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Research paper

Soot Particulate Emission from A Single Cylinder Direct Injection Diesel Engine

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Abstract

Soot formation, which occurs mainly because of imperfect combustion, affects engine. Engine components tend to wear hence reduce engine performance. In the present study, soot particle collection and analysis was carried out in a relatively simple and low-cost method. The first objective is to identify the level of opacity percentage of the soot at different engine speeds and loads. The second objective is to obtain the mass of soot using Alkidas theory. The last objective is to measure and obtain the size of soot particles. The opacity was measured using a Bosch Gas Analyser and soot particles from the engine were simultaneously collected using TEM grids inserted into the exhaust manifold. Alkidas's correlation was used to convert soot opacity to soot mass. The TEM instrument was used to produce images of the collected soot particles and at once, enable the measurement of the size of the particles. The results from this study shows that, soot opacity and mass emitted increase as the engine speed and load increase. It was observed that soot particle size become smaller at higher engine speeds and loads. From TEM image analyses, the range of size of soot obtained is 26 nm to 84 nm.

Keywords: *diesel engine; opacity; soot mass; soot size; TEM*

1. Introduction

Deterioration of air quality is due to uncontrolled air pollution such as from vehicle emissions. The causes of the pollution are primarily emissions from internal combustion engine which currently affect a number of countries that are now experiencing the global warming problem [1]. An advantage of using diesel fuel is less fuel consumption compared to gasoline for the same power output while a disadvantage is that the smoke produced has an unpleasant smell and a dark black color. According to Reitz [2], the fuel injected into the gas tank of the vehicle is typically consumed in this way: about 18% of the supplied energy is used to move the car, 62% by losses sustained by the engine and exhaust and 20% to turn on vehicle accessories. However, diesel engine emits dangerous gases such as soot, nitrogen oxides (NOx). sulfur oxides (SOx) and also noise pollution [2].
Soot generally is a solid consisting of about eight carbon and one part of hydrogen [3]. The information related to the size of the soot particles play a crucial role because the size influences the types of wear that occur in the engine's components [4]. Researchers, designers and manufacturer conducted a study to identify the content and composition of soot, soot formation process, as well as the properties of the soot, like its size and mass. The formation of soot in the engine causes wear on the components. Soot produced in the cylinder may attach to the cylinder wall where it will be pushed by the piston rings into the crankcase [5,6] and at the same time will cause degradation of lubricating oil in the crankcase [7].
In the present paper, analysis of soot opacity using Gas Bosch Analyser and soot particles size and agglomeration behaviour using TEM at different loads and engine speeds was carried out with the aim to further understand soot particle formation and emission in a diesel engine.

2. Methodology

This experiment requires several important equipments. Examples of the instruments used are dynamometer, dynamometer controller, diesel engine Yanmar TF90 and Bosch Gas analyser as shown in the schematic diagram in Figure 1.
The opacity of soot obtained from the exhaust of the engine was measured using Bosch gas analyser. Meanwhile, soot particles were collected using a TEM grid and were later projected on a TEM instrument for imaging. Measurement of soot particle diameter was performed using software that comes with the TEM instruments. Diameter of detected primary particles were measured and averaged for size analysis.

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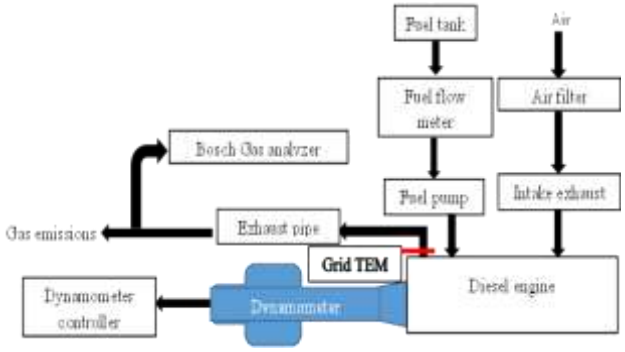


Fig. 1: Diesel engine emission measurement system

Figure 2 presents the flow chart of the experiment which shows the full cycle of the tests performed in the study.

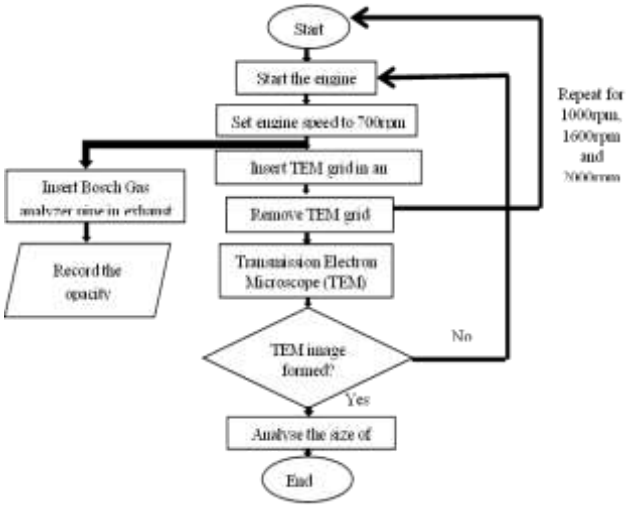


Fig. 2: Flow chart of the experiment

The correlations proposed by Alkidas [8] and Homan [9] were used to change the opacity of soot to mass of soot (mg/m^3).

The value of opacity is converted to soot mass applying equations in (1) and (2) [8,9];

$$Bn = Op \times 10 \tag{1}$$

and

$$m = v \times 581.4\left[\ln\left(\frac{10}{10\text{-}Bn}\right)\right]^{1.413} \tag{2}$$

where Bn is Bosch number (in the range of 1 to 10), Op opacity value in percentage (%), m mass of soot (kg) and v cylinder volume (m^3) at EVO which, in this case v = 0.000478 m^3.

3. Results and Discussion

Figure 3 shows that the percentage of soot opacity increases when the load is increased at every engine speed while Figure 4 shows the opacity increases as the engine speed increases. In other words, the opacity of the soot is affected by the engine speeds and the load applied. Similar results were reported by Elango and Senthilkumar [10] in which the opacity of the exhaust increases as the load increases. This is thought to be due to poor volatility and improper mixture of fuel droplets at high loads.

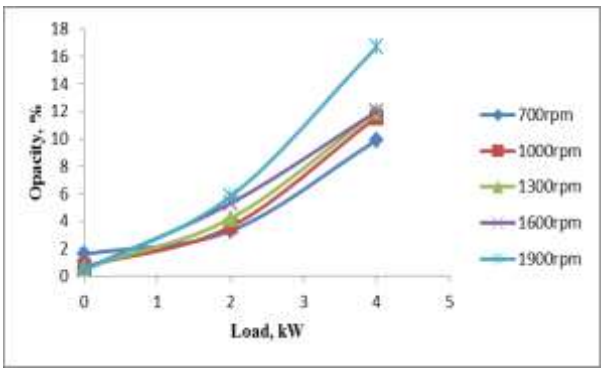


Fig. 3: Profile of opacity against load

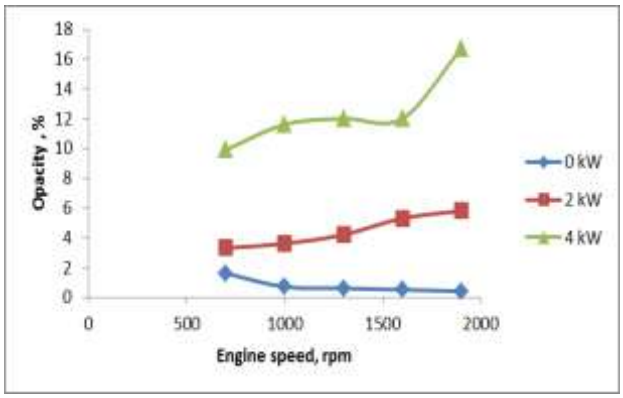


Fig. 4: Profile of opacity against engine speed

Figure 5 indicates that the engine speed affects the torque of the engine. Increasing the engine speed will increase the engine's torque. For instance, when the engine speed is 700 rpm at 2kW load, the torque is 3.3kN while at 4kW, torque is 9.7kN.

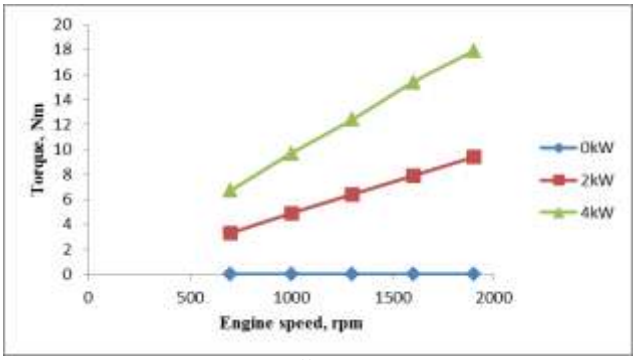


Fig. 5: Torque at different speeds and loads

Figure 6 shows the brake power against engine speed. At 4 kW and 2 kW load, the power increases when the engine speed increases. This tallies with the theory stated. However, the power is uniform at 0 kW load. This is because the torque in this state is 0 Nm. This fact can be proved also in Figure 5 in which the engine speed at 0kW not affected or change with torque. To conclude, the power will only increase when there is a load applied on the engine.

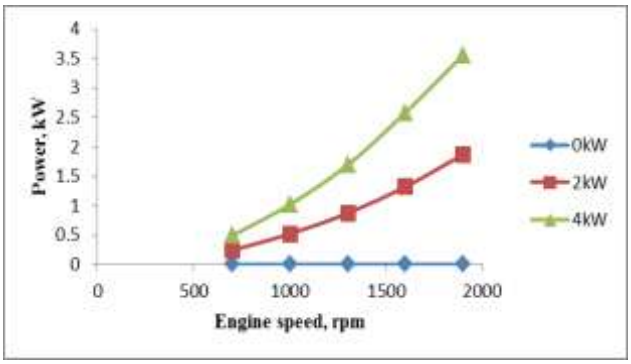


Fig. 6: Power at different speeds and loads

Figure 7 indicates the relationship of soot mass with engine speed. The soot mass calculated with Alkidas correlation [8] increases with increasing engine speed. From the figure, the mass of soot at 0 kW load slightly decreases with increasing engine speed. The mass is low at this load because the present of opacity was very little as shown in Figure 4.

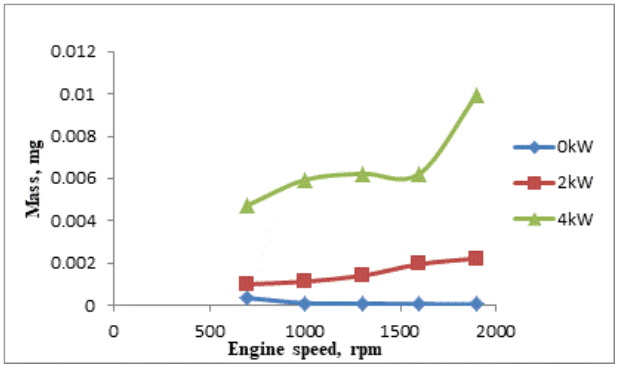
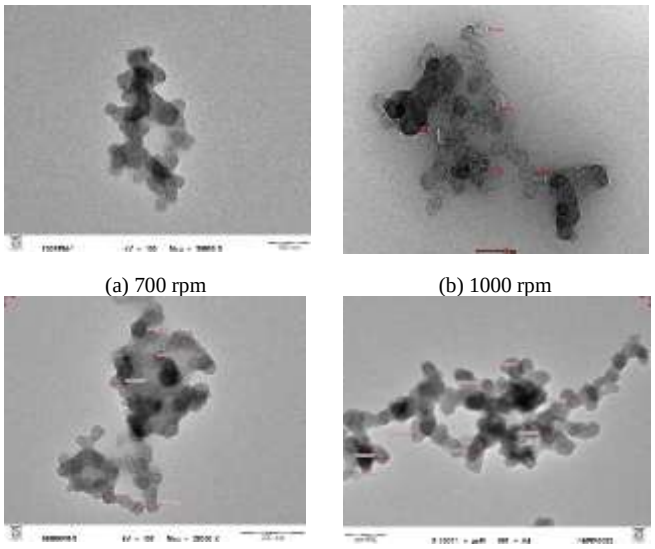


Fig. 7: Soot mass at different engine speeds and loads

At 2 kW and 4 kW loads, the mass of soot increases as the engine speed increases. Via Alkidas technique [8], the opacity of soot can be converted into mass. This means, if the opacity increases, the mass will also increase. This experiment also shows that the mass increases as the load increases similar to the results of Elango and Senthilkumar [10]. As load increases, fuel quantity injected is increases, and at higher engine speeds, improper mixing of fuel and air would occur therefore causes more soot to form.

The size of soot is measured at 700 rpm, 1000 rpm, 1600 rpm and 2000 rpm for applied loads of 0 kW, 2 kW and 4 kW using TEM imaging technique. Transmission Electron Microscopy (TEM) is a useful tool to examine the structure of the soot. Images obtained were then analysed to obtain the size of the soot particles.

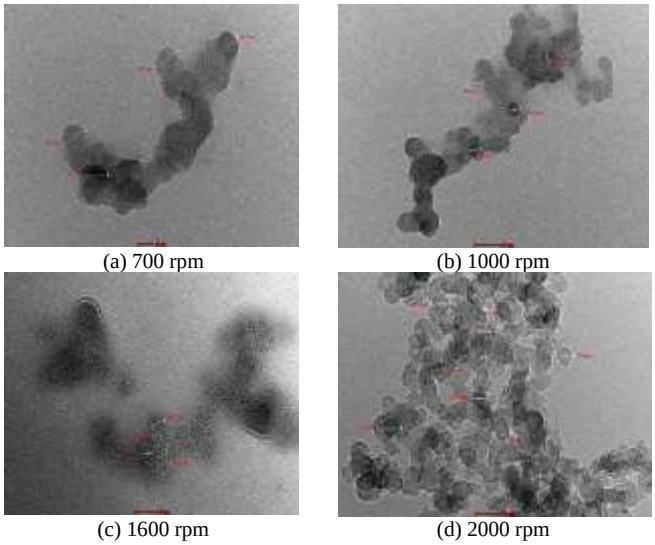
Figure 8, Figure 9 and Figure 10 illustrate the different sizes of soot particles and agglomeration of soot particles at different engine speeds and loads. It is clear from the images, that the number of soot particles increases with engine speeds and loads similar to soot opacity and soot mass profiles. It can also be observed that agglomeration of soot also increases with speeds and loads.



(a) 700 rpm (b) 1000 rpm

(c) 1600 rpm (d) 2000 rpm

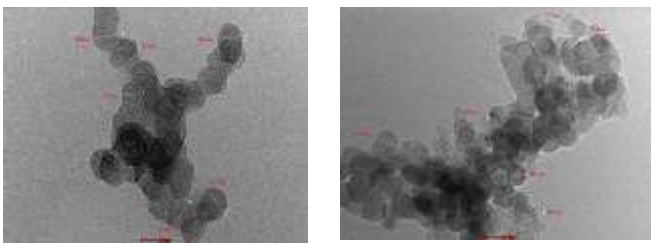
Fig. 8: TEM image for soot particles at 0kW at different engine speeds



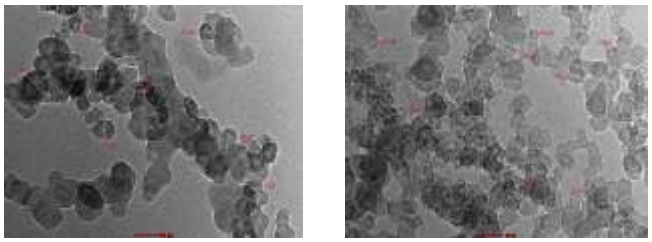
(a) 700 rpm (b) 1000 rpm

(c) 1600 rpm (d) 2000 rpm

Fig. 9: TEM image for soot particles at 2kW at different engine speeds



(a) 700 rpm (b) 1000 rpm



(c) 1600 rpm (d) 2000 rpm

Fig. 10: TEM image for soot particles at 4kW at different engine speeds

Soot particles in all images were measured to obtain the range of size of the soot collected on the TEM grid. The size range was found to be 26 nm to 84 nm. The range obtained was in similar range with the previous studies, which reported a size range of 17.5 - 32.5 nm [11], 10-45 nm [12], 10-50 nm [13] and 20-50 nm [4]. The average diameter from all the particles in the image was calculated. Table 1 shows the average size of soot particles at each load engine speed and load.

Table 1: Average size of soot particles in nanometers (nm) obtained from TEM images at different engine speeds and loads

		LOAD	
RPM	0kW	2kW	4kW
700	75.29	33.45	31.1
1000	83.7	35.77	36.84
1600	42.02	28.43	38.62
2000	62.11	30.58	26.21

Figure 11 shows a profile of average diameter against engine speeds at different engine loads. It can generally be observed that the size of the soot particles decreases with engine speed and load. In contrast, mass of soot increases with engine speed and load as observed in Figure 7. This observation shows that at higher engine speeds more soot are formed but the soot particles size becomes smaller. This findings may be in opposite with other works, therefore further study has to be performed.

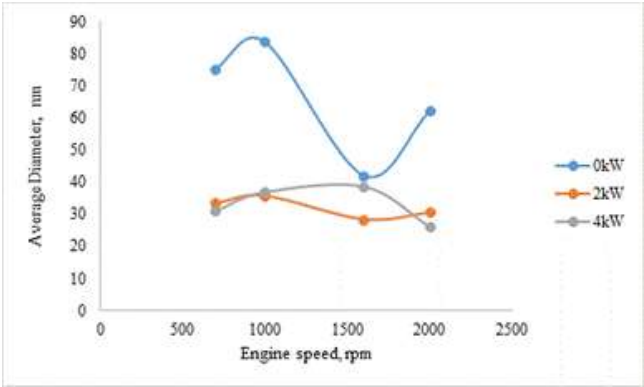


Fig. 11: Average soot particle diameters at different engine speeds and loads

4. Conclusion

From the experiment, the percentage of soot opacity and size is measured at 700 rpm, 1000 rpm, 1600 rpm and 2000 rpm of engine speed on 0 kW, 2 kW and 4 kW load. This study investigated the opacity and size of soot particles as it is known to affect the wear on engine components, the engine's performance as well as the environment. As the load and engine speed increase, the percentage of soot opacity increases. Next, the experiment proved that when the soot opacity increases, the soot mass, soot particle numbers and the extent of soot agglomeration increase accordingly. However, soot particles size is observed to reduce at higher speeds and loads. The size range of the soot in the exhaust was 26 nm to 84 nm close to other reported findings.

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