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EFFECTS OF INLET AIR TEMPERATURE ON PERFORMANCE AND EMISSIONS OF A DIRECT INJECTION DIESEL ENGINE OPERATED WITH ULTRA LOW SULFUR DIESEL FUEL

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ABSTRACT

Experiments were conducted with a commercially available six cylinder, water cooled, turbocharged, direct injection diesel engine operated over a range of inlet air temperatures. Air flow rate decreased and fuel flow rate increased with an increase in inlet air temperature, which reduced the air-fuel ratio of the engine. Engine efficiency decreased and exhaust gas temperature increased with an increase in inlet air temperature Injector needle lift data also confirmed that the fuel consumption increased with an increase in inlet air temperature. Rate of heat release analysis showed that the premixed and diffusion burning peaks were reduced with an increase in inlet air temperature. Results also showed that the brake specific NOx and CO emissions increased with an increase in inlet air temperature. Average in-cylinder temperature increased with an increase in inlet air temperature, which might be a reason for higher NOx emissions. Particulate matter (PM) emissions were lower at lower inlet air temperature and increased at higher temperature.

Keywords: Diesel, Combustion, Emission.

1. INTRODUCTION

In the near future, it is likely diesel powered engines will be used more widely due to their high thermal efficiency and superior fuel economy compared to gasoline engines. However, emissions of NO_X and particulate matter (PM) are higher with diesel engines compared to gasoline engines and these emissions have to be improved to meet future emissions regulations without significantly decreasing the fuel economy advantages.

Engine manufacturers and various researchers have studied a number of strategies for reducing exhaust emissions including exhaust gas recirculation (EGR), high pressure injection, electronically controlled injection, multiple fuel injections, redesigning the combustion chamber and others [1-8].

The Environmental Protection Agency (EPA) has proposed an ultra low (15ppm) sulfur diesel fuel beginning in 2006. The introduction of ultra low sulfur diesel fuel might reduce particulate emissions, particularly the PM associated with sulfates. Also, sulfur sensitive exhaust gas aftertreatment may be used to reduce other emissions from the exhaust gas [9-10]. Many studies have been performed with biodiesel and oxygenated diesel fuels and almost all of them showed a significant potential to reduce emissions [11-15].

Apart from these techniques and fuel formulations, how an engine with electronic control module (ECM) behaves with the variation of inlet air temperature (air going into the inlet manifold after passing the intercooler) is the main focus of this study. With changes in inlet air temperature, variation of combustion, engine performance and emissions will be presented in a systematic way.

2. EXPERIMENTAL SET-UP

Experiments were conducted with a Cummins 5.9L, turbocharged, water cooled, six-cylinder, 4-valves per cylinder direct injection (DI) diesel engine. The experimental system consisted of an engine, dynamometer, controller, combustion analysis instrumentation, and different emissions analyzers. The engine was fitted with an ECM that monitors engine performance and controls different events automatically, especially the start of injection (SOI), injection timing advancement or retardation.

Figure 1 presents a diagram of the Cummins 5.9L ISB turbo-diesel engine and test cell instrumentation. Specifications of the test engine are shown in Table 1. The engine uses a Bosch VP-44 type rotary distributor fuel pump. The injectors have 7 holes and a 152 deg spray cone angle.

The fuel consumption was monitored using a Sartorious model EA60EDE-IOUR precision scale, with

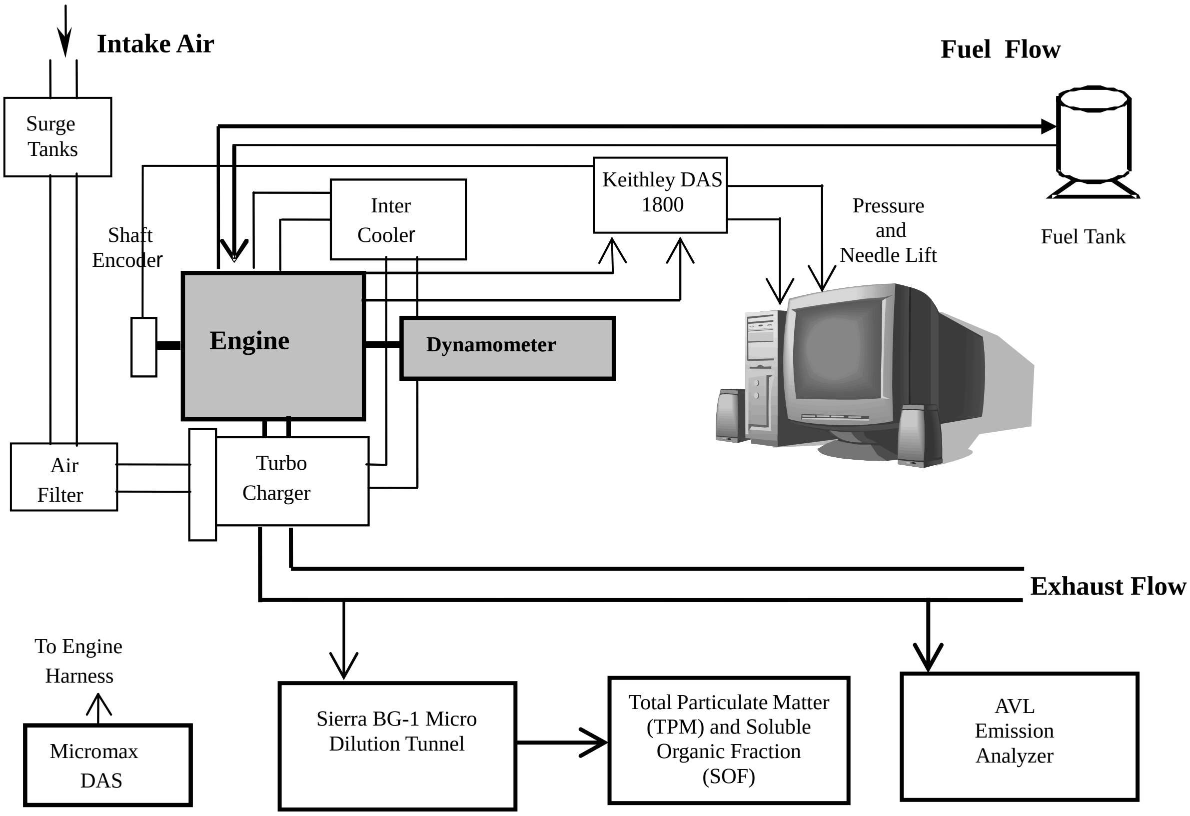

Fig 1. Schematic diagram of the experimental system

an accuracy of ± 2 grams. Cylinder pressure was measured using Kistler piezoelectric pressure transducer model 6067B. A Hall-effect proximity sensor, installed by Wolff Controls Corporation, was used to measure needle-lift in the injector. Cylinder number six was instrumented for cylinder pressure and needle lift data. An AVL 364 shaft encoder installed on the engine crankshaft, along with a Keithley DAS 1800 data acquisition board enabled 0.1 CA degree resolution acquisition of these signals.

Table 1: Specifications of the tested engine

Engine	Six-cylinder DI Diesel Model Year 2000
Advertised Power	235 hp @ 2700 RPM
Bore X Stroke	102 mm X 120 mm
Compression Ratio	16.3
Displacement	5.9 L
Injection System	Bosch VP-44 Rotary Distributor Pump
Swirl Ratio	2.45
Aspiration	Turbocharged

Table 2 shows properties of the fuels used in this study. The test fuel includes an ultra low sulfur diesel fuel “BP15” (US 2006 standard). Fuel was tested several times to check the consistency and repeatability of their properties. The ultra low sulfur diesel BP15 fuel has a sulfur level of 15 wt. ppm.

Table 2: Selected fuel properties

Properties	BP15
Cetane Number	50.5
Density, gm/cm^3	0.837
Viscosity @ 40 C, cSt	2.48
Flash Point, C	63
IBP, C	167.4
Calorific Value, Btu/lb	18219
Sulfur Content, wt%	0.0015
Aromatic Content, wt%	21.2

For the engine testing, the BP15 diesel fuel was evaluated using mode 4 of the AVL 8-Mode test protocol [16]. The engine operating conditions were calculated based on the rated peak torque, power and speed of the engine. Table 3 indicates the loads and speeds for the test engine to conduct AVL 8-Mode tests. All the tests were performed at a steady state condition with the test engine operating at 378 ft-lb and a constant speed of 1408 rpm as shown in Table 3 for AVL mode 4.

Before measurements were obtained, the engine was warmed up for more than an hour at idle to bring the engine coolant temperature to roughly 90 ^{o}C. Experiments were conducted by changing the inlet air temperature and keeping all other variables as constant as possible. As mentioned earlier, the engine was fitted with a turbocharger and compressed hot air coming out from the turbocharger was cooled in an aftercooler to control the inlet air temperature. Water circulation to the aftercooler was manipulated to control the inlet manifold air temperature. Inlet manifold air temperature was varied between 30 ^{o}C and 60 ^{o}C and all the combustion, performance and emissions data were collected.

Table 3: AVL 8-Mode test protocol

Mode	RPM	Torque (ft-lb)	Weighting Factor
1	800	No load	0.35
2	1025	77	0.0634
3	1199	252	0.0291
4	1408	378	0.0334
5	2700	80	0.084
6	2605	178	0.1045
7	2605	307	0.1021
8	2491	426	0.0734

For particulate mass emissions, PM samples were collected by using a Rupprecht and Patashnick model 1105 Tapered Element Oscillating Microbalance (TEOM) PM mass analyzer which measures the real time particulate mass concentration [17-18]. Exhaust gas was sampled via a Sierra Instruments BG-1 mini-dilution tunnel with constant dilution air/sample flow ratio of 10:1 and total flow of 100 (liters/min). One portion of the diluted exhaust flow of 3 lpm was passed through the TEOM for 5 minutes to get real time PM data.

Gaseous emissions were measured using an AVL CEB II emissions analyzer. Undiluted exhaust gas was collected via a heated sample line, which was maintained at 190^{o}C.

A Leeds & Northrup "Micromax" data acquisition system logged the real-time engine speed, torque and power, lubricating oil, fuel consumption and coolant temperatures, as well as, exhaust emissions via an AVL CEB II emissions analyzer.

3. RESULTS AND DISCUSSION

Experiments were conducted with the ultra low sulfur diesel fuel BP15. During the engine tests, the data acquisition and analytical instruments were used to monitor engine operating conditions such as, temperatures, intake air flow, turbo boost pressure, fuel consumption, particulate matter, gaseous emissions, in-cylinder pressure and injector needle lift. From each test point, all the gaseous emissions were recorded over a one hour period. Based on the power output for each test mode, all the gaseous emissions were calculated on a brake-specific basis. Error bars represent 95% confidence intervals, and were determined based upon methods previously described by Moffat [19].

3.1 Combustion Characteristics

Several measurements obtained from the engine experiments are plotted in Figures 2-6, including: the needle lift, cylinder pressure-time histories. Engine was operated at 1408 rpm with an external load of 378 ft-lbs with no other change in engine operation except inlet air temperature. The engine used in these experiments is a commercial engine fitted with an electronic control module designed to compensate injection timing according to the fuel properties such as density, calorific value, etc.

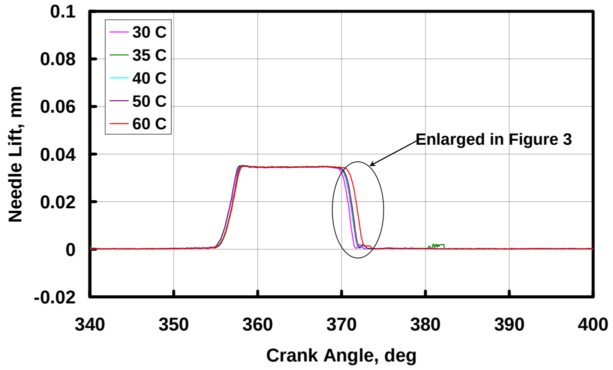

Fig 2. Injector needle lift with the variation of inlet air temperature

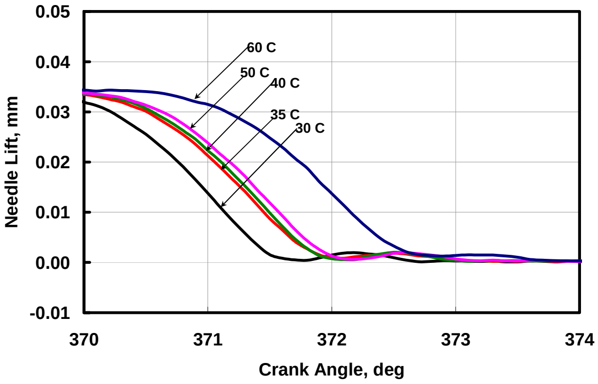

Fig 3. Enlarged needle lift with the variation of inlet air temperature

Needle lift data with the variation of inlet temperature is shown in Figure 2 and Figure 3. Needle lift data mainly shows start of injection (SOI) event and end of injection (EOI) event. Figure 2 shows that the SOI events with the variation of inlet temperature are almost same however, EOI events are not occurring at the same time. An enlarged view of the EOI of Figure 2 is presented here in Figure 3. Evidently, the higher the inlet air temperature, the higher the crank angle at which the EOI event occurs, which suggest that the fuel consumption increases with an increase in inlet air temperature.

An increase in inlet air temperature will affect the cylinder pressure-time history. Cylinder pressure with the variation of inlet air temperature is presented in Figure 4. A small decrease of cylinder pressure was observed with an increase in inlet air temperature. However, the peak pressures were observed at the same crank angle.

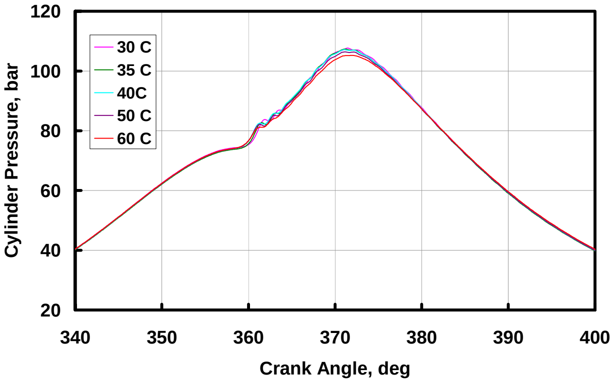

Fig 4. Cylinder pressure with the variation of inlet air temperature.

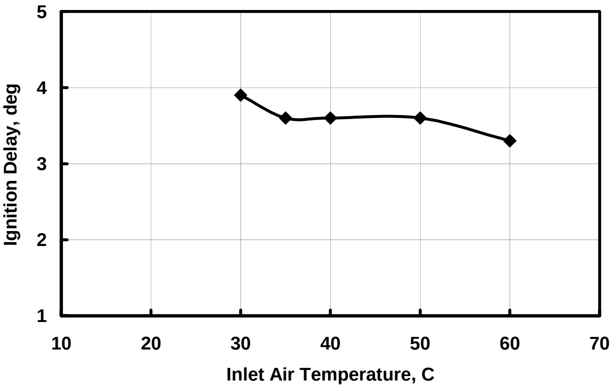

Fig 5. Ignition delay with the variation of inlet air temperature

The effects of increased inlet air temperature on the ignition delay and heat release history are shown in Figures 5 and 6, respectively. In order to obtain better insight into the self-ignition tendency at different inlet air temperature, Figure 5 was prepared by plotting the ignition delay (as defined as the period of time from the start of injection to the start of combustion) vs. the inlet air temperature. The intake air temperature affect the ignition delay due to its effect on charge conditions during the delay period. As expected, ignition delay decreases with an increase in inlet air temperature, because higher inlet air temperature reduces the time to vaporize the fuel to make a combustible mixture.

Figure 6 shows rate of heat release (ROHR) analysis for BP15 fuel when inlet air temperature changes from 30 ^{o}C to 60 ^{o}C. The start of combustion is indicated by the crank angle degree (CAD) when the ROHR curve moves from negative to positive value. The curves in Figure 6 are quiet consistent with the above statement, that is, the higher the inlet air temperature, the earlier the start of combustion. On the other hand, the higher the inlet air temperature, the lower the premixed and diffusion burning peaks. It is also true that the premixed combustion stage decreases with shorter ignition delay. Average cylinder temperature with the variation of inlet air temperature is also presented in Figure 7. Average cylinder temperature increases with an increase in inlet air temperature. Almost an average of 150 ^{o}K cylinder temperatures increased when inlet air temperature changes from 30 ^{o}C to 60 ^{o}C. This change in average cylinder temperature will play an important role on engine out NO$_X$ emissions which will be discussed later.

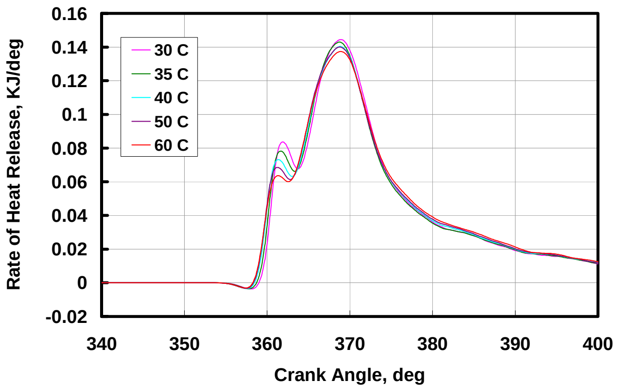

Fig 6. Rate of heat release with the variation of inlet air temperature.

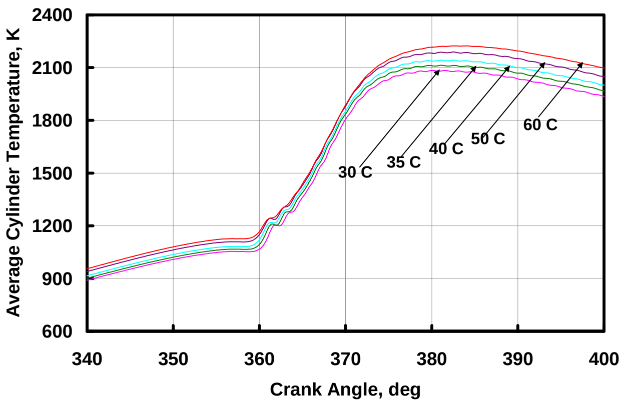

Fig 7. Average cylinder temperatures with the variation of inlet air temperature

3.2 Engine Performance

Several measurements obtained from the engine are plotted in Figures 8-11, including: air and fuel consumption, air fuel ratio, exhaust gas temperature, specific fuel consumption and efficiency.

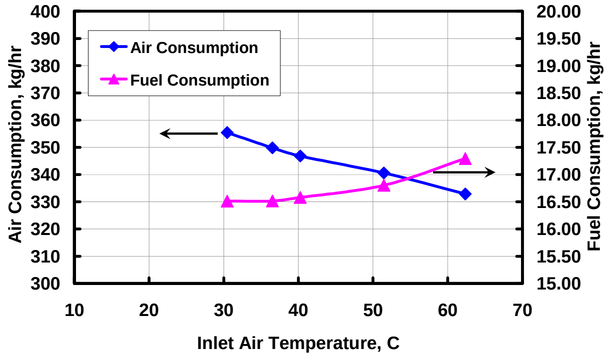

Fig 8. Air consumption and fuel consumption with the variation of inlet air temperature.

Air flow rate and fuel flow rate with the variation of inlet air temperature are shown in Figure 8. Fuel flow rate increases with an increase in inlet air temperature, which was also mentioned earlier in needle lift data analysis. As expected, air flow rate decreases with increase in inlet air temperature. Therefore, it is obvious that the air fuel ratio should decrease with an increase in inlet air temperature (Figure 9). Similarly, specific fuel consumption should also increase with an increase in inlet air temperature and which is confirmed in Figure 10. Specific fuel consumption measurements are consistent with the exhaust gas temperature, namely higher the specific fuel consumption, the higher the exhaust gas temperature (Figure 10). Efficiency also decreases with an increase in inlet air temperature (Figure 11).

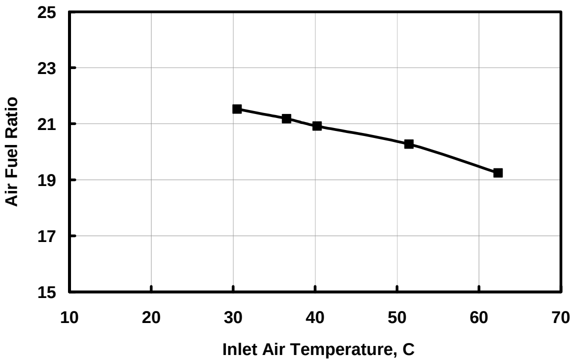

Fig 9. Air fuel ratio with the variation of inlet air temperature

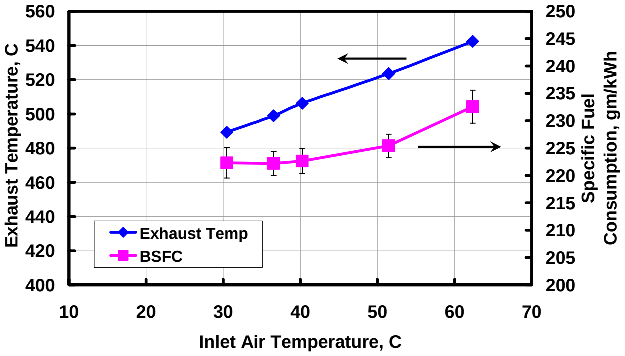

Fig 10. Specific fuel consumption and exhaust gas temperature with the variation of inlet air temperature.

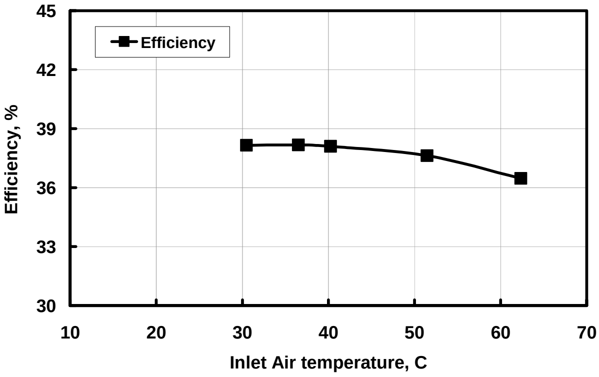

Fig 11. Thermal efficiency with the variation of inlet air temperature

3.3 Exhaust Emissions

All the gaseous and PM emissions were measured and some of them are presented here on brake specific basis. CO emissions increase and hydrocarbon emissions decrease with an increase in inlet air temperature might be due to the decrease in air-fuel ratio with an increase inlet air temperature (Figure 9). NOx emissions increase with an increase in inlet air temperature (Figure 13). Average cylinder temperature (Figure 7) seems to be one of the reasons for increasing NOx emissions. However, reduction of NOx with decrease in premixed burn peak is no longer true in this particular experiment. It is not possible to make any conclusion about PM emissions (Figure 13). It seems that the PM emissions are going down at low inlet air temperature and opposite happens at higher inlet air temperature.

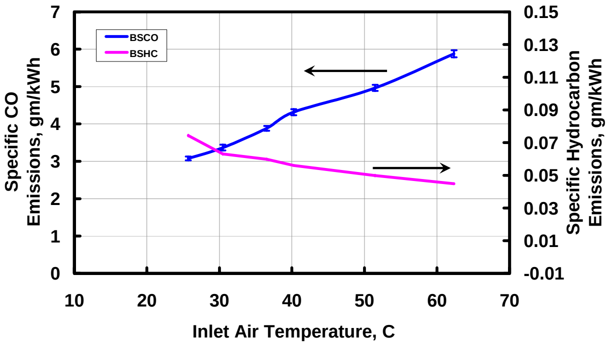

Fig 12. CO and hydrocarbon emissions with the variation of inlet air temperature

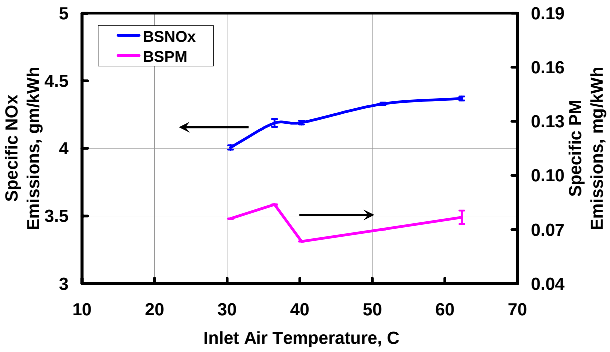

Fig 13. NOx and PM emissions with the variation of inlet air temperature

4. SUMMARY

Experiments were conducted with an ultra low sulfur BP15 diesel fuel. Combustion characteristics, engine performance and emissions were examined with the variation of inlet air temperature. Some findings from the present study can be summarized as follows:

1. End of injection timing increases with an increase in inlet air temperature. Cylinder pressure, premixed burn peak and diffusion burn peak decrease with an increase in inlet air temperature. Average cylinder temperature increases with an increase in inlet air temperature.

2. Air-fuel ratio decreases, specific fuel consumption increases and thermal efficiency decreases with an increase in inlet air temperature.

3. Hydrocarbon emissions decrease and NOx emissions increase with an increase in inlet air temperature. PM emissions decrease at low inlet air temperature and opposite happens at high inlet air temperature.

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