International Journal of Engineering & Technology, 7 (4.39) (2018) 304-307

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper



Combustion Analysis of Thermal Barrier Coated Diesel Engine Using $Fecl_3$ as Fuel Additive

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Abstract

In this current study, combustion and emission parameters of a thermal barrier coated(TBC) compression ignition(CI) engine were studied. Ferric chloride ($FeCl_3$) as fuel additive was mixed in diesel to enhance the combustion and emission characteristics of the engine. The results revealed that coated engine operated with $FeCl_3$ mixed diesel increased the combustion duration with a reduction in ignition delay resulting in improved brake power. The maximum pressure rise occurs nearer to top dead centre in case of coated engine that to without TBC engine . The peak cylinder pressure reached to 53.5 bar for diesel as compared to 54.56 bar in case of $FeCl_3$ added diesel in uncoated engine. While in case of coated engine the peak cylinder pressure reached 54.18 and 56 bar for diesel and $FeCl_3$ mixed diesel respectively. The thermal barrier coating (TBC) enhanced the combustion characteristics, resulting efficient utilization of fuel leading to reduced engine emissions except nitric oxide emission.

Keywords: *Coating; combustion; emissions, ferric chloride; ignition delay.*

1. Introduction

Population explosion and industrialization of the world have led to sharp rise in the transportation sector. More number of vehicles both commercial as well as private is plying through different modes of transit leading to a steady rise in the environmental pollution [1]. Overall the climate is slowly becoming hostile which instinct to restrain vehicular emissions that cause pollution. Research works are going on to find additives for diesel fuel that will maintain the performance of diesel and simultaneously decrease the emissions. Ferric chloride is one such metallic additive that can help in constraining the pollution also keeps the performance intact.

Shaafi and Velraj [2] studied the impact of alumina nano-particles in the combustion and emission analysis of compression ignition (CI) engine with soybean biodiesel blend. They concluded that mixing capability of alumina nano-particles along with high oxygen content of soybean helps in decreasing HC and CO emissions but a slight hike in NO_x emissions was observed. Brake thermal efficiency was notably more with alumina nano-particle. Kannan et al. [3] investigated in a CI engine with $FeCl_3$ added in biodiesel and reported a drop in brake specific fuel consumption (BSFC) and an rise in BTE .Patnaik et al. [4] investigated the effect of $FeCl_3$ fuel additive in CI engine and reported an enhancement in BTE by 8% along a drop in CO and HC emissions, while NO_x and carbon dioxide (CO_2) emissions were increased indicating the superior combustion achieved in presence of $FeCl_3$. Aalam and Saravanan [5] tested the effect of nano metal oxide blended with mahua biodiesel on CI engine and the results indicate increase in peak cylinder pressure with reduction in CO and HC emission while NO_x increased slightly as compared to base result.

The use of thermal barrier coating (TBC) considered by different researchers to reduce heat loss from the combustion chamber as a consequence improves the engine thermal efficiency with reduced engine emissions.

Hüseyin [6] investigated the effect of vegetable oil in diesel engine where the piston and valves surfaces are coated with zirconium oxide (ZrO_2). Insulating effect of the coated surfaces reduced the heat transfer through the walls resulting considerable lower emission of HC and CO emissions when running with blends of vegetable oil, while NO_x emission increased due to elevated combustion temperature.

Aydin et al. [7] studied the impact of thermal barrier coating (TBC) on diesel engine performance running with waste cooking oil biodiesel. Experimentation was performed with 100 µm of NiCrAl as bond coat and 400 mm of top coat consists of 88% ZrO_2, 4% MgO and 8% Al_2O_3. BSFC decreased with the use of biodiesel for coated engine, also noise of the engine reduced due to coating because of shortened ignition delay. Abedin et al. [8] investigated application of TBC on combustion chamber to improve combustion characteristics of biodiesels and reported an enhanced brake power with drop in fuel consumption. The HC and CO emissions are decreased with rise in NO_x emissions. YSZ is a preferred ceramic for coating on piston, valves and cylinder head of engines due to its better thermal fatigue resistance at high temperature working conditions [9].

The present work is to evaluate the impact of $FeCl_3$ on the combustion and emission characteristics of a CI engine coated with YSZ. The investigation was conducted with diesel; $FeCl_3$ added diesel in the CI engine with and without thermal barrier coating.

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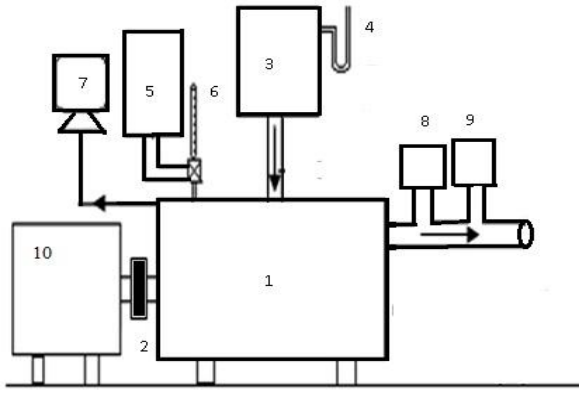
2. Experimentation

2.1. Experimental Setup

The engine used was a single cylinder, 4 strokes CI engine (Kirloskar, India) with power 3.5 kW at 1500 rpm coupled to eddy current dynamometer. The in-cylinder pressure was measured, through a piezo sensor (PCB Piezotronics, Depew, NY). A Kubler (Germany) digital rotary encoder was used to measure the engine speed. Performance and combustion analysis was done using "Engine SoftLV" Software. AVL-444 multi-gas analyzer proficient to measure CO, HC, CO_2, O_2 and NO percentage in the exhaust gas was used to analyze emissions. AVL-437 smoke meter was used to check smoke opacity. Documentation and analysis of the experimental data was performed by a computerized data acquirement system (DAS).

2.2. Experimental Procedure

Experimental data were recorded in each load when the exhaust temperature reached the steady state. The observations were recorded thrice and there average values were considered for final computation. The block layout of the experimental setup is shown in Fig. 1.



1. Engine
2. Coupling
3. Air box
4. Manometer
5. Fuel tank
6. Burette
7. DAS
8. Gas analyzer
9. Smoke meter
10. Dynamometer

Fig. 1: Block layout of the experimental setup.

Mixing of $FeCl_3$ was done with steady stirring for three hours for proper mixing, quantity used was 0.2 gL^{-1}.The properties of diesel and diesel+$FeCl_3$ were documented by the authors in previous articles [10, 11] . Engine operations were done firstly with diesel only and diesel with $FeCl_3$. After completing the test with baseline piston and valves were replaced with coated piston and valves to repeat the experimentation. The detail of coating synthesis by plasma spray method was documented by the authors in previous articles [10, 11].

3. Results and Discussion

3.1. Linear p–V

The relation of cylinder pressure with subsequent cylinder volume right through the engine operating cycle can be depicted on a linear *p–V* diagram as showed in the Fig. 2. It is observed that enclosed area for diesel+$FeCl_3$ in coated engine (C) case was larger than other cases. This represents that work per cycle is higher for diesel+$FeCl_3$ in coated engine. Primary reason for the trend is because of TBC that leads to rise in-cylinder temperature by reducing the heat loss. With the addition of $FeCl_3$ it helps in releasing higher amount of energy as its catalytic action helps in oxidation of HC formed at the initial stage of combustion.

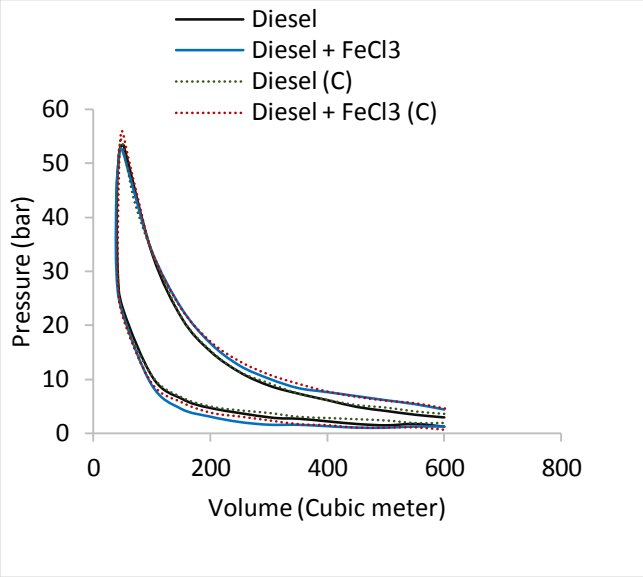


Fig. 2: Linear *p–V* diagram.

3.2. Cylinder Pressure versus Crank Angle

The graduation of combustion pressure versus crank angle (CA) at full load condition for uncoated and coated engine is illustrated in Fig. 3. The mean of 100 cycle's of combustion pressure values were recorded for each CA. It is evident from the graph that there is significant peak cylinder pressure rise was observed when experiments were done in the coated engine, a possible reason for this could be the oxidation of unburnt HC and lower heat loss resulting in high energy release. The peak cylinder pressure reached to 53.5 bar for diesel as compared to 54.56 bar in case of $FeCl_3$ added diesel in uncoated engine. While in case of coated engine the peak cylinder pressure reached 54.18 and 56 bar for diesel and $FeCl_3$ added diesel respectively.

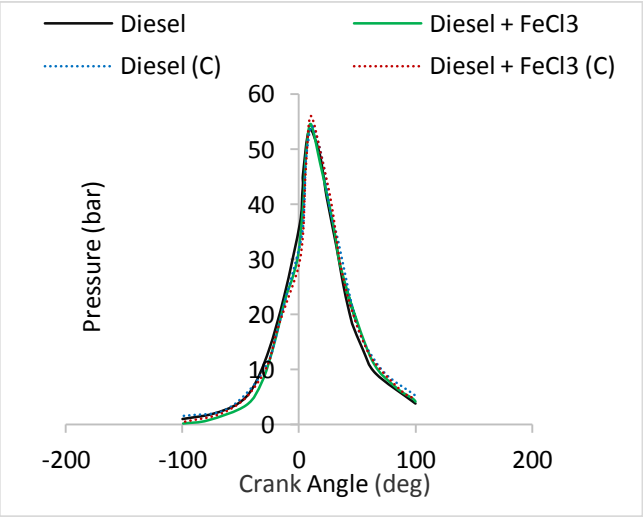


Fig. 3: Graduation of combustion pressure with crank angle.

3.3. Rate of Pressure rise

Fig. 4 depicts the nature of pressure rise rate of all the engine operating conditions used for assessment. It is apparent from the plot that combustion while operating with diesel only generated highest noise. The peak pressure rise rate for diesel found to be 6.00 bar/^{0}CA at 9.1^0 after top dead centre (ATDC). In case of $FeCl_3$ added diesel the maximum pressure rise was 4.98 bar/^{0}CA

at 7.75^0 ATDC. For coated engine running with diesel alone maximum pressure rise reached 5.49 bar/^{0}CA at 8.6^0 ATDC, while for $FeCl_3$ added diesel maximum pressure rise reached 5.07 bar/^{0}CA at 7.34 ^{0} ATDC.

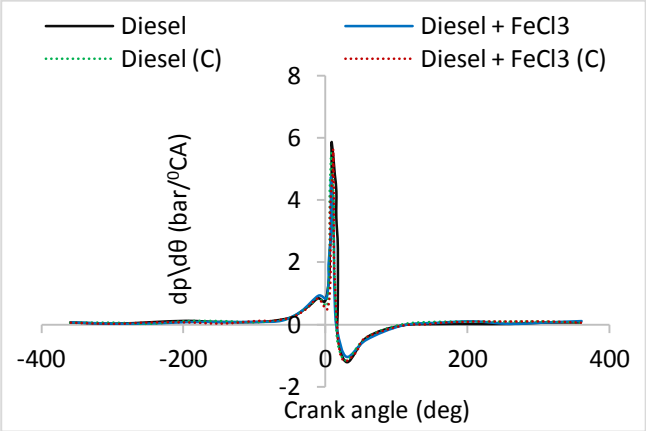


Fig. 4: Rate of pressure rise versus crank angle.

3.4 Ignition Delay

Ignition delay is a key characteristic in combustion study. Table 1 depicts the change in ignition delay for Diesel, Diesel + $FeCl_3$ for coated and uncoated engine. The angle (degree) can be transformed to time (ms) by using equation (1) [5]:

$$t = \frac{°CA}{N \bullet \left(\frac{min}{60}\right) \bullet \left(\frac{360}{rev}\right)} \bullet 1000 \quad (1)$$

Ignition delay presented in the Table 1 refers to the time difference between the start of injection and start of combustion. Ignition delay depends upon fuel atomization, intake air pressure, engine speed, air–fuel ratio, fuel type and quality. Ignition delay affects the peak cylinder pressure, engine noise, vibrations and mechanical stress [12]. From the Table 1 it is clear that ignition delay reduced in presence of $FeCl_3$ as additives in diesel contrast to diesel operation in both uncoated and coated engine. The findings of ignition delay agree with the rate of pressure rise curve as well as the pressure versus crank angle and linear p-v curve.

Table 1: Ignition delay characteristics

Load	Ignition Delay	
	^{0}CA	ms
Diesel		
0	19.13	2.125555
50	18.64	2.071111
80	18.27	2.030000
Diesel + $FeCl_3$		
0	15.86	1.762222
50	15.10	1.677777
80	14.88	1.653333
Diesel in coated engine		
0	18.70	2.077777
50	18.21	2.023333
80	17.84	1.982222
Diesel +$FeCl_3$ in coated engine		
0	12.21	1.356666
50	11.72	1.302222
80	11.10	1.233333

3.5 Combustion Duration

The combustion duration was estimated based on the duration between the start of combustion and 90% cumulative heat release. From Table 2 it is evident that with hike in load the combustion duration increases. The introduction of $FeCl_3$ in both coated and uncoated case increased the combustion duration that signifies better combustion. This may be due to the high heat release due to the catalytic impact of $FeCl_3$ that improved the oxidation of hydrocarbons, in case of coated piston due to higher in cylinder temperature reached along with oxidation of hydrocarbons the combustion duration is highest in case of coated engine when run with$FeCl_3$ added diesel.

Table 2: Overall combustion duration

Load	Combustion duration	
	^{0}CA	ms
Diesel		
0	24.13	2.68111
50	25.11	2.79000
80	26.95	2.99444
Diesel + $FeCl_3$		
0	29.55	3.28333
50	30.29	3.36555
80	31.78	3.53111
Diesel in coated engine		
0	27.57	3.06333
50	28.31	3.14555
80	28.91	3.21222
Diesel +$FeCl_3$ in coated engine		
0	31.32	3.48000
50	32.79	3.64333
80	33.13	3.68111

3.6 Exhaust Emissions

Variation of exhaust emissions CO, HC and NO versus engine load are presented in Fig. 5,6 and 7 respectively along with their correlation to the combustion phenomenon. CO emissions reduces with the rise in engine load may be owing to boost in-cylinder temperature resulting improved combustion. Catalytic impact of $FeCl_3$ intensify the oxidation of CO into CO_2.

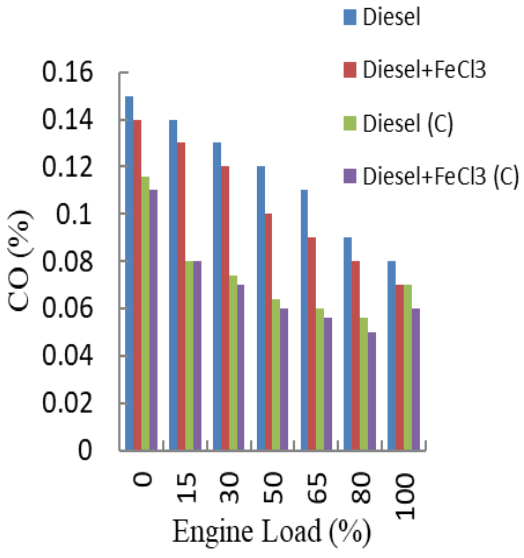


Fig. 5: Variation in CO emission with engine load.

Unburnt hydro carbon arises due to incomplete combustion of fuel present in the combustion chamber. The deviation of HC emission at different engine load as shown in Fig. 11. With hike in engine load HC emission decreases, because of the increase in ignition centres at higher loads enhances the ignition energy leading to improved combustion characteristics. Due to boost in combustion temperature as an effect of drop in heat loss in coated engine along with the presence of $FeCl_3$ decreases the HC emissions significantly .

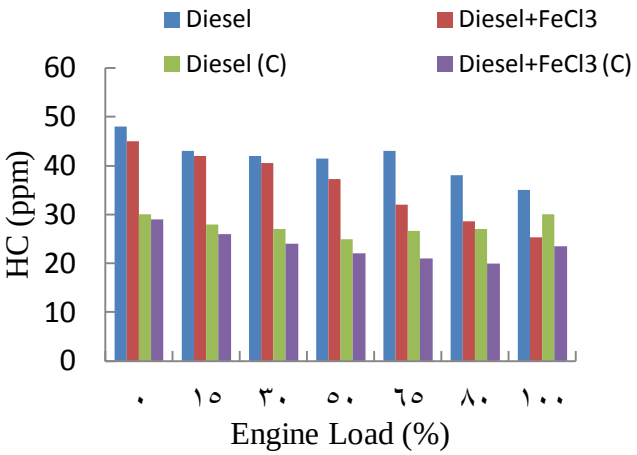


Fig. 6: Variation in HC emission with engine load.

NO emission increases with rise in mean combustion gas temperature. Though in theory if the combustion duration increased then the mean combustion temperature decreases but in this case due to TBC the heat loss was minimised which helped in sustaining the temperature achieved in initial combustion phase and when $FeCl_3$ starts the oxidation of HC more heat released hence temperature further increases due which the NO formation was quite significant.

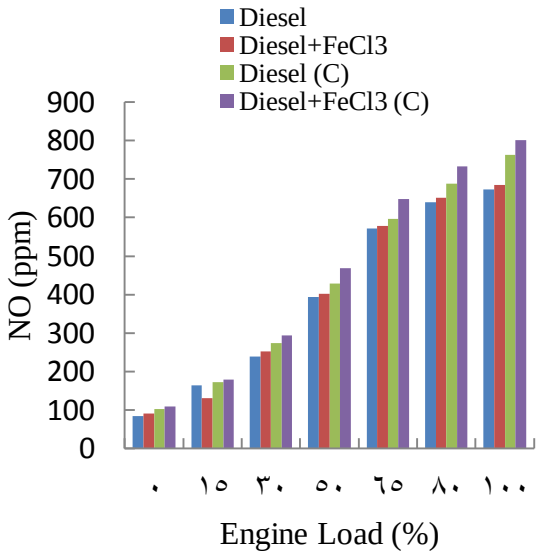


Fig. 7: Variation of NO emission engine load.

4. Conclusions

Results and its analysis obtained from the combustion analysis is summarized below.

- $FeCl_3$ as an additive is helpful in improving the combustion process which is seen from the linear p-v diagram also it helped in decreasing the rate of pressure rise which in turn reduced the vibration, mechanical stress and noise if the engine.
- Effect on ignition delay when $FeCl_3$ was added as additive was quite significant. Diesel added with $FeCl_3$ displayed lower ignition delay in both uncoated and coated case. Since the ignition delay was lower the combustion duration increased indicating efficient combustion of the mixture.
- Catalytic impact of $FeCl_3$ that forms a high valent iron-oxo species also helps in increasing the combustion duration as it oxidizes the HC which releases more amount of energy as well as in the coated engine the combustion temperature was higher that facilitated reduction in the CO and HC emissions. On the other hand the NO emissions increased because of the same reason.

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