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Performance and Emissions Analysis of Intercooled Direct Injection Diesel Engines Used for Power Generation during Day and Night Times Operation – A Case Study

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Abstract This paper presents the results of a study carried out to analyze the exhaust gas composition and the plant performance in terms combustion efficiency and Specific Fuel Consumption (SFC) of a diesel engine used for electrical power generation, when operated in day time and night time. For the study, 17MW turbocharged, intercooled direct injection diesel engine consisting of 18 cylinders was used. The results showed a reduction (2.34%) in SFC in the night time operation in which the charge air temperature was lower and relative humidity was higher than those of the day time. The combustion efficiency as well as overall efficiency was found to be increased by 1% in the night time. The CO in the exhaust showed a reduction (13%) in the night time, indicating efficient combustion. The O_2 showed a slight increase (1.8%) in the night time. However, NO_x in the exhaust was found to be increased almost four fold despite the reduction in the exhaust gas temperature and increased moisture in the charge air compared to the day time. The reason for the increase in NO_x was attributed to the increase in excess air. The lower combustion temperature was not sufficient to suppress the NO_x formation.

Keywords Exhaust gases, Combustion efficiency, Specific fuel consumption, Diesel engines

1. Introduction

Diesel engine exhaust is composed of a mixture of many different toxic chemicals that are harmful to human being and to the environment. These emissions have relationship to the charge air parameters that controls the combustion inside the cylinder. On the other hand charge air parameters also have an effect on the engine performance. The toxic chemicals of most concern in diesel exhaust are the oxides of nitrogen (nitric oxide, nitrogen dioxide), carbon monoxide, sulphur dioxide, aldehydes, primarily formaldehyde, acetaldehyde and acrolein, and various hydrocarbons particles. The higher average temperature of combustion of diesel engines generates more oxides of nitrogen than gasoline engines.

NO and NO_2 are the most important oxides of nitrogen and these kind of nitrogen oxides are generally called NO_x emissions. NO is a toxic gas which is formed during combustion at high temperature zones in the combustion chamber (i.e. the automobile engines, power plants and furnaces). Many research carried out in the area of exhaust gas analysis in relation to the fuel types and other operating parameters are for small engines, primarily used in automobiles. However, the effect of toxic exhaust gas produced in large capacity diesel engines is significant as the fuel burnt in a comparatively small period is very large. Therefore, it is very important that these engines are operated under conditions that reduce NO_x emissions without sacrificing the engine performance.

According to preliminary investigations carried out at the *Heladhanavi* Thermal Power Plant in *Puttalum* District in Sri Lanka, it has been observed that Specific Fuel Consumption (SFC) has shown a considerable variation in day time and night time operations owing to the fact that significant changes in the ambient temperature and the relative humidity in the area, the plant is situated. *Heladhanavi* Power Plant is a 100MW thermal power plant, consisting of six *Watseka* 18V46 turbocharged, intercooled direct injection diesel engines, each with a capacity of 17MW.

The present study was carried out to analyze the exhaust gas composition and the plant performance in terms combustion efficiency and SFC of this intercooled direct injection diesel engine used for electrical power generation.

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2. Literature Review

Many studies have been carried out to determine the effects of fuel composition on the exhaust gasses. They were more on the use of fuel mixtures such as Liquid Petroleum Gas (LPG) and bio fuels. The effect of them on the cylinder pressure development and the characteristic of exhaust gasses have been studied[1, 2]. Several studies have been reported on the effect of Exhaust Gas Recirculation (EGR) on emissions[3, 4], main focus being to control NO_x emissions. In these studies reductions in NO_x have been reported to a different degrees depending upon other variables such as charge air temperature and percentage of EGR. In a recent study, the combined effect of EGR and Cetane improver has been found to reduce the NO_x emissions by 25% with a slight increase in carbon monoxide (CO), hydro carbon (HC) and smoke opacity[5]. Especially biodiesel increases NO_x in the exhaust of diesel engines which are predominant when the temperature in the combustion chamber is high as reported by many authors[6 – 8]. Several factors affects for the decrease in NO_x emissions with the increase of EGR. The introduction of CO_2 and H_2O that have higher specific heat capacities results in a lower exhaust temperature during the combustion which gives less NO_x production. Water vapor and CO_2 are also dissociated during combustion and modifies the combustion process and results in a decrease in flame temperature giving less NO_x[9, 10].

The effects of intake air humidity on the performance of a turbo-charged 4-cylinder diesel engine have been investigated by Asad etal, 2012. In this study, the relative humidity of the intake charge was varied from 31 to 80% at a fixed ambient air temperature of 26°C. The results indicated that increasing the intake air moisture leads to a reduction of NO_X emissions by 3-14% under the test conditions. The CO and HC emissions were found to be largely insensitive to the humidity levels and were otherwise extremely low[11].

The effect of charge air properties on the efficiency and SFC has also been reported by several researehers[12 -18]. These studies focussed on the effect from the moisture in the charge air or in the fuel on the diesel engine performance[19]. Lin and Jeng (1996) reported findings of a study on the effect of humidity and temperature of intake air on the performance and the emission characteristics of diesel engines. According to this study air consumption rate, brake torque, and nitrogen oxide in the exhaust were found to be decreased, while specific fuel consumption, carbon monoxide and sulphur dioxide increased with the temperature and the humidity of charge air[20]. Inlet air temperature and the air-to-fuel ratio also have a significant effect on the maximum in-cylinder pressures and its position relative to the cylinder top dead center, the shape of the pressure rise curve, and the heat relese rates[21]. In a study carried out by Maiboom (2008) the charge air temperature in a diesel engine was varied from 20°C to 38°C and found that increase in charge air temperature at constant boost pressure resulted in a slight decrease in rate of heat release. The increase of inlet temperature with exhaust gas recirculation has contrary effects on combustion and emissions, for example, the reduction of NO_x emissions with increased inlet temperature [10].

3. Method

A *Watseka 18V46* turbocharged, intercooled engine that consists of 18 cylinders was used for the experiments. This was a recently 48,000 running hour maintenance completed engine at 54,890h. All the injector pumps and injector nozzles were in good condition. Cylinder head, piston and liner maintenances have been done recently. The load of the engine was set at 17MW.

The measurements were taken during the day time and the night time in order to change the ambient conditions. Time of running during which all measurements were taken was four hours in each of day time and night time. During the running periods, flue gas composition, fuel consumption, charge air temperature and relative humidity, and the pressure development in the cylinders were measured.

To analyze the exhaust gas composition, the gas analyzer Test 350 XL/M instrument was used. The measurement probe was inserted into the stack through an opening provided on the stack pipe and three measurements were obtained.

The measurements on fuel consumption were carried out during the same time periods. The readings of the individual fuel racks of the engine were recorded with a marking on the rack to see the amount of fuel injected in to the engine. The electrical energy exported during four-hour period was also obtained by the energy meters installed in the plant during the same time periods.

Also during the four hour periods in day time and night time experiments, the ambient and charged air properties (temperature and humidity) were measured in one hour intervals.

The pressure developments inside the cylinders were analyzed using the "Leman Permit XL analyzer". The analyzer was connected to the combustion chamber through the indicator cock on the cylinder head and pressure inside was recorded for four cycles. Then the recorded values were fed into the computer. The pressure (p) curves and the rate of change of pressure with respect to crank angle (a), (dip/da) curves were plotted by using *Premet* software v 4.12.

4. Results and Analysis

4.1. Exhaust Gas Composition

Table 1 shows the average values of the ambient pressure, temperature and relative humidity (RH) measured in day time and night time. Also listed in the table are the charge air conditions before after and cooler in day time and night time operations.

Table 2 shows the average compositions of the exhaust gasses recorded in day time and night time operations. Also given in the table are the ambient and charge air temperatures, and the exhaust gas temperatures.

Table 1. Ambient and charge air properties

Time	Ambient air			Charge air (After turbo)		
	Pressure (bar)	Temp (°C)	RH%	Pressure (bar)	Before cooler Temp (°C)	After cooler Temp (°C)
Day	1	33	45	4	176	65
Night	1	27	86	4	172	59

Table 2. Average composition of flue gas in day and night time operation

Parameter	Day time	Night time
Ambient air temperature °C	33	28
Charge air temperature °C	68	62
Exhaust Gas Temperature °C	389	365
O_2%	11.60	11.78
CO_2%	7.07	6.94
CO ppm	283.67	246.33
NO_x (mg/Nm^3@ 15%O_2)	33.33	120.00
SO_x (mg/Nm^3@ 15%O_2)	335.93	702.70
Moisture (%)	7	4.5

The excess air was calculated using the following formula [22].

$$\%\ Excess\ air = \frac{\%\ O_2 measured}{20.9 - \%\ O_2 measured}$$

For day time;

$$\%\ Excess\ air = \frac{11.6}{20.9 - 11.6} x100 = 124.73$$

For night time;

$$\%\ Excess\ air = \frac{11.78}{20.9 - 11.78} x100 = 129.16$$

According to Table 2 the average exhaust gas temperature of the engine reduces by 24℃ in the night time. Also the moisture in the air during night is higher than that of the day time as recorded in Table 1. The higher specific capacity of water compared to oxygen and nitrogen results in lower flame temperature hence the exhaust gas temperature[9, 10]. Because of low temperature and the presence of moisture in the charge air, the density of air increases and the amount of CO generated is also reduced as per the improvement in the combustion. CO_2% of the flue gas had reduced as the amount of fuel burnt is reduced due to improvement of fuel consumption.

Although the forrmation of NO_x is inhibited by the reduction in flame temperature[9], in this study the NO_x formation was found to incraese in the night time, despite the reduction in flame temperature. This could be due to more excess air in the night time as well as increased moisture that provides nessessary O_2 for the formation of NO_x. The reduced flame temperature in the night seemed to be insignifcant to prevent or drastically reduce the formation of NO_x. On the other hand increase in excess air supply in the night could have contributed to increase the nitrogen in the charge air, hence the formation of NO_x.

The CO was found to be reduced by about 13% in the night time indicating a complete combustion and the higher combustion efficiency. At the same time, CO_2 was reduced slightly (about 2%) in the exhaust. This indicated that in the total exhaust, the other components especially the NO_x has increased as shown in the Table 2. The increase of NO_x in the night was almost four fold.

4.2. Combustion Efficiency

The combustion efficiency was calculated using Seigert formula[22].

$$q_A = (T_s - T_a)\left(\frac{A_2}{21 - O_2} + B\right)$$

$$\eta = 100 - q_A$$

Where,

$q_A = Flue\ gas\ losses$

$T_s = Flue\ gas\ temperature\ (^oC)$

$T_a = Charge\ air\ temperature(^oC)$

$O_2 = Volumetric\ oxygen\ concentration\ (\%)$

$A_2 = Constant\ (depends\ on\ the\ fuel) = 0.68$

$B = Constant\ (depends\ on\ the\ fuel) = 0.007$

$\eta = Combustion\ efficiency$

For day time;

$$q_A = (389 - 68)\left(\frac{0.68}{21 - 11.6} + 0.007\right) = 25.468$$

$$\eta = 100 - 25.468 = 74.532\%$$

For night time;

$$q_A = (365 - 63)\left(\frac{0.68}{21 - 11.78} + 0.007\right) = 24.387$$

$$\eta = 100 - 24.387 = 75.617\%$$

According to the calculations using Seigert formula, only a small improvement (by 1%) in combustion efficiency can be obtained in the night time operation.

4.3. Overall Efficiency and SFC

Table 3 gives the actual fuel consumption and the energy exported in the same period. The overall efficiency of the engine was calculated by using the following equation with the Lower Heating value (LHV) of fuel used as 40.54MJ/kg.

$$\eta = \frac{Electrical\ Energy\ generated\ per\ hour \times 100}{fuel\ mass\ consumed\ per\ hour \times LHV}$$

Table 3. Energy Exported and fuel consumption per hour

Time	Energy exported (MWh)	Fuel consumption (kg/h)	Efficiency (%)
Day	16.8	3620	41.2
Night	16.85	3549	42.2

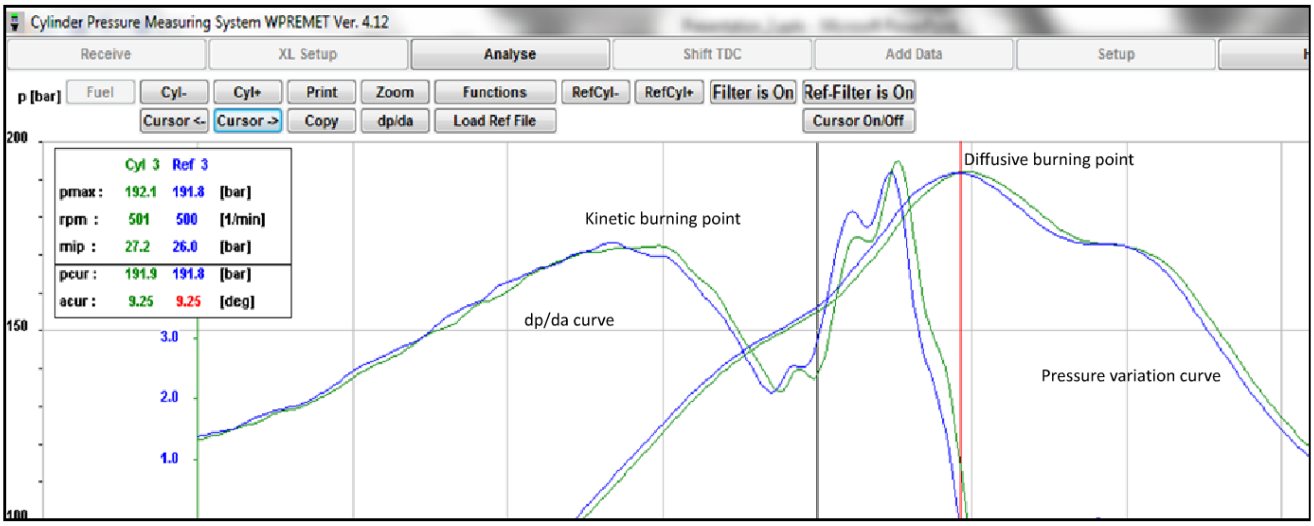

Figure 1. Pressure and pressure derivative with respect to crank angle for day time and night time operation

As per the calculations, during the day time, the fuel consumption was 3620 kg/h and for the night time, it was 3549 kg/h which gives a fuel saving of 71kg/h in the night time operation. The efficiency for day time is 41.2% and for the night time is 42.2% with the exported amount of energy. This is an improvement of 1% for the night compared to the day time for a decrease of 6℃ charge air temperature. This is in agreement with the combustion efficiency calculated using the Seigert formula.

The SFC was calculated using the data in Table 3 and with 17MW power output, for day time and night time operations. SFC in the day time was 213kg/MWh and it was 208kg/MWh in the night time, giving 2.34% reduction in the night time.

4.4. Pressure Development

The pressure (p) and (dip/da) curves versus the crank angle (a) after Top Dead Center (TDC) were plotted by using *Premet* software v 4.12 and a sample of which is shown in Figure 1. The right shifted curve is for the night time. In all the cylinders, the maximum pressure development was found to be delayed in night time compared to day time value, the maximum and minimum values being 3^{o} and 0.75^{o} after TDC.

The kinetic burning and diffusive burning points were also found to be delayed in the night time. The delay in kinetic burning (premixed burning) signifies that atomization occurs closer to the TDC and initiates the combustion at a higher pressure. The higher Mean Indicated Pressure (MIP) during night time is an indication that total energy per cycle is high. Hence the power increases while maintaining the same speed. As the power is regulated at 17MW, the fuel consumption is automatically reduced by the controlled mechanism giving less fuel consumption during night time where the charge air temperature is low and the humidity is high. These are in agreement with the similar studies reported for small capacity automotive diesel engines[14].

5. Conclusions

In conclusion, the performance of the diesel engines used for power generation was found to be improved when operated in the night time with lower charge air temperature and higher humidity compared to the day time, giving fuel savings. Based on the study the following conclusions were made.

- The combustion and the overall efficiency in the night time were both improved by 1%. Though this is a small amount, the savings in fuel is very much significant, the value being 71kg/h in this occasion. Also the SFC was reduced by 2.34% in the night time compared to the day time.
- The emission of CO was found to reduce indicating improved combustion in the night time.
- On the other hand, emissions of NO_x were found to be increased significantly due to the increased excess air. The lower flame temperature expected in the night time owing to the presence of high content of moisture and low charge air temperature was not sufficient to reduce the NO_x emissions.

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