or as part of camouflage paint. It is also used in toners for laser printers and copiers. The demerits of soot emission however outweighs the merits overwhelmingly as compounds from soot, particularly sulphur dioxides and nitrogen oxides, combine with moisture to form acid rain which worsens water quality. It damages soil and crops, and changes nutrient balances in various ecosystems.

According to the international civil aeronautics organisation (ICAO) report (2013), commercial air traffic has steadily increased in the past in terms of passenger revenue kilometres and the trend continues with an estimated annual growth rate of 3.4 – 6.1 %. The emitted particulate matter (PM), mainly soot, is of special interest because it alters the Earth's radiation budget by absorbing and scattering solar radiation. Soot, particularly diesel exhaust pollution, accounts for over one quarter of the total hazardous pollution in the air [1]. Among these diesel emission components, particulate matter has been a serious concern for human health due to its direct and broad impact on the respiratory organs. The size of those tiny particles is directly linked to the terrible trouble they cause. Particles smaller than a speck of dust, and less than 1/30th the width of a human hair, can easily pass through the nose and throat, penetrate and embed in the lungs, and enter the blood stream. The smallest particles cause the largest amount of damage because they can penetrate furthest into the lungs and in some cases react directly with DNA.

It was further opined by Omiduarborna; *et al*, [2] that health professionals associated PM_{10} with chronic lung disease, lung cancer, influenza, asthma, bronchitis, many other respiratory illnesses and increased mortality rate. However, recent scientific studies suggest that these correlations be more closely linked with fine particles ($PM_{2.5}$) and ultra-fine particles ($PM_{0.1}$) and further added that long-term exposure to urban air pollution containing soot increases the risk of coronary artery disease [3].

With these serious consequences of continuously emitting soot into the atmosphere, this research looks at two different, novel and locally fabricated and designed methods for measuring the amount of soot emitted since most of the already established and used instruments are highly specific, automated and expensive. Environmental monitoring and air pollution research in Africa and most developing countries are less common because of the attendant problems of instrumentation and high cost.

2. Literature/Theoretical Underpinning

In Nigeria, much attention is given to general industrial pollution mostly from soil and water or pollution from oil industries. Not much is done in air with reference to pollution from generators and mobile transportation sources [4, 5, 6, and 7]. In other studies, only casual references are made to the gravity of the problem of pollution from these emission sources [8, 9]. The situation of increased pollution from mobile transportation source and power generating sets is on the increase in per capital vehicle/generators ownership, thus resulting to high increase in the concentration of pollutants in the air, consequently increasing health risk on human population.

The atmosphere surrounding the Earth is a mixture of gases. In some places, human activities have added other gases to the atmosphere, which are called pollutants. Most of the gases are produced by the burning of fuel in the combustion chamber of automobiles. The burning of fuels releases a large amount of carbon dioxide into the atmosphere. This is thought to cause global warming. Other pollutant gases which are released into the air when fuels are burned include carbon monoxide, sulphur dioxide and nitrogen dioxide. The incomplete combustion of fuels also releases small particles of solids, such as carbon into the air. These particles and gases released, inadvertently raises the concentration of these gases above what it should be in clean dry air. The rise in the concentration of these gases in the atmosphere play major roles in impacting ill-effect on the health of humans, animals, plants, infra-structures and on the environment in totality. Carbon monoxide for instance, is toxic and can lead to death [10].

2.1 Sources of Soot Emission

The power to move a car comes from burning fuel in an engine. Pollution from cars comes from the by-products of this combustion process via the exhaust and from evaporation of the fuel itself [11].

2.1.1 Evaporative Emissions

Hydrocarbon pollutants also escape into the air through fuel evaporation. With today's efficient exhaust emission controls and today's gasoline formulations, evaporative losses can account for a majority of the total hydrocarbon pollution from current model cars on hot days when ozone levels are highest.

2.1.2 Residential Sources

Nearly half of the world's population lack access to modern energy, relying on burning solid fuels including wood, charcoal, agricultural residues, dung and coal in open fires or rudimentary stoves for cooking and heating. These stoves are often operated indoors, where smoke pollution exposure can be extremely high without adequate ventilation. Women and children are particularly at risk since they typically spend more time indoors in close proximity to the stove. According to the U.S. EPA, [12] globally, approximately 21% of BC emissions are from residential solid fuel use for cooking and heating in the developing world. As economies develop and access to cleaner fuels expands, the proportion of people depending on traditional solid fuel combustion for cooking and heating is projected to decrease, although the overall total is likely to increase due to population growth.

2.1.3 Transport Sources

Transport is typically the largest source of soot emissions in developed countries. It contributes a lower (but growing) share of total soot emissions in developing countries where per capita vehicle ownership has historically been relatively low [13]. Globally, approximately 55% of transport-related BC emissions are from on-road diesel engines, 31% from off-road and 7% each from on-road gasoline engines and shipping. BC emissions are projected to rise in developing countries due to growth in the transport sector [14, 15]. Because emissions from diesel combustion contain few cooling co-pollutants, controlling emissions from diesel engines appears to offer the highest potential for reducing near-term warming of all the BC mitigation options available [13]. The most common vehicle emission control measures are a diesel particulate filter (DPF) in the exhaust tailpipe or diesel oxidation catalysts. DPFs are widely used in developed countries and have substantially reduced both PM2.5 and BC emissions (although they may only modestly reduce fuel efficiency). However, the effectiveness of DPFs depends on the use of low-sulphur diesel fuel, which is generally not widely available or used in many developing countries [12]. In addition, older vehicles with poorly-maintained engines common in developing countries limit the potential effectiveness of technical emission tailpipe control strategies. Many tailpipe and non-technical emission control measures (such as vehicle registration, inspection and maintenance, technology certification/verification programs) may be less effective in developing countries that lack the necessary infrastructure [12].

2.1.4 Industrial Sources

The main industrial sources of soot emissions, including brick kilns, coke ovens (mainly from iron and steel production), industrial boilers, and oil and gas flaring, contribute around 20% of total soot emissions [12]. According to Clean Air Task Force, [16] burning fuels in traditional, small-scale brick kilns is a significant source of air pollution in many developing countries [17].

2.1.5 Agriculture and Open Burning Sources

According to U.S. EPA, [12] open biomass burning contributes more to global soot emissions than any other sector, affecting nearly 340 million hectare per year. Furthermore, this sector also relies on use of wildfires and prescribed burns for purposes such as ecosystem, pest and disease management. Satellites have observed the extent of forest and biomass burning activity around the world, including the "arc of deforestation" in Brazil, Central America (e.g. Yucatan Peninsula), southeast Australia, southern Africa and southeast Russia.

Table 1: Main sectors contributing to global soot emissions and their share of total emissions

Source	*Description*	Shear of total emissions
Open biomass burning	Natural wildfires and anthropogenic forest fires, grassland fires, and burning of agricultural waste.	36%
Residential cooking, heating and lighting	Burning of solid fuels (coal and biomass) in open fires or rudimentary stoves for cooking and heating, as well as kerosene lanterns for lighting; woodstoves for space heating in developed countries.	25% (of which 4% is from woodstove in developed countries.
Ort	Diesel engines used in on- and off-road vehicles(including heavy-duty and light-duty trucks, construction equipment and farm vehicles); gasoline engines, including cars and motorcycles; ships and aircraft.	19%
Industry	Stationary sources, including brick kilns; iron and steel production; thermal power generation plants; industrial boilers; gas flaring.	19%

2.2 Black Carbon and Climate Change

Black carbon (BC) has recently emerged as a major contributor to global climate change, possibly second to CO_2 as the main driver of change [18]. Black Carbon particles strongly absorb sunlight and give soot its black colour. BC is produced both naturally and by human activities as a result of the incomplete combustion of fossil fuels, bio-fuels, and biomass.

BC is a primary aerosol emitted directly at the source from incomplete combustion processes such as fossil fuel and biomass burning and therefore much atmospheric BC is of anthropogenic origin [18].

BC warms the climate in two ways. When suspended in air, BC absorbs sunlight and generates heat in the atmosphere, which warms the air and can affect regional cloud formation and precipitation patterns [18]. When deposited on snow and ice, it absorbs sunlight, again generating heat, which warms both the air above and the snow and ice below, thus accelerating melting. Climate effect will dissipate if BC emission is reduced.

Different types of soot contain different amounts of BC- generally the blacker the soot, the more of a warming agent it is. Fossil fuel and bio fuel soot are blacker than soot from biomass burning [19]. Control technologies that reduce Black Carbon include retrofitting diesel vehicles with filters to Capture Black Carbon, fuel switching (e.g. from diesel to natural gas in buses), and replacement of inefficient cook stoves with cleaner alternatives. Adopting these alternatives would have Positive co-benefits for public health especially in developing world.

Soot may cause adverse health effects following exposure through inhalation, ingestion or thermal contact. Soot acts as a carrier for various toxic substances, like polycyclic aromatic HCs and heavy metals which causes Carcinogenic and Cardiovascular diseases, (Cardiac arrhythmia and heart failure often leading to death). High level of exposure most especially in children leads to Respiratory diseases such as asthma, bronchitis, chronic cough, sinusitis and colds [20].

2.3 Air Quality Index

AQI is an index for reporting daily air quality in the United States US EPA, [21] It gives information on how clean or polluted the air is, and what associated health effects might be of concern for individuals. The AQI focuses on health effects individuals may experience within a few hours or days after breathing polluted air.

The AQI runs on a yardstick of 0 to 500. The higher the air quality index (AQI) value the greater the level of air pollution, and the greater the health concern. For example, an AQI value of 50 represents good air quality with little potential to affect public health, while an AQI value over 300 represents hazardous air quality [21]

Table 2: Air quality index value and the level of health concern according to US EPA [21]

QIA Range	Air quality condition
0-50	Good
51-100	Moderate
101-150	Unhealthy for sensitive group
151-200	Unhealthy
201-300	Very Unhealthy
301-500	Hazardous

2.4 Emission standards

Table 3: Nigeria ambient air quality (NAAQ) standard according to [22]

Pollutants	Av time	Limits
PM	1hr	250µg/m3
SO_2	1hr	0.01ppm
	24hr	0.1 ppm
NO_2	1hr	0.04 ppm
	24hr	0.06 ppm
CO	1hr	10ppm
	8hr	20ppm
HC	3hr	0.6ppm

3. Materials and Methods

Two methods were adopted for this research which are as follows;

3.1 Method A

A fabricated metal (basket-like) was firmly fixed to the exhaust of a diesel engine generator (JMG. P220H_2) generating set. The white paper was soaked in ground nut oil then dried in an ADAM PW124 model oven at 35^0C for three hours. Thereafter, the dried paper was weighed and then fixed to the closed end of the fabricated metal attached to the exhaust of the generating set at a distance of 40cm. The generating set was switched on and allowed to run for an hour, the amount of soot emitted which adhered to the pre-weighed paper was carefully detached from the exhaust. The detached paper and content was then weighed again using the same analytical balance. The difference in weight was expressed as the amount of soot emitted. The procedure was repeated for two, three, four, and five hours each in triplicates and the results obtained were recorded.

Plate 1: Fabricated apparatus for Method A used to trap emissions from generator

3.2 Method B

In this procedure, a fabricated cylindrical metal tube was firmly fixed to the exhaust of a two- stroke engine, a tiger-brand model generating set. The other open end of the tube was placed 10cm just above a 250ml half-filled beaker with distilled water. The generating set was switched on and allowed to run for an hour and the amount of soot emitted was collected over water in the beaker. The soot and water mixture were then filtered using a pre-weighed Filtron qualitative circle filter paper. The filtrate was then air dried for twenty-four (24) hours and then weighed again using the same (ADAM PW 124) analytical balance. The difference in weight was expressed as the amount of soot emitted. The procedure was repeated for two, three, four, and five hours each in triplicates and the results recorded. These methods were non-standard but were only developed for the purpose of this research, and for easy measurement of emitted soot.

Plate 2: Fabricated apparatus for Method B used to trap emissions from generator

4. Results and Discussion

Table 2: Amount of soot emitted with time and volume of fuel used

Time (Hours)	Soot Emitted (g) Method A	Soot Emitted (g) Method B
1	2.2778±0.2247	0.1342±0.0606
2	1.7587±0.1425	0.3196±0.0705
3	1.8301±0.0922	0.3911±0.0081
4	2.5572 ± 0.1103	0.4613±0.0036
5	3.2260 ± 0.1231	0.5822±1.322

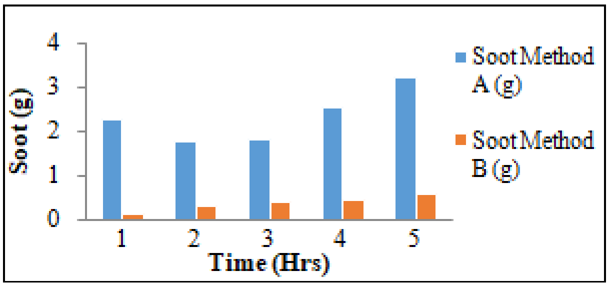

Figure 1: Bar chart of soot Emissions

Table 4 and Figure 1 are the tabular and graphical representation of the various weights of soot obtained from methods A and B. In method A, the quantity of black carbon emitted ranged from 1.7587±0.1425g to 3.2260 ± 0.1231g while method B ranged from 0.1342±0.0606g to 0.5822±1.322g. In both methods, the general trend was a positive correlation between the amount of soot emitted and the time of running the generating set in hours. Thus, as the number of hours of running the power generating set was increased, the quantity of the emitted soot also increased.

However, there was a significant difference between the amount of soot emitted in method A and that of B. While more of the soot was collected in method A, much less was collected from B. In all the observations, the quantity of soot emitted in method A was approximately five times that emitted from B except the observation at one hour of measurement where the difference was as much as twenty times. The increased amount of soot emitted from method A was however not unexpected as diesel-powered engines produced more carbon than gasoline-powered engines due to a higher incomplete combustion rate because of the increased number of carbon chains in diesel oil.

As regards efficiency, it should not be inferred that method A was better than method B based only on the amount of carbon collected. As we have seen, the choice of fuel has a vital role in the amount of carbon black or soot emitted. Furthermore, the age and mechanical state of the different engines could have a contributory effect on the quantity of emission. A new and sound engine would be more efficient and invariably have low emissions while the converse is true for an old and less efficient engine.

5. Conclusion

Soot measurement using any of the proposed methods (A and B) was quit feasible, reliable and would not cost a fortune to carry out. In this study, the quantity of soot emitted by the diesel engine, power generating set (JMG P220H-2) between 1-5 hours of operation was found to be in the range of 1.7587±0.1425g to 3.2260 ± 0.1231g while that from the Tiger brand, gasoline, power generating set was in the range of 0.1342±0.0606g to 0.5822±0.0322g.

Though with method A, more soot was collected or measured than B, its efficiency over B could however not be inferred because method A was with diesel fuel while method B was with gasoline or premium motor spirit, this burns more than the former.

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6. Other Recommendations

Further research is recommended in the following areas;

1) The method B could be repeated with the same diesel engine as A so that the results compared in order to draw inferences on their efficiencies.
2) There is the need to use flow meters for the characterization or separation of gases from the generator exhaust. This may enable for the spectroscopic determination of the actual amount of black carbon or soot.
3) With regards to the factors affecting physical adsorption (adsorption of gas on solid), substances with higher adsorptive capacity, greater than that of an ordinary paper, like the whatman No 1 filter paper should be used.
4) The adsorbent to be used should be activated by making the surface area of the adsorbent rough basically to increase the Capacity of adsorption.
5) The engine should be allowed to cool down very well before restarting for results consistency.
6) Time and nature of the engine should be considered for results accuracy.

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