MATEC Web of Conferences **405**, 03006 (2024) https://doi.org/10.1051/matecconf/202440503006
ICASMMT 2024

Experimental Analysis of Diesel Engine Performance and Emissions with the Integration of Cyclonic Separator Device

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Abstract. The high population density and demographic dynamics have triggered a boom in the uptake of larger and more fuel-efficient diesel goods vehicles because diesel is cheaper than gasoline. Nevertheless, availability of diesel engines has lead to an increase of pollution especially in the urban area. This research examines whether a cyclonic separator which is an attachment device mounted on the vehicle exhaust system can sufficiently reduce particulate emissions from diesel engines. Thanks, the cyclonic separator is used to gather particles of size from 1μm to 50μm, to control the emission of diesel exhaust pollutants. Although we find that the utilization of the device decreases the pollution emission, our study shows that the installation of the device causes backpressure leading to a marginal reduction in thermal efficiency of between 0.8% to 1.01%. Nevertheless, the cyclonic separator can be considered one of the possible means to solve the problem of reduction of emissions of diesel engines and protect urban environment from pollution.

1 Introduction

Over the last few decades there has been a shift in the transport system throughout the world popularized by rising number of vehicles. This has been occasioned by population growth and expansion and urbanization, resulting to an ever increasing demand for personal and commercial cars. Of these, diesel-powered goods vehicles have become most preferred mainly because of its fuel economy and because diesel is cheaper than gasoline. While this trend has undoubtedly contributed to economic growth and improved logistics, it has simultaneously given rise to a pressing environmental concern: increasing pollution concentrations, particularly in over populated cities or even towns.

While the use of diesels helps consumers' pocket, it has led to a significant increase of particulate emissions. These emissions; fine particulate matter and aerosols are known to

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have adverse health impacts on populaces in urban settings and have negative impacts on air quality in cities globally. According to Kittelson, diesel particulate matter is composed of solid and liquid particles which are in the size range of ultrafine particles which are most dangerous as they can enter the lungs in humans [3].

There has been a realization in various studies to call for the reduction of diesels emissions. For example, Pope and Dockery found close relationship between fine particulate matter and morbidity and mortality rates in the Urbana [2]. In addition, this exposure has been rated by the World Health Organization (WHO) as cause carcinogenic to human (IARC, 2012) thus underlining the importance of developing measures to reduce exposure to diesel particles.

There are many strategies put forward in the last few years to control unsafe emissions specially diesel particulate. Diesel Particulate Filters (DPFs) hold lots of potential and Johnson reports that filtration efficiency for particle mass ranges from 90% and above [3]. However, DPFs have some drawbacks like the need for regeneration and maybe slight reductions in fuel economy. Fuels blends and engine alterations have also been studied; biodiesel blends have been found to contribute to cut down particulate emission [4].

This study focuses on another promising solution: the cyclonic separator. This new gadget in the form of an attachment – mounted at the end of the exhaust pipe for engines using Diesel as fuel – is being proposed to filter out particulate emissions before they hit the air. Cyclonic separation method is not new, this technology has been used in air pollution control appliances for some decades now [5].

More precisely, the cyclonic separator deals with particles with a size of 1 to 50 microseconds, which accounts for a major portion of the emissions of diesel engines. This range will also be especially important as it is generally held to encompass the respirable fraction of particulate matter, which is most hazardous as observed by Oberdörster et al., in their review of the effects of nanoparticles and nanostructured materials [6].

Our study aims to establish the efficiency of the cyclonic separator in eliminating particulate emissions, and as a feasible intervention to address the pollution issue resulting from diesel vehicles within cities. From testing, we analyze not only the ability of the device to capture particles but also the effect of the same on the engine. Such an approach enables us to determine the cyclonic separator's feasibility as a practical solution that optimizes vehicle operation and minimizes its impact on the environment.

First observations show that although the cyclonic separator produces a good reduction of pollutants in emission gasses, its integration provokes a minimal rise in backpressure within the exhaust system. This results in a little back pressure, in which thermal efficiency is found to drop by a maximum of 0.8 to 1.01 percent. These outcomes echo other analyses of exhaust after-treatment devices, for example the work done by Millo et al. on the effects of DPFs on engine performance we found comparable efficiency losses [7].

However, this comes at a very small compromise on the power of the engine, whereas the cyclonic separator reduces particulate emissions by a large extent, the cutter makes a powerful argument for the use of this technology to curb air pollution in cities. This seems to agree with the literature review carried out by Reşitoğlu et al. which envisages the use of various strategies in emissions abatement from diesel engine [8].

The increasing rate of vehicular traffic that has become the hallmark of most cities around the world has compounded the problem of environmental degradation by providing numerous pollutive sources. The solutions provided including the cyclonic separator present the cities of the world with a way through which the effects of economic development can be managed without polluting the environment [9-10]. Therefore, this study seeks to present a comprehensive assessment of the cyclonic separator's suitability which would enhance the flow of valuable information for the discussion of the sustainability of urban transportation and control of air pollution.

Hence by extending upon the existing literature and introducing a distinctive method to Particulate matter reduction, this work aims at furthering the knowledge on Emission control technologies and real life case applications. The conclusions discussed herein are rather important for the development of environmental policy and urban planning as well as for the automotive industry on its way to finding better solutions for sustainable transport.

2 Materials and methods

2.1 Diesel engine set up

This study utilizes a standard diesel engine with the given specifications and performance characteristics and it will also ensure the engine is calibrated and in good working condition before the experimental phase. Cyclonic separator is designed and fabricated as per the designs shown in this paper and integrated with a diesel engine. Ensured the proper fitting and compatibility with the engine's outlet system. After installation the cyclonic separator in the exhaust line outlet of the engine will allow the effective particulate separation.

Instrumentation employs a comprehensive set of sensors and instruments to measure engine parameters. These key parameters include engine speed, torque, and fuel consumption rate, exhaust gas temperature and pressure differentials across the cyclonic separator. Data Acquisition system implements a data acquisition system to collect the real time data from the sensors to ensure the synchronization of the data acquisition with engine operating parameters.

Experimental design establishes a baseline by running the diesel engine without the cyclonic separator to capture the standard performance and emission characteristics. The second experiment will be with cyclonic separator in the same manner and capturing the performance and emissions. Emission analysis employed an exhaust gas analyzer to measure the concentrations of oxides of nitrogen (NO_X), carbon monoxide (CO) and other relevant emissions parameters in the exhaust gas. It will also collect the samples of particulate matter and analyze the particulate emissions.

Performance testing dynamically assesses the engine's performance by measuring the output, thermal efficiency, and specific fuel consumption. This also monitors the combustion stability through in-cylinder pressure measurements. Data is analyzed statistically to identify the trends and quantify the impact of cyclonic separator on engine performance and emissions. It will also be compared with the results with the baseline date to evaluate the effectiveness of the cyclonic separator.

The experiments were conducted multiple times to ensure the repeatability at least three times and the average will be considered. These results are also supported by the related literature or some theoretical frameworks. Through careful application of these materials and methods the further objective of the study is to give an accurate estimation of the cyclonic separator beneficial in improving the performance and emissions of the diesel engine and can pave the way for further improvement in using sustainable engine technologies.

2.2 Design of cyclonic separator

The cyclonic separator shown in the following figure is designed to fulfill the task of gathering particulates in the exhaust of a diesel engine. The process is operational in this respect whereby the dust laden gas stream enters the cyclone barrel in a rotary fashion. This specific entry imposes a spiral flow pattern onto the gas particles within the gas stream after it has left the strut. During the gas flow through the cyclone barrel, the particulates have a tendency to follow the walls of the barrel pursuant to the centrifugal force occasioned by the circular motion. Then they descend along the conical part of a cyclone and arrive at the bottom end of the cone where collection of the separated particles occurs. The conical structure provides the force of gravity whereby the particulates are drawn to the bottom then have a central dust outlet. At the same time the rotating gas traces a trajectory along the wall up to the vertex of the conical frustum. Nevertheless, in the center of the cone examined above, the direction of the gas flow is opposite. The gas then prefers to bubble out through the cyclone gas outlet tube which is at the tip of the cone. This positioning makes it possible that the gas together with the particulates will be removed from the cyclone at two different ports. To sum up, the methods used in cyclonic separator include centrifugal force and settling chamber to collect réal part.and the side part is collected by the gas stream. These swirling motions that are caused by the tangential entry of the gas stream into the cyclone barrel and hence providing the basic mechanism for the separation process thus providing a dust outlet where particle accumulations can be made, and a gas outlet tube at the apex of the cone where cleaned gas can easily escape.

When designing a cyclonic separator, there are several critical parameters that must be considered most especially trapping or collection efficiency and the pressure drop across the cyclone. These two aspects however are central mostly and other factors are usually related to these two. One of the important characteristic dimensions of the cyclone is the inlet width; the first decision that needs to be made during the design process. This is done by the aid of an empirical efficiency expression. The parameter, therefore, lies within the particle size, at which the trapping efficiency tends to half of the maximum value called $d_{0.5}$ given in Eq. 1. In other words, this empirical formula provides estimation of the cyclone inlet width, which is one of the important parameters affecting the general efficiency of the separator. In light of the understanding gained from Rosin, Rammler, and Intelmann, engineers can optimize the design so as to optimize the trapping or collection efficiency, so that a considerable number of particulates are captured. In effect, trapping efficiency, pressure drop and Rosin Rammler Intelmann empirical efficiency expression is the conceptual framework on which the cyclonic separator is built on. These factors altogether enhance the performance and utility of the separator in relation to the innovative requirements of trapping and s separation of particles from the gaseous phase.

$$d_{0.5} = (9u_e \; B_e 2H_c / 2\pi N_s V_e \big(\rho_\rho - \rho_e\big) \; (1)$$

The given equation has some fundamental design parameters of cyclonic separator, such as dynamic viscosity of exhaust gas (μc), Inlet width of the cyclone (Be), height of cyclone inlet (He), effective number of turns by the stream (Ns), volume flow rate of the exhaust gas (Ve), density of particulate in the gas (ρp) and density of exhaust gas (ρe). The inlet height (He) is traditionally fixed on twice the inlet width and other dimensions are related to standard ratios. This equation is also adopted in the method of measuring the pressure drop which is a very sensitive parameter in measurement of the cyclonic system efficiency and performance. With these equations, designers will be in a good position to design the dimensions and characteristics of the cyclonic separator to enable it perform its role of separating the particles from the exhaust gas efficiently. For this study, a cyclonic separator has been carefully built to capture particles with sizes up to 3 μm to suit the exhaust system of a Kirloskar 7 kW single cylinder diesel engine of a constant speed. The construction of the cyclonic separator incorporate 1.25 mm thickness aluminum sheet metal. The main features of the designed cyclonic separator, which define its performance characteristic, are illustrated in the following figure. This customized separator is proposed to improve the capability for collecting the particulate matter, focusing on the exhaust features of the particular layout of the diesel engine.

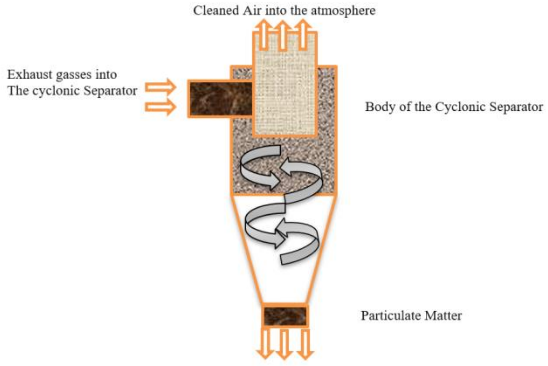

Fig. 1. Cyclonic Separator and its components

2.3 Experimental work

The experimental set up used for testing the performance of the designed cyclonic separator is shown schematically in the figure. Without attaching the cyclonic separator to the exhaust system, the engine was run at a constant speed of 1500 rpm at different load conditions. The fuel consumption and back pressure on the engine were measured. Modern sophisticated particulate measuring devices are now available to determine the size and mass of the particulate emission from diesel engines. The engine exhaust was bubbled through water in the collecting vessel as in the figure. The particulate matter gets separated and retained in water. The contents of the collecting vessel after passing the exhaust gas for a definite period of time almost 30 minutes was transferred to a separate vessel and preserved for analysis later. To determine the particulate mass, the water was then filtered using a standard filtering apparatus. After filtering, the filter paper along with the particulates was carefully transferred to an oven maintained at a constant temperature of 105^{o}C. After drying for about an hour, the filter paper along with the particulates was removed from the oven, cooled to room temperature and weighed to determine the mass of particulates. The cyclonic separator was then fitted to the exhaust system and the same procedure was repeated to determine the mass of the particulates and the back pressure when using the separator at the different loads. The trapping efficiency of the cyclonic separators is calculated using the expression, where m is the total mass of the particulates entering the cyclone and m is the mass of particulates leaving the cyclone.

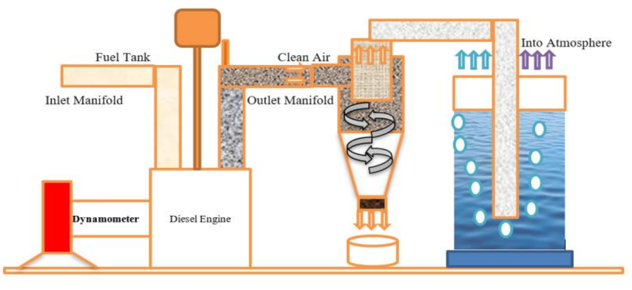

Fig. 2. Experimental Set up fitted with cyclonic Separator

3 Results & Discussion

The experimental results involve comparison of the diesel engine performance with and without integration of cyclonic separator through various factors including brake power, fuel consumption, brake thermal efficiency, back pressure and particulate mass emissions. The following section analyzes these results in detail in relation to the graphical data presented in this paper.

On figure 3, brake power can be seen against the load. In line with expectations, brake power is found to grow with the increasing loads on the engine due to the rise in fuel inlet with increasing loads. The highest brake power observed was 7.128 kW at maximum load 12 kg irrespective of the cyclonic separator. It became apparent that the brake power level is not affected by the presence of the separator – the device does not hinder the ability of the engine to produce power in relation to load conditions. This result underscores the fact that the cyclonic separator has relatively little effect on the mechanical characteristics of the engine, meaning that backpressure imposition does not have a disruptive effect on the generation of power.

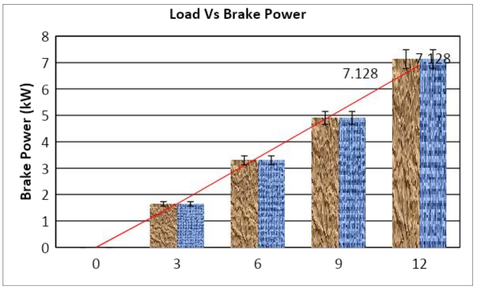

Fig. 3. Load vs Brake Power

The variation of fuel consumption in relation to load is depicted in figure 4. With a corresponding increase in load, fuel rate rises in a manner typical of operation of a diesel engine. When the cyclonic separator was not used the fuel rate at maximum load (12 kg) was 1.958 kg/hr and when the cyclonic separator was in use the fuel consumption was a little lower 1.763 kg/hr. This is due to the increase of back pressure by the cyclonic separator though it has a small effect on combustion efficiency. The rise in the levels of fuel consumption underlines the importance of the actual fuel-to-air mixture and emissions regulation, as the separator causes restriction of flow of exhaust gases requiring extra fuel.

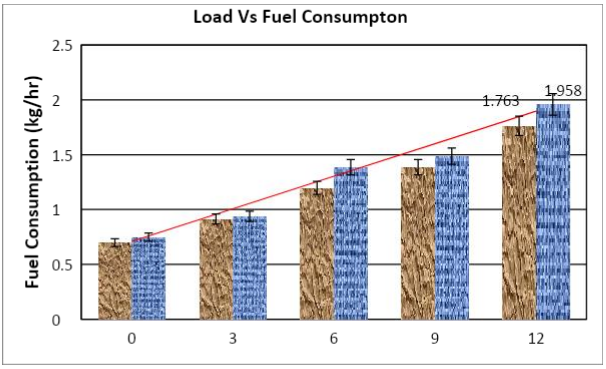

Fig. 4. Load vs Fuel Consumption

The BTE is presented in Figure 5 by load. The BTE improves with load and reaches the maximum value of 32.16% at the non-separating case; 30.12% at 12 kg load at the use of a separator. The cause of the 2.04% difference in BTE when using the cyclonic separator is the increase in back pressure and therefore; reduced efficiency of the engine in converting fuel to useful work. This decrease in efficiency is one major demerit of a cyclonic separator to stress that while it enhances the emission levels reduction it also decreases the engine efficiency. However, since shorter apart distances mean lower emissions of particulates, which is detrimental to the environment, this may be acceptable for pollution sensitive locations.

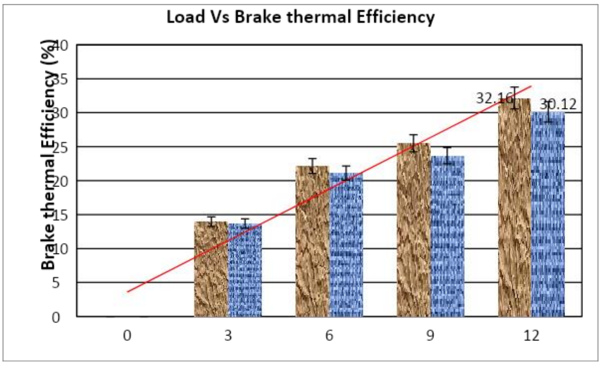

Fig. 5. Load vs Brake Thermal Efficiency

Figure 5 shows a relative relationship between back pressure and load. There is only a slight increase in back pressure from 1.01bar to 1.06bar for increase in load without cyclonic separator. But at the same time as soon as the cyclonic separator is installed the back pressure increases to 2.13 gm/kW-hr at the maximum loads compared to 0.68 gm/kW-hr without a separator. This shows a significant rise in back pressure implying that the exhaust of the engine is restricted by the separator thus increasing the resistance of the exhaust system of the engine. It also provides more back pressure, which leads to a slightly lower thermal efficiency and fuel consumption rate mentioned above. This finding is expected since the exhaust treatment devices such as the cyclonic separator typically raises the back pressure.

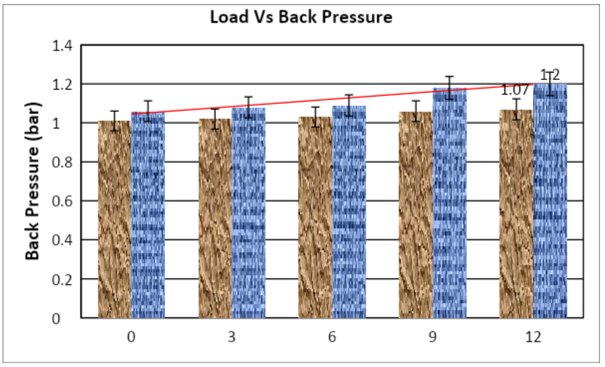

Fig. 6. Load vs Back Pressure

As it can be seen in figure 7, there exists a negative relationship between particulate mass and load. With increase in load, the particulate mass reduces, this could probably be as a result of better combustion at higher loads. With the integration of the cyclonic separator, remarkable reduction of total solid is achieved from 2.13 gm/KW-hr to 0.68 gm/KW-hr, thereby giving 1.45 gm/KW-hr reduction. This result proves the efficiency of the cyclonic separator in the reduction of particulate emissions and validates the integration of the cyclonic separator in the reduction of diesel engine pollutants. The decrease in particulate emissions is most effective in areas where the quality of air is known to be politically incorrect, that is, in cities.

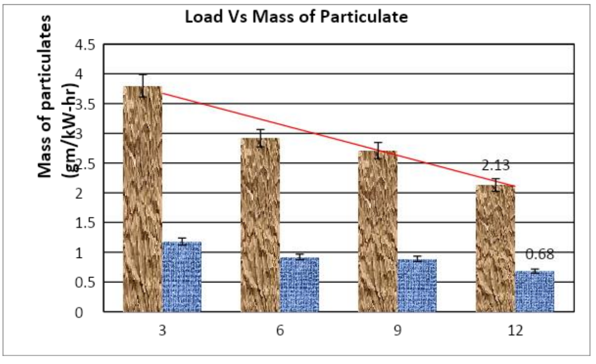

Fig. 7. Load vs Mass of Particulate

4 Conclusion

The integration of a cyclonic separator in the diesel engine significantly reduces particulate emissions, enhancing environmental performance. However, the separator introduces a notable increase in backpressure, leading to slight reductions in brake thermal efficiency and increased fuel consumption. Despite these drawbacks, the environmental benefits, particularly in emission reduction, underscore the potential of the cyclonic separator as a valuable tool in the quest for sustainable diesel engine technologies. Future work could focus on optimizing the separator's design to minimize back pressure while maintaining high particulate trapping efficiency.

- Maximum brake power of 7.128 kW was achieved at a load of 12 kg, unaffected by the cyclonic separator.
- The cyclonic separator reduced fuel consumption from 1.958 kg/hr to 1.763 kg/hr at maximum load, despite causing increased backpressure.
- Brake thermal efficiency dropped by 2.04% (from 32.16 to 30.12%) when using the cyclonic separator due to higher back pressure.
- Backpressure increased significantly from 1.06 bar to 2.13 gm/kW-hr with the cyclonic separator, indicating restricted exhaust flow.
- The cyclonic separator effectively reduced particulate emissions from 2.13 gm/kW-hr to 0.68 gm/kW-hr, highlighting its strong impact on emission reduction.

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