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Article in *Thermal Science* · January 2021

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MODELLING OF POST-INJECTION STRATEGIES OF ETHANOL AND EXPERIMENTAL ANALYSIS OF THE USE OF ETHANOL IN THE FORM OF DUAL FUEL AND EMULSION IN DIESEL ENGINE

by

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Original scientific paper

<https://doi.org/10.2298/TSC1191223073G>

In this research, as the first stage, the effects of the ethanol on engine performance and emissions under the fumigation and emulsion method were experimentally investigated under part load and various engine speed conditions. Diesel-ethanol blend containing 5% ethanol by volume was used as the mixture fuel. In the fumigation method, ethanol was used at the same rate and 99.9% purity as the emulsion method. As the second stage, the effects of ethanol post injection on engine performance and pollutant emissions were investigated in the experimental engine modeled in AVL Boost simulation program and compared with the experimental results. Simulation post injection tests were performed separately after the main injection at 3° CA (P1) and 7° CA (P2). In the experimental studies, NO_x emission decreased with the emulsion method (E5) at low and high engine speeds. In post injection strategies, NO_x emission in general increased due to improved combustion and increased in-cylinder temperature with P1 (first post injection) and P2 (second post injection) strategies. Soot emission decreased significantly with E5. This improvement in soot emissions was approximately 87% in post injection strategies.

Key words: ethanol emulsion, fumigation, dual fuel combustion, post injection, emissions, Diesel engine

Introduction

One of the dominant sources of emissions of NO_x, CO and particulate matter (PM) in Europe is the transport sector [1]. Therefore, the environmental impacts of pollutant emissions arising from the use of internal combustion engine vehicles are gradually increasing [2]. Emissions such as NO_x, CO, and HC have significant direct and indirect damages especially on human health [3]. Although it is possible to reduce diesel-based pollutant emissions with alternative fuel blends, this improvement can be further enhanced by fuel injection strategies [4-6]. The use of light alcohol fuel such as ethanol and methanol with approximately 35% and 30% oxygen content has a significant potential for better fuel performance as it improves pollutant emission values and provides better combustion [7, 8]. The biggest advantage of ethanol blended fuels is their low soot levels due to the high volatility of ethanol and the oxygen in ethanol [9]. In addition, ethanol can be used in compression ignition (CI) engines without any modification, as an emulsion with diesel fuel in certain proportions or by fumigation directly to the inlet port with some simple modifications [10, 11]. However, ethanol has difficulties such

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as not being homogeneous with diesel fuel for a long time and net phase separation due to low cetane number, low autoignition temperature and density difference [12]. An emulsifier should be added to diesel-ethanol mixtures to form emulsions without this clear phase separation problem [13, 14]. Furthermore, heating the mixture provides an important convenience for keeping ethanol-diesel mixtures homogeneous and longer without phase separation. In particular, the higher the amount of ethanol in the mixture, the faster the phase separation at room temperature. However, the phase separation time of the blends whose temperature is increased up to 40 °C is longer [15]. In the fumigation method, higher amounts of ethanol can be used in the Diesel engine, as the ethanol is atomized directly into the inlet air. In addition, the fumigation method reduces ignition delay and combustion becomes more effective [16, 17]. However, this method requires a fuel tank, a new fuel system, additional injector and electronic control system [18].

Injection strategies are very effective methods to improve exhaust emissions. In post injection, a small amount of fuel is injected shortly after the main injection. Thus, with the turbulence re-formed in the cylinder, combustion is improved and smoke emission reduction occurs [19, 20]. Furthermore, post-injection start moment, injection duration and the amount of fuel injected are very effective in reducing harmful emissions [20]. Tsang *et al.* [21] investigated the effects of ethanol with fumigation method with different ratios of ethanol at five different engine loads at constant engine speed. They controlled ethanol fumigation with an electronic control system. Hebbbar *et al.* [22] in their study using ethanol fumigation method in Diesel engine, they found that NO_x emission was reduced by approximately 15%. Bhale *et al.* [23] studied the effect of biodiesel and ethanol blend in Diesel engine. They found that CO and NO_x emissions decreased but HC emissions increased. Hansdah and Murugan [16] used the fumigation ethanol method in a single cylinder Diesel engine. Test results showed that NO_x emission decreased, but extended by 2-3° CA in the ignition delay period. Zhu *et al.* [24] conducted experiments using the method of fumigation with biodiesel and different proportions of ethanol at constant engine speed, five different engine loads. In the test results, engine performance increased with a 5% ethanol blended fuel, and NO_x and PM emissions decreased. Lee *et al.* [25] in their study on single-cylinder engine with dual injectors, constant low engine speed and different engine load conditions, they found that as the ethanol ratio increased, PM and NO_x emissions decreased but PM emissions increased again at low engine loads. Taghizadeh-Alisaraei and Rezaei [26] investigated the effects of 2, 4, 6, 8, 10, and 12% ethanol blend on engine performance and emissions at full engine load and at different engine speeds. Ethanol content above 8% increased the ignition delay, causing the engine knocking. Abu-Qudais *et al.* [10] researched the effects of ethanol use on diesel emissions by using fumigation and emulsion method in a single-cylinder Diesel engine. They found that the best ethanol content for the fumigation method was 20% and the best mixing ratio for the emulsion method was 15%. They discovered that there was a 51% reduction in smoke emission with the fumigation method, and a 32% reduction in smoke emission with the emulsion method. Sandalci *et al.* [27] investigated the effects of different proportions of ethanol-diesel blends with emulsions on performance and emissions. They reported that as the ethanol ratio in the blend increased, the smoke emission decreased, but the CO emissions increased. Cong [28] examined the effects of post-injection with different amounts of fuels in the study. They have found that the high amount of fuel injected as post was a significant negative effect on the heat release rate (HRR) due to the lack of sufficient oxygen. He noticed that the HRR of post injection with a high amount of fuel was lower than the HRR of the main injection. But when the amount of fuel was reduced in post injection, the HRR increased and the CO emission decreased. Chen

et al. [19] reported that the exhaust gas temperature increased with post-injection and soot emissions decreased due to the start of re-combustion, but HC and CO emissions increased rapidly when late post-injection occurred. Li *et al.* [20] investigated the effect of post-injection on emissions in Diesel engine. They tried different rates of post injection and different start of post injection. They noted that as the time between the main spray and post injection increased, there was a decrease in NO_x emissions, but an increase in HC and CO emissions. They also reported that PM emissions decreased with increasing post-injection distance compared to the main injection, but increased again with increasing distance.

In this study, as the first of two-stages, fig. 1, the effects of using ethanol with emulsion and fumigation methods on engine performance and pollutant emissions were investigated experimentally in a tractor engine. Contrary to many studies in recent years, the motivation of this research in this step was to investigate the effect of the heated ethanol blend on pollutant emissions because there was little research on the effects of the heated ethanol diesel blend. The ethanol used in the experiments was 99.9% pure. The degree of purity of ethanol is an important parameter in emulsions made with diesel. Because the higher the water content in ethanol, the easier the phase separation [29]. At the second stage, the effects of post-injection strategies were examined using pure ethanol in the engine modeled in the AVL Boost software and the simulation test results were compared with the experimental study results. In the simulation post-injection tests, unlike literature, only ethanol was used as the post-injection fuel. It was ensured that the energy given to the cylinder in diesel single injection experiments and the total energy given to the cylinder in double injection (main + post) experiments were equal. The number of such naturel ethanol-containing studies on off-road engines is quite low in the literature. In addition, especially considering the increase in the number of off-road vehicles in agricultural lands, experimental and simulation studies aimed at reducing pollutant emissions from these vehicles are very important. Simulation tests will provide important reference for experimental studies in injection strategies studies.

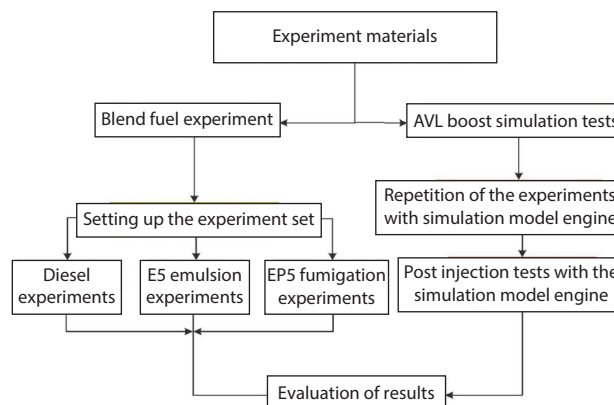


Figure 1. Stages of the study

Method and process

Diesel engine and test equipment

The schematic of the test system is shown in fig. 2. Experiments were performed on a 3-cylinder turbocharged diesel tractor engine whose the properties are shown in tab. 1. In the catalog characteristics of the engine, the maximum torque is achieved at 1600 rpm, while the

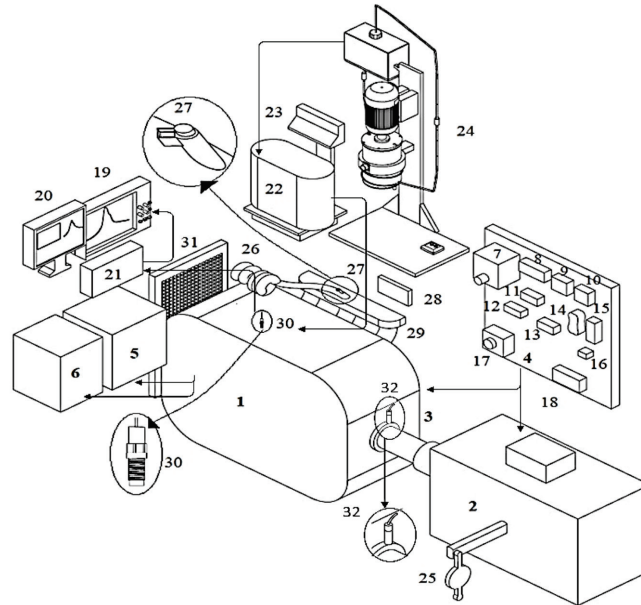


Figure 2. Schematic diagram of the engine test set-up; 1 – engine, 2 – direct current dynamometer, 3 – shaft, 4 – control panel, 5 – AVL emission analyzer, 6 – AVL emission analyzer, 7 – direct current motor controller, 8 – load indicator, 9 – voltmeter, 10 – ampermeter, 11 – engine speed indicator, 12 – coolant inlet temperature, 13 – coolant outlet temperature, 14 – exhaust temperature, 15 – fuel temperature, 16 – air moisture meter, 17 – emergency stop button, 18 – date and clock, 19 – oscilloscope, 20 – computer, 21 – amplifier, 22 – fuel tank, 23 – precision balance, 24 – fuel mixer, 25 – load cell, 26 – turbochargers, 27 – low pressure injector, 28 – Arduino ECU, 29 – intake port, 30 – pressure sensor, 31 – radiator, and 32 – proximity speed sensor

Table 1. Properties of experiment engine

Parameters	Specifications
Cylinder number	3
Engine volume	2.9 L
Aspiration	Turbocharge
Bore x stroke	104 × 115 mm
Compression ratio	17:1
Cooling system	Water cooled
Maximum output	36 kW
Rated speed	2450 rpm

maximum engine power is achieved at 2000 rpm. Engine loading process precisely controlled by direct current engine drive controller at every speed. Engine torque was measured with a loadcell and engine speed was measured with a proximity sensor. Engine cooling water, exhaust gas, and fuel temperatures were instantly controlled during the test period using *K*-type thermocouples. Fuel consumption measured with electronic precision scales. Ethanol was added up to 5% of the amount of diesel to form the emulsion. Exhaust gas emissions were measured with AVL Dicom 4000 and AVL 415S analyzers. Intra-cylinder pressures were measured with AVL HG14P type piezoelectric pressure sensor and recorded with LeCroy oscilloscope. The engine has mechanical injectors. Diesel and emulsion experiments fuels were injected directly into the cylinder using these mechanical injectors. In the fumigation method, to injection ethanol, the gasoline injector was placed in the intake manifold as shown in fig. 3 to injection in the flow direction of the inlet air. Before the injector was installed, the amount of fuel injected

by the injector was measured and calibrated. Arduino control card was developed in accordance with these data and engine speed data to control ethanol injection. In addition, the turbocharger of the engine facilitated the evaporation of ethanol due to pressurized and accelerated air in the fumigation method.

Test procedure

Before the emulsion method experiments, homogeneous residence times of ethanol-diesel emulsion fuel were determined. Ethanol was added to diesel in proportions of 5%, 10%, 15%, 20%, and 30%. Isopropanol was added to 2% ratio each of these mixtures to form homogeneously without phase separation. Because, for ethanol-diesel mixtures to be homogeneous, emulsification is a very important step [30]. It should also be mixed with a mixer for a long time. A special electric mixer, shown in fig. 4, was designed for this process. All blends were mixed with the cross blades of this mixer at 2000 rpm. The emulsion, drawn from the sealed chamber of the mixer by an electric pump, was injected back into the same chamber with a nozzle. The blend fuels were continuously mixed in re-circulation and at constant engine speed. In addition, the blend was heated at different temperatures between +7 °C and 50 °C. However, as the ethanol ratio increased, the temperature of the emulsion fuel was raised to prevent phase separation and crystalline structure. In fuel tests, it was determined that the optimum temperature in terms of phase separation time was between 30 °C and 40 °C. Moreover, crystal appearance and phase separation occurred when all the mixtures were cooled to +7 °C. In engine experiments, the temperature of the emulsion fuel was kept constant at 35 °C with a thermostat. The water content in ethanol is an important problem for diesel-ethanol blends because it increases phase separation [29]. For this reason, ethanol with a purity of 99.9% was used in engine experiments. The E5 fuel was formed with 5% ethanol, 2% isopropanol and 93% diesel for the emulsion method in engine experiments.

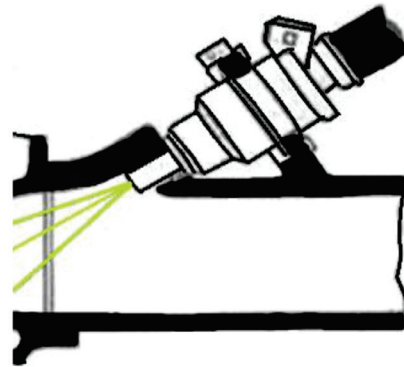


Figure 3. Location diagram of ethanol injector in intake manifold

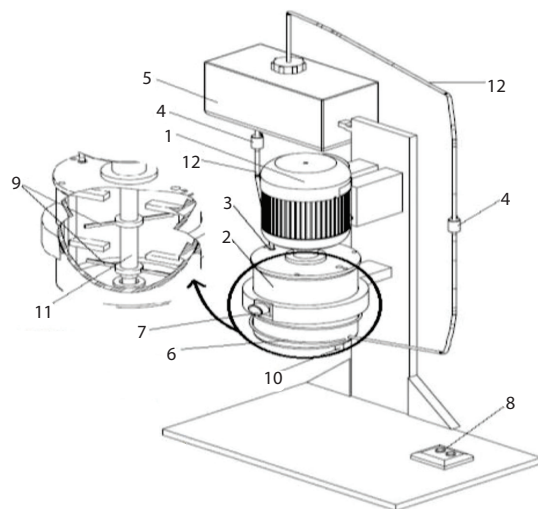


Figure 4. Electric mixer system with temperature control and fuel pump; 1 – AC motor, 2 – mixing chamber, 3 – fuel injection nozzle, 4 – fuel pump, 5 – fuel tank, 6 – heater, 7 – thermostat control, 8 – system control, 9 – blender propeller, 10 – fuel output for main tank, 11 – blender shaft, and 12 – fuel line

For the fumigation method, ethanol with the same properties was used. The low pressure injector was mounted in the area of the intake manifold close to the intake valve, allowing tangential injection the flow direction of the inlet air. Ethanol in the external fuel tank was pressurized by an electric pump and sent to this injector. Reduced instruction set computer based electronic card was developed to control the injector and fuel pump. This card controlled ethanol spraying according to engine speed with the help of a sensor that detects engine speed. In engine experiments, 5% ethanol (EP5) fuel was used for the fumigation method. The all tests were applied with intervals 100 rpm between 1100 rpm 2200 rpm at part-load.

Simulation post injection

The experiment engine model was built using AVL Boost Simulation 2016 V software. In order to verify the model, the simulation model engine power running with diesel fuel and the experimental engine power data were examined on the graph. It was observed that the simulation engine power and the experimental engine power data coincided harmoniously. In order to verify the validity of the calibration of the model, separate models were developed for E0 and EP5 (fumigation method) fuels on the same model engine. Simulation engine power and experimental engine powers were examined on the graph. In the two separate comparisons shown in fig. 5, the engine power data almost overlapped. The overlap of experimental and simulated engine power data showed that the calibration of these models was at an acceptable level.

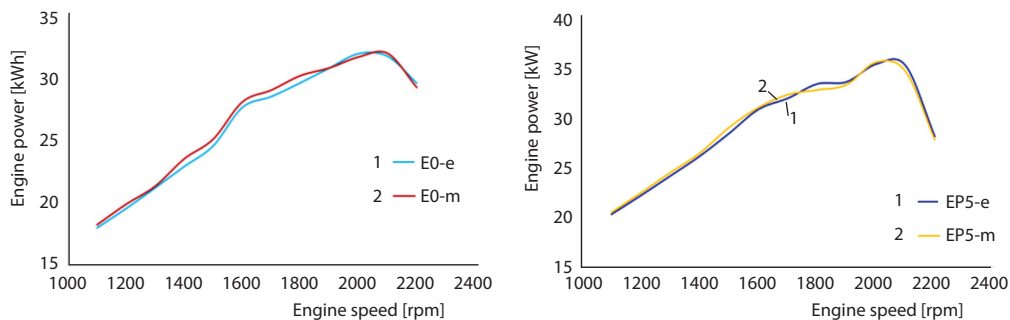


Figure 5. Experimental and simulation engine power difference ratio

Post injection is a small amount of fuel injected after the end of the main injection. Post-injection strategies can be used to reduce harmful emissions. In addition, post-injection simulation tests are also a reliable reference point for the potential impact of experimental studies on performance and emissions. Post injection tests were applied by spraying ethanol in the model engine running only with diesel. After the diesel main fuel was injected, 5% ethanol was injected. The amount of post injection ethanol was used such as the amount of ethanol used in emulsion and fumigation methods. After the diesel main fuel was injected, 5% ethanol was injected in both post-injection strategy. Thus, the total fuel energy amount (diesel ethanol) in the

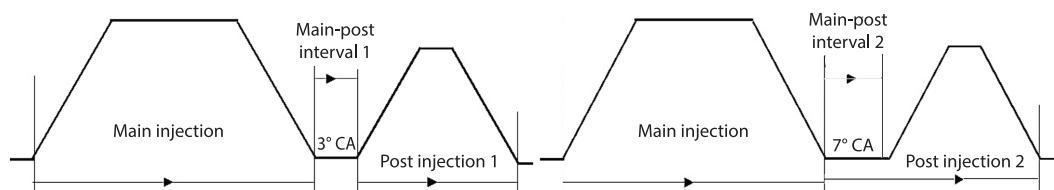


Figure 6. Post injection strategies

three working processes (emulsion-fumigation-post injection) was equal. Two post injection tests were performed separately. Due to the high self-ignition temperature of ethanol, 3° CA and 7° CA displayed in fig. 6 were preferred at the post injection time near the end of the main fuel injection. Because late post injection has a negative effect on HC and CO emissions [30].

Results and discussions

In this section, the experimental results of the effects of E0 (diesel), E5 (5% ethanol blend), and EP5 (5% ethanol) fuels on emission and performance are presented below. Furthermore, the model simulation results of P1 (post injection 1) and P2 (post injection 2) post-injection strategies are given.

Pollutant emissions

The change in NO_x emissions is shown in fig. 7. The NO_x emissions decrease by 5.7% on average with E5 fuel compared to E0 fuel, with an average increased by 13.59% on EP5 fuel. The NO_x emission decreased 5.7% with E5. But with E5 fuel it slightly increased at medium speeds. This increase may be due to the high evaporation temperature and auto-ignition temperature of the blend depending on the proportion of ethanol in the emulsion [31]. Moreover, the binding emulsifier and fuel pyrolysis substances contained in the emulsion can react with nitrogen and increase the concentration of NO_x emission [32]. NO_x emission increased by 13.59% with EP5 fuel in the fumigation method. In the fumigation method, the start of burning of ethanol vapor, which provides a good mixture with the turbocharged intake air in the test engine, before diesel injection can cause the cylinder temperature to increase relatively and the main fuel diesel to burn better. Therefore, NO_x emissions increase due to the temperature increase in the cylinder [33].

In post injection strategies, NO_x emission in general increased due to improved combustion and increased in-cylinder temperature with P1 (1st post injection) and P2 (2nd post injection) strategies. In the P2 strategy, NO_x emissions have increased noticeably, especially at medium and later speeds. The reason for this increase may be a sudden increase in temperature due to the burning of the ethanol sprayed after leaving the main combustion zone a little and the burning of unburned diesel fuel. In post injection strategies, NO_x emission in general increased due to improved combustion and increased in-cylinder temperature with P1 (1st post injection) and P2 (2nd post injection) strategies. In the P2 strategy, NO_x emissions have increased noticeably, especially at medium and later speeds. This increase in NO_x emission after P2 can be a sudden increase in temperature for the cylinder, with the effect of oxygen in ethanol and the re-turbulence movement in the cylinder with ethanol jets injected as combustion continues [34].

Figure 8 shows the changes in soot emission. Soot emission decreased by 36.08% with

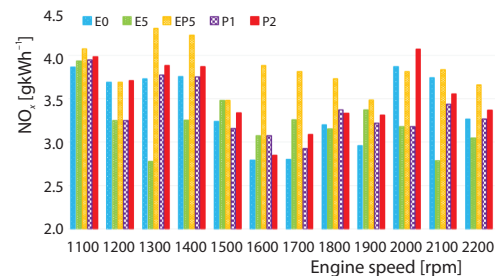


Figure 7. The effect of ethanol on NO_x emissions

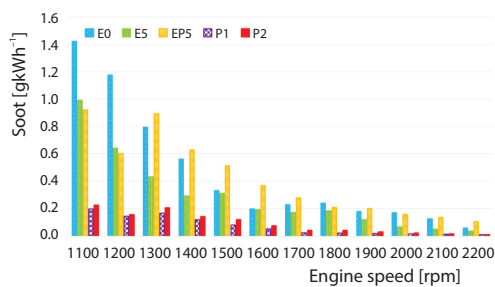


Figure 8. The effect of ethanol on soot emissions

E5 fuel. The soot emission was characteristically reduced as the in-cylinder temperature increased at high engine speeds. However, the reduction in soot emission with EP5 fuel was low. In addition, soot emission increased at medium engine speeds with EP5 fuel compared to diesel fuel.

Soot emission decreased by 84.27% and 80.30%, respectively in the P1 and P2 strategies. In addition, there was about 87% improvement in soot emission in both strategies at high speeds. Since the P1 post injection strategy was closer to the main injection than the P2 strategy, it had more impact on the soot emission. Early post-injection is highly effective in reducing soot emissions due to acceleration of combustion in the last phase [35].

Performance characteristics

Engine power changes are shown in fig. 9 and engine torque changes in fig. 10. Engine torque and power increased with both emulsion and fumigation method. While this increase in engine torque was 2.41% with the emulsion method, it was 10.89% with the fumigation method. The reason for the higher increase in engine power with the fumigation method may be the improvement of diesel combustion due to the combustion of ethanol vapor, which mixes well with the pressurized inlet air. In addition, the use of oxygen-containing fuels has the effect of improving the premix combustion phase and diffusion combustion phase [36]. Engine power and torque increased due to the effect of pure ethanol on combustion in post injection initiatives. The reason why the increase in engine power with the P2 post injection strategy was less than the increase in P1 engine power was that although post injection has a positive effect on turbulence, the temperature inside the cylinder might drop as ethanol absorbs heat until it ignites and may cause negative combustion.

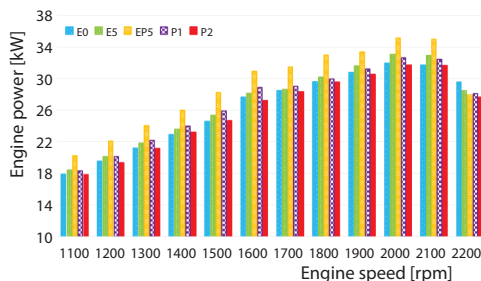


Figure 9. The effect of ethanol on engine power

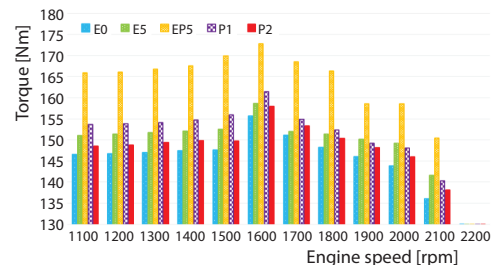


Figure 10. The effect of ethanol on engine torque

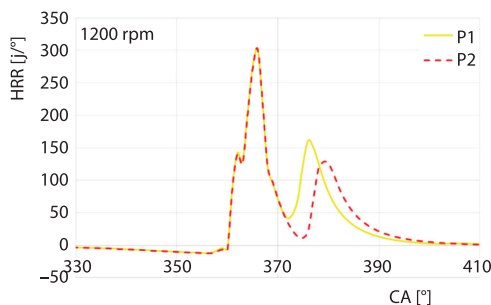


Figure 11. Change of HRR with ethanol post injection at 1200 rpm

The variations of the HRR of P1 and P2 post injections at low, medium and high engine speeds are shown in figs. 11-13. The effect of post injection on HRR is seen with the formation of the second peak. The second peak point of all HRR varied depending on the ethanol spraying time. Although the amount of ethanol sprayed was the same in all post injections, the second peak point decreased in the P2 (after 7 ° CA) strategy, but the duration of the second peak increased.

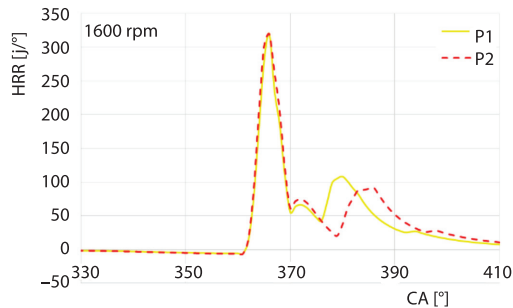


Figure 12. Change of HRR with ethanol post injections at 1600 rpm

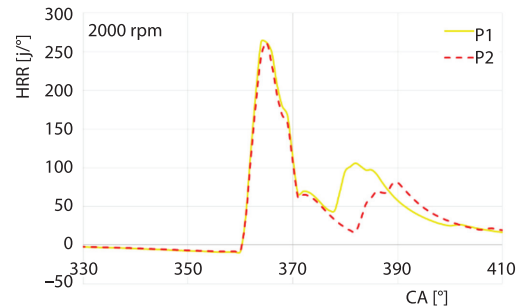


Figure 13. Change of HRR with ethanol post injections at 2000 rpm

Conclusions

In this study, emulsion and fumigation method was used in experiments carried out with ethanol in the Diesel engine. Post injection tests were performed numerically separately at two different times in the AVL Boost 2016v program as 3° and 7° CA after the main injection and the results were obtained as follows.

- It was observed that the formation of ethanol and diesel emulsions at 30-35 °C significantly prolonged the phase separation and transition time to heterogeneous crystal structure.
- The ECU to control the ethanol injector in fumigation method can be developed easily and cost-effectively with arduino.
- The emulsion method is advantageous in terms of reducing pollutant emissions.
- Injecting ethanol as post-injection fuel after diesel main injection contributed to improving engine performance and pollutant emissions. Also, P1, whose post injection time was close to the main injection, improved the soot emission.
- Injecting ethanol as post-injection fuel after diesel main injection contributed to improving engine performance and pollutant emissions. In addition, P1, whose post-injection time was close to that of the main injection, improved soot emission more than P2.
- The developed model and multi injection method can be used to as an important reference point for ignition delay, engine performance and possible chemical effects on emissions values.

Nomenclature

CA – crank angle, [°]
 CI – compression ignition
 HRR – heat release rate

PM – particulate matter
 P1 – post injection 1
 P2 – post injection 2

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