EFFECT OF CETANE IMPROVER ADDITION INTO DIESEL FUEL Methanol Mixtures on Performance and Emissions at Different Injection Pressures

by

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In this study, methanol in ratios of 5-10-15% were incorporated into diesel fuel with the aim of reducing harmful exhaust gasses of Diesel engine, di-tertbutyl peroxide as cetane improver in a ratio of 1% was added into mixture fuels in order to reduce negative effects of methanol on engine performance parameters, and isobutanol of a ratio of 1% was used as additive for preventing phase separation of all mixtures. As results of experiments conducted on a single cylinder and direct injection Diesel engine, methanol caused the increase of NO_x *emission while reducing CO, HC,* CO_2*, and smoke opacity emissions. It also reduced torque and power values, and increased brake specific fuel consumption values. Cetane improver increased torque and power values slightly compared to methanol-mixed fuels, and reduced brake specific fuel consumption values. It also affected exhaust emission values positively, excluding smoke opacity. Increase of injector injection pressure affected performances of methanol-mixed fuels positively. It also increased injection pressure and* NO_x *emissions, while reducing other exhaust emissions.*

Key words: *engine performance, exhaust emissions, methanol, cetane improver, Diesel engine*

Introduction

Climate changes caused by global warming and negative effects of these changes have become primary problems of our day [1]. Developed countries seek for solutions with crucial agreements such as international United Nations Framework Convention on Climate Change, Vienna Convention for the Protection of the Ozone Layer, Convention on Long-Range Transboundary Air Pollution, and Kyoto protocol. Again, due to energy requirements increasing along with the increase of world population, increase in air pollution can be slowed down, yet can not be stopped.

Overall air pollution is caused by motor vehicles with a ratio of 47%, industries of 19%, thermal power-plants of 18%, and residences of 16% [2]. Use of motor vehicles in land, air and navigation transport is constantly increasing. This situation has directed researches into conducting studies for decreasing vehicle-derived pollutants. Diesel engines are commonly

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used in cargo carrier vehicles and larger engineering vehicles particularly due to economic fuel consumption and high efficiency.

There are a number of structural studies conducted on particularly fuel system for reducing polluting emissions resulting from Diesel engines as well as comprising Diesel engine fuels. These studies can be examined as fuels capable of substituting petroleum-derived diesel fuel and as additives to petroleum fuel. There are varieties of additives that can be used as additive for diesel fuel. Alcohols that are commonly used in particularly spark ignition engines have been used as additives in compression ignition engines as well. Ethanol and methanol are the most commonly used diesel fuels for being economical.

A number of automotive companies and environment protection institutions accepted that methanol is the one with the highest popularity among alternative alcohol fuels [3, 4]. One of greatest reason for this can be ranked as production of methanol from a variety of substances, its low cost compared to alternative fuels and causing a cleaner combustion. In addition, it can be produced from a number of substances and can cost less than almost all alternatives [5, 6].

Methanol can be used by mixing with diesel fuel in a certain ratio as it has profoundly low cetane number (CN). In the literature, there are studies on the effect of methanol addition into diesel fuel on performance and emission parameters of Diesel engines. Wang *et al.* [7] examined combustion characteristics by sending vaporized methanol into inlet manifold of a Diesel engine. At the end of the analyses, maximum cylinder pressure (MCP) decreased, maximum heat release rate (MHRR) increased and cylinder temperature decreased on low loadings. On high engine loadings, increase was seen in all three values. Chen *et al.* [8] examined combustion characteristics of diesel fuel – methanol mixtures, and revealed that methanol caused increase of MCP values, MCP values increased further with the increase of methanol amount within fuel. Wei *et al.* [9] injected methanol into inlet manifold of a Diesel engine, and revealed effects of manifold. According to test results, methanol caused the increase of MCP and MHRR values, prolonged ignition delay period and shortened combustion period. In addition, it caused decrease of exhaust gas temperature, T_{ex}, and thermal efficiency values. Moreover, methanol reduced HC and CO emissions, and reduced NO_x and soot emission. In their study, Liu *et al.* [10] revealed that methanol caused the increase of CO and HC emissions, decrease of NO_x and smoke emissions, slight increase of brake specific fuel consumption (BSFC) and a remarkable increase in MCP values as a result of tests performed by adding high ratios of methanol (42-50%) into diesel fuel. Pan *et al.* [11] examined combustion characteristics and emission parameters of diesel fuel-methanol blends in a Diesel engine. Consequently, they showed that methanol addition caused increase of MCP and MHHR values, decrease of NO_x and soot emissions, and increase of HC and CO emissions. In their study, Geng *et al.* [12] examined effects of methanol addition into diesel fuel in different ratios on combustion characteristics and particular matter (PM) emissions. As a result, they exhibited that methanol caused decrease of PM amount at low and intermediate loadings and increase at high loadings. They again revealed that methanol caused increase of MHRR and further increase of MHRR along with increase of methanol ratio within the mixture. Ruina *et al.* [13] incorporated 2-ethylhexyl nitrate, cyclohexyl nitrate, and 2-methoxyethyl ether individually in a ratio of 0.3% as cetane improver, C_{IMP}, into diesel fuel – methanol blend comprising 10% methanol. As a result, they revealed that C_{IMP} caused increase of MCP and MHRR and decrease of NO_x and smoke emissions while it caused increase of HC and CO emissions, and exhaust gas temperature and thermal efficiency values were close to those of diesel fuel. Huang *et al.* [14] examined on the performance and emissions of the diesel--methanol blend at different the fuel delivery advance angles. They presented that the engine thermal efficiency increases and the diesel equivalent BSFC decreases with increase in the methanol mass fraction of the diesel-methanol blends. However, increase in the fuel delivery advance angle will achieve a better engine thermal efficiency when the Diesel engine is operated using the diesel-methanol fuel blends. According to test results, CO and smoke emissions decreased, there is not a large variation in HC emission and NO_x emission increased with using methanol. Huang *et al.* [15] examined on the combustion characteristics and heat release analysis of the diesel-methanol blend at different the fuel delivery advance angles. As a results, methanol increased MHRR, ignition delay, maximum rate of pressure rises and MCP values.

This study is aimed to provide comprehensive experimental data on the effect of adding methanol on the emissions and performance of a Diesel engine. Cetane improver used for minimize to negative effect on CN of methanol. There are numerous works related diesel-methanol blends and cetane improver. The present study is contained effects of different IP (IP) in addition to previous studies. In this study, firstly effect of methanol on engine performance and exhaust emissions was examined. Secondly, effect of C_{IMP} addition into diesel-methanol fuels was investigated. Lastly, performance and emission parameters of all test fuels were examined at different injector, IP.

Materials and methods

Test engine and fuels

Four-stroke, direct injection and water-cooled engine given to specifications in tab. 1 was used in the tests.

Petroleum derived euro diesel (PED) fuel was used as the main fuel in the tests. Industrial methanol added into PED had 99% purity, and was supplied from a local company. Isobutanol was used in the test in order to enable homogeneity of PED-methanol blends and prevent phase separation. As methanol added into PED decreased CN value, di-tertbutyl peroxide (DTBP) was used as C_{IMP} for the mixtures. The blends occurred from 5-10% and 15% methanol. The DTBP added 1% for each blend. All blend fuels contained 1% isobutanol. The features of blend fuels constituted by mixing these fuels are given in tab. 2.

Table 1. The specifications of test engine

Engine model	Superstar
Engine type	4-stroke direct injection
Cylinder number	1
Total cylinder volume [cm^3]	0.77
Stroke, [mm]	100
Compression rate	17:1
Maximal engine power [$kWmin^{-1}$]	6.62 kW (9 HP) at 1800 rpm
Maximal engine speed [min^{-1}]	2300
Cooling system	Water cooled
Injection angle [°CA]	28-35 °CA
Injection pressure [bar]	175

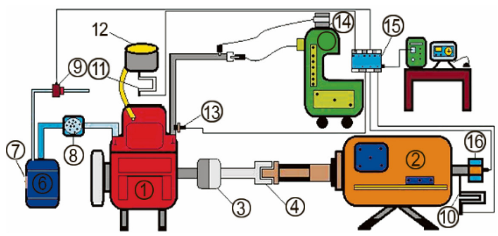

Figure 1. Schematic of the test equipment
1 – test engine, 2 – hydraulic dynamometer, 3 – coupling, 4 – shaft, 5 – gas analyzer, 6 – air balance tank, 7 – orifice plate, 8 – inlet air filter, 9 – differential pressure sensor, 10 – load cell for torque, 11 – load cell for fuel consumption, 12 – fuel tank, 13 – PT100, 14 – opacimeter, 15 – data acquisition, 16 – speed sensor

Test apparatus

The experiments were carried out in a test arrangement shown schematically in fig. 1. In the tests, 450 Nm capacity hydraulic dynamometer was used for loading of engine, CAS model SBA 200L load-cell for measuring torque, CAS (model BCL-1L load-cell capable

Table 2. Some fuel properties of test fuels

	M0	M5	M10	M15	M5DBTP	M10DBTP	M15DBTP
Density [kgm^{-3} at 15 °C]	841.5	840.8	841.2	841.6	841.3	841.9	842.2
Kinetic viscosity [mm^{2}s^{-1} at 40 ° C]	3.20	3.05	3.08	3.17	3.14	3.15	3.19
Cold point [°C]	–9.8	–9	–8.7	–7.9	–9.2	–9.3	–9
Cold filter plugging point [°C]	1	1	–5	–9	–10	1	–9
Corrosion of Cu 3 h [50 °C]	1 a	1 a	1 a	1 a	1 a	1 a	1 a
LHV [calgr^{-1}]	46.49	45.21	44.92	44.64	45.18	44.90	44.06
Water content [ppm]	16.07	232.6	144.3	63.92	23.50	24.42	22.65

of measuring time-dependent fuel amount difference for fuel consumption, and Bosch BEA-350 and MRU optima 7 for exhaust gas measurements. Accuracies of all the measurements and the uncertainties in the calculated results are shown in tab. 3.

Table 3. Accuracies of the measurements and the uncertainties in the calculated results

	Accuracy	Uncertainty	
Fuel weight [g]	±0.01	–	
Engine speed [rpm]	±1%	–	
Load [g]	±1	–	
Engine torque [Nm]	–	±0.20%	
Engine power [kW]	–	±0.31%	
Fuel consumption [gs^{-1}]	–	±0.66%	
BSFC [gkW^{-1}h^{-1}]	–	±1.14%	
BTE [%]	–	±0.27%	
Bosch BEA 350	Accuracy	MRU optima 7	Accuracy
CO [vol.%]	±0.001	CO [ppm]	±20
CO_2 [vol.%]	±0.01	CO_2 [vol.%]	±0.05
HC [ppm]	±1	NO_x [ppm]	±5
Smoke opacity [vol.%]	±0.01	T_{ex} [°C]	±2

Test method

The tests were performed in Automotive Laboratory of Aksaray University, Aksaray, Turkey. The tests were firstly performed for all test fuels at 175 bar pressure being standard injector IP. Afterwards, tests were performed at 170 and 165 bar IP, respectively, by descending 5 by 5 units. Engine works very irregularly below 165 bar pressure. Then, tests were performed at 185 and 195 bar IP, respectively, by ascending 10 by 10 units. Engine could not operate above 195 bar IP. Therefore, the tests for all test fuels and IP were performed with 200 rpm intervals between 1000-2000 rpm by changing engine load when the engine was in full gas position. The CO, HC, CO_2, and NO_x emissions were converted into [$gkW^{-1}h^{-1}$] unit as in the study of Pilusa *et al.* [16].

Result and discussion

All test results were presented firstly as results obtained with the original IP, 175 bar, and then as the results in engine speeds obtaining maximum engine torque and maximum engine power.

Engine performance

Figure 2 can show engine torque and power changes of PED and mixture fuels at original injector IP. Maximum engine torque value for all fuels was obtained at an engine speed of 1600 rpm. As seen in fig. 2, methanol caused the decrease of engine torque values, and torque values decreased down to approximately 17.3% on average with the increase of methanol ratio within the mixture. Increase was seen in engine torque values with DBTP addition into the mixtures of approximately 6.44% on average compared to M5 fuel, approximately 12.18% on average compared to M10 fuel, approximately 7% on average compared to M15 fuel. The fact that methanol caused the decrease of engine torque values can be explained by the fact that lower heating value (LHV) of methanol was lower than that of PED, that it lowered combustion energy and that methanol led to a bad combustion by prolonging ignition delay [7] by lowering CN. These results show similarity with the results revealed in [17-19].

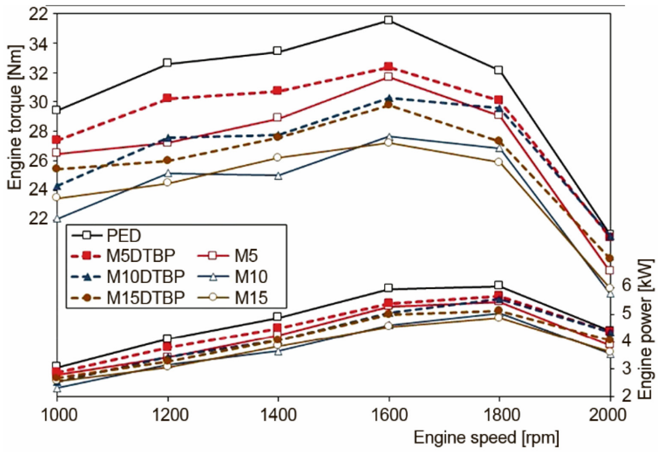

Figure 2. Engine torque and power values at 175 bar of IP

As can be seen from the figure, maximum power was obtained at 1800 rpm engine speed. The main reason for low power in methanol addition may be its having lower LHV. Also, as can be seen from tab. 2, methanol caused the decrease of viscosity and density of the mixture fuels. As lowering of fuel viscosity causes pumping and injection losses, maximum fuel distribution within the cylinder failed and combustion worsened. Furthermore, engine power decreased as fuel amount taken in a unit time inside the cylinder was reduced due to the fact that decrease of fuel density caused less fuel injection in the cylinder as mass. Similar results were also revealed in studies of Guo *et al.* [17] and Yilmaz [20].

Maximum engine torque and power change of the test fuels at different injector IP is given in fig. 3. Increase of IP can homogeneously distribute into air as it lessened droplet diameter of sprayed fuel, thereby increasing combustion performance. Maximum torque values

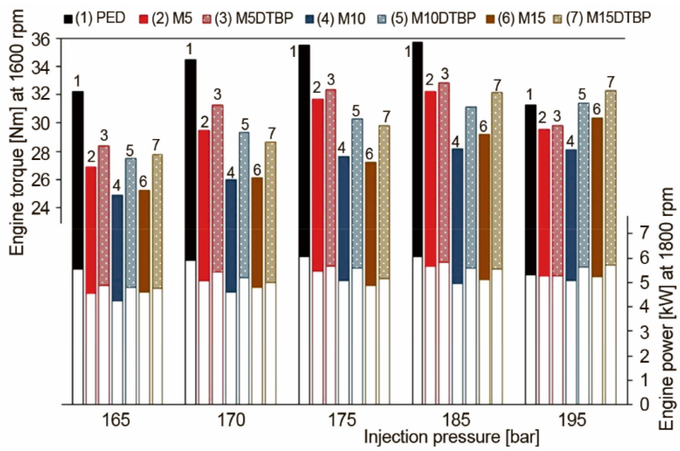

Figure 3. Variations of maximum torque and power values at different IP

of PED, M5, M5DBTP, and M10 fuels were obtained at 185 bar IP while maximum torque values of M10DBTP, M15, and M15DBTP fuels were obtained at 195 bar IP. The fuel gets more atomized with increase of IP for fuels with high methanol content and it exhibited a better combustion performance thanks to C_{IMP}. It is seen that increase in IP affected methanol-containing fuels positively. The fact that PED, M5, and M5DBTP fuels provide lower engine power at 195 bar IP may be explained with the inability to use the air in the cylinder walls with decrease of inertia of fuel droplets in combustion chambers of which diameters are reduced with increasing pressure.

Figure 4 shows BSFC and brake thermal efficiency (BTE) changes of test fuels at 175 bar IP. Methanol addition into the mixtures caused the increase of BSFC values, and BSFC values increased more as methanol ratio within the solution increased. On mixture with PED fuel, BSFC values obtained with M5, M10, and M15 fuels increased for approximately 4.43, 9.54, and 16.76% on average, respectively. The used C_{IMP} caused the decrease of BSFC values for approximately 2.1% on average compared to M5 fuel, approximately 1% on average compared to M10 fuel and approximately 3.26% on average compared to M15 fuel. The fact that methanol caused the decrease of LHV caused the increase of BSFC values of the mixture fuels. In addi-

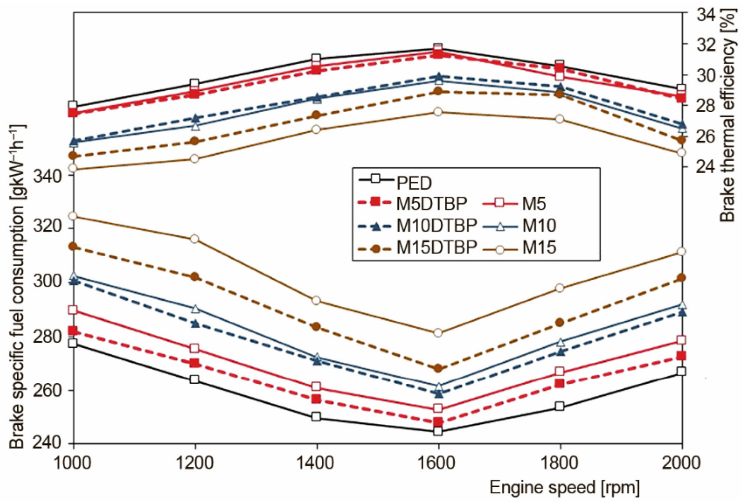

Figure 4. The BSFC and BTE values at 175 bar of IP

tion, high heat of vaporization of methanol led slower distribution of the fuel into the air via slower vaporization and increased BSFC by affecting combustion negatively [17, 18, 20, 21].

Figure 5 shows BSFC and BTE values obtained at different IP at maximum torque and power revolutions. Methanol-mixed fuels affected BSFC values at different IP with C_{IMP} addition.

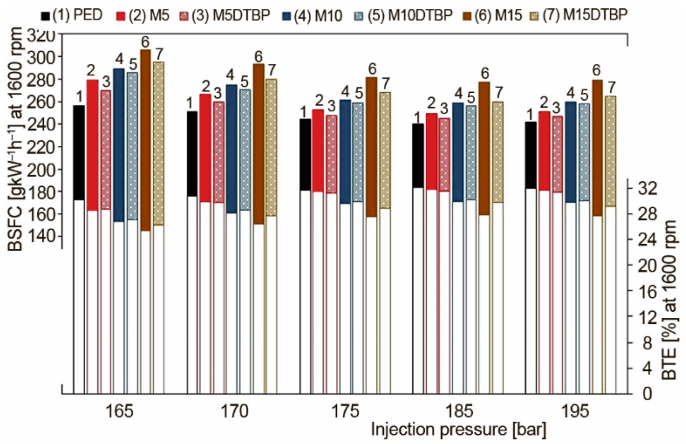

Figure 5. Variations of BSFC and BTE values at different IP

Exhaust emissions

Temperature of exhaust gasses inside the combustion cylinder is one of the most important parameters affecting the exhaust emissions. Exhaust gas can be changed in accordance with fuel features and engine operation parameters. Change of exhaust gas temperature, T_{ex}, and smoke opacity values with engine speed at 175 bar IP is shown in fig. 6. Methanol addition into PED fuel caused the increase of gas temperature, and exhaust gas temperature value increased up to 9% as methanol ratio within the mixtures increased. Exhaust gas temperature values increased more with DBTP addition. Exhaust gas temperature values increased with the fact that methanol decreased CN and prolonged ignition delay period in addition to beginning of more fuel combustion.

The main reason for formation of smoke opacity is that there is not sufficient oxygen inside the cylinder during combustion. In addition, low vaporization speed of the fuel also

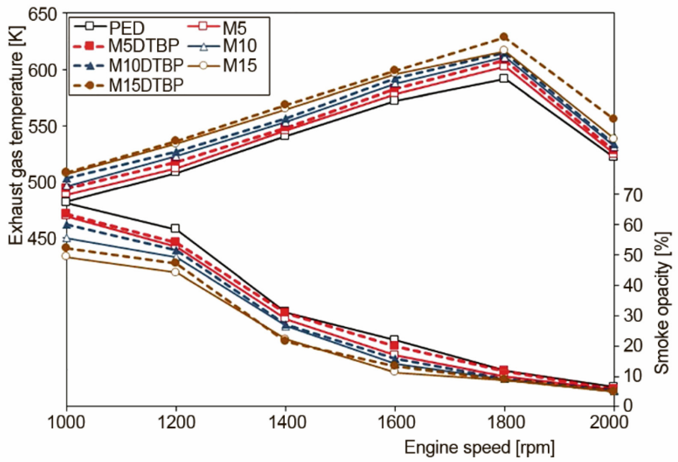

Figure 6. Exhaust gas temperature and smoke opacity values at 175 bar of IP

caused increase of smoke opacity. Methanol enabled the decrease of smoke opacity values of the mixture fuels down for 29.6% on average due to its oxygen content and having better volatility. The C_{IMP} addition increased CN and increased smoke opacity for approximately 5% on average as it prolonged combustion period. Authors in [22-24] revealed similar results in their studies relating to methanol.

Exhaust gas temperature, T_{ex}, and smoke opacity change based on IP at 1600 rpm and 1800 rpm engine speeds is shown in fig. 7. Increase in injector IP caused the fuel to be more atomized and combustion efficiency to enhance, thereby increasing exhaust gas temperature. Increase in IP led to cleaner combustion and lower smoke opacity as it enabled more homogeneous air-fuel mixture. High methanol addition decreased smoke opacity at all IP.

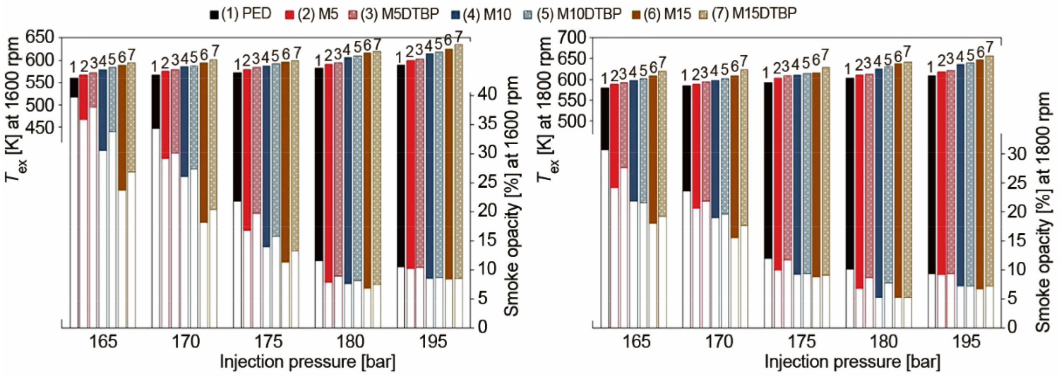

Figure 7. Variations of T_{ex} and smoke opacity values at different IP

Change of CO and CO_2 emission values based on engine speed is presented in fig. 8. Methanol lessened formation of CO emission thanks to oxygen in its content as CO emission formation is largely dependent on oxygen amount taken inside the cylinder. Carbon atoms reacting as a result of combustion are turned into CO_2 by taking sufficient oxygen thanks to oxygen within methanol. As methanol ratio within the mixture increased, CO emission values decreased down to approximately 29.33% on average. Some decrease was seen in CO emissions with DBTP addition. Authors in [17, 18, 21] revealed similar results in their studies.

Increase of methanol ratio within the mixture caused the decrease of CO_2 values. It even decreased DBTP, CO_2 emissions down to 29% on average compared to PED fuel. Less carbon atom inclusion of methanol compared to PED caused lower CO_2 emission release. The results obtained show similarity with results of [25, 26].

The CO emission data obtained at 175 bar and 185 bar IP were very close. The lowest CO emission values for methanol-mixed fuels were obtained at 185 bar IP. This result shows that combustion efficiency of the mixture at 185 bar pressure was better. The CO and CO_2 emissions changes at different IP are presented in fig. 9. Methanol decreased CO_2 emissions at all pressures compared to PED. The lowest CO_2 emission value at 1600 rpm and 1800 rpm engine speeds was obtained at original IP.

The HC and NO_x emissions presence in combustion products shows that the fuels were not completely burned. Figure 10 shows changes of test fuels at 175 bar IP. Less hydrogen atom inclusion of methanol compared to PED enabled a poor mixture by increasing air-fuel ratio value of oxygen within methanol, and the fact that methanol had higher exhaust gas temperature compared to PED caused the decrease of HC emissions for approximately 44.38%. This decrease was enhanced up to approximately 48.6% on average with

DBTP addition. Authors in [17, 19, 21, 27] also revealed that methanol caused the decrease of HC emissions.

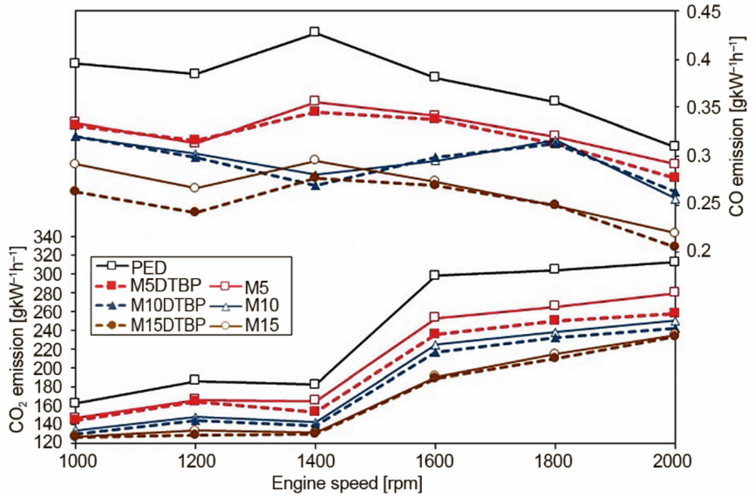

Figure 8. The CO and CO_2 emission values at 175 bar of IP

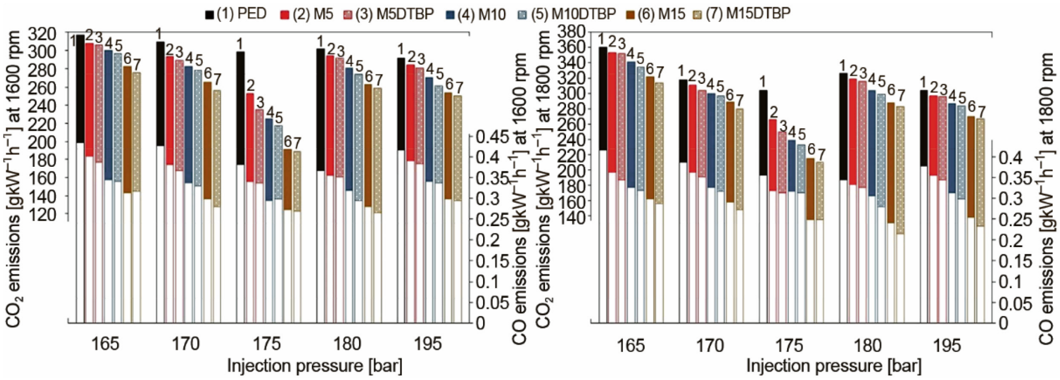

Figure 9. The CO and CO_2 emission values at different IP

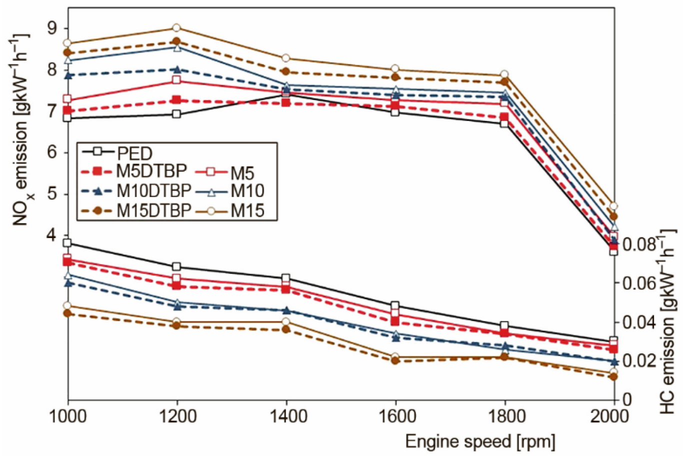

Figure 10. The HC and NO_x emission values at 175 bar of IP

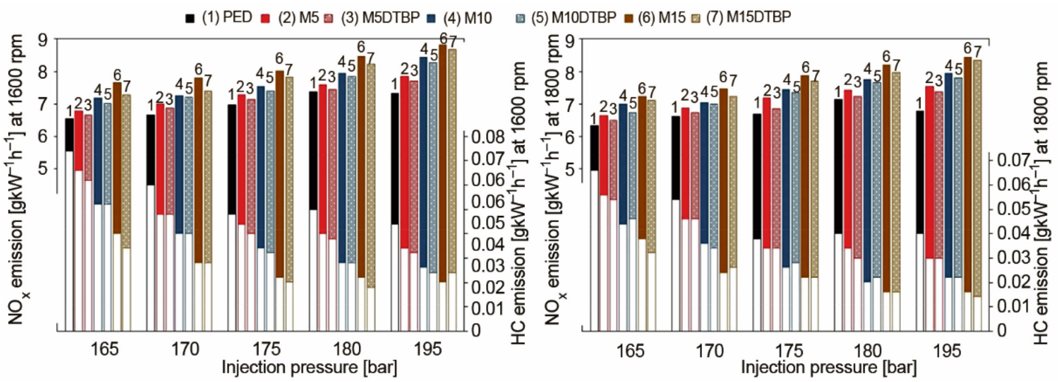

Figure 11. The HC and NO_x emission values at different IP

The nitrogen and oxygen atoms react at high temperatures and cause NO_x emission on discharge into atmosphere. Increase in exhaust gas temperature led to the increase of NO_x values in methanol-mixed fuels. The NO_x values of high methanol-containing mixtures exhibited approximately up to 22% increase on average compared to PED. Moreover, oxygen inclusion of methanol revealed more oxygen with which nitrogen atoms can react. The C_{IMP} improved combustion by increasing CN and enabled reaction of oxygen with carbon and hydrogen atoms, thereby leading to decrease of NO_x emissions [21, 28, 29].

Figure 11 shows the effect of different IP on HC and NO_x emissions of methanol. Increase of IP enabled the fuel to get more atomized and further distribution into air and led to decrease of HC emissions by improving combustion. With the increase of IP, HC emission values of methanol-mixed fuels decreased compared to PED. Increase in injector IP increased NO_x emissions due to increasing exhaust gas temperature. Both increase of IP and increase of methanol ratio within the mixture led to more increase of NO_x emissions.

Conclusions

The test results obtained can be examined under three different headings: effects of methanol on performance and emission parameters, effects of C_{IMP} addition into PED-methanol mixtures, and evaluation of data obtained from the test fuels at different IP.

- Methanol addition into PED fuel affected engine torque, engine power and BSFC values negatively. One of the main reasons for this was that low LHV possessed by methanol lowered the energy resulting from combustion. Other reasons were that low viscosity of methanol increased pumping and injection losses, that low density of methanol caused less fuel in mass to cylinder and that the fuel was vaporized slower due to high heat of vaporization of methanol.
- The fact that methanol increased exhaust gas temperatures of mixed fuels also caused the increase of NO_x emissions. Moreover, methanol decreased CO, CO_2, HC, and smoke opacity emissions thanks to clean combustion with its low carbon atom content and high volatility.
- The DBTP addition into PED-methanol mixtures increased CN, thereby prolonging ignition delay period. This affected combustion positively and improved engine performance parameters. The C_{IMP} addition had positive effects on all emissions, excluding smoke opacity.
- Increase of injector IP increased combustion efficiency due to enabling shrinking droplet diameter of the fuel and making it more atomized. This enables more homogenous mix-

ture of the fuel with air, thereby enhancing combustion efficiency and affecting engine performance parameters positively. Particularly better performance values were obtained at 185 bar IP. Increase of IP affected engine performance positively in methanol-mixed and C_{IMP}-supplemented fuels. As increase of IP increased gas temperature, it caused further increase of NO_x emissions. Moreover, increase in IP affected other emissions positively.

Consequently, methanol usability for reducing air pollution resulting from Diesel engines is suitable. Negative effects of methanol on engine performance parameters despite generally decreasing harmful exhaust gasses have been remarkably eliminated with C_{IMP} addition into methanol-mixed fuels and increase of IP.

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