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Review

Effects of Boron Additive to Engine Fuels and Oils on Combustion, Performance and Emissions of Internal Combustion Engines

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Abstract: Most of internal combustion engines (ICEs) use fossil fuels which are estimated to finish in near future. Researchers are investigating ways to improve existing fuels performance one hand while trying to find alternative fuels to petroleum fuels on the other hand. Mainly studied subject by ICEs is to ensure efficient combustion of fossil fuels and reduce petroleum fuels consumption and emissions. Best practical and economical method to achieve this is using various fuel additives. Boron is considered as a promising additive for fossil fuels. Boron is extremely explosive and flammable when meeting the certain conditions and no gas emission is emitted unlike conventional fuels as a result of this exothermic reaction. Due to these beloved features, studies have been performed since 1950s by boron as an alternative fuel. However, specially designed combustion system and pure oxygen are desired for using pure boron. Boron also seems promising additive for improving combustion of fossil fuels due to its higher energy density. It can increase efficiency and reduce fuel consumption and emissions when added to fuels. Advances in nanotechnology facilitated boron addition into fuels and oils. This study investigated effects of boron addition into fuels and oils on combustion, performance and emissions.

Keywords: Internal Combustion Engine; Boron Additive; Combustion; Engine Performance; Emissions

1. Introduction

Petroleum fuels have been used widespread in internal combustion engines (ICEs). However, fossil fuel resources are limited and atmosphere and environment are significantly polluted due to burning of these fuels though harmful emissions were substantiality limited by legal restrictions in recent years [1–4]. Hence, researchers are working intensively on alternative fuels that will replace with petroleum fuels in future. Alternatively, studies on fuel additives are ongoing to improve fossil fuels properties and reduce emissions [5–8]. Boron is thought a promising fuel in future and it can be suitable additive for fossil fuels. Boron has potential to increase amount of energy released during combustion due to its high energy content [9–11]. It is also stated that boron can increase combustion efficiency and reduce harmful emissions when it is added to conventional fuels [12–15]. Boron particles were firstly used as a fuel additive in rocket development studies between 1950–1970 and it was determined that boron particles could significantly increase fuel energy content but there were problems with ignition, flame stability and flame extinction for boron–doped fuel combustion [15–18]. Boron–containing fuel and oil additives are commercially produced and widely sold in market nowadays through developments in nanotechnology. However, comprehensive research is required to determine whether these additives provide claimed positive effects by manufacturers. The aim of this review study is to examine effects of adding boron–containing additives to commercial engine fuels or engine oil on combustion, performance and emissions of ICEs. Thus, it is thought that effects of boron–containing additives can be generalized and created an infrastructure for future studies by evaluating together the results of studies in the literature.

2. Literature on Boron

There are not abundant studies in literature on using boron as a fuel or an oil additive in ICEs to examine its effects on combustion, performance and emissions. It is thought that high prices of pure nano sized boron have an impact on shortage of studies. Thus, the other economical boron containing additives were used instead of pure boron in most of studies. On the other hand, specially designed combustion system and pure oxygen for combustion of pure boron are desired [16–18]. Pure boron or boron–containing additives were used as an additive in gasoline [1, 20–22], methanol (M) [24], ethanol (E) [6, 25, 26], methanol–gasoline blends [27, 28], ethanol–gasoline blends [24, 27–29], diesel fuel [12, 23, 29–34], diesel–biodiesel blend [31], diesel–natural gas (CNG) dual fuel [32], diesel–biogas (BG) dual fuel [33], JP5 fuel [34], marine gas oil [23] and engine oil [2–4, 13, 14, 35–38] in the papers in the literature. The effects of boron additive on friction, wear, lubrication, combustion, performance and emissions were examined in the performed researches. The present review study aims to evaluate together the results of the studies conducted on boron additives to fuels and oils in order to express the practical applications and guide future studies.

3. Effect of Boron Additive on Combustion

3.1. Effect of Boron Additive to Fuels on Combustion

Küçükosman et al. [21] experimentally investigated combustion characteristics of fuel droplets which obtained with addition 2.5% various materials containing boron (B) nanoparticles i.e., amorphous boron (AB) having 87% and 96% purity, aluminum dodecaboride (AlB_{12}) and magnesium diboride (MgB_2) and aluminum (Al) nanoparticles to gasoline. A high speed camera and thermal camera were used in the study. It was determined that all materials including boron particles increased maximum flame temperature as seen in **Figure 1a**. It was declared that this was due to high energy content of boron. It was also determined that flame speed increased slightly as seen in **Figure 1b** and flame extinction time was shortened as seen in **Figure 1c** when used additives AB having 96% purity and MgB_2. It was also reported that materials including boron nanoparticles generally shorten ignition delay time and using Al and magnesium (Mg) nanoparticles with boron can contribute to combustion improvement.

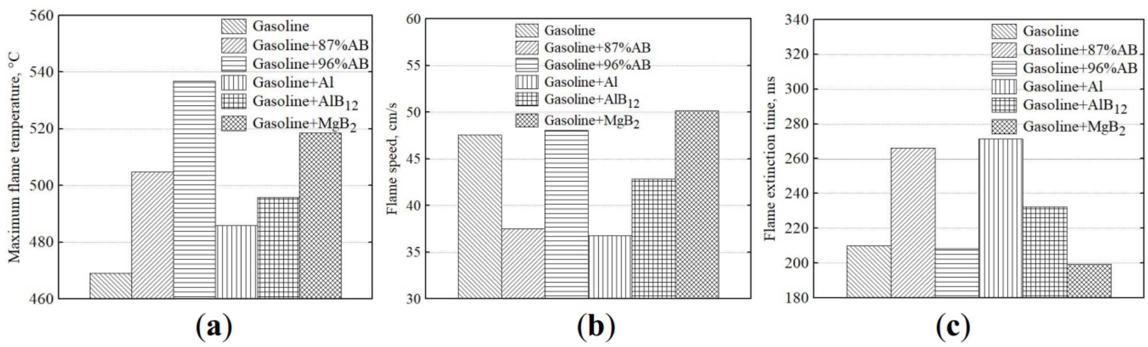

Figure 1. Effects of using various boron including additives in gasoline on (**a**) maximum flame temperature; (**b**) flame speed; and (**c**) flame extinction time [21].

Yontar et al. [39] experimentally examined combustion characteristics of fuel droplets of gasoline, diesel fuel and trimethyl borate (TMB–[$(CH_3O)_3B$]) and triethyl borate (TEB–[$B(OCH_2CH_3)_3$]) which including boron, hydrogen (H) and oxygen (O). It was observed that flame structure of gasoline and diesel fuel droplets was brighter and larger than TMB and TEB fuels. It was determined that boron containing fuels had higher maximum flame temperature and burn rate constant as seen in **Figure 2a,b**. It was also determined that ignition delay time and flame extinction time were shortened when using boron including fuels as seen in **Figure 2c,d**. It was stated that this was due to improvement of combustion via TMB and TEB fuels caused by the presence of oxygen in chemical structure. It was also determined that TMB had higher maximum flame temperature and burn rate constant and shorter ignition delay time and flame extinction time than TEB.

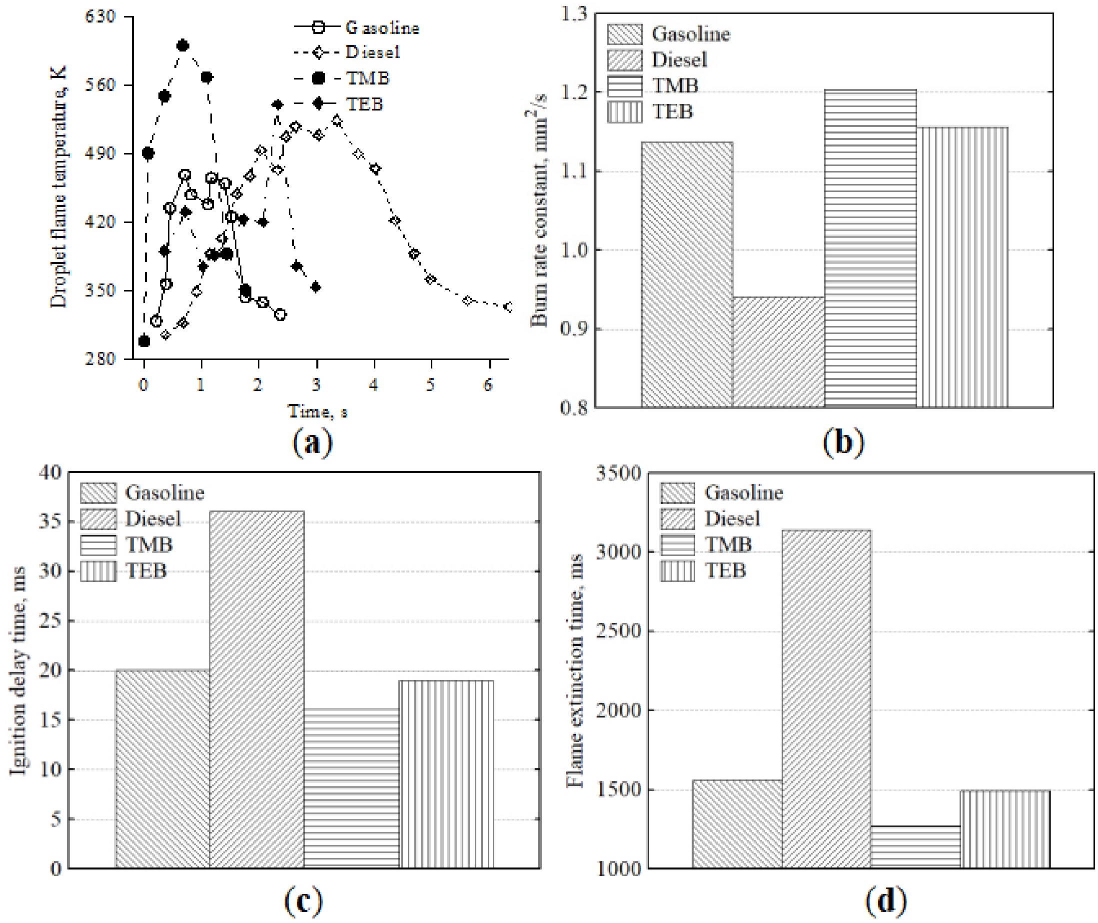

Figure 2. Variation of (**a**) flame temperature; (**b**) burn rate constant; (**c**) ignition delay time; and (**d**) flame extinction time for gasoline, diesel, TMB and TEB fuels droplet [39].

Gültekin et al. [19] experimentally examined effects of TMB addition to gasoline on combustion, performance and emissions. It was determined that combustion began earlier and heat release rate values reduced when TMB was added to gasoline except for engine load of 25% ss seen in **Figure 3a–d**. It was declared that lean fuel–air mixture was sourced from entering a small amount of fuel to the cylinder at 25% engine load caused delayed combustion and sudden heat release. **Figure 4a–d** shows the variation of cylinder pressure at different engine loads when various amounts of TMB were added to gasoline. It was determined that lower maximum cylinder pressure values were formed for all fuel blends due to less fuel sent to the cylinder at low loads but it was determined that maximum cylinder pressure increased as load raised as seen in the figures. It was reported that highest maximum cylinder pressure of 30.51 bars was achieved with pure gasoline at 100% load. It was also determined that adding TMB to gasoline reduced maximum cylinder pressure and decreases in pressure increased by rising TMB ratio. Conversely, it was determined that combustion was slightly delayed at low load (25%) but combustion occurred earlier as load increased. It was stated that this was due to accelerating of combustion due to hydrogen and oxygen in TMB.

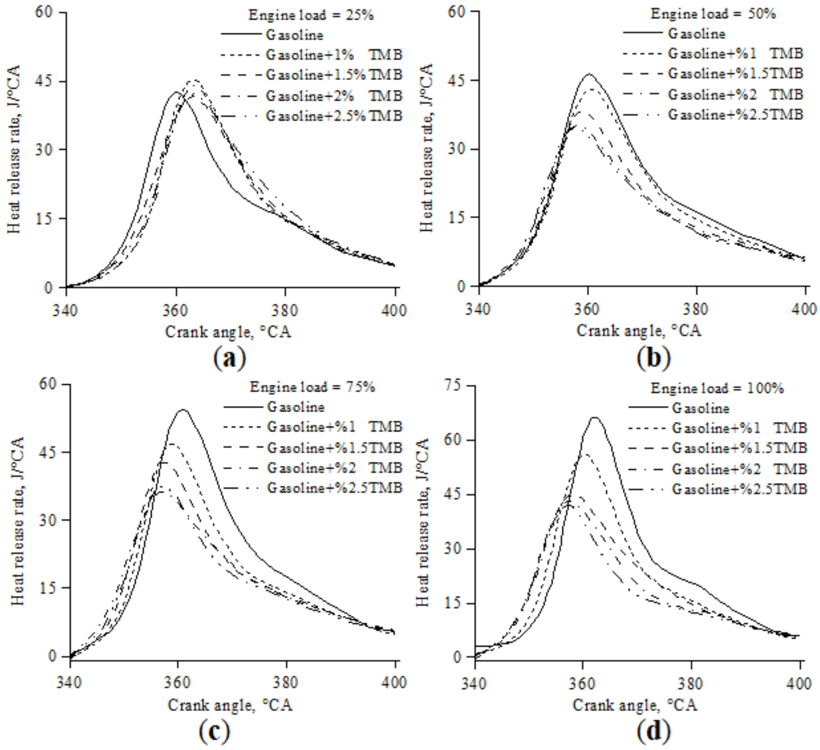

Figure 3. Variation of heat release rate for addition of TMB to gasoline with engine load of (**a**) 25%; (**b**) 50%; (**c**) 75%; and (**d**) 100% [19].

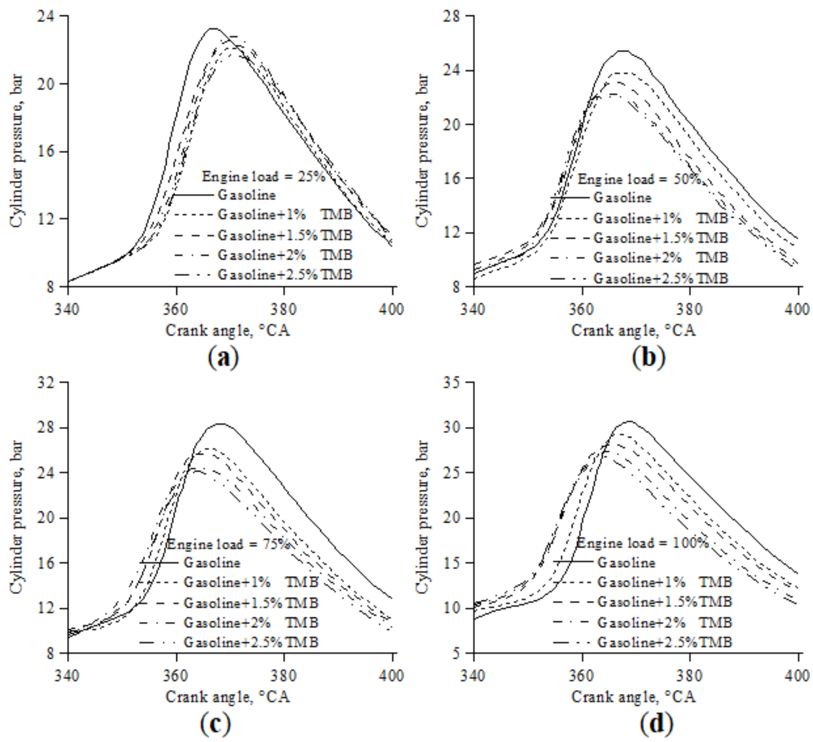

Figure 4. Variation of cylinder pressure for addition of TMB to gasoline with engine load of (**a**) 25%, (**b**) 50%, (**c**) 75% and (**d**) 100% [19].

Figure 5a–d shows the variation of start of combustion and combustion duration at different loads when different amounts of TMB were added to gasoline. It was declared that start of combustion time was determined as burning time of 10% fuel–air mixture and combustion duration was determined as burning time of 90% fuel–air mixture. It was stated that onset of combustion time varied depending on composition of fuel–air mixture, properties of fuel and temperature of gases in cylinder before ignition. It was determined that onset of combustion and combustion duration shortened since load increased due to engine worked at higher temperatures by rising load. On the other hand, adding TMB to gasoline caused to shorten combustion onset and combustion durations. It was stated that TMB reduced the start of combustion and combustion durations by enabling fuel to oxidize more easily thanks to its oxygen contain [19].

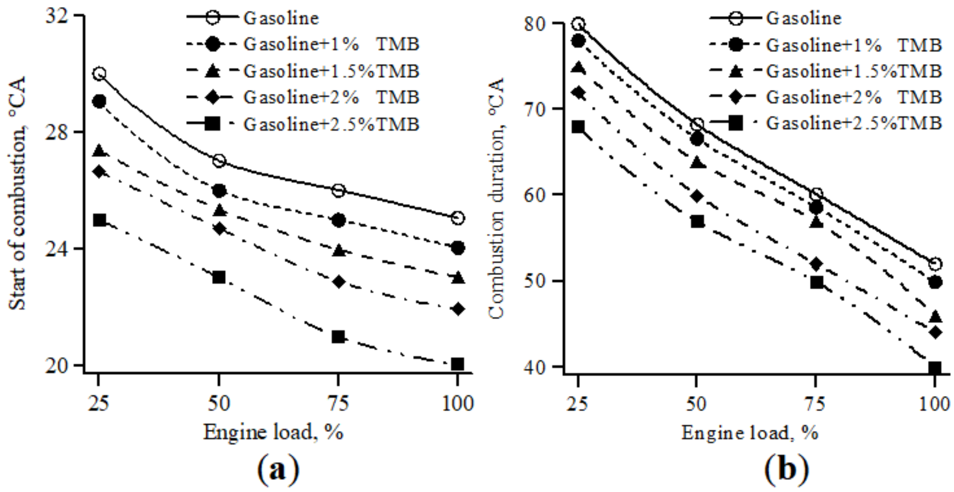

Figure 5. Variation of (**a**) start of combustion; and (**b**) combustion duration for addition of TMB to gasoline [19].

Degirmenci et al. [24] experimentally examined combustion characteristics of methanol, ethanol and TMB fuels and their blends. A high–speed camera and thermal camera were used in the study. It was determined that pure methanol and ethanol created a yellow flame during combustion while TMB and its blends created a green flame, but methanol–TMB blends initially gave a green flame and flame turned yellow near to burn out. It was stated that green flame was formed as a result of burning of boron in TMB. **Figure 6a–b** shows the variation of flame temperature and flame extinction time for methanol, ethanol and TMB fuels and their blends. It was determined that TMB gave higher maximum flame temperature than methanol and ethanol and maximum flame temperature increased by rising TMB ratio. It was stated that this was due to high energy content of boron. On the other hand, it was determined that maximum flame temperature reduced with rising alcohol content in the blends. It was stated that this was due to low energy content of alcohol fuels. Conversely, it was determined that TMB gave a notably lower flame extinction (burning) time than methanol and ethanol while ethanol gave lower burning time than methanol. It was stated that this was due to higher reaction rate and faster evaporation of TMB than alcohols and combustion time was prolonged as a result of more difficult evaporation of alcohols due to their ability to absorb humidity from environment. Conversely, it was determined that methanol–TMB blends gave shorter burning time than ethanol–TBM blends and burning time was extended by rising TMB ratio in the blends. It was stated that this was due to lack of homogeneous mixture.

Yakın et al. [26] experimentally investigated effects of sodium boron hydride (SBH) addition to 5% ethanol–gasoline blend (E5) and 5% methanol–gasoline blend (M5) on engine performance and emissions. **Figure 7a** shows the variation of exhaust gas temperature (EGT) with engine speed for gasoline and E5, E5+SBH, M5+SBH blends. It was determined that blends including alcohol and SBH gave lower EGT than gasoline and ethanol additive reduced EGT more than methanol. It was stated that decrease in EGT was sourced from reducing combustion temperature due to lower calorific value and higher latent heat of evaporation of alcohol fuels. On the other hand, it was stated that slight increase in EGT with SBH addition to alcohol fuels was due to rising combustion temperature which sourced from hydrogen and boron in SBH. Behçet et al. [27] experimentally investigated effects of SBH addition to 10% ethanol–gasoline (E10) and 10% methanol–gasoline (M10) on engine performance and emissions. A SI test engine was used in the study in Ref. [27]. **Figure 7b** shows variation of EGT with engine speed for all tested fuels at full load. It was declared that EGT raised with rising engine speed for all tested fuels due to more energy was carried by exhaust gases since contact time of hot gases with cylinder wall reduced with rising engine speed. It was determined that lowest EGT aroused by E10+SBH blend while highest EGT obtained by gasoline sourced from combustion temperature which depends on thermal efficiency and air fuel ratios of fuels.

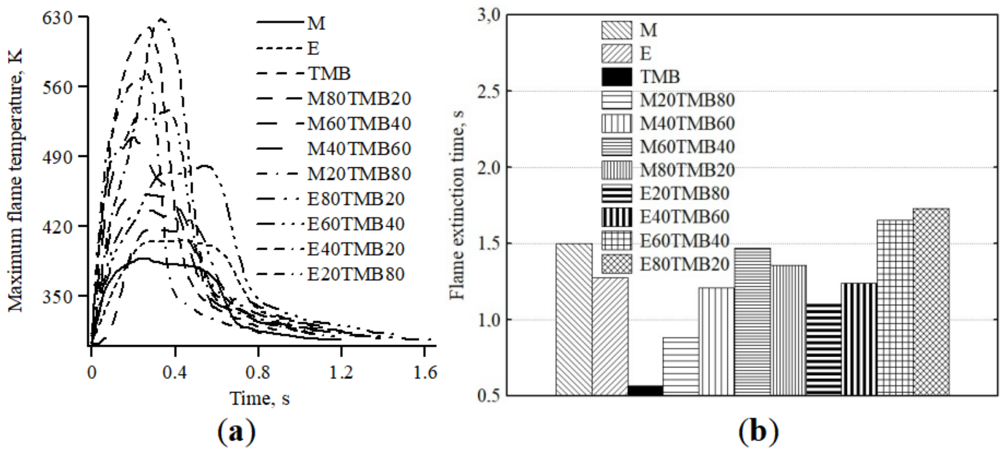

Figure 6. Variation of (**a**) maximum flame temperature; and (**b**) flame extinction time for methanol, ethanol and TMB fuels and their blends [24].

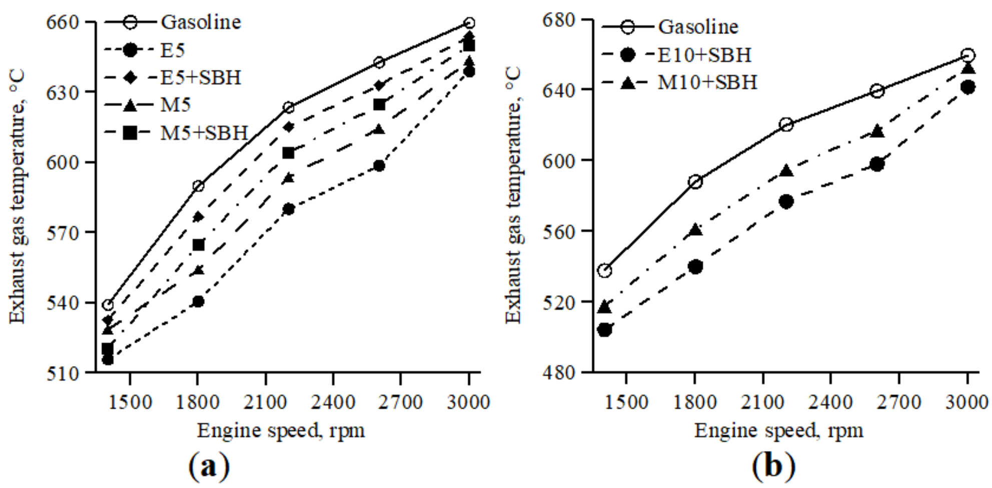

Figure 7. Variation of exhaust gas temperature by engine speed for (**a**) gasoline and E5, E5+SBH, M5+SBH blends [26]; and (**b**) gasoline and E10+SBH, M10+SBH blends [27].

Yontar et al. [29] experimentally examined combustion characteristics of diesel and TMB fuels and their blends. It was determined that TMB gave higher maximum flame temperature and shorter ignition delay and combustion duration than diesel fuel. It was stated that this was due to high energy content and high reaction rate of TMB. Hence, it was determined that maximum flame temperature was increased and ignition delay and combustion duration were shortened by rising TMB ratio as seen in **Figure 8**.

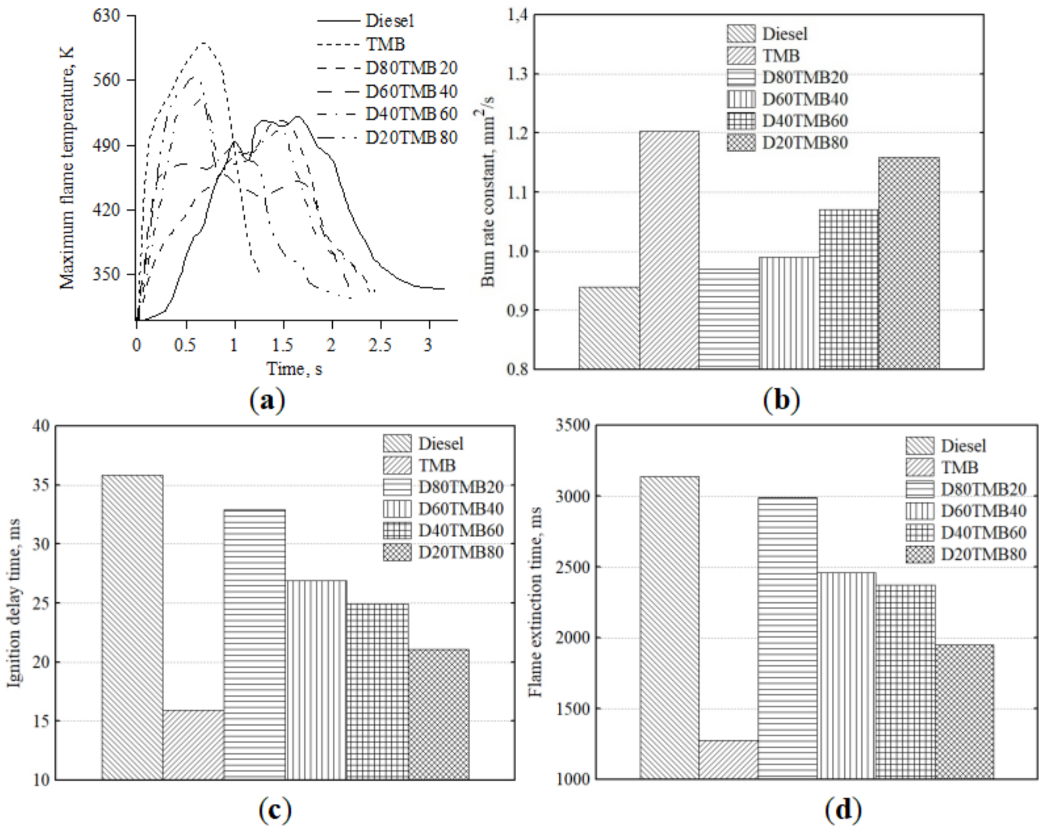

Figure 8. Variation of (**a**) maximum flame temperature; (**b**) burn rate constant; (**c**) ignition delay time; and (**d**) flame extinction time for diesel and TMB fuels and blends [29].

Mehta et al. [30] experimentally investigated effects of adding 0.1% Span80 and 0.5% aluminum (Al), iron (Fe) and boron (B) nanoparticles separately to diesel fuel on engine performance and emissions. **Figure 9a** shows the variation of cylinder pressure by degree crank angle (°CA) for Al, Fe and B nanoparticles addition to diesel fuel. It was declared that maximum cylinder pressures for the blends including Al, B and Fe nanoparticles and pure diesel fuel were obtained as 55, 59, 60 and 62 bars, respectively. It was determined that addition of nanoparticles generally reduced cylinder pressure compared to diesel fuel. It was stated that decreases in cylinder pressure was sourced from shortened ignition delay time and earlier start of combustion due to nanoparticles had different physical and chemical properties than diesel fuel. **Figure 9b** shows the variation of EGT with engine load for Al, Fe and B nanoparticles addition to diesel fuel. It was determined that EGT increased with rising engine load and nanoparticle addition generally caused to increase of EGT. It was stated that more fuel was injected to cylinder with rising engine, which caused to rise of combustion temperature and EGT. On the other hand, it was reported that combustion temperature and EGT increased due to high energy content of nanoparticles and micro explosions during combustion created by nanoparticles. It was determined that EGT was raised by 9%, 7% and 5%, respectively with addition of Al, Fe and B nanoparticles to diesel fuel.

Çakmak and Özcan [31] experimentally investigated effects of adding 50, 100 and 200 ppm of boron oxide–B_2O_3 (BO) nanoparticles to diesel–biodiesel blend including 20% biodiesel (BD20) on engine performance and emissions. **Figure 10a–c** show that effects of adding 50, 100 and 200 ppm of BO nanoparticles to BD20 blend on cylinder pressure, pressure rise rate and heat release rate. It was determined that blends including BO gave lower cylinder pressures than BD20 blend before start of combustion and after start of combustion until middle of uncontrolled combustion phase. It was stated that this was sourced from heat transfer from hot gases in cylinder and hot engine parts to fuel molecules due to rising of heat conduction coefficient via BO nanoparticles. It was determined that maximum cylinder pressure increased slightly for rates of 100 ppm and 200 ppm BO nanoparticles addition. Maximum cylinder pressures for BD20, BD20BO50, BD20BO100 and BD20BO200 blends were determined as

48.69, 48.60, 50.31 and 50.61 bar, respectively. It was stated that blends including BO caused to increase in cylinder pressure during expansion period compared to BD20 blend. It was evaluated that this was sourced from delayed combustion and shifting heat release towards to expansion period for blends including BO as seen in **Figure 10b**. It was stated that delay in combustion was sourced from reducing boiling and distillation point temperatures of blends including BO and slowing down mixture formation rate after ignition delay due to high viscosity of blends including BO. It was concluded that amount of burned fuel in diffusion combustion phase increased. Maximum heat release rate values for BD20, BD20BO50, BD20BO100 and BD20BO200 fuels were determined as 25.7, 25.93, 25.32 and 22.41 J/°CA, respectively. Conversely, reducing burning speed of blends including BO caused to reduce of pressure rise rate as in **Figure 10c**. Maximum pressure rise rate values for BD20, BD20BO50, BD20BO100 and BD20BO200 fuels were determined as 3.01, 2.77, 2.75 and 2.89 bar/°CA, respectively. Additionally, it was determined that combustion duration was prolonged with blends including BO though ignition delay time for all fuels was about 7°CA. Combustion duration values for BD20, BD20BO50, BD20BO100 and BD20BO200 fuels were determined as 65, 77, 78 and 78 °KMA, respectively. It was stated that shifting combustion process towards expansion period with blends including BO caused to extend of combustion duration as seen in **Figure 10b**.

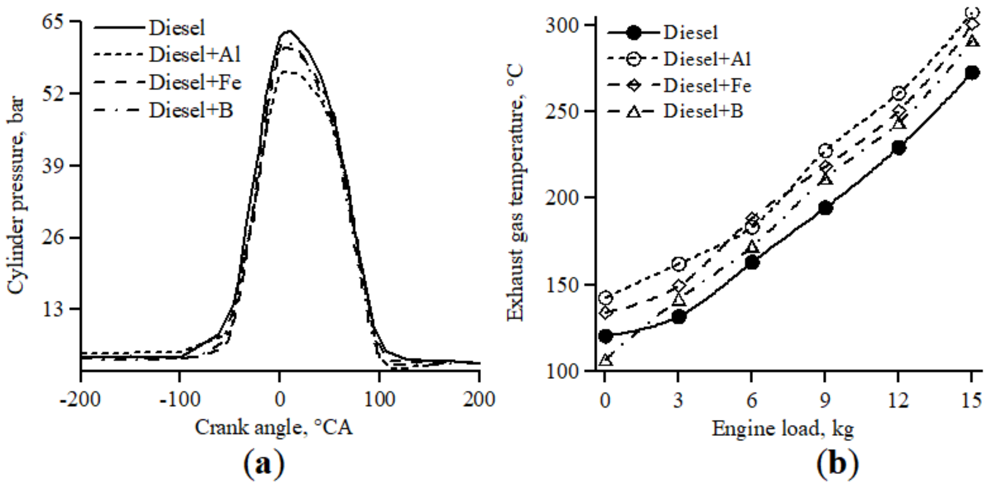

Figure 9. Variation of (**a**) cylinder pressure; and (**b**) exhaust gas temperature for addition of Al, Fe and B nanoparticles to diesel fuel [30].

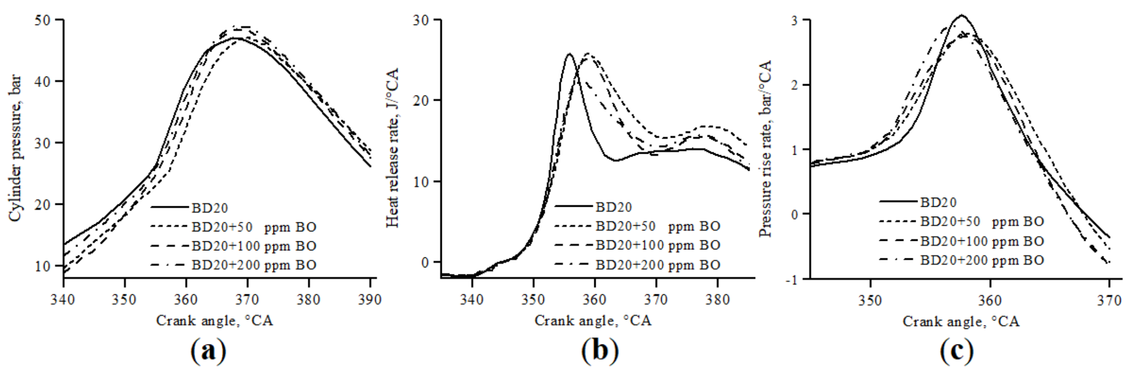

Figure 10. Variation of (**a**) cylinder pressure; (**b**) heat release rate; and (**c**) pressure rise rate with addition of BO to diesel–biodiesel (BD20) blend [31].

Kül and Akansu [32] experimentally investigated effects of 50 and 100 ppm boron nanoparticles addition to diesel fuel in a diesel–natural gas (CNG) dual fuel engine on engine performance and emissions. **Figures 11a,b, 12a,b** and **13a,b** show the variation of heat release rate and cylinder pressure with °CA by using pure diesel fuel and 500, 1250 and 2000 g/h of CNG with diesel fuel and 0, 50 and 100 ppm of nano boron additive in diesel–CNG dual fuel engine. It was determined that rising amount of CNG reduced heat release rate and cylinder pressure in dual fuel operation. It was stated that this was since there was not enough time for complete combustion of CNG by rising amount of CNG due to delay in injection time of diesel fuel. Conversely, it was determined that heat release rate increased before top dead center (BTDC) with pure diesel fuel, while heat release rate increased after top dead center (ATDC) during dual fuel operation by rising amount of CNG. It was stated that this was sourced from extended ignition delay time and delayed combustion process by rising amount of CNG due to low cetane number of CNG. It was stated that rising EGT with rising amount of CNG in **Figure 14a** was the indicator of delayed combustion process. It was concluded that heat release rate and cylinder pressure reduced by rising CNG ratio due to delayed combustion. Conversely, it was also stated that ignition delay period was prolonged due to negative heat release sourced from liquid diesel fuel absorbing heat from environment to evaporate during ignition delay (344–360 °CA) and thus temperature dropped in cylinder and start of the combustion delayed. It was declared that maximum negative heat release was determined as –7.29 J/°CA with pure diesel fuel when injection time was kept constant as 16 °CA–BTDC. It was stated that negative heat release decreased to –6.78 and –6.85 J/°CA with 50 and 100 ppm nano–boron was added to diesel fuel and thus ignition delay time decreased by 7% and 6%. It was also stated that reducing amount of diesel fuel injected into cylinder reduced ignition delay time by rising amount of CNG in dual fuel operation. It was stated that negative heat release rate reduced by reduction of injected diesel fuel to cylinder since amount of CNG increased and ignition delay time shortened by boron addition. It was determined that negative heat release rates at 100 Nm engine load was determined as –6.36, –6.47 and –6.39 J/°CA for 500 g/h CNG, –6.04, –5.91 and –5.80 for 1250 g/h CNG and –5.12, –4.97 and –5.03 J/°CA for 2000 g/h CNG when 0, 50 and 100 ppm nano–boron additives were used. It was declared that rising amount of CNG and nano B additive reduced negative heat release rate during ignition delay period and also decreases in negative heat release increased engine efficiency and reduced specific fuel consumption. It was also stated that 50 ppm nano–boron additive reduced further negative heat release rate than 100 ppm. Alternatively, it was stated that nano–boron additive and rising amount of CNG also reduced maximum heat release rate and maximum cylinder pressure. It was determined that maximum heat release rates at 100 Nm engine load was determined as 111.78, 98.04 and 97.52 J/°CA for pure diesel fuel, 86.17, 82.53 and 86.97 J/°CA for 500 g/h CNG, 70.59, 69.43 and 68.48 for 1250 g/h CNG and 51.37, 48.04 and 51.55 J/°CA for 2000 g/h CNG when 0, 50 and 100 ppm nano–boron additives were used. It was determined that maximum cylinder pressure values at 100 Nm engine load was determined as 38.79, 36.74 and 36.75 bar for pure diesel fuel, 35.96, 36.09 and 35.57 bar for 500 g/h CNG, 34.45, 34.07 and 33.67 bar for 1250 g/h CNG and 32.18, 31.85 and 31.84 bar for 2000 g/h CNG when 0, 50 and 100 ppm nano–boron additives were used. Accordingly, it was stated that advancing fuel injection time of diesel fuel for diesel–CNG dual fuel operation could provide more efficient combustion and lower fuel consumption compared to pure diesel fuel by shortening ignition delay time [32].

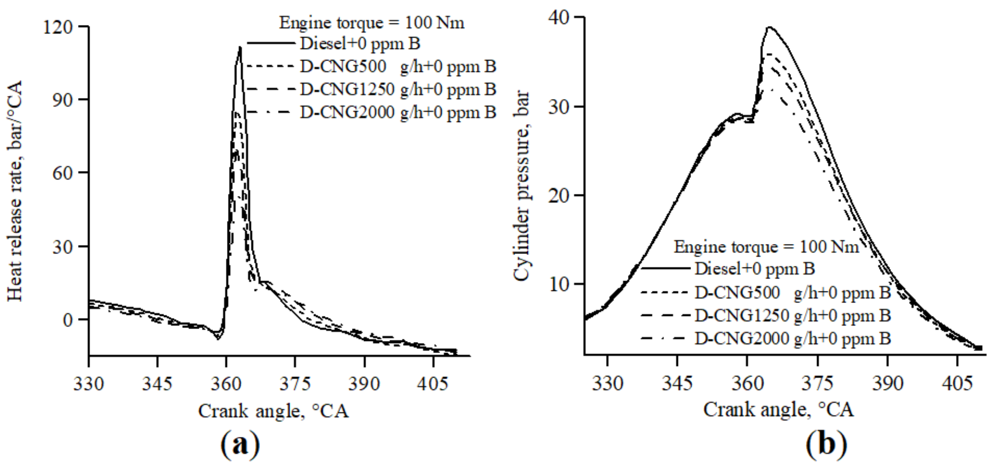

Figure 11. Variation of (**a**) heat release rate; and (**b**) cylinder pressure for diesel–CNG dual fuel engine [32].

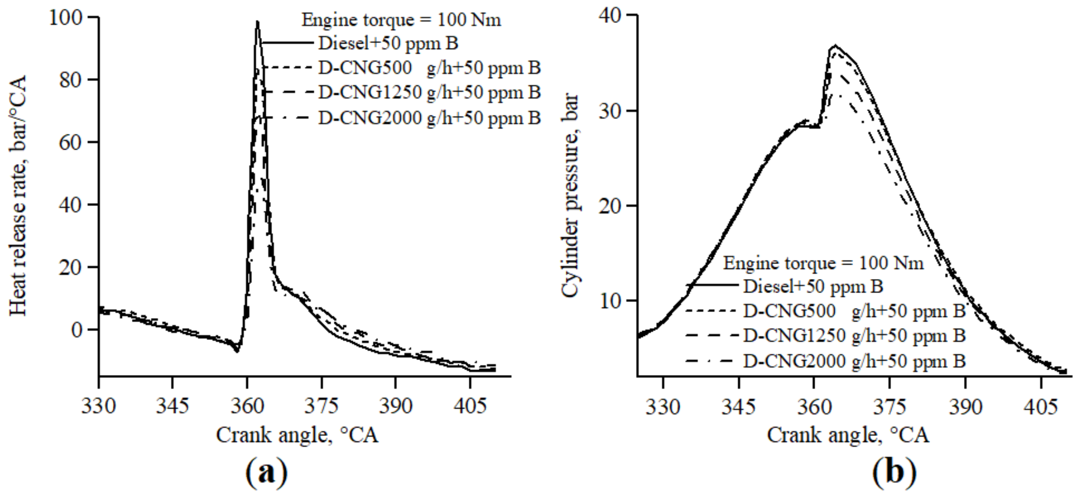

Figure 12. Variation of (**a**) heat release rate; and (**b**) cylinder pressure for diesel–CNG dual fuel engine during 50 ppm B addition [32].

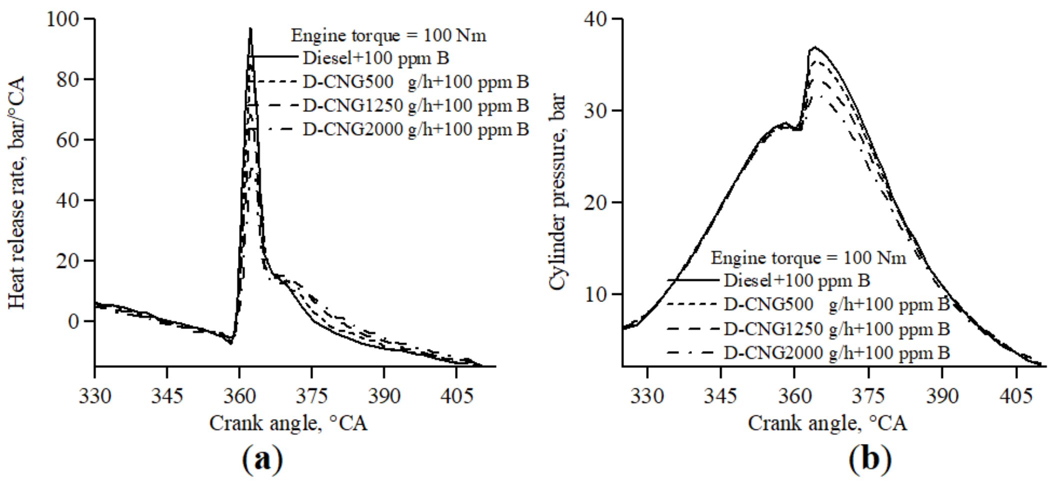

Figure 13. Variation of (**a**) heat release rate; and (**b**) cylinder pressure for diesel–CNG dual fuel engine during 100 ppm B addition [32].

Figure 14a shows the variation of EGT with engine torque for adding different amounts of boron nanoparticles to diesel fuel in diesel–CNG dual fuel operation. It was determined that EGT values obtained with pure diesel fuel were lower than diesel–CNG dual fuel engine and EGT for all fuels increased by rising engine load due to rising amount of fuel sent to cylinder. It was also determined that B additive to diesel fuel and rising amount of CNG for diesel–CNG dual fuel operation increased EGT. It was stated that boron additive raised combustion temperature and thus EGT due to its high energy content of boron. It was also stated that combustion sagged in expansion process due to delayed combustion of CNG, hence EGT increased by rising amount of CNG [32]. Polat et al. [33] experimentally investigated effects of adding 100 ppm boron nanoparticles to diesel on engine performance and emissions for diesel–biogas (BG) dual fuel engine at different amounts (0.5, 1, 2 L/min) of BG. **Figure 14b** shows the variation of EGT with engine load with adding boron nano particles to diesel fuel in diesel–BG dual fuel engine. It was determined that EGT increased by rising engine load and it was stated that this was due to more fuel being sent to cylinder by rising engine load. It was also determined that boron addition to diesel fuel and use of BG with diesel fuel reduced EGT. It was determined EGT reduced by 8.6% for Diesel+B, 14.4% for Diesel+B+0.5BG, 21%

for Diesel+B+1BG and 23.4% for Diesel+B+2BG compared to diesel fuel. It was stated that this was due to boron nanoparticles increased heat transfer from combustion chamber to cylinder walls during combustion and carbon dioxide (CO_2) gas in BG slowed down flame speed and drawn heat from combustion chamber which reduced the combustion temperature and also EGT.

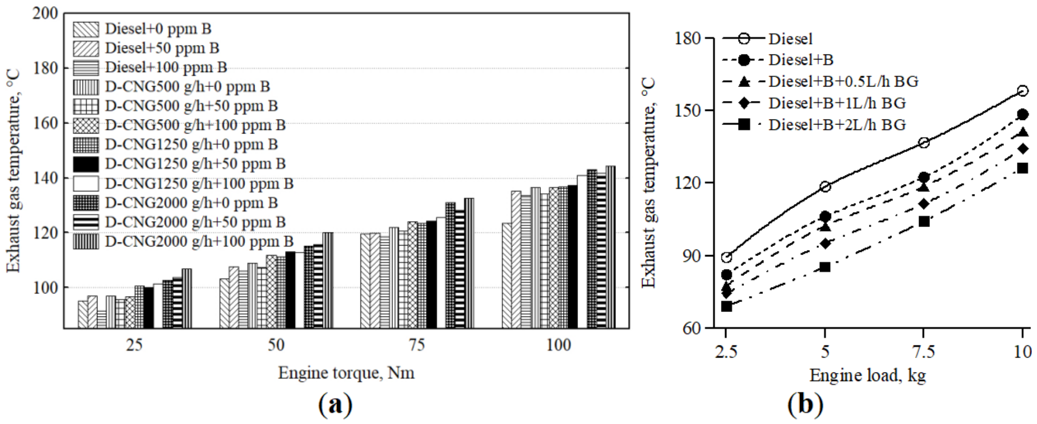

Figure 14. Variation of exhaust gas temperature for (**a**) diesel–CNG dual fuel engine with various B nanoparticles addition [32] and (**b**) diesel–BG dual fuel engine with B nanoparticles addition [33].

Fisher et al. [34] experimentally investigated effects of adding different amounts of nano–Al and Ti–Al–B metallic nanoparticle (MNP) mixture to JP5 fuel on combustion, performance and emissions. **Figure 15a,b** show the variation of cylinder pressure by addition of n–Al nanoparticles and MNP mixture to JP5 fuel. It was determined that cylinder pressure reduced by rising amount of n–Al and MNP addition to JP5 fuel. It was determined that cylinder pressure reduced by 1.5 bar on average when nanoparticle additives were used. It was stated that this was due to shortening of ignition delay time by nanoparticle addition as seen in **Figure 16a,b**. It was determined that ignition delay time was shortened by a maximum of 4% when 4% MNP nanoparticle additive was used. It was stated that shortening of ignition delay time was due to rising cetane number with nanoparticle addition.

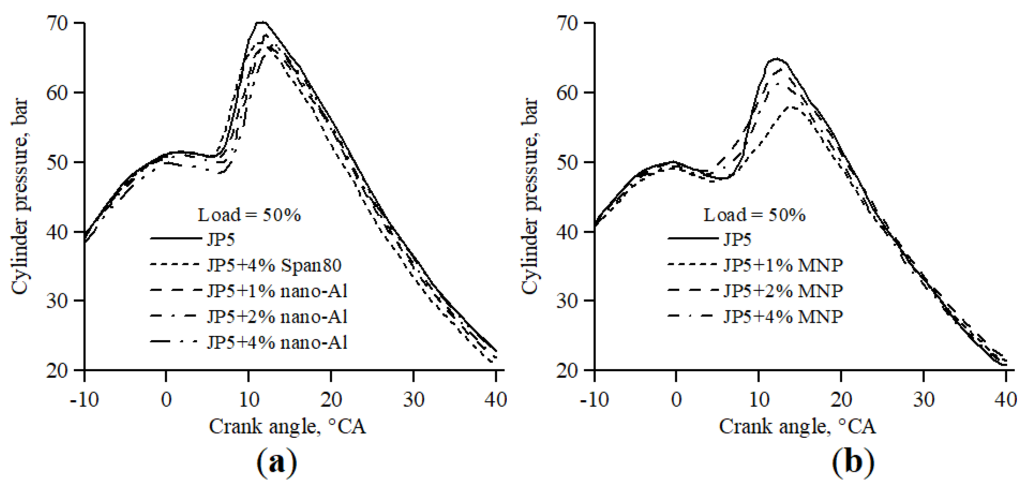

Figure 15. Variation of cylinder pressure for addition of (**a**) n–Al nanoparticles; and (**b**) Ti–Al–B metallic nanoparticles (MNP) mixture to JP5 fuel [34].

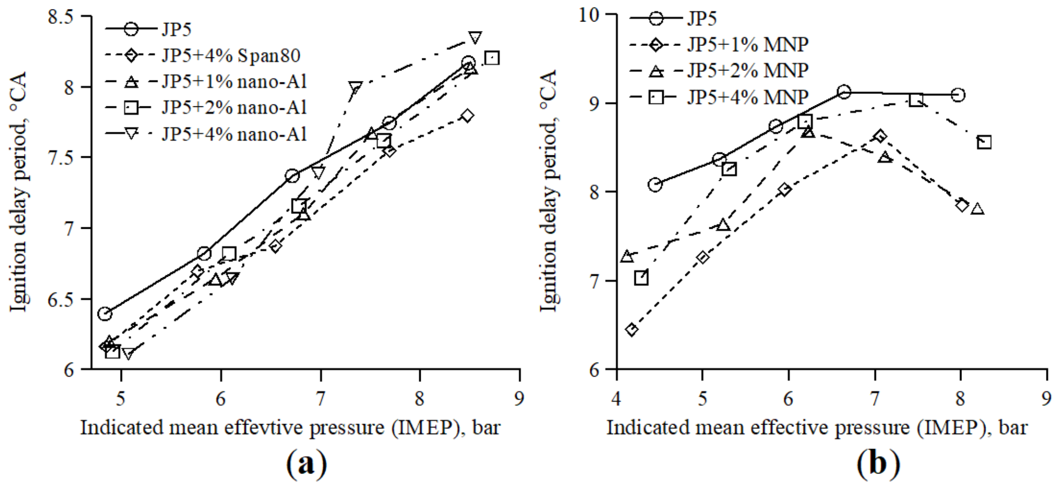

Figure 16. Variation of ignition delay period for addition of (**a**) n–Al nanoparticles; and (**b**) Ti–Al–B metallic nanoparticles (MNP) mixture to JP5 fuel [34].

Figure 17a,b show the variation of maximum pressure location with engine load for different amounts of n–Al and MNP addition to JP5 fuel. It was determined that maximum pressure point was shifted forward with nanoparticle addition. It was stated that maximum pressure point varied inversely with ignition delay time and maximum pressure point was shifted forward consequently shortening ignition delay time with nanoparticle addition. It was also declared that this caused to extend of combustion duration. **Figure 18a,b** show the maximum heat release rate with engine load with different amounts of n–Al and MNP addition to JP5 fuel. It was determined that maximum heat release rate increased by rising engine load. It was stated that this was due to rising amount of fuel sent to cylinder by rising engine load. Conversely, maximum heat release rate reduced with nanoparticle addition. It was stated that this was due to shortening of ignition delay time with nanoparticles addition [34].

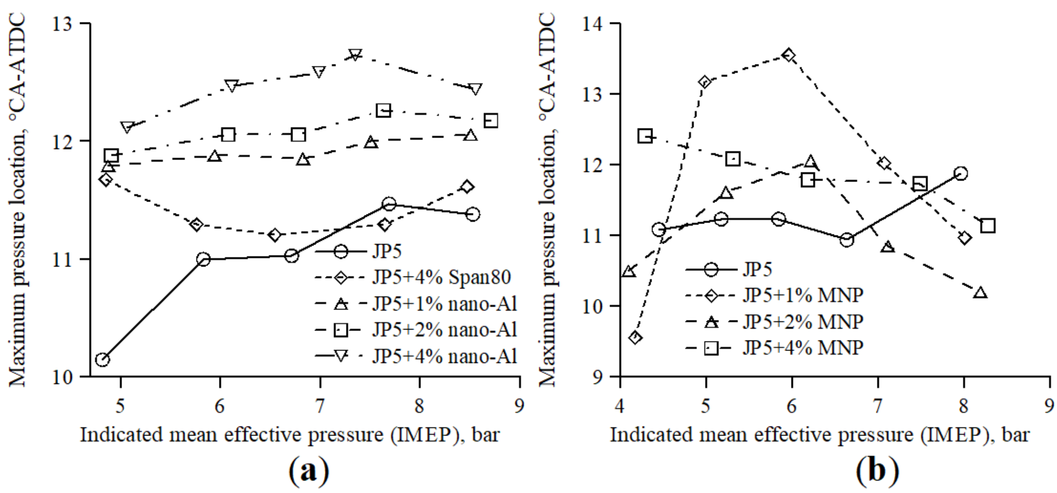

Figure 17. Variation of maximum pressure location for addition of (**a**) n–Al nanoparticles; and (**b**) Ti–Al–B metallic nanoparticles (MNP) mixture to JP5 fuel [34].

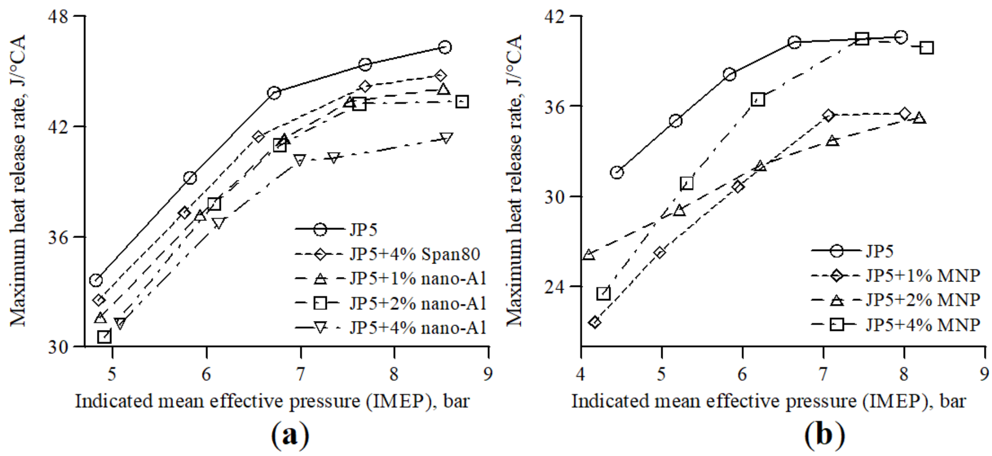

Figure 18. Variation of maximum heat release rate for addition of (**a**) n–Al nanoparticles; and (**b**) Ti–Al–B metallic nanoparticles (MNP) mixture to JP5 fuel [34].

Figure 19a,b show the combustion (burn) duration with engine load with different amounts of n–Al and MNP addition to JP5 fuel. It was determined that burn duration firstly reduced with rising engine load due to shortening of ignition delay time, but it increased as engine load further increased due to rising amount of fuel sent to cylinder. Conversely, combustion duration increased by nanoparticle addition due to shortening of ignition delay time [34].

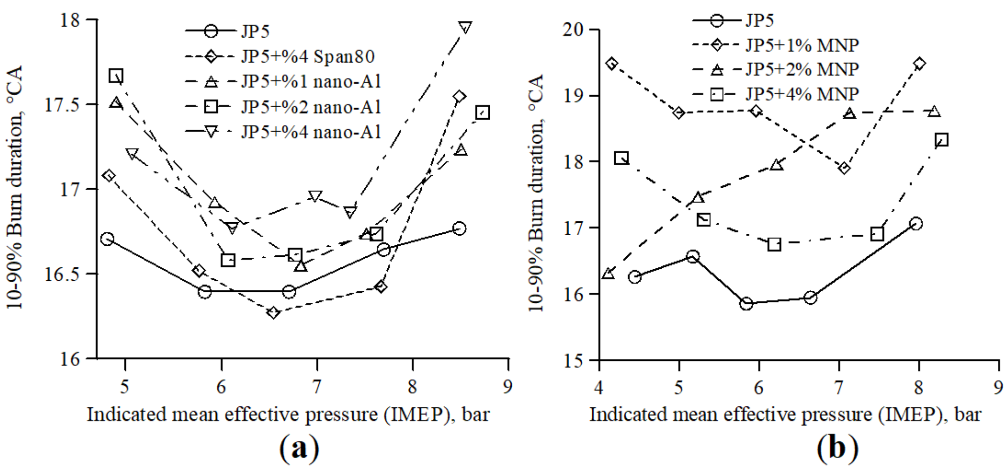

Figure 19. Variation of burn duration for addition of (**a**) n–Al nanoparticles; and (**b**) Ti–Al–B metallic nanoparticles (MNP) mixture to JP5 fuel [34].

Figure 20 shows the images of injector tips for diesel, n–Al and MNP addition to JP5 fuel. As seen in the figure, while no significant carbon deposits in the injector used with diesel fuel, a lot of carbon deposits formed in the injectors used with n–Al and MNP added to JP5 fuel. It was stated that the injectors were renewed twice in the experiments carried out with n–Al and MNP added JP5 fuel. It was declared that this was due to the n–Al and MNP nanoparticles not burning completely during combustion [34].

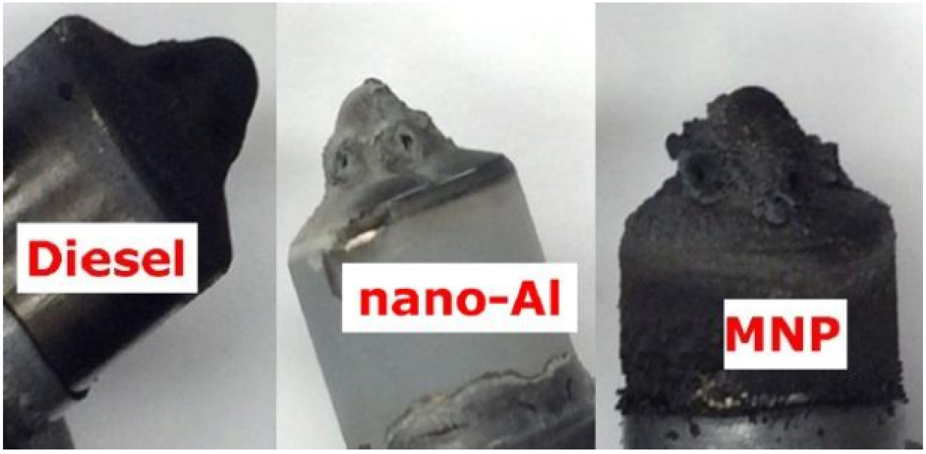

Figure 20. Images of injector tips for diesel and n–Al nanoparticles and Ti–Al–B metallic nanoparticles (MNP) mixture addition to JP5 fuel [34].

3.2. Effect of Boron Additive to Oils on Combustion

Orman [36] experimentally examined effects of hexagonal boron nitrate (hBN) additive to engine oil on performance and emissions of a two–stroke gasoline engine. **Figure 21a** shows the variation of EGT with engine load for pure and hBN additive engine oil. It was determined that EGT increased by rising engine load, while it reduced with hBN addition to engine oil. It was stated that this was due to improved tribological properties of engine oil and also combustion via hBN additive. Karataş and Yüksel [38] experimentally examined effects of using pure and boron–added 10W–40 engine oil in a diesel engine on engine performance and emissions. **Figure 21b** shows the variation of EGT with engine speed for pure and boron–added engine oil. It was determined that rising engine speed and boron additive to engine oil increased EGT as seen in the figure. It was determined that when boron was added to engine oil EGT increased by 1.488%, 0.49% and 0.476% for 1500, 1750 and 2000 rpm, respectively when compared to pure engine oil. It was stated that boron–added engine oil reduced gas leakages and heat transfer from combustion chamber by creating better oil film on cylinder surfaces and this increased the combustion temperature and also EGT.

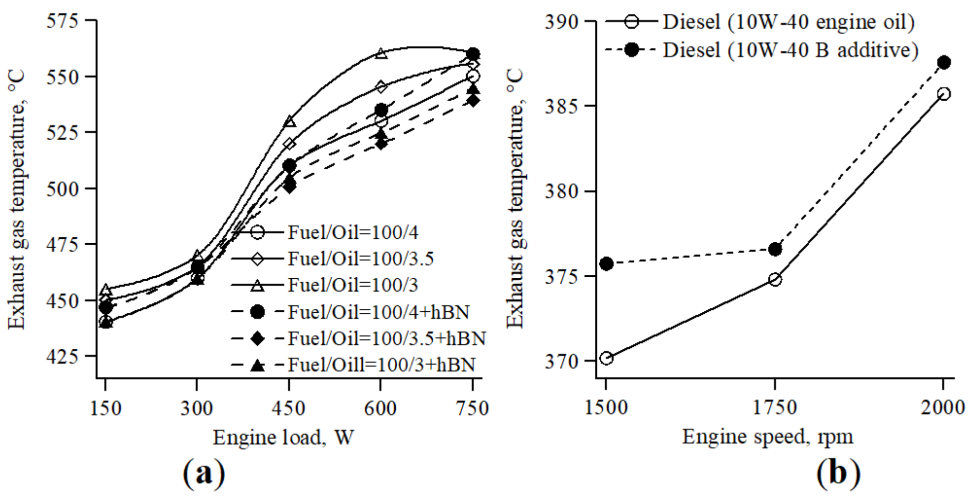

Figure 21. Variation of exhaust gas temperature for (**a**) pure and hBN additive lube oil in a two stroke gasoline engine with engine load [36]; and (**b**) pure lube oil (10W40) and B additive lube oil in a diesel engine with engine speed [37].

Ramteke and Chelladurai [13] conducted an experimental study by adding 1% boron nitrate (BN) to 20W–40 engine oil in a single–cylinder, four–stroke diesel engine. **Figure 22a,b** show the variation of cylinder pressure with crank angle at different engine loads for pure and 1% BN including engine oil. It was declared that lower cylinder pressures obtained with pure engine oil as seen in **Figure 22a**. It was stated that combustion pressure reduced as a result of inadequate air–fuel mixture in cylinder due to increased gas leakages from piston rings sourced from lack of sufficient oil film. Conversely, cylinder pressure increased when 1% BN was added to engine oil as seen in **Figure 22b**. It was stated that rise of combustion pressure was due to rising amount of air–fuel mixture in cylinder because BN additive created a sufficient oil film between cylinder surfaces and rings which reduced friction losses and gas leakages from the rings and thus engine power improved.

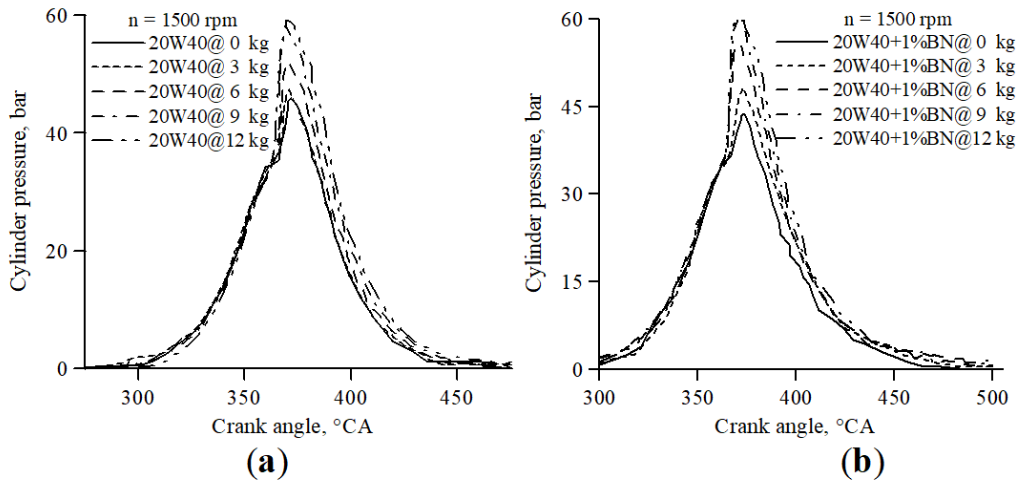

Figure 22. Variation of cylinder pressure for **(a)** pure lube oil (20W–40) and **(b)** BN additive lube oil in a diesel engine [13].

4. Effect of Boron Additive on Engine Performance

4.1. Effect of Boron Additive to Fuels on Engine Performance

Sertkaya and Akbıyık [1] experimentally examined effects of various boron–containing additives on engine performance and emissions of a gasoline engine. It was declared that four different boron–containing additives, named A, B, C and D for commercial reasons were added to gasoline at rates of 0.7%, 1.4% and 2.1%. It was determined that that additive A caused to increase in torque at blending ratios of 0.7% and 2.1% and a decrease at blending ratio of 1.4%, while additives B and C caused to increase in torque at all blending ratios. It was reported that additive D increased torque at only blending ratio of 0.7%. Reduction rates in torque for A, B, C and D additives at blending ratio of 0.7% were determined as 0.3–3.4% and increment rates for same additives at the same blending ratio were determined as 1.1–5.2%. It was stated that changes in torque under 1.2% can be sourced from measurement error. **Figure 23a** shows the variation of torque with engine speed at blending ratio of 0.7% for all boron–containing additives. It was determined that all additives provided an increase in torque compared to gasoline up to speed of 3500 rpm, while only additive A gave higher torque than gasoline at speeds above 3500 rpm. Since contents of additives other than boron were not known in details for commercial reasons, increases in torque were considered to be due to high energy content of boron. **Figure 23b** shows the variation of brake specific fuel consumption (BSFC) with engine speed for all boron–containing additives. It was determined that all boron–containing additives provided a reduction in BSFC compared to gasoline under most operating conditions. It was declared that Additive B gave lower BSFC values than gasoline at all engine speeds, while additive A gave higher BSFC values than gasoline at 1500 and 2000 rpm and additives C and D gave higher BSFC values than gasoline at 1500, 2000 and 5000 rpm. Considering lowest BSFC values, it was determined that additives A, B, C and D provided about 2.1–9.5% reduction in BSFC compared to gasoline. It was stated that reductions in BSFC sourced from boron–containing additives enable gasoline to burn more efficiently.

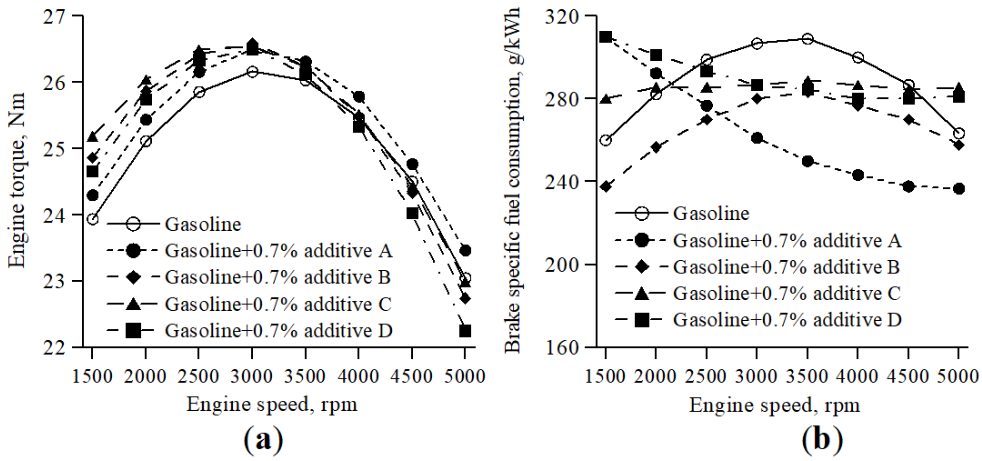

Figure 23. Variation of (**a**) engine torque; and (**b**) brake specific fuel consumption with engine speed for using different boron including additives in gasoline [1].

Gültekin et al. [19] experimentally examined effects of adding different amounts of TMB to gasoline on combustion, performance and emissions. **Figure 24a,b** shows the variation of brake thermal efficiency (BTE) and BSFC with engine load for TMB addition to gasoline at different ratios. It was stated that minimum BSFC was achieved when BTE reached its maximum due to BTE was a quantity that varied inversely with BSFC. It was reported that BTE and BSFC were negatively affected due to lack of a homogeneous air–fuel mixture in cylinder at low loads and deterioration of combustion at high loads. Conversely, it was determined that BTE increased and BSFC reduced by rising TMB ratio. It was reported that maximum BTE was 16.5% and minimum BSFC was 495.31 g/kWh at 75% load and 2.5% TMB ratio. It was stated that improvement in BTE and BSFC was sourced from advancement of combustion due to oxygen and boron in TMB.

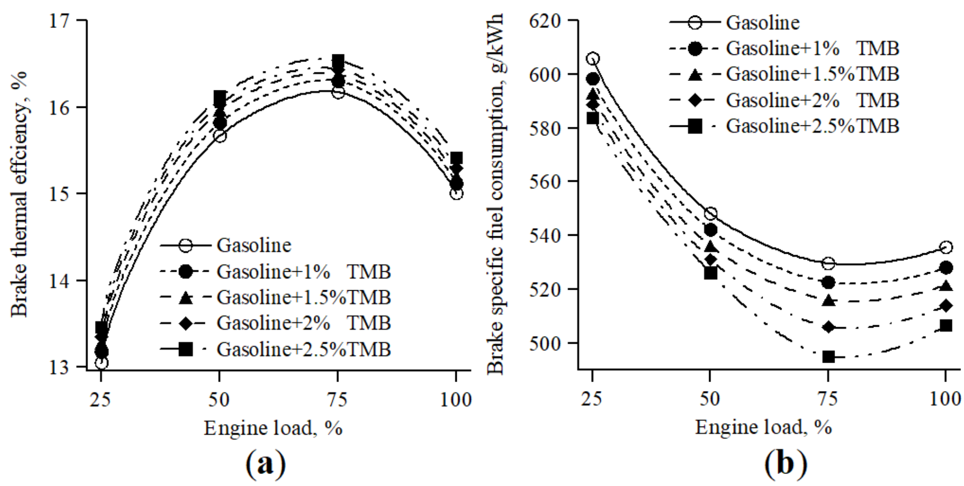

Figure 24. Variation of (**a**) brake thermal efficiency; and (**b**) specific fuel consumption with engine load for different amount of TMB addition to gasoline [19].

Simsek et al. [20] investigated effects of adding a boron containing additive namely Octamix to gasoline at different ratios on engine performance and emissions. It was declared that blends were prepared by adding Octamix which contains ammonia borane (NH_3BH_3), trioctyl borate ($C_{24}H_{51}BO_3$) and ethyl alcohol (C_2H_6O) to gasoline at ratios of 0.5, 1, 2 and 3%. Measurements were made under different loads at constant speed of 3000 rpm. It was reported that each experiment was repeated three times and results obtained were averaged to minimize errors arising from measurements. **Figure 25a,b** show the variation of BTE and BSFC with engine load for Octamix addition to gasoline at different ratios. As seen in **Figure 25a**, it was determined that 0.5% Octamix additive provided a little increase in BTE, while it reduced with additives above this ratio. It was stated that Octamix provided an increase in BTE at 0.5% additive ratio due to its higher octane number than gasoline, but it prevented formation of homogeneous air–fuel mixture due to its high viscosity, which caused to worsening of combustion and decrease of BTE by rising blending ratio. It was determined that maximum BTE was 22.8% at 0.5% blending ratio and minimum BTE was 16% at 3% blending ratio. Accordingly, it was determined that highest increase was 4.65% and highest decrease was 17.58% in BTE when compared to gasoline. As seen in **Figure 25b**, it was determined that Octamix additive caused an increase in BSFC. It was stated that this was sourced from lower calorific value of Octamix and thus BSFC increased continuously by rising additive ratio. It was reported that highest increase in BSFC compared to gasoline was 23.143% with 3% additive ratio at 1000W load.

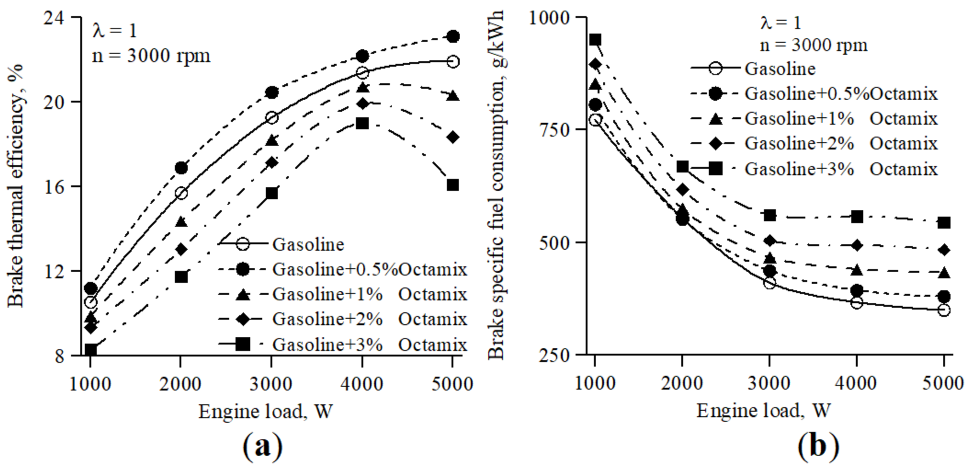

Figure 25. Variation of (**a**) brake thermal efficiency; and (**b**) brake specific fuel consumption with engine load for different amount of Octamix addition to gasoline [20].

Yakın et al. [26] experimentally examined effects of SBH addition to 5% ethanol–gasoline (E5) and 5% methanol–gasoline (M5) blends on performance and emissions. **Figure 26a** shows the variation of torque with engine speed for gasoline and E5, E5+SBH, M5, M5+SBH blends. It was determined that E5, M5 and M5+SBH blends gave higher torque than gasoline, while E5+SBH blend gave lower torque than gasoline. It was stated that increases in torque was sourced from improvement of combustion due to oxygen content of the blends. It was also stated that alcohol–containing fuels increase engine volumetric efficiency due to their high latent heat of evaporation and this contributed to increase of torque. Conversely, it was stated that decrease in torque for E5+SBH blend was due to relatively lower calorific value of this blend and decrease in combustion temperature due to cooling effect of ethanol. Moreover, it was stated that SBH addition to E5+SBH blend could negatively affect fuel injection and cause incomplete combustion. Similarly, M5+SBH blend gave lower torque than M5 blend. It was determined that M5+SBH blend gave 1.2–3.7% increase in torque, while E5+SBH blend gave 1–1.6% decrease in torque compared to gasoline. **Figure 26b** shows the variation of BTE with engine speed for gasoline and E5, E5+SBH, M5 and M5+SBH blends. It was determined that BTE increased more when methanol was added to gasoline than ethanol and addition of SBH to ethanol and methanol blends increased BTE further. Hence highest BTE values were obtained with M5+SBH blend. It was stated that increases in BTE were sourced from increased combustion efficiency via alcohol fuels due to their oxygen content and engine volumetric efficiency due to their cooling effects. It was also stated that SBH additive increased amount of energy released during combustion due to hydrogen and boron in SBH and thus further increasing BTE. It was declared that increases in BTE were determined as 5.8–10.9% for E5+SBH blend and 7.8–14.5% for M5+SBH blend compared to gasoline. **Figure 26c** shows the variation of BSFC with engine speed for gasoline and E5, E5+SBH, M5 and M5+SBH blends. It was determined that methanol additive increased BSFC more than ethanol additive. Conversely, SBH addition to E5 blend caused a slight decrease in BSFC, while SBH addition to M5 blend caused to increase of BSFC further. It was stated that increases in BSFC with blends were due to their lower calorific value compared to gasoline. It was stated that BSFC increased more when methanol–containing fuels were used since calorific value of methanol was lower than ethanol. It was declared that increases in BSFC were determined as 1–2.8% for E5+SBH blend and 5.4–7.9% for M5+SBH blend compared to gasoline.

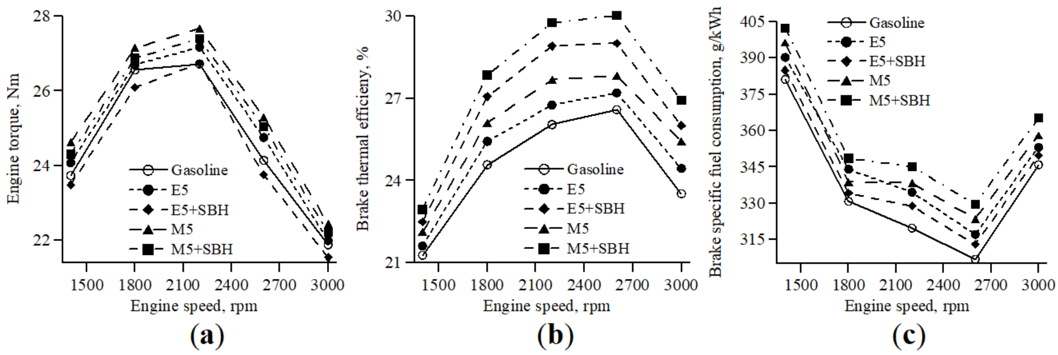

Figure 26. Variation of (**a**) engine torque; (**b**) brake thermal efficiency; and (**c**) brake specific fuel consumption with engine speed for gasoline and E5, E5+SBH, M5 and M5+SBH blends [26].

Behçet et al. [27] experimentally examined effects of SBH addition to E10 and M10 blends on performance and emissions. **Figure 27a** shows the variation of torque with engine speed for gasoline, E10+SBH and M10+SBH blends. It was determined that maximum torque was obtained around 2000 rpm for all fuels. It was declared that this was due to decrease in engine volumetric efficiency and increase in mechanical losses after 2000 rpm. It was also determined that M10+SBH blend gave higher torque than gasoline, while M10+SBH blend gave lowest torque values. It was declared that these variation was due to fuel properties i.e., energy content, density, viscosity, octane number which are largely efficient on combustion. It was stated that M10+SBH blend improved combustion due to higher oxygen content, higher latent heat of vaporization of methanol which increased engine volumetric efficiency and also torque. Reasons of reduction in engine torque with E10+SBH blend were explained with lower calorific value of ethanol and deterioration of injection and also combustion due to higher viscosity of SBH. **Figure 27b** shows the variation of BTE with engine speed for gasoline, E10+SBH and M10+SBH blends. It was determined that BTE for all fuels increased up to 2500 rpm due to low heat lost from cylinder walls but it reduced after 2500 rpm. It was also determined that highest BTE was obtained with M10+SBH blend, while lowest BTE values realized with gasoline. BTE values of E10+SBH and M10+SBH blends were also higher than gasoline. It was declared that this increase in BTE was due to complete combustion due to oxygen in alcohols and hydrogen in SBH besides increase in engine volumetric efficiency which sourced from higher air fuel ratio and latent heat of evaporation of alcohols. **Figure 27c** shows the variation of BSFC with engine speed for gasoline, E10+SBH and M10+SBH blends. It was determined that maximum BSFC was gained with M10+SBH blend, while lowest BSFC was realized with gasoline. It was declared that this increase in BSFC was due to lower heating values of alcohols. It was also determined that E10+SBH and M10+SBH blends were higher than gasoline since higher density and viscosity of SBH.

Yakın et al. [28] experimentally examined effects of SBH addition to 20% ethanol–gasoline (E20) blend on performance and emissions. **Figure 28a** shows the variation of torque with engine speed for gasoline, E20 and E20+SBH blends. It was determined that torque increased up to 2200 rpm and it reduced after 2200 rpm due to reduction in engine volumetric efficiency and raised mechanical losses. It was declared that fuel properties of calorific value, viscosity, octane number, density directly affected combustion and engine performance. It was also determined that highest torque occurred with E20 blend, while lowest torque was obtained by E20+SBH blend. It was declared that higher torque with E20 blend was due to better combustion via oxygen in ethanol and higher latent evaporation of ethanol which raised engine volumetric efficiency. It was also declared that reduction in torque with E20+SBH blend was sourced from deterioration of injection efficiency and incomplete combustion. **Figure 28b** shows the variation of engine power with engine speed for gasoline, E20 and E20+SBH blends. It was determined that highest power was obtained with gasoline while lowest power occurred by E20+SBH blend hence there was 4.71% reduction in power with E20 blend and 7.62% by E20+SBH blend. It was declared that this decrease in power was sourced from lower calorific values of ethanol and lower octane number of SBH. **Figure 28c** shows the variation of BSFC with engine speed and **Figure 28d** with NOx for gasoline, E20 and E20+SBH blends. It was declared that BSFC of E20 and E20+SBH blends were higher than gasoline due to lower calorific value of ethanol and higher viscosity of SBH. It was determined that BSFC with E20 and E20+SBH blends increased by 5.02% and 6.57% compared to gasoline.

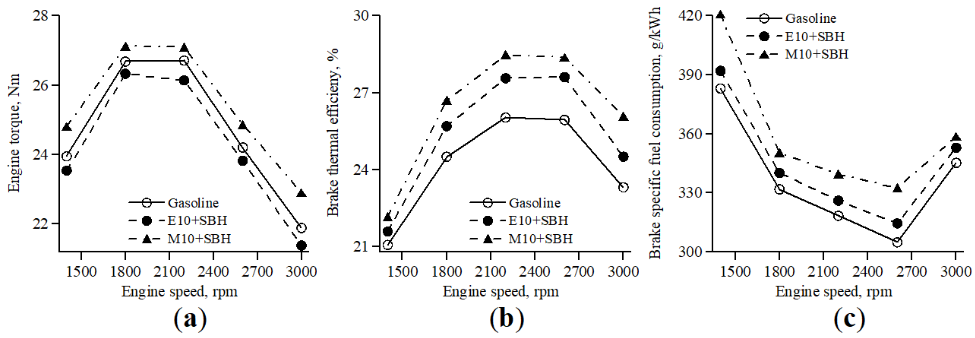

Figure 27. Variation of (**a**) engine torque; (**b**) brake thermal efficiency; and (**c**) brake specific fuel consumption with engine speed for gasoline and blends of E10+SBH10 and M10+SBH10 [27].

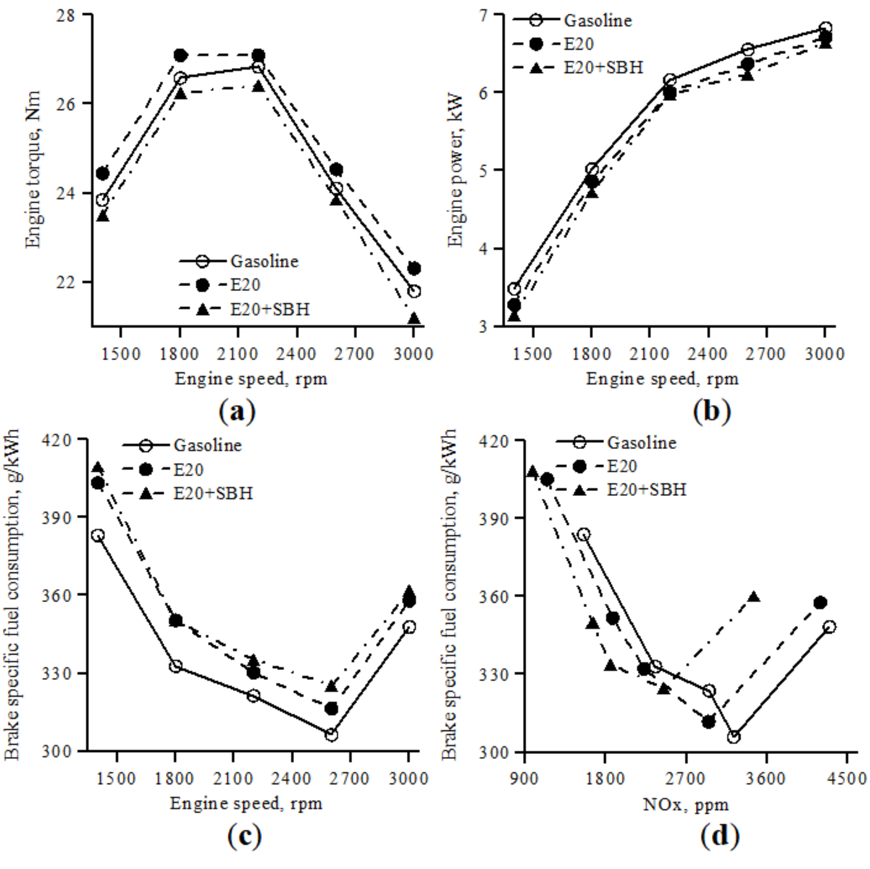

Figure 28. Variation of (**a**) engine torque; (**b**) brake thermal efficiency; and (**c**) brake specific fuel consumption by engine speed and (**d**) brake specific fuel consumption by NOx for gasoline, E20 and E20+SBH blends [28].

Dogu et al. [22] examined relatively effects of adding boron–containing materials such as BP (borax pentahydrate–$Na_2B_4O_75H_2O$), AB (anhydrous borax–$Na_2B_4O_7$) and BA (boric acid–H_3BO_3) to gasoline with alternative fuels and fuel blends such as natural gas (CNG), liquefied petroleum gas (LPG), 10% CNG–gasoline (CNG10), 5%LPG–gasoline

(LPG5), 25 and 50% acetone–gasoline (A25 and A50), 50% naphthalene–gasoline (N50) on engine performance and emissions. **Figure 29a** shows the variation of torque for gasoline, alternative fuels and blends. It was stated that torque obtained with gasoline was 108 Nm and it was 9.2% lower than catalogue value. It was declared that this could be due to environmental conditions, properties of tested gasoline and wear condition of engine. Conversely, it was determined that lower torque values were generally obtained with alternative fuels and blends than gasoline. It was determined that decreases in torque were about 4.9%, 9.5%, 17.4%, 8.5%, 3.6%, 3.9% and 3.2% for CNG, LPG, CNG10, LPG5, A25, A50 and N50 respectively compared to gasoline. It was also determined that addition of BP, AB and BA additives to gasoline reduced torque by 4%, 4.4% and 4.4% respectively compared to gasoline. Similar variations were obtained in engine power as seen in **Figure 29b.** It was stated that decreases in torque and power with gaseous fuels and their blends i.e. CNG, LPG, CNG10 and LPG5 were sourced from reduction of the volumetric efficiency as seen in **Figure 29c**. Conversely, it was stated that reduction in torque and power for boron–containing blends was sourced from lower calorific value of boron–containing blends and boron including materials not dissolve completely in gasoline due to their different chemical properties and worsening combustion. **Figure 29d** shows the variation of BSFC for examined fuels and blends. It was determined that BSFC decreased by 13% and 5% for CNG and CNG10 blend, increased by 1.5% for LPG and decreased by 7.1% for LPG5 blend compared to gasoline. It was stated that BSFC reduced as a result of CNG and LPG improving combustion and increasing combustion efficiency due to their high hydrogen/carbon ratio. It was determined that BSFC decreased by 22.2% and 25.7% for A25 and A50 blends. It was stated that acetone had oxygen, high octane number and easy evaporation property, thus it increased combustion efficiency and reduced BSFC compared to gasoline. It was determined that N50 blend increased BSFC by 5.1% and it was stated that lower calorific value of naphthalene besides its inability of complete combustion due to high carbon/hydrogen ratio increased BSFC. Conversely, it was determined that BP additive to gasoline reduced BSFC by 5.8%, AB additive increased by 0.4% and BA additive reduced by 15.2%. It was stated that reductions in BSFC was due to high energy content of boron. However, it was stated that BSFC may be increased slightly as a result of worsening combustion due to AB additive in solid form not being completely dissolved in gasoline.

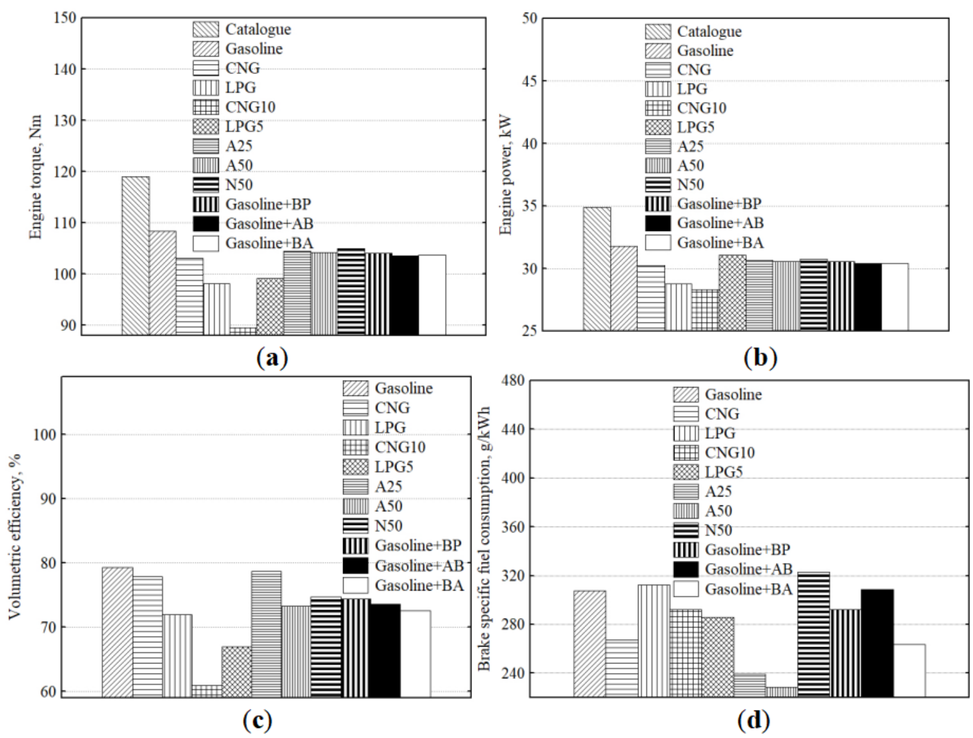

Figure 29. Variation of (**a**) engine torque; (**b**) engine power; (**c**) volumetric efficiency; and (**d**) brake specific fuel consumption for various alternative fuels and blends and different boron including additions to gasoline [22].

Mehta et al. [30] experimentally examined effects of adding aluminum (Al), iron (Fe) and boron (B) nanoparticles to diesel fuel on engine performance and emissions. Al, Fe and B nanoparticles were separately added to diesel fuel at ratio of 0.5%. **Figure 30a** shows the variation of BTE with engine load for Al, Fe and B nanoparticles addition to diesel fuel. It was determined that higher BTE values were obtained especially at medium and high loads for Al and Fe nanoparticles addition to diesel fuel, while B nanoparticles provided an improvement in BTE only at 3 and 12 kg loads. It was stated that nanoparticles increased BTE by rising combustion temperature and combustion efficiency due to their higher calorific value. It was also stated that nanoparticles provided an additional contribution to increase of BTE due to improved combustion by shortening ignition delay period due to their rapid evaporation. It was declared that addition of Al, Fe and B nanoparticles increased BTE by 9%, 4% and 2% compared to diesel fuel. **Figure 30b** shows the variation of BSFC with engine load for Al, Fe and B nanoparticles addition to diesel fuel. It was determined that addition of Al nanoparticles reduced BSFC except for 3 kg load, while Fe and B nanoparticle additives caused an increase in BSFC except for high loads (12 and 15 kg). However, it was reported that increases or decreases in BSFC was quite small. It was stated that Al nanoparticle additive gave maximum 7% decrease in BSFC.

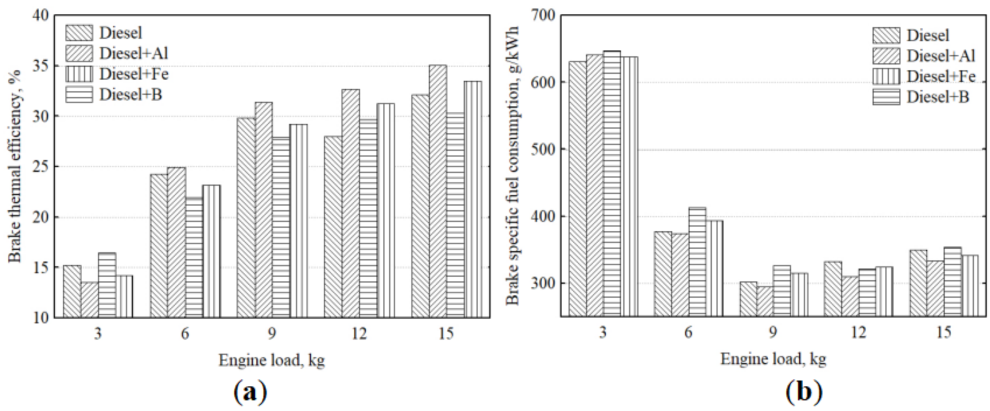

Figure 30. Variation of (**a**) brake thermal efficiency; and (**b**) brake specific fuel consumption for Al, Fe and B nanoparticles addition to diesel fuel [30].

Çakmak and Özcan [31] experimentally investigated effects of adding different amounts (50, 100 and 200 ppm) of boron oxide–B_2O_3 (BO) nanoparticles to diesel–biodiesel blend containing 20% canola biodiesel (BD20) on engine performance and emissions. **Figure 31a,b** show the variation of BTE and BSFC with engine load for different amounts of boron oxide–B_2O_3 (BO) addition to BD20 blend. It was determined that small changes in BTE and BSFC were not proportional to BO nanoparticles concentration. Moreover, it was stated that changes in BTE and BSFC for BD20+50ppmBO and BD20+200ppmBO nanofuels were below uncertainty values. However, it was stated that BTE increased by 0.96% and BSFC decreases by 1.66% compared to BD20 blend. Accordingly, it was stated that positive effect of BO additive on engine performance occurred at 100 ppm additive value, and uncertainty value BTE and BSFC was approximately ±0.82%.

Kül and Akansu [32] experimentally examined effect of 50 and 100 ppm boron (B) nanoparticles addition to diesel fuel on engine performance and emissions in a diesel–natural gas (CNG) dual fuel engine. **Figure 32a** shows the variation of BTE with torque (load) for 50 and 100 ppm boron nanoparticles addition to diesel fuel in diesel and diesel–CNG dual fuel engines. It was declared that different amounts of i.e. 500 g/h (CNG500), 1250 g/h (CNG1250) and 2000 g/h (CNG2000) were supplied to engine through intake manifold for diesel–CNG dual fuel operation. It was determined that BTE values obtained with diesel fuel were higher than diesel–CNG dual fuel engine and BTE values for all fuels increased with rising engine load. Conversely, boron additive increased BTE at all engine loads for diesel fuel operation and it was determined that BTE increased by 2.66% and 1.36% for 50 and 100 ppm boron addition at 100 Nm load. It was stated that boron increased combustion efficiency and also BTE by shortening ignition delay time and rising amount of energy released during combustion due to its high energy content. It was stated that BTE constantly reduced for diesel–CNG dual fuel operation and boron additive could only provide small increases in BTE at some loads. It was stated that CNG ignited difficultly due to its very low cetane number and it required more time to burn completely due to its low flame speed and thus temperature and pressure in cylinder reduced and BTE decreased during dual fuel operation. It was also stated that rising amount of CNG reduced air entering to cylinder and engine volumetric efficiency and also decreased BTE. **Figure 32b** shows the variation of BSFC with torque for different amounts of boron nanoparticles addition to diesel fuel for diesel–CNG dual fuel engine. It was determined that BSFC values of diesel fuel engine were lower than diesel–CNG dual fuel engine and BSFC values for all fuels reduced with rising load. It was determined that boron additive to diesel fuel reduced BSFC, while rising amount of CNG in dual fuel operation increased BSFC. It was stated that variation in BSFC was sourced from variation in BTE as BSFC was varied in opposite with BTE.

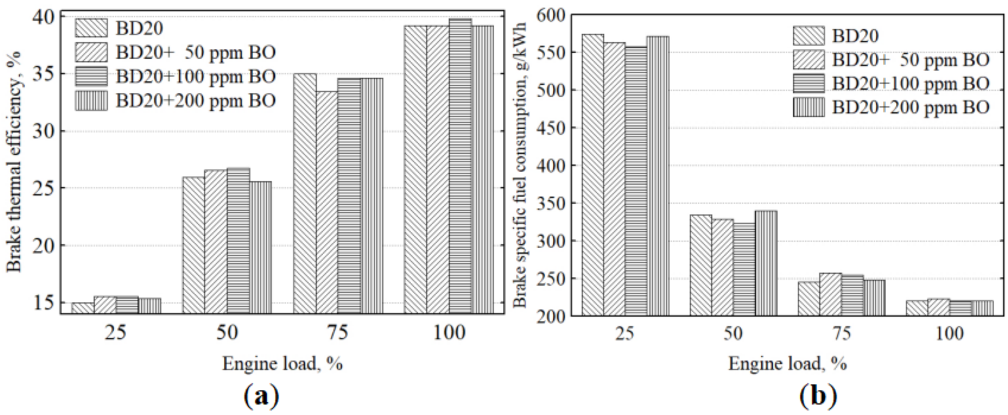

Figure 31. Variation of (**a**) brake thermal efficiency; and (**b**) brake specific fuel consumption with engine load for different amount of boron oxide (BO) addition to diesel–biodiesel blend (BD20) [31].

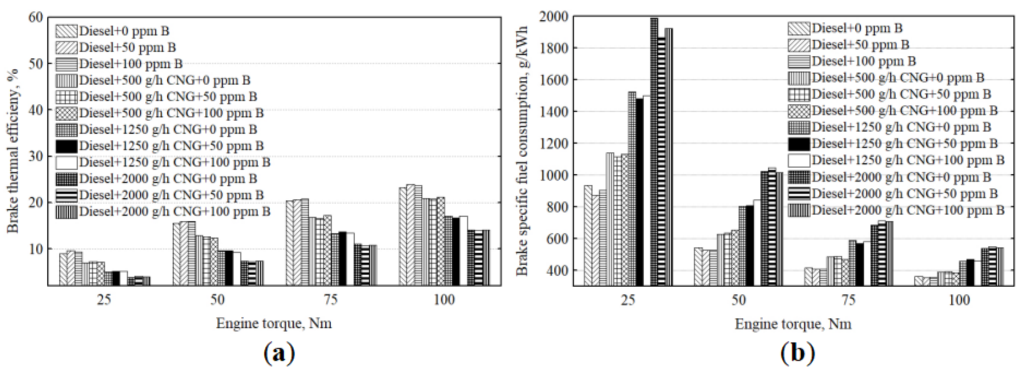

Figure 32. Variation of (**a**) brake thermal efficiency; and (**b**) brake specific fuel consumption with engine torque for different amount of boron (B) nanoparticles addition to diesel–natural gas (CNG) dual fuel engine [32].

Polat et al. [33] experimentally investigated effects of adding 100 ppm boron (B) nanoparticles to diesel fuel on engine performance and emissions in a diesel–BG dual fuel engine at different amounts (0.5, 1, 2 L/min) of BG. **Figure 33a,b** show the variation of BTE and BSFC with engine load for different amount of boron nanoparticles addition to diesel–BG dual fuel engine. It was determined that highest BTE values were obtained with boron addition to pure diesel fuel. It was explained that increase in BTE was sourced from higher calorific value and higher cetane number of diesel fuel containing boron nanoparticles, high catalytic effect in chemical reactions during combustion, larger surface area to volume ratio and high energy density of boron. Conversely, it was declared that BTE gradually reduced during dual fuel operation with rising amount of BG. It was stated that decrease in BTE by using BG was due to lower energy content of biogas, lower cylinder temperature and reduction of flame speed sourced from CO_2 in biogas. It was stated that another reason for reduction of BTE at dual fuel operation was deterioration of combustion efficiency sourced from decreasing engine volumetric efficiency due to introduction of biogas through intake manifold. It was determined that boron–added diesel fuel provided an 8.04% increase in BTE, while Diesel+B+0.5BG, Diesel+B+1BG and Diesel+B+2BG mixtures reduced BTE by 9.41%, 19.38% and 32.2%, respectively. It was determined that minimum BSFC values were obtained with addition of boron to pure diesel fuel. It was stated that this was due to diesel fuel containing boron has highest energy content. Conversely, BSFC was increased always at dual fuel operation by rising amount of BG. It was stated that increase in BSFC was due to deterioration of combustion and reduction in BTE due to deficiency of oxygen in combustion chamber as a result of decrease in engine volumetric efficiency. It was determined that boron–addition to diesel fuel provided 8.42% decrease in BSFC, while Diesel+B+0.5BG, Diesel+B+1BG and Diesel+B+2BG mixtures increased BSFC by 10.94%, 28.01% and 60.02%, respectively.

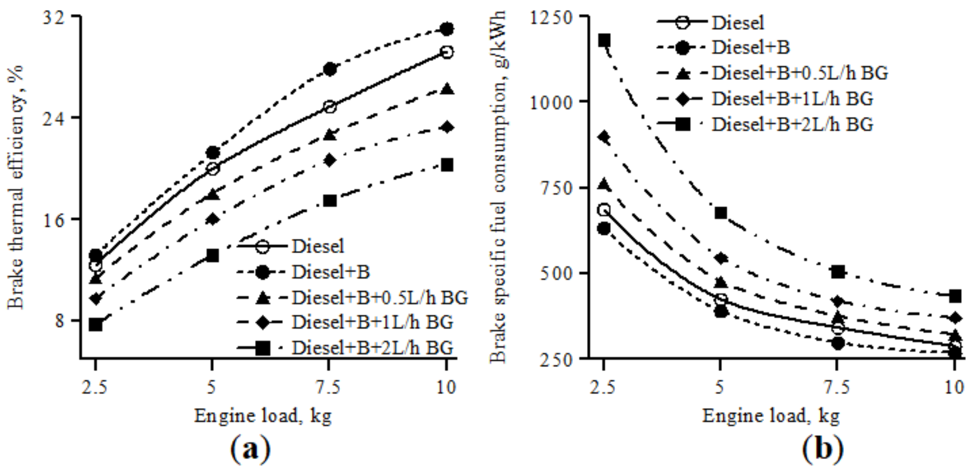

Figure 33. Variation of (**a**) brake thermal efficiency; and (**b**) brake specific fuel consumption with engine load for different amount of boron (B) nanoparticles addition to diesel–biogas (BG) dual fuel engine [33].

Simsek et al. [12] examined experimentally effects of adding a boron–containing additive namely Octamix to diesel fuel on engine performance and emissions. **Figure 34a** shows the variation of BSFC with engine load for Octamix addition to diesel fuel at different ratios. It was declared that blends were prepared by adding Octamix to diesel fuel at ratios of 0.5, 1, 2 and 3%. It was determined that BSFC decreased up to 1% blending ratio and then increased. It was stated that Octamix provided more heat and higher pressure during combustion due to its higher calorific value than diesel fuel, thus more useful work produced and BSFC reduced. It was also stated that oxygen, hydrogen and boron in Octamix improved combustion and increased combustion efficiency, hence Octamix additive provided an improvement in BSFC up to a 1% blending ratio. It was declared that Octamix additive reduced density and energy content of blend after 1% blending ratio, thus BSFC increased due to use of more fuel. It was also stated that Octamix additive caused deterioration of combustion due to increase in combustion temperature after 1% blending ratio, which increased BSFC. It was determined that BSFC values at 500 W engine load were 900, 870, 850, 930 and 950 g/kWh for 0.5, 1, 2 and 3% Octamix blending ratios, and lowest BSFC values were obtained with 1% Octamix addition. It was also determined that there was a 7.8% improvement in BSC with 1% Octamix at 2500 W load. Fisher et al. [34] experimentally investigated effects of adding different amounts of n–Al and MNP to JP5 fuel on combustion, performance and emissions. **Figure 34b** shows the variation of fuel consumption rate for n–Al and MNP addition to JP5 fuel. It was determined that fuel consumption rate reduced notably with n–Al additive while it was increased with MNP additive. It was stated that fuel consumption rate enhanced unpredictably for JP5 fuel during the second test and the reason of this could be carbon deposits at injector tips which affecting negatively fuel injection. It was determined that fuel consumption rate reduced by 17% with n–Al additive but it was raised by 5% with MNP additive.

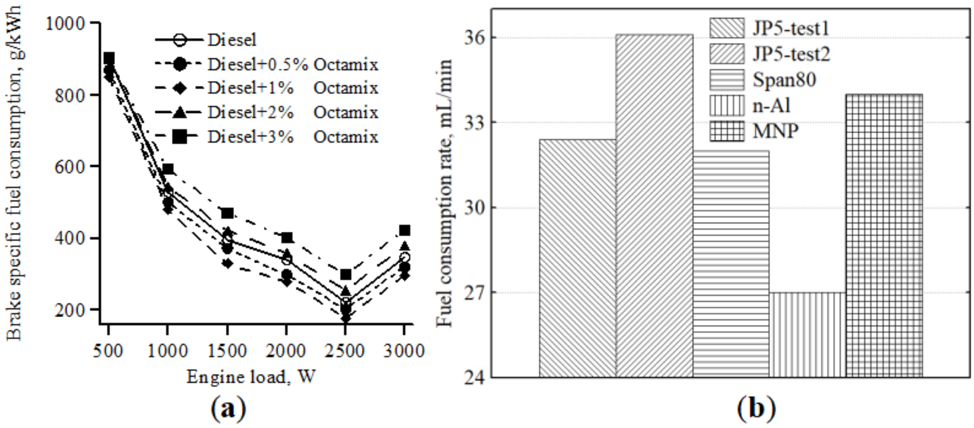

Figure 34. Variation of (**a**) brake specific fuel consumption for different amount of Octamix addition to diesel fuel [12]; and (**b**) fuel consumption rate for n–Al nanoparticles and Ti–Al–B metallic nanoparticles (MNP) mixture addition to JP5 fuel [34].

4.2. Effect of Boron Additive to Oils on Engine Performance

Akbıyık et al. [2] examined comparatively performance, emissions and oil properties for pure and boron added 10W–40 engine oil in gasoline and CNG fueled engines at start–up and end of 50 hours working period. **Figure 35a,b** show the variation of engine torque and BSFC with time for pure and boron additive engine oils. It was declared that maximum torque was measured as 28.45 Nm at 3000 rpm during star–up with boron added engine oil and minimum torque was measured as 24.29 Nm at 4500 rpm after 50 hours with pure engine oil for gasoline engine as seen in **Figure 35a**. Maximum torque was also measured as 23.23 Nm at 3500 rpm at star–up with boron added oil and minimum torque was measured as 18.57 Nm at 4500 rpm after 50 hours with pure oil for CNG engine. It was determined that pure engine oil reduced torque by 2.5% while boron added engine oil reduced torque by 1.9% compared torque values at start up and after 50 hours for gasoline engine. It was also determined that pure engine oil reduced torque by 9.6%, while boron added engine oil reduced torque by 7.6% compared torque values at start up and after 50 hours for CNG engine. Moreover, it was stated that reduction in amount of boron added engine oil was less than pure engine oil and boron added engine oil had positive effects on reducing friction and wearing of moving engine parts. It was declared that minimum BSFC was determined as 290.15 g/kWh at 3500 rpm during star–up with boron added lube oil and maximum BSFC were determined as 338.99 g/kWh at 4500 rpm after 50 hours with pure engine oil for gasoline engine as seen in **Figure 35b**. Minimum BSFC was also determined as 252.64 g/kWh at 3500 rpm during star–up with boron added lube oil and maximum BSFC was determined as 301.91 g/kWh at 4500 rpm after 50 hours with pure engine oil for CNG engine. It was determined that pure engine oil increased BSFC by 2.5%, while boron added engine oil increased BSFC by 2% compared BSFC values at start up and after 50 hours for gasoline engine. It was also determined that pure engine oil increased BSFC by 10%, while boron added engine oil increased BSFC by 8.3% compared BSFC values at start up and after 50 hours for CNG engine. It was stated that boron additive to engine oil reduced BSFC in both gasoline and CNG engines.

Figure 36a,b show the variation of engine torque and BSFC with engine speed for pure and boron additive engine oil (10W40) in gasoline and CNG fuelled engines. It was declared that measurements were taken at the engine start–up and end of 50 hours. It was declared that torque of gasoline engine reduced slightly, while torque of CNG engine increased with boron–added engine oil as seen in **Figure 36a**. It was determined that torque reduced by 0.4–1.3% with boron–added engine oil compared to additive–free engine oil for gasoline engine, while torque increased by 1.3–2.1% with boron added engine oil compared to additive–free engine oil for natural gas engine. However, it was stated that variations in torque below the measurement uncertainty (1.2%) might be sourced from measurement error. **Figure 36b** shows the variation of BSFC with engine speed for pure and boron–added engine oil in gasoline and natural gas engines. It was declared that BSFC of both gasoline and CNG engines reduced with boron–added engine oil. It was determined that BSFC reduced average of 3.4% and 7.1% for gasoline and CNG engines with boron–added engine oil. It was stated that improvement in BSFC was due to reducing friction between moving engine parts by boron additive [3].

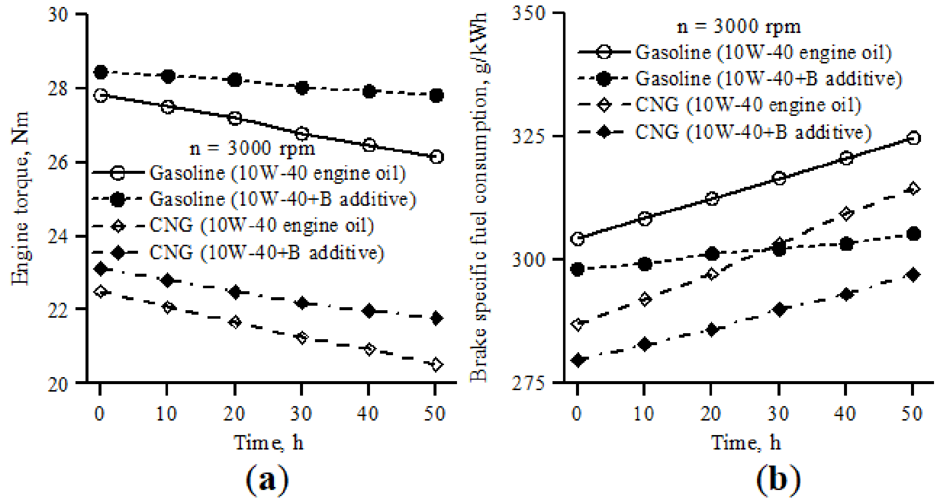

Figure 35. Variation of (**a**) engine torque; and (**b**) brake specific fuel consumption with time for pure and boron added engine oil (10W–40) [2].

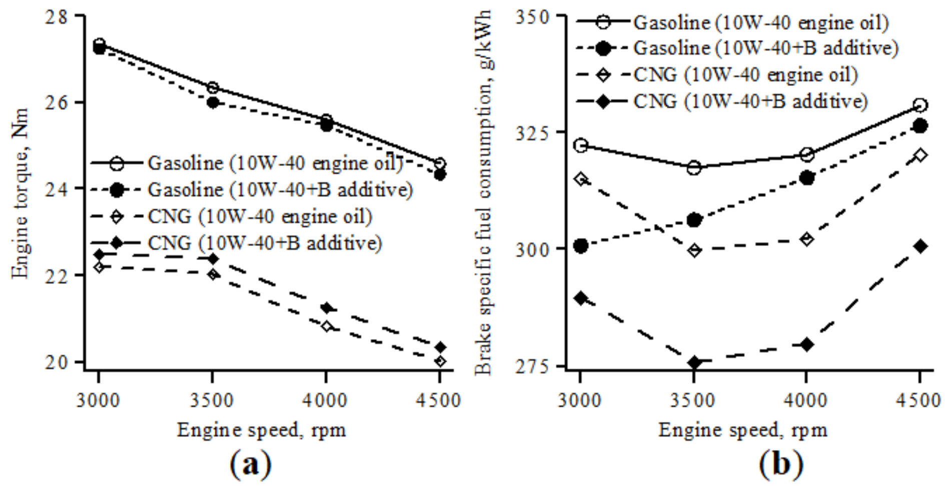

Figure 36. Variation of (**a**) engine torque; and (**b**) brake specific fuel consumption with engine speed for pure and boron added engine oil (10W–40) [3].

Orman [36] experimentally examined effects of hBN additive to engine oil on performance and emissions of a two–stroke gasoline engine. **Figure 37a–c** show the variation of air excess ratio (AER), total fuel consumption (TFC) and BSFC with engine load for pure and hBN additive lube oil in a two stroke gasoline engine. It was declared that AER increased by rising engine load but it showed a reducing trend at maximum load as seen in **Figure 37a**. It was stated that this was due to more fuel being sent to cylinder by rising engine load. Conversely, AER increased as fuel/oil ratio increased and hBN was added to engine oil. It was stated that this was due to reducing carbon in fuel–oil blend which improved combustion and engine performance. It was stated that TFC reduced with hBN additive due to reducing friction between moving engine parts and combustion efficiency increased while TFC increased by rising engine load due to increasing fuel sent to cylinder to produce more power as seen in **Figure 37b.** It was also reported that hBN additive reduced oil consumption by 12.5% at fuel/oil ratio of 100/4. Conversely, BSFC reduced by rising load and hBN additive due to reasons cited above as seen in **Figure 37c.**

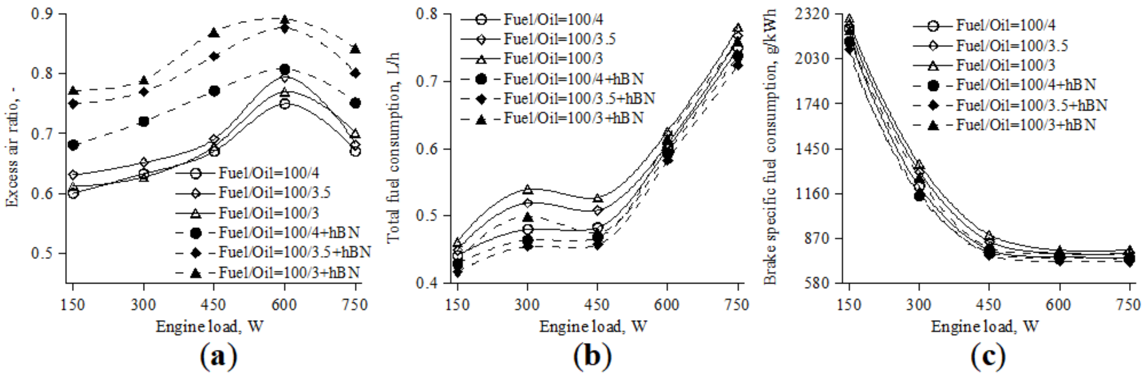

Figure 37. Variation of (**a**) air excess ratio; (**b**) total fuel consumption; and (**c**) brake specific fuel consumption with engine load for pure and hBN additive lube oil in a two stroke gasoline engine [36].

Karataş and Yüksel [37] experimentally examined effects of pure and boron–added 10W–40 engine oil performance and emissions of a diesel engine. **Figure 38a,b** showed the variation of torque and BSFC with engine speed for pure and boron added engine oil in a diesel engine. As seen in **Figure 38a**, torque increased with boron including engine oil. It was determined that maximum torque was measured as 29.56 Nm at 1750 rpm with pure engine oil and highest torque was measured as 30.74 Nm at 2000 rpm with boron added engine oil after 100 hours operation. It was stated that this was due to boron reducing friction and wear by preventing direct contact of metallic surfaces especially at high loads. It was also stated that boron contributed to rising engine performance and engine life by filling wear surfaces and making surfaces smoother. It was determined that torque increased by 7.455% at 1500 rpm, 8.31% at 1750 rpm and 2.508% at 2000 rpm when boron additive was used. It was stated that boron addition up to 15% to engine oil contributed to rising of torque and engine oil usage time due to reduction of gas leakages and friction by filling the gaps between moving engine parts and enhancing lubricity. BSFC also reduced by rising engine speed and lower BSFC values happened with boron additive as seen in **Figure 38b**. It was determined that BSFC decreased by 12.288% at 1500 rpm, 14.641% at 1750 rpm and 14.095% at 2000 rpm with boron added engine oil. It was reported that 1 liter engine oil was saved at the end of 100 hour operating period with boron added engine oil.

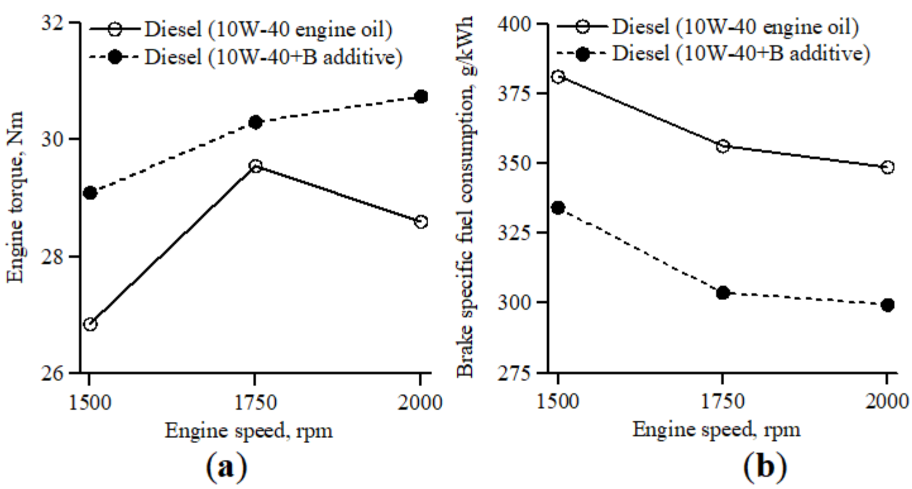

Figure 38. Variation of (**a**) engine torque; and (**b**) brake specific fuel consumption with engine speed in case of using pure and B additive engine oil (10W–40) [37].

Ramteke and Chelladurai [13] experimentally examined effects of adding hBN to 20W–40 engine oil on engine performance and emissions. **Figure 39a,b** shows the variation of BTE and BSFC with engine load for pure and hBN additive engine oil in a diesel engine. It was determined that increase in BTE and decrease in BSFC were obtained at all engine loads with 1% hBN added engine oil. It was stated that highest increase in BTE was obtained as 8.4% at 9 kg engine load and highest decrease in BSFC was obtained as 4.2% with 1% hBN addition at idle operating condition. It was stated that improvement in BTE and BSFC was due to boron containing additive reducing friction between moving engine parts. **Figure 39c** shows the variation of TFC with engine speed for pure and BN and BA additive 20W–50 engine oil in a diesel engine. It was declared that TFC was determined by adding 4% boron nitride (BN) and 4% boric acid–H_3BO_3 (BA) additives to engine oil, respectively. It was declared that TFC increased with rising engine speed for both pure and boron containing engine oil while TFC reduced with BN and BA containing engine oils. It was declared that BA additive provided a greater reduction in TFC than BN additive. TFC was determined as 17,315 L/h for pure engine oil, 16,864 L/h for 4% BN added engine oil and 16,696 L/h for BA added engine oil. It was also determined that there was a 2.7% decrease in TFC with 4% BN addition and 3.6% decrease with 4% BA addition. It was stated that decrease in TFC was sourced from reduction of friction between moving engine parts via boron containing additives.

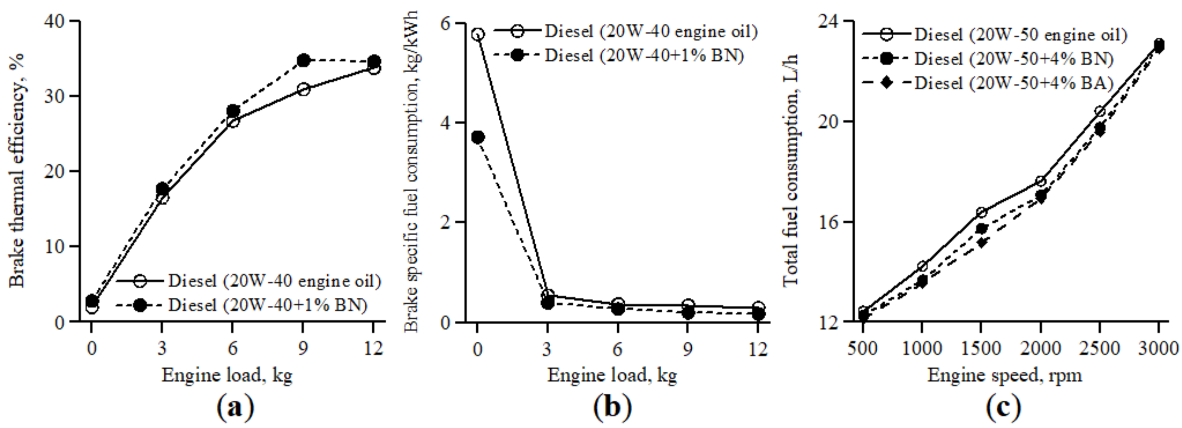

Figure 39. Variation of (**a**) brake thermal efficiency; (**b**) brake specific fuel consumption with load for pure and hBN additive 20W–40 engine oil [13] and **(c)** total fuel consumption by engine speed for pure and BN and BA addition to 20W–50 engine oil [4].

5. Effect of Boron Additive on Emissions

5.1. Effect of Boron Additive to Fuels on Emissions

Figure 40a shows the variation of carbon monoxide (CO) emissions with engine speed when boron–containing additives were used in gasoline at rate of 0.7%. It was declared that CO emissions occur when fuel does not burn completely due to not enough oxygen in combustion process or not enough time for combustion. Hence, amount of CO emissions depends notably on operating conditions and it tends to reduce with improvement of combustion as a result of increase in turbulence in combustion chamber with rising engine speed. As seen in **Figure 40a**, higher CO values were generally obtained when boron–containing additives were used compared to gasoline. It was declared that additive A had lowest CO emission, followed by additives C, B and D, respectively. It was determined that maximum increase in CO emissions was 18% by additive A, 28% by additive B, 20% by additive C and 29% by additive D. It was reported that increases in CO emissions were due to disassociation reactions that occur as a result of rising combustion temperature due to high energy content of boron. **Figure 40b** shows the variation of hydrocarbon (HC) emissions with engine speed when boron–containing additives were used in gasoline. As seen in **Figure 40b**, lower HC values were obtained when boron–containing additives were used compared to gasoline.

It was declared that additive C gave lowest HC emissions followed by additives B, D and A, respectively. It was determined that maximum reduction in HC emissions was 34% by additive A, 36% by additive B, 46% by additive C and 32% by additive D. It was stated that HC emissions occurs in cold parts of combustion chamber where flame cannot reach, such as far corners of cylinder and ring crevices and it tends to decrease due to increasing turbulence with rising engine speed as similar to CO emission. It was also stated that increase in combustion temperature contributed to reducing HC emissions when boron–containing additives were used due to high energy of boron [1].

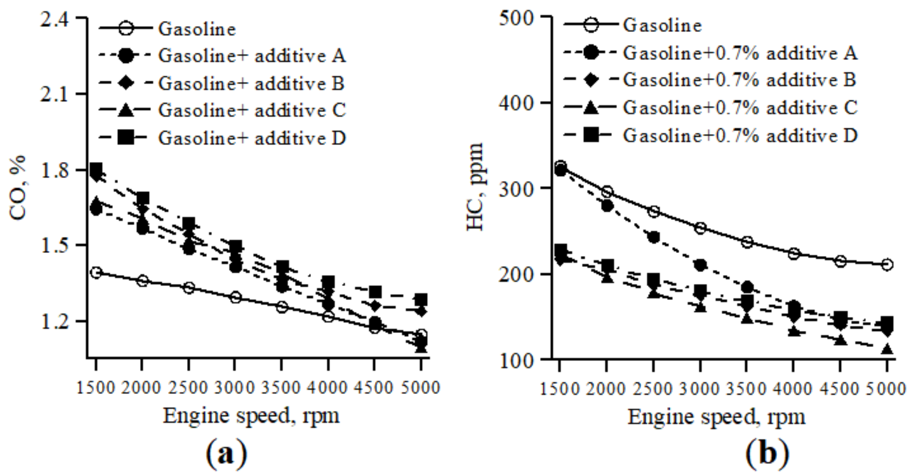

Figure 40. Variation of (**a**) CO; and (**b**) HC emissions with engine speed for addition of different boron including additives to gasoline [1].

Figure 41a shows the variation of CO emissions with engine load when TMB was added to gasoline at different ratios. It was declared that CO emissions reduced when TMB additive was used and lowest CO emissions for all fuels occurred at 75% engine load and 2% TMB ratio at all engine loads. It was stated that decrease in CO emissions was sourced from rising combustion efficiency due to oxygen content of TMB. It was determined that CO emissions reduced by 3.4, 6, 7.6 and 12.1% for 1, 1.5, 2 and 2.5% TMB. **Figure 41b** shows the variation of HC emissions with engine load when TMB was added to gasoline at different ratios. It was declared that HC emissions reduced when TMB additive was used and lowest HC emissions for all fuels occurred at 75% engine load and 2% TMB at all engine loads. It was stated that decrease in HC emissions was due to increase in combustion efficiency due to oxygen content of TMB. It was determined that HC emissions decreased by 4, 8.7, 10 and 14.4% on average for 1, 1.5, 2 and 2.5% TMB. **Figure 41c** shows the variation of nitrogen oxides (NOx) emissions with engine load when TMB was added to gasoline at different ratios. It ws declared that NOx emissions increased when TMB additive was used and highest NOx emission values for all fuels occurred at 75% engine load. It was stated that increase in NOx emissions with TMB addition was sourced from rising of combustion temperature due to oxygen content of TMB. It was determined that NOx emissions increased by 6.7, 23.5, 41.4 and 57.2% on average for 1, 1.5, 2 and 2.5% TMB. **Figure 41d** shows the variation of CO_2 emissions with engine load when TMB was added to gasoline at different ratios. It was declared that CO_2 emissions increased when TMB additive was used and highest CO_2 emission values for all fuels occurred at 75% engine load and 2% TMB at all engine loads. It was stated that increase in CO_2 emissions was sourced from improved combustion due to oxygen content of TMB which increased conversion rate of CO to CO_2. It was determined that CO_2 emissions increased by 15% at all engine loads when 2.5% TMB was added to gasoline [19].

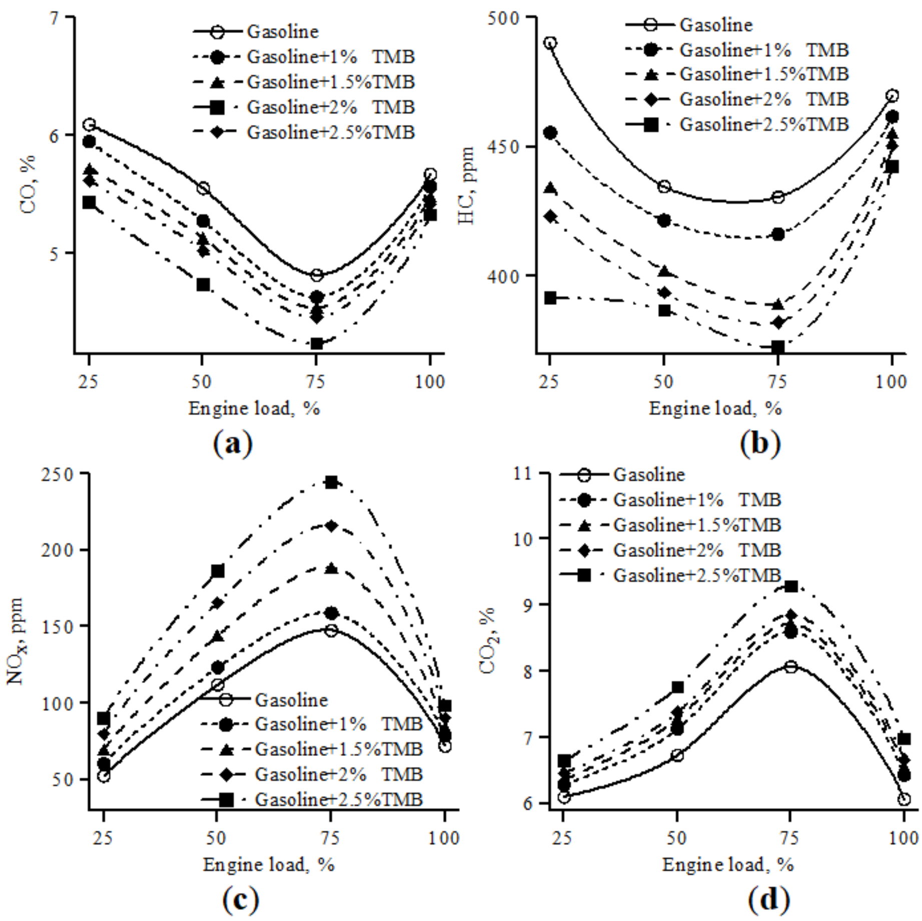

Figure 41. Variation of (**a**) CO; (**b**) HC; (**c**) NOx; and (**d**) CO_2 emissions with engine load for different amount of TMB addition to gasoline [19].

Figure 42a,b show the variation of CO and HC emissions with engine load when Octamix was added to gasoline. It was declared that CO and HC emissions generally decreased with rising engine load. Conversely, CO and HC emissions decreased for 0.5% Octamix additive compared to gasoline, but they increased when Octamix ratio increased further. Hence, lowest CO and HC values were obtained at 0.5% Octamix ratio at all engine loads. It was stated that increase in CO and HC emissions with rising Octamix ratio was sourced from higher viscosity of Octamix than gasoline which worsen fuel atomization and combustion efficiency. It was determined that CO and HC emissions reduced by 8.05% and 6.41% for 0.5% Octamix ratio at 1000 W engine load, while CO and HC emissions increased by 29.66% and 41.99% for 3% Octamix ratio. **Figure 42c,d** show the variation of NOx and CO_2 emissions with engine load for Octamix addition to gasoline. It was declared that NOx and CO_2 emissions generally increased with rising engine load for all fuels. Conversely, NOx and CO_2 emissions increased for 0.5% Octamix ratio, but NOx and CO_2 emissions were reduced with rising Octamix ratio. Thus, highest NOx and CO_2 emissions were obtained at 0.5% Octamix ratio at all engine loads. It was stated that increase in NOx emissions was sourced from rising oxygen and combustion temperature as a result of improved combustion, but decrease in NOx was sourced from worsening of combustion. It was determined that NOx emissions reduced by 7.63% for 0.5% Octamix ratio at 5000 W engine load while NOx emissions increased by 11.64% for 3% Octamix ratio. It was stated that variation in CO_2 emissions was related to combustion efficiency. It was determined that CO_2 emissions increased by 8.05% for 0.5% Octamix ratio at 4000 W engine load while CO_2 emissions reduced by 29.71% for 3% Octamix ratio [20].

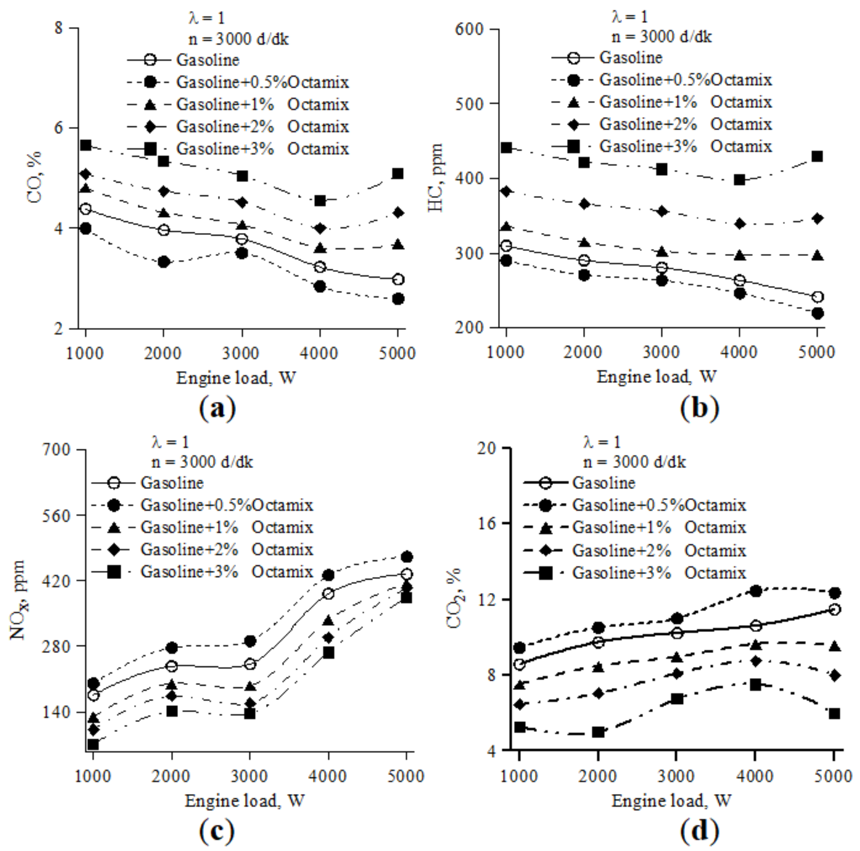

Figure 42. Variation of (**a**) CO; (**b**) HC; (**c**) NOx; and (**d**) CO_2 emissions with engine load for different amount of Octamix addition to gasoline [20].

Figure 43a shows the variation of CO emissions with engine speed for gasoline, E5, E5+SBH, M5 and M5+SBH blends. It was declared that CO emission is toxic and harmful to human health and occurs as a result of incomplete combustion. It was stated that incomplete combustion arises due to excessively lean or rich fuel–air mixture, improper ignition timing and deficient oxygen. It was declared that all blends gave lower CO emissions than pure gasoline. Conversely, adding SBH to E5 blend reduced further CO emissions, while adding SBH to M5 blend caused to rising slightly CO emissions. Hence, lowest CO emissions were obtained with E5+SBH5 blend. It was determined that CO emissions reduced by 50–91% for E5+SBH5 blend and 25–69% for M5+SBH blend. It was stated that oxygen content of alcohols and hydrogen content of SBH improved combustion and reduced CO emissions with blends. Conversely, CO emissions for all fuels increased up to 2200 rpm and then reduced. It was stated that this was sourced from more homogeneous fuel–air mixture was obtained due to mounting turbulence in combustion chamber by rising engine speed. **Figure 43b** shows the variation of HC emissions with engine speed for gasoline, E5, E5+SBH, M5 and M5+SBH blends. It was stated that HC emissions are also harmful to human health and also environment. It was stated that HC emissions mostly occurs in low–temperature regions of combustion chamber where flame cannot reach such as ring crevices and far corners of combustion chamber. It was declared that HC emissions reduced due to more homogeneous fuel–air mixture and rising combustion temperature by rising engine speed. Conversely, E5 blend gave lower HC emissions than gasoline, while M5 blend gave close but higher HC emissions to gasoline. It was stated that oxygen content of E5 blend improved combustion which resulting in decrease in HC emission, but low calorific value of methanol reduced combustion temperature and caused to rising HC emissions despite presence of oxygen in M5 blend. E5+SBH blend gave very close but lower HC values than gasoline while M5+SBH blend gave highest HC values as SBH addition to E5 and M5 blends increased HC emissions. It was determined that HC emissions reduced by 7.4–12.3% for E5+SBH blend and increased by 6.5–50% for M5+SBH blend compared to gasoline. It was stated that increases in HC emission was sourced from falling of combustion temperature prematurely due to rapid burning of hydrogen and boron in SBH. **Figure 43c** shows the variation of NOx emissions with engine speed for gasoline, E5, E5+SBH, M5 and M5+SBH blends. It was declared that alcohol–containing E5 and M5 blends gave lower NOx values than pure gasoline and also adding SBH to E5 and M5 blends reduced NOx emissions further. Thus, lowest NOx values were obtained with M5+SBH blend. It was determined that NOx emissions reduced by 12.63%, 19.65%, 28.37% and 36.03% for E5, E5+SBH, M5 and M5+SBH blends compared to gasoline. It was declared that formation of NOx varies to depend on the combustion temperature, amount of oxygen in combustion chamber and reaction time. It is declared that NOx emissions begin to occur at temperatures above 1800 K and it is advised mixing of oxygen and hydrogen–containing additives to conventional fuels to reduce NOx emissions and improve engine performance. Recently, alcohol fuels have been added to conventional fuels to improve combustion via oxygen content and nanoparticle additives were added to conventional fuels to shorten ignition delay. Conversely, alcohols reduce NOx emissions by lowering combustion temperature due to cooling effect and low calorific values. Additionally, it was stated that superior flame speed of alcohols, hydrogen and boron in SBH contributes to reduction of NOx emissions by shortening combustion duration. **Figure 43d** shows the variation of CO_2 emissions with engine speed for gasoline, E5, E5+SBH, M5 and M5+SBH blends. It was declared that all blends gave higher CO_2 values than gasoline and M5 blend gave higher CO_2 values than E5 blend. Conversely, adding SBH to E5 blend increased CO_2 emissions while adding SBH to M5 blend reduced CO_2 emissions slightly. CO_2 is main indicator of completion of combustion in ICEs though CO_2 emissions cause global warming. It was stated that addition of oxygen–containing additives such as alcohols etc. to conventional fuels improves combustion and increases CO_2. It was also stated that hydrogen in SBH increases CO_2 by providing more efficient combustion. It was determined that CO_2 increased by 8.51%, 34.48%, 30.46% and 25.95% for E5, E5+SBH, M5 and M5+SBH blends compared to gasoline [26].

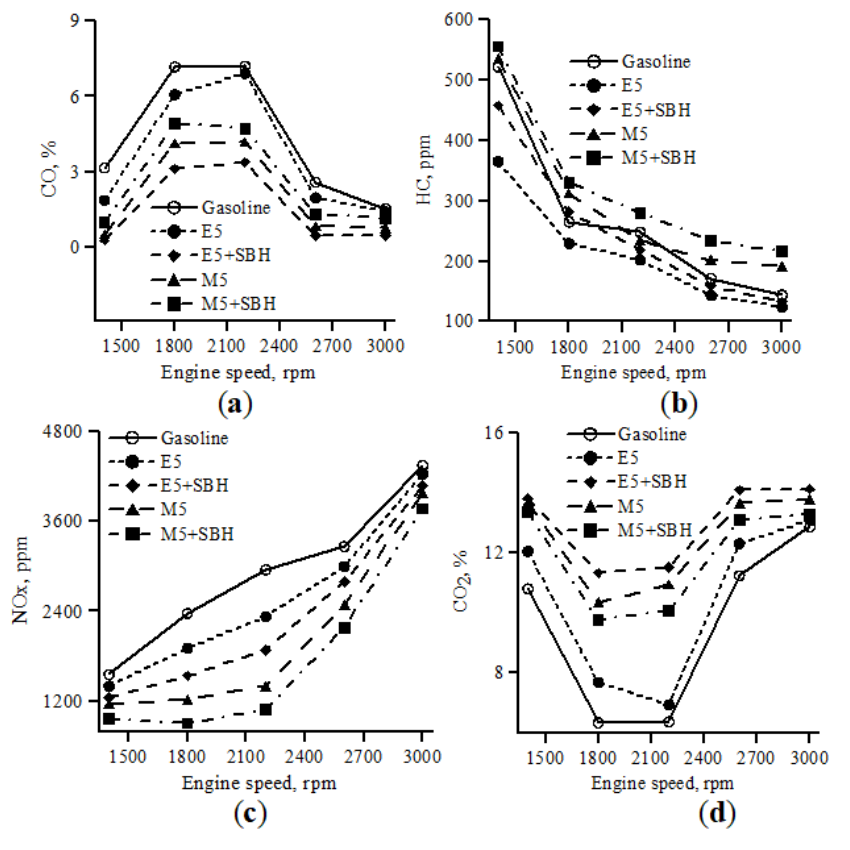

Figure 43. Variation of (**a**) CO; (**b**) HC; (**c**) NOx; and (**d**) CO_2 with engine speed for gasoline and E5, E5+SBH, M5 and M5+SBH blends [26].

Figure 44a shows the variation of CO emissions with engine speed for gasoline, E10+SBH and M10+SBH blends. It was determined that addition of alcohols and SBH to gasoline reduced CO emissions at all engine speeds and lowest CO emissions was obtained with M10+SBH blend while highest ones realized with gasoline. It was also determined that CO emissions were reduced by 31.04% and 53.7% with E10+SBH and M10+SBH blends compared to gasoline. It was declared that decrease in CO emissions was sourced from improved combustion due to oxygen in alcohols and hydrogen in SBH. **Figure 44b** shows the variation of HC emissions with engine speed for gasoline, E10+SBH and M10+SBH blends. It was determined that E10+SBH blend reduced HC emissions while M10+SBH blend increased HC emissions so lowest HC emissions was obtained with E10+SBH blend while highest ones was obtained with M10+SBH blend. It was also determined that HC emissions were reduced by 9.36% with E10+SBH and increased 9.43% with M10+SBH blend compared to gasoline. It was declared that this increase in HC emissions was sourced from lower calorific value and formation of inhomogeneous air fuel mixture due to leaning effect of methanol. **Figure 44c** shows the variation of NOx emissions with engine speed for gasoline, E10+SBH and M10+SBH blends. It was determined that NOx emissions were raised with engine speed while addition of alcohols and SBH to gasoline reduced NOx emissions. It was also determined that lowest NOx emissions were obtained with E10+SBH blend while highest ones occurred with gasoline. It was declared that decrease in NOx emissions was sourced from reduced combustion temperature via cooling effect of alcohols and faster combustion by proving hydrogen in SBH. **Figure 44d** shows the variation of CO_2 emissions with engine speed for gasoline, E10+SBH and M10+SBH blends. It was determined that addition of alcohols and SBH to gasoline raised CO_2 emissions and highest CO_2 emissions were obtained with M10+SBH blend while lowest ones occurred with gasoline. It was also determined that CO_2 emissions were raised by 11.2% and 19.51% with E10+SBH and M10+SBH blends compared to gasoline. It was declared that increase in CO_2 was sourced from improved combustion due to oxygen in alcohols and hydrogen in SBH [27].

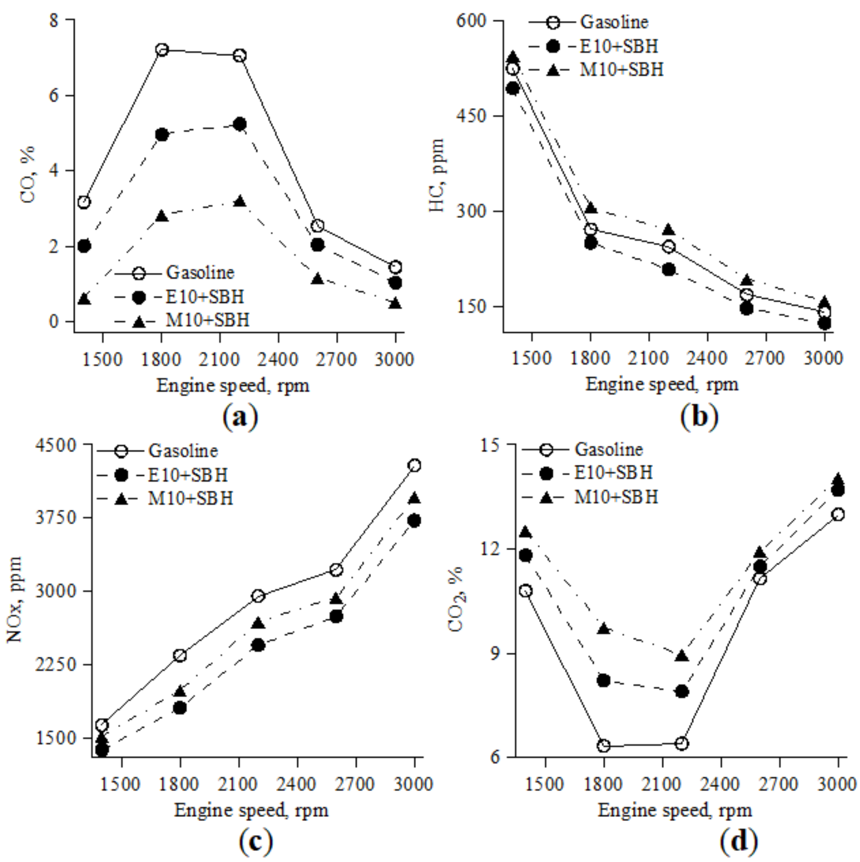

Figure 44. Variation of (**a**) CO; (**b**) HC; (**c**) NOx; and (**d**) CO_2 with engine speed for gasoline, E10+SBH and M10+SBH and blends [27].

Figure 45a shows the variation of CO emissions with engine speed for gasoline, E20 and E20+SBH blends. It was determined that lowest CO emissions were obtained with E20+SBH blend while highest CO emissions occurred with gasoline at all engine speeds. It was also determined that CO emissions were reduced by 19.34% and 22.06% with E20 and E20+SBH blends compared to gasoline. It was declared that reduction of CO emissions was sourced from improved combustion due to oxygen in ethanol and hydrogen in SBH. **Figure 45b** shows the variation of HC emissions with engine speed for gasoline, E20 and E20+SBH blends. It was determined that lowest HC emissions were obtained with E20+SBH blend while highest HC emissions occurred with gasoline at all engine speeds. It was also determined that HC emissions were reduced by 15.6% and 29.6% with E20 and E20+SBH blends compared to gasoline. It was declared that decrease in HC emissions was sourced from improved combustion due to oxygen in ethanol and hydrogen in SBH. **Figure 45c** shows the variation of NOx emissions with engine speed for gasoline, E20 and E20+SBH blends. It was determined that lowest NOx emissions were obtained with E20+SBH blend while highest NOx emissions occurred with gasoline at all engine speeds. It was declared that decrease in NOx emissions was sourced from reduced combustion temperature due to higher latent heat of vaporization of ethanol and faster combustion of hydrogen in SBH. **Figure 45d** shows the variation of CO_2 emissions with engine speed for gasoline, E20 and E20+SBH blends. It was determined that highest CO_2 emissions were obtained with E20+SBH blend while lowest CO_2 emissions occurred with gasoline at all engine speeds. It was also determined that CO_2 emissions were raised by 8.47% and 16.28% with E20 and E20+SBH blends compared to gasoline. It was declared that increase in CO_2 emissions was sourced from completed combustion via oxygen in ethanol and hydrogen in SBH [28].

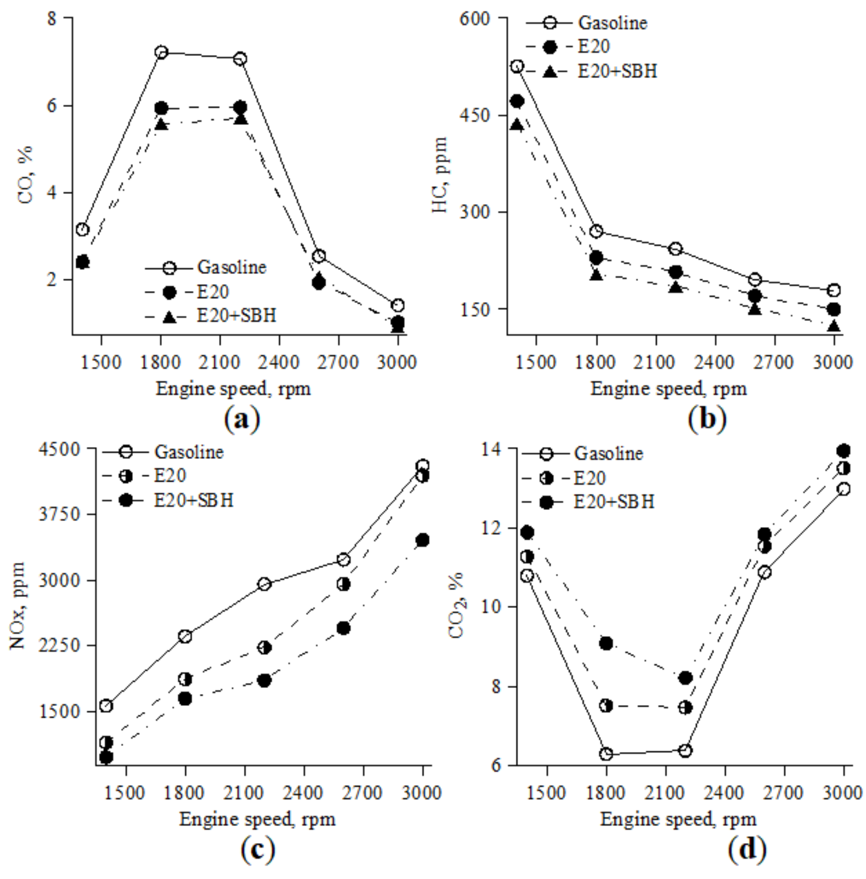

Figure 45. Variation of (**a**) CO; (**b**) HC; (**c**) NOx; and (**d**) CO_2 with engine speed for gasoline, E20 and E20+SBH [28].

Figure 46a–d shows the variation of CO, HC, NOx and CO_2 emissions when different boron containing additives were added to gasoline and various alternative fuels and blends were used. As seen in **Figure 46a,b**, it was determined that CO and CO_2 emissions were reduced by 99.1% and 10.8% compared to gasoline when CNG was used. It was stated that this was due to CNG had a very low carbon/hydrogen ratio. It was determined that CO emissions were reduced by 59.1% while CO_2 emissions increased by 4.9% when LPG was used. It was stated that this was due to LPG improved combustion by providing more homogeneous fuel–air mixture. However, it was determined that CO and CO_2 emission values increased for CNG10 and LPG5 blends were used compared to pure gaseous fuels. It was stated that this was sourced from incomplete combustion which resulted from decrease in engine volumetric efficiency due to introduction of gaseous fuels through the intake manifold. Conversely, it was determined that CO_2 emissions increased slightly when acetone (A25 and A50) blends were used, while CO emissions decreased by 11.1% for A25 blend and 7.6% for A50 blend. It was stated that this was due to complete combustion sourced from oxygen content and evaporation at low temperatures of acetone. It was determined that CO and CO_2 emissions increased by 0.9% and 1.8% when naphthalene (N50) blend was used. It was stated that this was sourced from high carbon/hydrogen ratio of naphthalene. It was determined CO emissions increased by 3%, 1.7% and 0.9%, and CO_2 emissions reduced by 2.5%, 5.1%, and 5.2% when boron–containing borax pentahydrate (BP), anhydrous borax (AB) and boric acid (BA) additives were added to gasoline. It was stated that this was sourced from boron–including additives having hydrogen and oxygen but no carbon. It was determined that HC emissions decreased by 81.5%, 51.3%, 29% and 34% for CNG and LPG fuels and CNG10 and LPG5 blends compared to gasoline as seen in **Figure 46c**. It was stated that this was due to CNG and LPG were in gas phase and provide complete combustion by creating more homogeneous fuel–air mixture due to low carbon/hydrogen ratio. It was determined that HC emissions reduced by 9.7% and 4.6% for A25 and A50 blends and increased by 5.5% for N50 blend compared to gasoline. It was stated that acetone reduced HC emissions by rising reaction rate during combustion, while naphthalene increased HC emissions by causing incomplete combustion due to its high carbon/hydrogen ratio. It was determined that HC emissions reduced by 0.2%, 6.7% and 2.7% when boron–containing BP, AB and BA additives were used. It was stated that this was due to improvement combustion via hydrogen and oxygen in boron–containing additives. It was determined that NOx emissions increased by about 4–5 times for CNG and LPG fuels and CNG10 and LPG5 blends compared to gasoline as seen in **Figure 46d**. It was stated that this was sourced from high combustion temperature of gaseous fuels due to their high calorific value. It was determined that NOx emissions increased by 13.6% and 6% for A25 and A50 blends and reduced by 4.1% for N50 blend compared to gasoline. It was stated that acetone increased combustion temperature and also efficiency due to its high octane number, while naphthalene gave incomplete combustion and low combustion temperature due to its high carbon/hydrogen ratio. It was determined that NOx emissions reduced by 11.1%, 17.8% and 18.3% when boron–containing BP, AB and BA additives were used. It was stated that this was due to boron–containing additives gave lower combustion temperature [22].

Figure 47a shows the variation of CO emission with engine load when Al, B and Fe nanoparticles were added to diesel fuel. It was declared that CO emissions reduced with rising engine load and there were increases in CO emissions up to 30% at low engine loads when Al and Fe were added to diesel fuel. It was stated that this was sourced from incomplete combustion as a result of deficient oxygen in combustion chamber due to using rich fuel–air mixture. It was determined that there was about 25–40% decrease in CO emissions compared to diesel fuel when Al and Fe additives were used as relatively leaner fuel–air mixtures were used at high engine loads. CO emissions were generally close to but lower than diesel fuel except for 6 kg engine load when B additive was used as seen in **Figure 47a**. It was stated that this was sourced from shorter ignition delay, faster combustion and higher combustion temperature due to its high energy content of boron additive. **Figure 47b** shows the variation of HC emission with engine load when Al, Fe and B nanoparticles were added to diesel fuel. It was declared that low HC emissions for all fuels were obtained at idle operation, while close HC values were obtained at other engine loads. Al additive gave lower HC emissions than diesel fuel except for 6 kg load, while Fe additive gave lower HC values than diesel fuel except for 12 and 15 kg loads. However, B additive gave higher HC emissions than diesel fuel except for 12 and 15 kg load. It was stated that micro explosions during combustion increased combustion temperature and reduced HC emission when Al and Fe additives were used, but B additive increased HC emission via dissociation reactions as a result of higher combustion temperature of B compared to Al and Fe additives. It was determined that Al and Fe additives reduced HC emissions by 8% and 4% compared to diesel fuel at maximum load of 15 kg. **Figure 47c** shows the variation of NOx emissions with engine load when Al, B and Fe nanoparticles were added to diesel fuel. It was declared that NOx emissions increased by rising engine load for all fuels. Al additive gave lower NOx values han diesel fuel up to 6 kg load, but higher NOx values were obtained with Al additive than diesel fuel at high loads. B additive gave lower NOx values than diesel fuel except for 6 kg load. Fe additive gave lower NOx values than diesel fuel except for idle operation. It was stated that decreases in NOx emissions were due to shortened burn duration via nanoparticle addition. It was determined that Al and B additives raised NOx emissions by 5% and 3% at maximum load of 15 kg. It was also declared particulate matter (PM) emissions raised by 12, 6 and 8% by addition of Al, B and Fe nanoparticles due to partly combustion of nanoparticles [34].

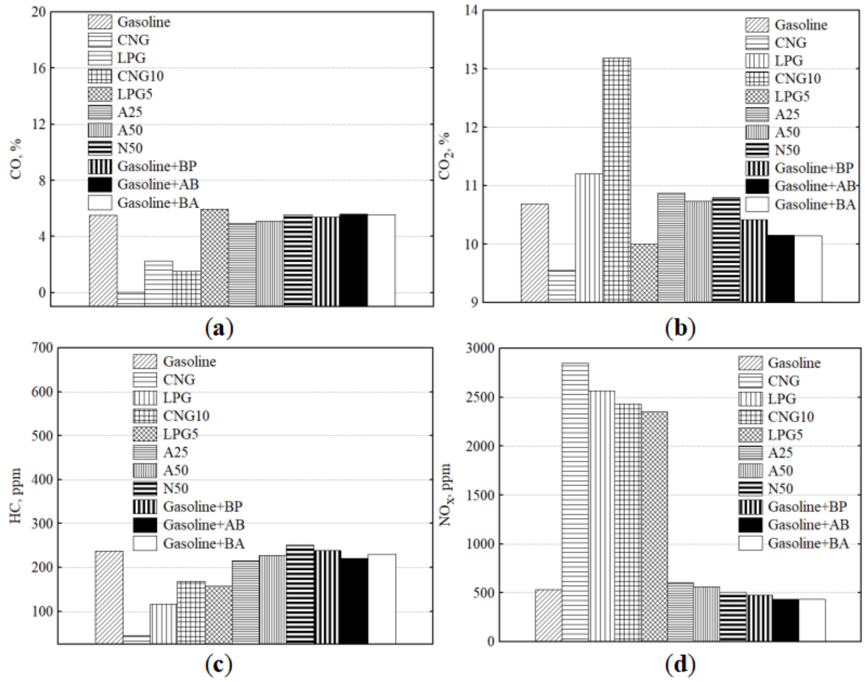

Figure 46. Variation of (**a**) CO; (**b**) HC; (**c**) NOx; and (**d**) CO_2 for various alternative fuels and blends and using different boron including additives with gasoline [22].

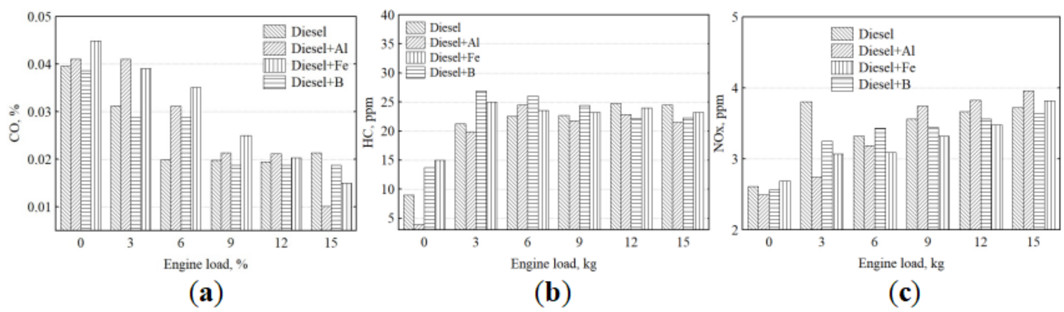

Figure 47. Variation of (**a**) CO; (b) HC; and (c) NOx emissions for Al, Fe and B additives with diesel fuel [34].

Figure 48a shows the variation of CO emissions with engine load when Octamix was added to diesel fuel at ratios of 0.5, 1, 2 and 3%. It was declared that CO emissions reduced up to 1% Octamix ratio, while CO values increased at 2% and 3% ratios compared to diesel fuel. CO values at load of 2500 W for 0.5%, 1, 2 and 3 Octamix blends were determined as 0.04%, 0.0307%, 0.0633% and 0.0787%, respectively. It was determined that there was 46.67% reduction in CO emissions at 1% Octamix ratio compared to diesel fuel. It was stated that Octamix additive improved combustion and reduced CO emissions by rising combustion temperature due to its oxygen content. Conversely, it was stated that CO emissions reduced due to rising combustion temperature up to 2000 W load, but CO emissions increased after load of 2500 W due to decrease in engine volumetric efficiency and combustion efficiency. **Figure 48b** shows the variation of HC emissions with engine load when Octamix was added to diesel fuel at ratios of 0.5, 1, 2 and 3%. It was declared that HC values reduced at 0.5% and 1% Octamix ratios, while HC emissions increased at 2% and 3% Octamix ratios. It was determined that there was 13.79% reduction in HC emissions with 1% Octamix ratio at load of 2500 W compared to diesel fuel. It was stated that Octamix reduced HC emission by improving combustion due to its oxygen and boron content. However, it was stated that HC emissions increased after load of 2500 W due to increase in friction losses and decrease in combustion efficiency. **Figure 48c** shows the variation of NOx emissions with engine load when Octamix was added to diesel fuel at ratios of 0.5, 1, 2 and 3%. It was declared that NOx values reduced at 0.5% and 1% Octamix ratios, while NOx emissions were raised at 2% and 3% Octamix ratios. It was determined that there was 15.663% reduction in NOx emissions with 1% Octamix ratio compared to diesel fuel. It was stated that Octamix additive reduced NOx emissions by lowering combustion temperature due to high latent heat of vaporization of its alcohol content. However, it was stated that NOx emissions increased at 2% and 3% Octamix ratios due to rising amount of nitrogen and oxygen. **Figure 48d** shows the variation of smoke emissions with engine load when Octamix was added to diesel fuel at ratios of 0.5, 1, 2 and 3%. It was declared that smoke values reduced at 0.5% and 1% Octamix ratios, while smoke emissions increased at 2% and 3% Octamix ratios. It was determined that there was 10.714% reduction in smoke emissions with 1% Octamix ratio compared to diesel fuel. It was stated that smoke reduced due to improving combustion via Octamix oxygen content, but smoke increased after 2% Octamix ratio as a result of incomplete combustion via high latent heat of vaporization of Octamix additive. **Figure 48e** shows the variation of CO_2 emissions with engine load when Octamix was added to diesel fuel at the ratios of 0.5, 1, 2 and 3%. It was declared that CO_2 values reduced at 0.5% and 1% Octamix ratios, while CO_2 emissions increased at 2% and 3% Octamix ratios. It was determined that there was 23.626% reduction in CO_2 emissions with 1% Octamix ratio compared to diesel fuel. It was stated that CO_2 emissions increased due to improving combustion via oxygen in Octamix, but CO_2 emissions reduced after 2% Octamix ratio as a result of incomplete combustion caused by high latent heat of vaporization of Octamix [12].

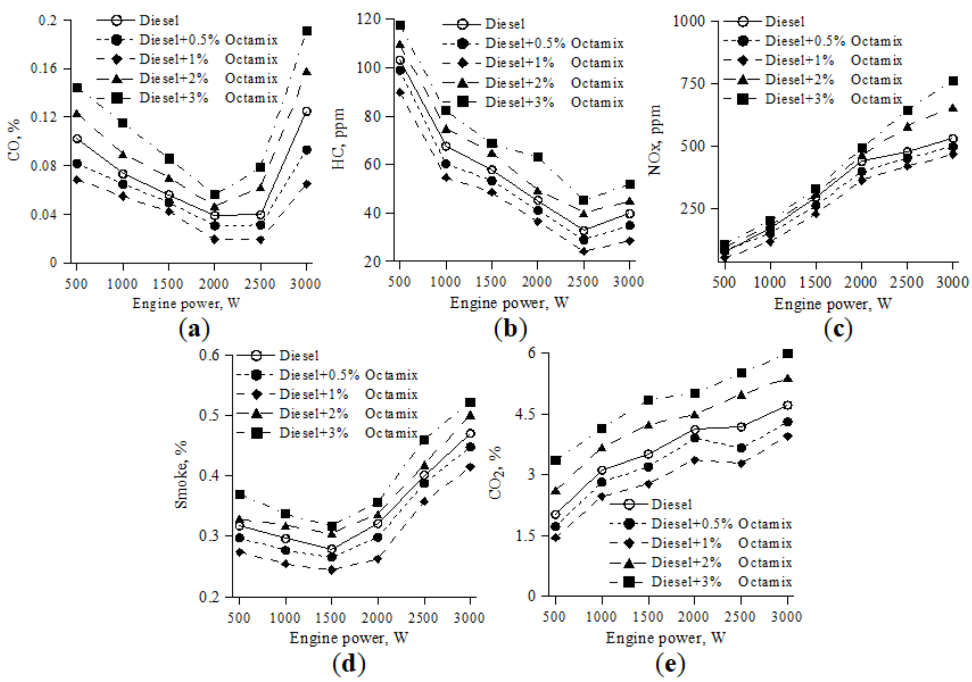

Figure 48. Variation of (**a**) CO; (**b**) HC; (**c**) NOx; (**d**) smoke; and (**e**) CO_2 emissions for different amount of Octamix addition to diesel fuel [12].

Figure 49a shows the effect of adding BO to BD20 blend on CO emissions. It was declared that CO emissions increased with 50 and 200 ppm BO additives, but a small decrease occurred with 100 ppm BO additive. It was determined that there was 6.44% and 22.38% increase in CO emissions for BD20BO50 and BD20BO200 nanofuels, while CO emissions reduced by 1.29% for BD20BO100 compared to BD20 blend. It was stated that catalytic effect of nanoparticles and increased high surface area/volume ratio improved combustion, but these effects were insufficient at 50 ppm BO addition. It was also stated that 200 ppm BO additive increased CO emissions due to deterioration of combustion by rising fuel viscosity. It was declared that best BO quantity for CO emissions reduction was 100 ppm. **Figure 49b** shows the effect of adding BO to BD20 blend on HC emissions. It was declared that nanoparticles addition reduced HC emissions compared to BD20 blend at all engine loads. It was determined that HC values reduced by 44.41%, 22.12% and 26.38% for BD20BO50, BD20BO100 and BD20BO200 blends compared to BD20 blend. It was stated that HC emissions reduced via more efficient combustion due to catalytic effect of BO nanoparticles which reducing activation energy required for oxidation of hydrocarbon molecules during combustion. However, it was stated that this effect partially decreased due to increased fuel viscosity at high nanoparticle quantity. **Figure 49c** shows the effect of adding BO to BD20 blend on NO emissions. It was determined that BD20BO50 nanofuel reduced NO emissions, but other nano fuels increased NO emissions. It was determined that NO emissions reduced by 6.05% for BD20BO50 nanofuel and increased by 14.90% and 25.08% for BD20BO100 and BD20BO200 nanofuels compared to BD20 blend. It was stated that NO formation increased due to extending combustion duration by adding BO nanoparticles. It was also stated that locally increased combustion temperature via catalytic effect of nanoparticles contributed to raising NO emissions. **Figure 49d** shows the effect of adding BO to BD20 blend on smoke emissions. It was declared that nanofuels increased smoke at all engine loads except for 25% load. It was stated that smoke was low level due to low amount of fuel injected and high excess air ratio at low load. It was stated that BO reduced smoke by evaporating fuel easily at low combustion temperature due to its catalytic effect. However, it was stated that smoke increased at high BO quantity as BO nanoparticles were in solid form thought hydrocarbon molecules adhering to surface of nanoparticles as a result of their catalytic effect reduced oxidation temperature of HC molecules to burn easier. Therefore, it was stated that rising BO quantity at high engine loads increased smoke emissions. It was determined that BD20BO50, BD20BO100 and BD20BO200 nanofuels increased smoke by 26.65%, 31.03% and 49.72% compared to BD20 blend [31].

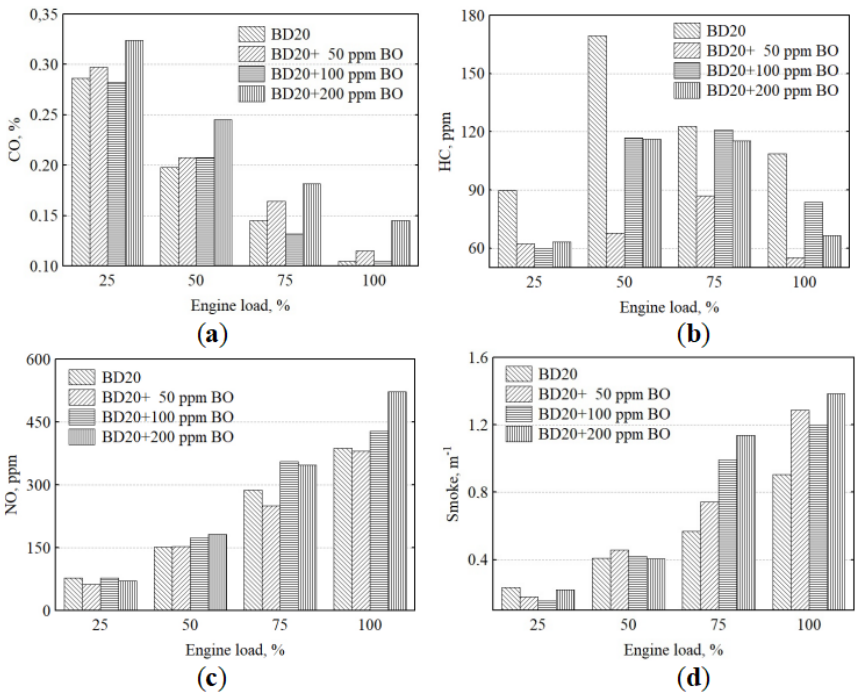

Figure 49. Variation of (**a**) CO; (**b**) HC; (**c**) NO; and (**d**) smoke with engine load for different amount of boron oxide (BO) additive in diesel–biodiesel blend (BD20) [31].

Figure 50a shows the variation of CO emissions with engine torque by addition of different amounts of boron nanoparticles to diesel fuel in a diesel–CNG dual fuel engine. It was declared that CO emissions increased by rising engine load due to operating with rich mixture as a result of rising amount of fuel sent to cylinder. It was declared that boron additive generally reduced CO emissions while they increased by rising amount of CNG. It was determined that CO emissions reduced by 22.4% and 23.6% with 50 and 100 ppm boron addition to diesel fuel at 100

Nm load with pure diesel fuel. It was stated that boron improved combustion and reduced CO emissions by rising combustion temperature due to its high energy content. Conversely, it was stated that raising amount of CNG increased CO emissions by reducing combustion temperature. It was also reported that reducing engine volumetric efficiency as a result of CNG passing through intake manifold contributed to rising CO emissions due to incomplete combustion. **Figure 50b** shows the variation of HC emissions with engine load by addition of different amounts of boron nanoparticles to diesel fuel in a diesel–CNG dual fuel engine. It was declared that HC emissions reduced by rising engine load due to rising combustion temperature as a result of increase in amount of fuel sent to cylinder. It was also declared that boron additive reduced HC emissions, rising amount of CNG caused to increase of HC emissions. It was determined that HC emissions reduced by 18.1% and 20% with 50 and 100 ppm boron addition to diesel fuel at 100 Nm engine load for pure diesel fuel. It was declared that decrease in HC emissions with boron addition was due to properties of boron that improved combustion, while increase in HC emissions by rising amount of CNG was due to incomplete combustion sourced from deficient air/oxygen as a result of reducing engine volumetric efficiency. **Figure 50c** shows the variation of NOx emissions with engine load by addition of different amounts of boron nanoparticles to diesel fuel in a diesel–CNG dual fuel engine. It was declared that NOx emissions increased by rising engine load increased due to rising combustion temperature and rising amount of CNG reduced combustion temperature and thus reduced NOx emissions. Conversely, boron addition to pure diesel increased NOx emissions, while boron addition to diesel–CNG dual fuel only gave small decreases in NOx emissions at low loads. It was determined that NOx emissions increased by 13.7% and 12.7% with 50 and 100 ppm boron addition to diesel fuel at 100 Nm load for pure diesel fuel. It was stated that decrease in NOx emissions by rising of CNG was due to extension of combustion duration and decrease in combustion temperature. **Figure 50d** shows the variation of CO_2 emissions with engine load by addition of different amounts of boron nanoparticles to diesel fuel in a diesel–CNG dual fuel engine. It was declared that CO_2 emissions increased by rising engine load due to more fuel was sent to cylinder. However, it was stated that rising amount of CNG sent to engine reduced CO_2 emissions by causing incomplete combustion. Conversely, it was determined that boron addition to diesel fuel caused to decrease in CO_2 emissions. It was determined that CO_2 emissions reduced by 4.2% and 3.1% for 50 and 100 ppm boron addition to diesel fuel at 100 Nm engine load for pure diesel fuel [32].

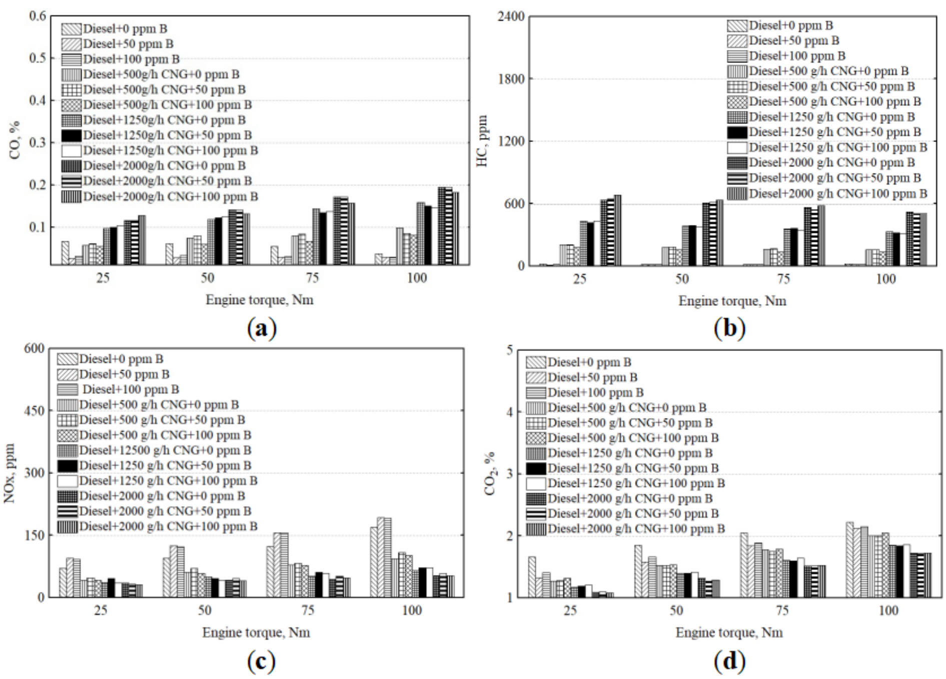

Figure 50. Variation of (**a**) CO; (**b**) HC; (**c**) NOx; and (**d**) CO_2 with engine torque for different amount of boron nanoparticles additive in a diesel–CNG dual fuel engine [32].

Figure 51a shows the variation of CO emissions with engine load for boron nanoparticles addition to diesel fuel in a diesel–BG dual fuel engine. It was declared that CO emissions for all fuels increased with rising engine load and it was stated that this was due to engine operating with a rich mixture as more fuel was sent to cylinder by rising engine load. It was determined that CO emissions reduced when boron was added to diesel fuel and it was stated that this was due to improving combustion and rising combustion efficiency via boron addition. Conversely, it was determined that CO emissions increased by rising BG ratio during dual fuel operation and it was declared that this was sourced from lessen combustion efficiency as a result of reducing engine volumetric efficiency due to BG passing through intake manifold and low combustion speed of BG. It was determined that CO emissions reduced by 22.2% by boron addition to diesel fuel during pure diesel operation, while it increased by 5.6%, 16.7% and 36.1% when 0.5, 1, 2 L/min BG was used. **Figure 51b** shows the variation of HC emissions with engine load when boron nanoparticles were added to diesel fuel in a diesel–BG dual fuel engine. It was declared that HC emissions reduced notably when boron was added to diesel fuel and it was stated that this was sourced from shortened combustion duration due to high catalytic effect of boron. Conversely, it was determined that HC emissions increased by rising BG ratio during dual fuel operation due to reduced combustion efficiency as a result of reducing engine volumetric efficiency and low combustion speed of BG. It was determined that HC emissions reduced by 23.5% for boron addition to diesel fuel during pure diesel operation, while it increased by 67.6%, 138.2% and 232.3% when 0.5, 1, 2 L/min BG was used. **Figure 51c** shows the variation of NOx emissions with engine load when boron nanoparticles were added to diesel fuel in a diesel–BG dual fuel engine. It was declared that NOx emissions for all fuels raised by rising engine load and it was stated that this was sourced from rising combustion temperature as a result of more fuel was sent to cylinder by rising engine load. Conversely, it was determined that NOx emissions reduced when boron was added to diesel fuel and BG was used. It was stated that this was sourced from reducing combustion temperature due to boron had high heat storage capacity and high thermal conductivity and BG had low calorific value. It was determined that NOx emissions reduced by 4.9% with boron addition to diesel fuel during pure diesel operation, while it reduced by 8.6%, 10.7% and 14.8% when 0.5, 1, 2 L/min BG was used [33].

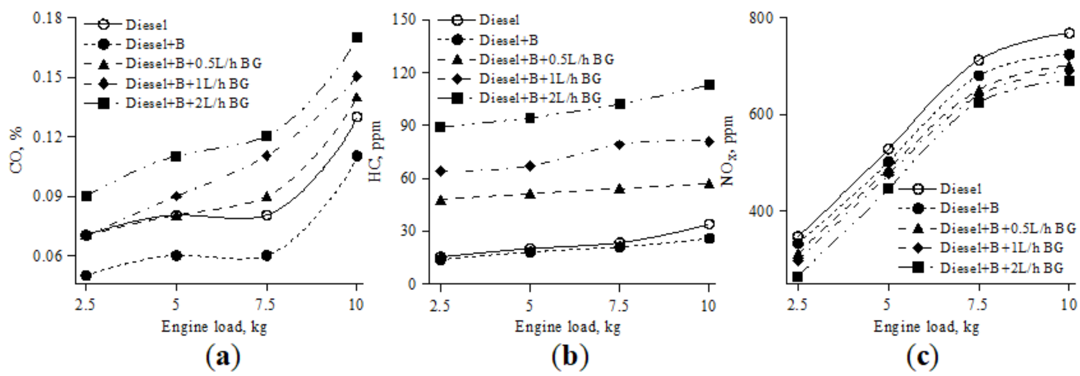

Figure 51. Variation of (**a**) CO; (**b**) HC; and (**c**) NOx emissions with engine load for boron nanoparticles additive in a diesel–BG dual fuel engine [33].

Figure 52a–d shows the variation of CO, HC, NOx and CO_2 emissions when nano–Al and MNP mixture was added to JP5 fuel. It was determined that CO emissions decreased with nano–Al additive and increased with MNP additive and it was stated that this was sourced from incomplete combustion as a result of rising amount of fuel sent to engine. Conversely, it was determined that HC emissions increased with nano–Al additive and reduced with MNP additive, and it was stated that it was not sourced from additives but it was due to operating condition of engine. It was determined that NOx emissions remained about same with nano–Al additive, but it was not sourced from additives but it was due to operating condition of engine. It was determined that CO_2 emissions remained about same for nano–Al additive, but increased by 21.1% for MNP additive, and it was declared that this was due to rising amount of fuel sent to engine when MNP additive was used [34].

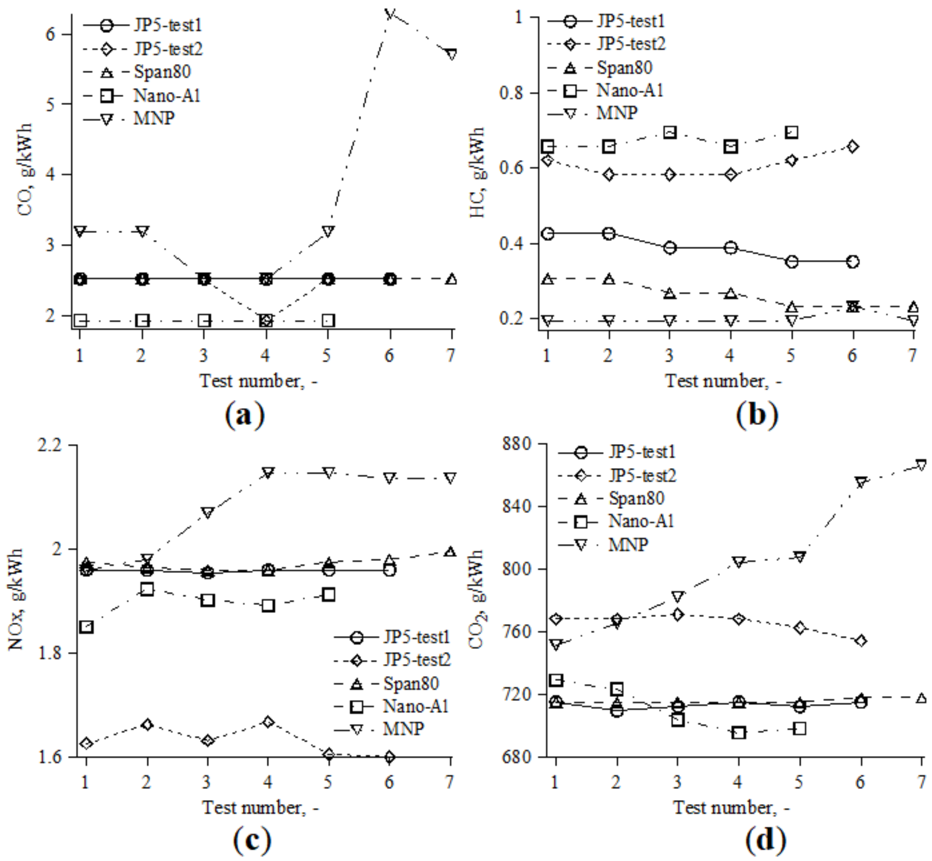

Figure 52. Variation of (**a**) CO; (**b**) HC; (**c**) NOx; and (**d**) CO_2 emissions for addition of n–Al nanoparticles and Ti–Al–B metallic nanoparticles (MNP) mixture to JP5 fuel [34].

5.2. Effect of Boron Additive to Oils on Emissions

Figure 53a shows the variation of CO emissions with engine speed for pure and 15% boron addition to 10W–40 engine oil in gasoline and CNG fuelled SI engine. It was declared that CO emission measurements were taken at beginning and end of 50 hours. It was determined that CO emissions for boron–added engine oil reduced about 8.4% at start–up and 11.4% at end of 50 hours for gasoline engine. It was also determined that CO emissions for boron–added engine oil reduced by 13.5% with gasoline and 15.7% for CNG engine at end of 50 hours. **Figure 53b** shows the variation of HC emissions with engine speed for pure and 15% boron added 10W–40 engine oil in gasoline and CNG fuelled SI engine. It was declared that HC emissions for boron–added engine oil increased slightly at speeds of 3000 and 3500 rpm and reduced slightly at speeds of 4000 and 4500 rpm when operating on gasoline, while they reduced slightly at speeds of 3000 and 3500 rpm and increased at speed of 4500 rpm when operating with CNG. It was declared that lowest HC values were measured at 3500 rpm while highest HC values were measured at 4500 rpm with both pure and boron–added engine oils. It was determined that HC emissions for boron–added engine oil reduced by 15% at start–up and 13% at end of 50 hours for gasoline engine. It was also determined that HC emissions for boron–added engine oil reduced by 5.2% with gasoline and 0.06% for CNG engine at end of 50 hours. **Figure 53c** shows the variation of NOx emissions with engine speed when using pure and 15% boron addition to 10W–40 engine oil in gasoline and CNG fuelled SI engine. It was declared that NOx emission measurements were taken at start–up and end of 50 hours. It was determined that NOx emissions for boron–added engine oil reduced by 3.6% at beginning and 3.5% at end of 50 hours for gasoline engine. It was also determined that NOx emissions for boron–added engine oil reduced by 10.7% with gasoline and 7.7% for CNG engine at end of 50 hours. **Figure 53d** shows the variation of CO_2 emissions with engine speed when using pure and 15% boron addition to 10W–40 engine oil in gasoline and CNG fuelled SI engine. It was declared that CO_2 emission measurements were taken at start–up and end of 50 hours. It was determined that CO_2 emissions for boron–added engine oil reduced by 1.5% at start–up and 0.02% at end of 50 hours for gasoline engine. It was also determined that CO_2 emissions for boron–added engine oil reduced by 7.35% with gasoline and 7.34% for CNG engine at end of 50 hours. It was declared that boron addition to engine oil had a positive effect on emissions [3].

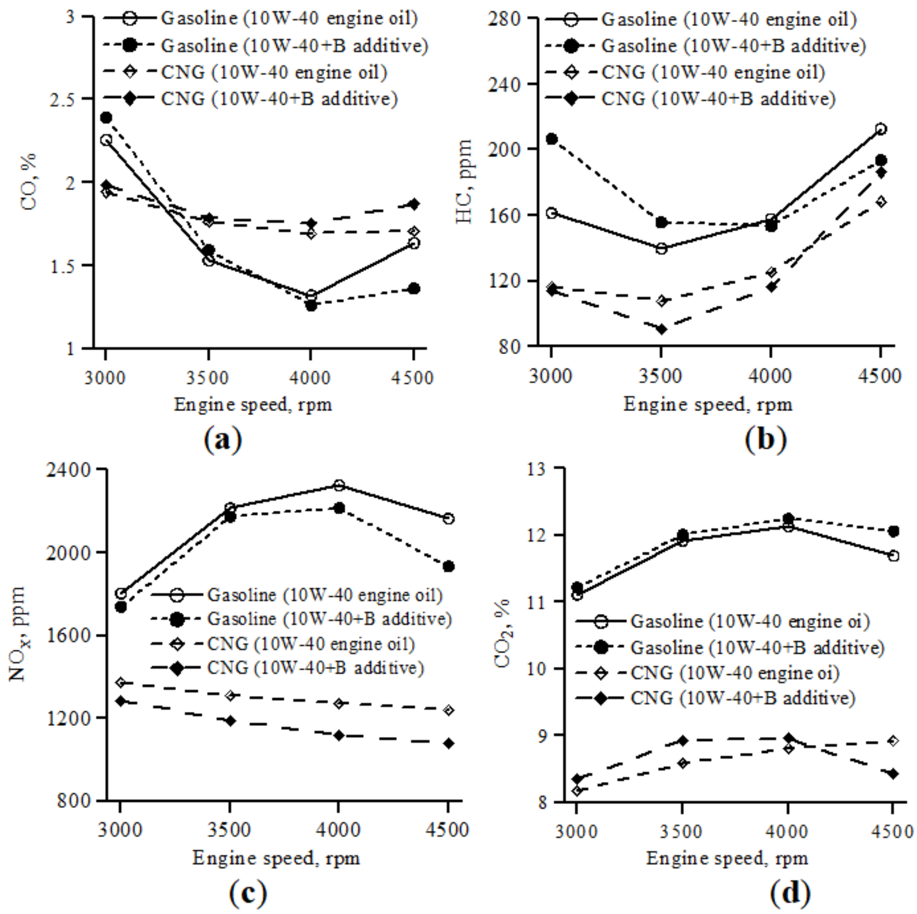

Figure 53. Variation of (**a**) CO; (**b**) HC; (**c**) NOx; and (**d**) CO_2 emissions with engine speed for pure and boron additive 10W–40 engine oil [3].

Figure 54a–c show the variation of CO, HC and CO_2 emissions with engine load when using pure and hBN added engine oil at different fuel/oil ratios in a two–stroke gasoline engine. It was determined that CO and HC emissions reduced by rising fuel/oil ratio and engine load and also hBN addition to engine oil. It was reported that decrease in CO and HC emissions was due to improved combustion with hBN addition to engine oil. It was also determined that CO_2 emissions increased by increasing fuel/oil ratio and engine load and also hBN additive to engine oil. It was reported that increase in CO_2 emissions was due to more efficient combustion hBN additive to engine oil. It was also determined that hBN additive made possible to consume less engine oil [36].

Figure 55a–d show the variation of CO, HC, NOx and CO_2 emissions with engine speed when using pure and boron–added 10W–40 engine oil in a diesel engine. It was determined that CO emission reduced by 29.43% at 1500 rpm and increased by 43.05% and 81.27% at 1750 and 2000 rpm when boron additive engine oil was used. It was determined that HC emission reduced by 51.58%, 50.18% and 84.41% at 1500, 1750 and 2000 rpm when boron additive was used. It was reported that changes in CO and HC emissions was due to improved combustion via boron addition to engine oil. It was determined that NOx emission reduced by 68.57%, 56.06% and 83.08% at 1500 rpm, 1750 rpm and 2000 rpm when boron additive was used. It was reported that this change in NOx emission sourced from reduced combustion temperature due to high heat conduction capacity of boron additive. It was determined that CO_2 emissions reduced by 57.83%, 43.68% and 68.72% at 1500, 1750 and 2000 rpm when boron additive was used. It was reported that boron additive to engine oil reduced friction and contributed to reduction of emissions [37].

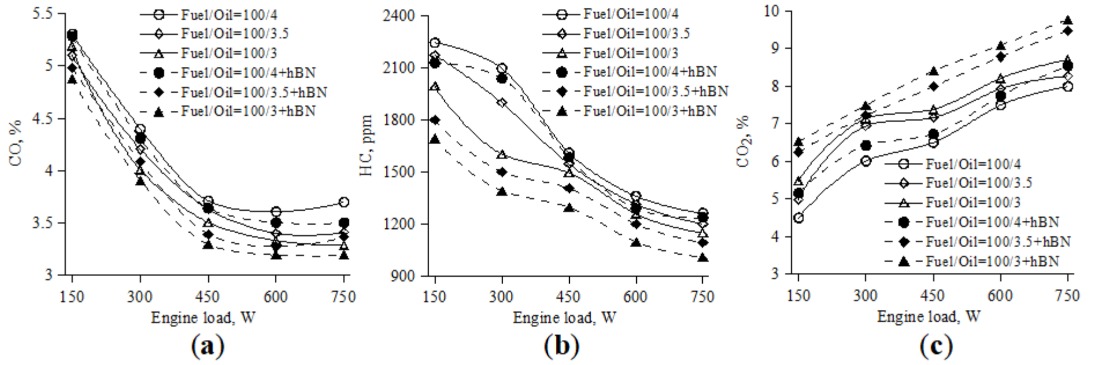

Figure 54. Variation of (**a**) CO; (**b**) HC; and (**c**) CO_2 emissions with engine load for pure and hBN additive engine oil [36].

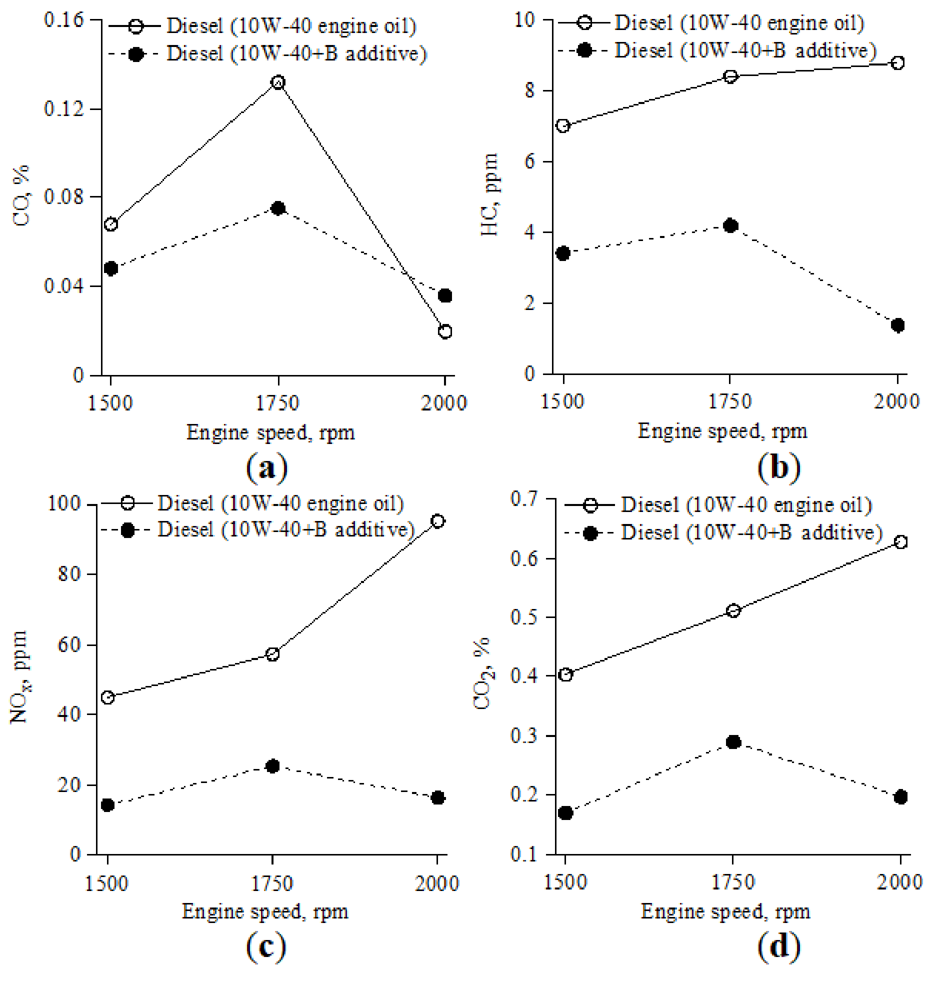

Figure 55. Variation of (**a**) CO; (**b**) HC; (**c**) NOx; and (**d**) CO_2 emissions with engine speed for pure and boron additive 10W–40 engine oil [37].

Figure 56a shows the variation of CO emissions with engine load when using pure and boron–containing 20W–40 engine oil in a diesel engine. It was declared that hBN was added to engine oil at ratios of 0.5, 0.75 and 1%. It was declared that CO emissions were reduced at all engine loads with 1% hBN addition to engine oil and it was determined that CO emissions decreased an average 46.15%. It was stated that decrease in CO emissions was due to hBN additive did not react with oxygen in combustion chamber as it was chemically stable. It was also declared that hBN additive prevented CO emissions transfer from lubricating oil to combustion chamber by creating sufficient oil film between piston rings and cylinder walls, and this contributed to reduction of CO emissions. **Figure 56b** shows the variation of HC emissions with engine load when using pure and boron–containing 20W–40 engine oil in a diesel engine. It was declared that HC emissions were reduced at all engine loads with 1% hBN addition to engine oil and it was determined that HC emissions reduced an average 55.95%. It was stated that hBN additive created better oil film between piston rings and cylinder walls by preventing leakages from lubricating oil to combustion chamber, and this increased combustion efficiency and reduced HC emissions. **Figure 56c** shows the variation of NOx emissions with engine load when using pure and boron–containing 20W–40 engine oil in a diesel engine. It was declared that NOx emissions were increased at all engine loads with 1% hBN addition to engine oil and it was determined that NOx emissions increased an average 40.03%. It was stated that increase in NOx emissions was sourced from reaction of nitrogen in hBN additive with oxygen in combustion chamber [13].

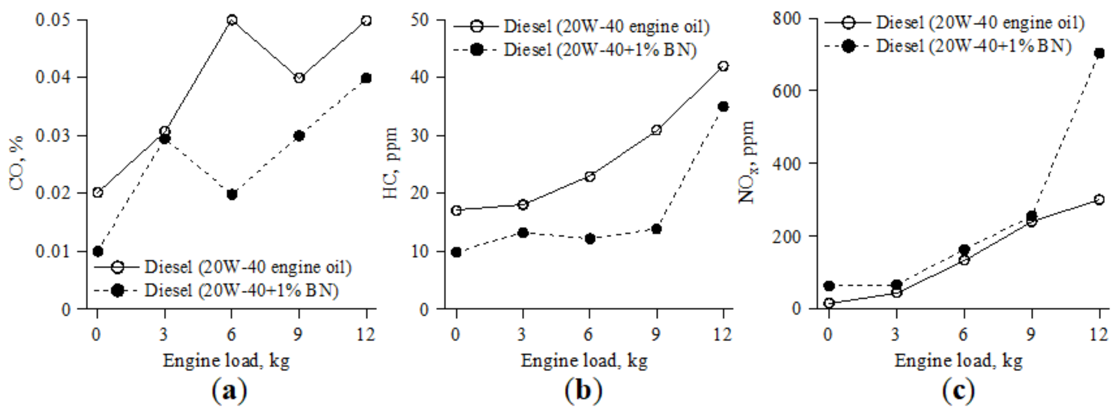

Figure 56. Variation of (**a**) CO; (**b**) HC; and (**c**) NOx emissions with engine load for pure and BN additive 20W–40 engine oil [13].

6. Conclusions

The presented study investigated the effects of boron addition to engine fuels and oils on the combustion, performance and emissions based on the literature. The following conclusions can be summarized from the findings.

- It was reported that boron containing materials usually provided increased maximum flame temperature and flame speed, shortened ignition delay time and combustion duration and an improved combustion.
- It was determined that addition of various boron–containing additives to gasoline at the rate of 0.7% increased torque by 1.1–5.2% at low and medium speeds, and reduced specific fuel consumption by 2.1–9.5% at medium speeds.
- It was determined that sodium boron hydride addition to 5% ethanol–gasoline blend reduced torque by 1–1.6% while it increased brake thermal efficiency by 5.8–10.9% and brake specific fuel consumption by 1–2.8% compared to gasoline. It was determined that sodium boron hydride addition to 5% methanol–gasoline blend increased torque by 1.2–3.7%, brake thermal efficiency by 7.8–14.5% and specific fuel consumption by 5.4–7.9% compared to gasoline. It was determined that sodium boron hydride addition to 10% ethanol–gasoline blend increased brake thermal efficiency and brake specific fuel consumption while it reduced torque compared to gasoline. It was determined that sodium boron hydride addition to 10% methanol–gasoline blend increased torque, brake thermal efficiency and specific fuel consumption compared to gasoline. It was determined that

sodium boron hydride addition to 20% ethanol–gasoline blend reduced torque by 1.64% and engine power by 5.1%, while it increased brake specific fuel consumption by 6.57% compared to gasoline.

- It was determined that addition of 0.5% boron–containing additive called Octamix to gasoline increased brake thermal efficiency slightly while rising Octamix ratio negatively affected brake thermal efficiency and specific fuel consumption.
- It was determined that borax pentahydrate, anhydrous borax and boric acid addition to gasoline reduced torque by 4%, 4.4% and 4.4%, respectively. It was also determined that the additives gave 5.8% decrease, 0.4% increase and 15.2% decrease in specific fuel consumption, respectively.
- It was determined that 0.5% boron nanoparticles addition to diesel fuel increased brake thermal efficiency by 8.2% and reduced specific fuel consumption by 3.4%. It was also determined that 50 and 100 ppm boron nanoparticles addition to diesel fuel increased brake thermal efficiency by 1.3–7.1% and reduced specific fuel consumption by 1.3–6.7%.
- It was determined that addition of boron–containing additive called Octamix to diesel fuel up to 1% ratio increased brake thermal efficiency by 3.19% and reduced specific fuel consumption by 7.8%. However, it was also determined that rising Octamix ratio negatively impacted brake thermal efficiency and specific fuel consumption.
- It was determined that boron nanoparticles addition at amounts of 50, 100 and 200 ppm to diesel–biodiesel blend containing 20% biodiesel increased brake thermal efficiency by 0.96% and reduced specific fuel consumption by 1.66%.
- It was determined that 50 and 100 ppm boron nanoparticles addition to diesel fuel in a diesel–natural gas dual fuel engine increased brake thermal efficiency by 1.4–6.3% and reduced specific fuel consumption by 1.3–6.2%.
- It was determined that boron nanoparticles addition to diesel fuel in a diesel–biogas dual fuel engine increased brake thermal efficiency by 8.04% and reduced specific fuel consumption by 8.42%. It was also determined that brake thermal efficiency reduced by 9.41–32.2% and specific fuel consumption increased by 10.94–60.2% at biogas ratios of 0.5, 1, 2 L/min.
- It was determined that nano–aluminum addition to JP5 fuel reduced fuel consumption by 17% while addition metallic nanoparticle mixture containing boron to JP5 fuel increased fuel consumption by 5%.
- It was determined that addition of 10% boron including additive to 10W–40 engine oil in a spark ignition engine reduced torque by 0.4–1.3% when operating on gasoline and increased torque by 1.3–2.1% when operating on natural gas. It was also determined that specific fuel consumption reduced by 3.4% and 7.1% when operating on gasoline and natural gas, respectively.
- It was determined that total fuel consumption decreased slightly and oil consumption reduced by 12.5% when hexagonal boron nitride containing engine oil was used in a two–stroke gasoline engine.
- It was determined that addition of 15% boron containing additive to 10W–40 diesel engine oil increased torque by 2.51–8.31% and reduced specific fuel consumption by 12.29–14.64%.
- It was determined that 1% hexagonal boron nitride addition to 20W–40 diesel engine oil increased brake thermal efficiency by 6.3% and reduced specific fuel consumption by 3.5%.
- It was determined that addition of 4% hexagonal boron nitride and 4% boric acid separately to 20W–50 diesel engine oil reduced total fuel consumption by 3.9–4% and 7.3%, respectively.
- It was determined that addition of various boron–containing additives to gasoline at different ratios reduced HC emissions by 28.7–46% and increased CO emissions by 7.4–29%.
- It was determined that addition of 1–2.5% trimethyl borate to gasoline reduced CO and HC emissions by 3.4–12.1% and 4–14.4%, while it increased NOx and CO_2 emissions by 6.7–57.2% and 15%.
- It was determined that addition of 0.5% Octamix to gasoline reduced CO, HC and NOx emissions by 8.05%, 6.41% and 7.63% while 3% Octamix addition increased CO, HC and NOx emissions by 29.66%, 41.99% and 11.64%. It was also determined that CO_2 emissions increased by 8.05% with 0.5% Octamix while CO_2 emissions were reduced by 29.71% with 3% Octamix addition.
- It was determined that sodium boron hydride addition to 5% ethanol–gasoline blend reduced CO, HC and NOx emissions by 50–91%, 7.4–12.3% and 19.65% compared to gasoline. It was determined that sodium boron hydride addition to 5% methanol–gasoline blend reduced CO, HC and NOx emissions by 25–69%, 7.4–12.3% and 36.03% compare to gasoline. It was determined that sodium boron hydride addition to 10% ethanol–gasoline

blend reduced CO and NOx emissions by 53.7% and 8.73% while it increased CO_2 emissions by 19.51% compared to gasoline. It was determined that sodium boron hydride addition to 20% ethanol–gasoline blend reduced CO and HC emissions, while it increased CO_2 and NOx emissions compared to gasoline.

- It was determined that borax pentahydrate, anhydrous borax and boric acid addition to gasoline increased CO emissions by 3%, 1.7% and 0.9% while they reduced HC emissions by 0.2%, 6.7% and 2.7% and CO_2 emissions by 2.5, 5.1% and 5.2%.
- It was determined that 0.5% boron nanoparticles addition to diesel fuel reduced CO emissions by 2.5–12% and increased HC and smoke emissions increased by 52% and 6%. It was also determined that boron nanoparticles addition at amount of 50 and 100 ppm to diesel fuel reduced CO, HC and CO_2 emissions by 21–60%, 12.5–38% and 3.3–20.3% while NOx emissions were raised by 12.4–35%.
- It was determined that addition of 1% boron–containing additive called Octamix to diesel fuel reduced CO, HC, NOx, smoke and CO_2 emissions by 46.67%, 13.79%, 15.66%, 10.714% and 23.63%. However, it was declared that raising Octamix ratio negatively affected emissions.
- It was determined that addition of 50, 100 and 200 ppm boron nanoparticles to diesel–biodiesel blend containing 20% biodiesel reduced CO, HC and NO emissions by 1.29%, 22.12% and 6.05% while smoke emissions were increased by 31.03%.
- It was determined that boron nanoparticles addition at amount of 50 and 100 ppm to diesel fuel in a diesel–natural gas dual fuel engine reduced CO, HC, NOx and CO_2 emissions by 4–8.1%, 1.6–12.5%, 3.6–16% and 0.6–20.3.
- It was determined that boron nanoparticles addition to diesel fuel in a diesel–biogas dual fuel engine reduced CO, HC and NOx emissions by 22.2%, 23.5% and 4.9%. It was also determined that using biogas at amount of 0.5, 1, 2 L/min increased CO, HC and NOx emissions by 5.6–36.1%, 67.6–232.3% and 8.6–14.8%.
- It was determined that nano–aluminum addition to JP5 fuel reduced CO emissions and increased HC emissions while NOx and CO_2 emissions remained as the same. It was also determined that boron–containing metallic nanoparticle mixture addition to JP5 fuel reduced HC emissions while CO, NOx and CO_2 emissions were raised.
- It was determined that addition of 10% boron additive to 10W–40 engine oil in a spark ignition engine did not significantly affect CO, HC and CO_2 emissions when operating on gasoline and natural gas while NOx emissions were reduced by 12.3% and 11.4% when operating on gasoline and natural gas, respectively.
- It was determined that hexagonal boron nitride addition to engine oil in a two–stroke gasoline engine reduced CO and HC emissions and increased CO_2 emissions.
- It was determined that addition of 15% boron–containing additive to 10W–40 diesel engine oil reduced CO, HC, NOx and CO_2 emissions by 29.43–43.05%, 51.58–84.41% and 68.57–83.08%, respectively.
- It was determined that 1% hexagonal boron nitride addition to 20W–40 diesel engine oil reduced CO and HC emissions by 46.15% and 55.95% while NOx emissions were increased by 40.03%.
- It can be said that boron–containing additives contributed to improvement of combustion, but effects of boron–containing fuel and oil additives on performance parameters such as power, torque, efficiency and fuel consumption were lower than their effects on emissions.
- Developments in nanoparticle and nanofluid industry made possible the producing of boron–containing additives efficiently. It is necessary to universalize the results by increasing the number of studies and extending the examined parameters on the use of boron–containing additives to become widespread using of them.

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Conflicts of Interest

The author declares no conflict of interest.

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