Proceedings of Automotive Science and Technology 1(1): 27-36 (2025)

ISASTECH2025

Effect of Diesel Fuel Produced from Lignite via Fischer-Tropsch Synthesis on Exhaust Emissions

Mersin Hürpekli

TÜBİTAK Rail Transport Technologies Institute(RUTE), Engine and Transmission Systems Group, Kocaeli, 41470, Türkiye

Abstract

This study investigated the effect of a liquid fuel (FT diesel), produced from lignite mined in Türkiye using the Fischer-Tropsch method, on exhaust emissions when used as an alternative to conventional diesel fuel in a compression ignition engine. The study also evaluated the effects of both fuels and injection timing on exhaust emissions by changing the fuel injection timing. The findings indicated that using FT diesel fuel initiates combus-tion earlier and increases in-cylinder gas temperatures.

The results indicate that FT diesel fuel can reduce hydrocarbon emissions by up to 50%, carbon monoxide emissions by 48.7%, carbon dioxide emissions by 7.8%, and soot emissions by up to 50% with appropriate in-jection strategies. Fuel properties and exhaust emissions indicate that FT diesel fuel is a suitable alternative fuel for diesel engines without requiring any modifications to the engine fuel system. It was also noted that emissions can be further reduced by optimizing injection strategies using FT diesel fuel.

Keywords: Coal to Liquid Fuel (CTL), Diesel Engine, Exhaust Emission, FT Diesel, Fuel Injection Timing.

http://dx.doi.org/10.29228/pastech.89068

1. Introduction

Diesel engines are widely utilized in transportation, power generation, and agricultural machinery due to their high efficiency, reliability, and durability [1]. However, the rapid depletion of fossil fuel resources and the tightening of emission regulations have negatively affected the widespread use of diesel engines [2]. The European Union (EU), as part of its commitments under the Paris Climate Agreement, has taken a leading role in emission regulation and continues to enforce stricter emission limits for diesel engines.

The EU Directive 2009/28/EC promotes the use of alternative fuels to mitigate greenhouse gas effects associated with petroleum-based fuels. With increasingly stringent emission standards, research efforts to improve combustion processes in diesel engines have intensified. Among the proposed solutions, the use of synthetic fuels and the optimization of fuel injection timing have shown significant potential for emission reduction.

In this study, diesel fuel synthesized from locally mined Turkish lignite via the Fischer–Tropsch (FT) process was investigated as an alternative to petroleum-based diesel. The effects of injection timing on exhaust emissions were analyzed. Türkiye holds approximately 3.2% of the world’s lignite reserves. As of 2017, coal accounted for 27% of Türkiye’s total primary energy consumption of 145.3 million tons of oil equivalent. The production of FT diesel in Türkiye is currently small-scale and primarily limited to academic research. Our previous publication [3] is among the few studies reporting the combustion characteristics of coal-derived FT diesel produced in Türkiye.

FT fuels can be utilized within existing fossil fuel infrastructure (e.g., pipeline systems), facilitating their commercialization [4]. Moreover, FT fuels, with their near-zero sulfur content, meet the U.S. EPA 2007 fuel requirements. However, the global commercialization of FT fuels has progressed relatively slowly.

In South Africa and China, coal-to-liquid (CTL) technologies are commercially implemented at lower costs com-pared to biomass-to-liquid (BTL) processes. In South Africa, SASOL Synfuels operates the world’s largest CTL facility in Secunda, near Johannesburg, processing approximately 45 million tons of coal annually to meet around 28% of the country’s diesel and gasoline demand [5]. In China, Synfuels China Technology operates CTL plants in Ejin Horo Banner, Ningdong, Tinlui, and Xiangyuan, forming the world’s second-largest CTL capacity after SASOL. These facilities convert approximately 20.36 million tons of coal into diesel and produce an additional 4.052 million tons of liquid by-products (including naphtha, LPG, sulfur, mixed alcohols, and ammonium sulfate).

Gasification is a thermochemical conversion process in which coal is transformed into a gas mixture composed of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4), tar, water vapor, and hydrogen sulfide. The composition of this syngas depends on raw material characteristics, the gasifying medium (steam, air, O_2, CO_2), the temperature and pressure inside the gasifier, and the type of catalyst used. The physical and chemical properties of the coal also significantly affect the composition of the syngas [6,7]. Depending on the type of coal and the gasifier design, syngas composition may vary. Li et al. [8] reported that syngas derived from Chinese lignite through FT synthesis contains approximately 36–45% H_2, 20–30% CO, 25–35% CO_2, 1–5% CH_4, and 1–3% N_2.

The Fischer–Tropsch synthesis is the process of converting syngas (CO + H_2) into hydrocarbons [9]. It can utilize syngas derived from natural gas [10,11], biogas [12], landfill gas [13], coal [14,15], or biomass [6,16] to produce synthetic liquid fuels or biofuels. As emission regulations in the transportation sector become increasingly stringent, FT diesel is considered a promising alternative to petroleum diesel [17,18]. Commercial vehicle engines typically operate on petroleum diesel; however, the use of coal-based FT diesel in compression ignition engines could help alleviate petroleum dependency while enabling the environmentally responsible use of coal resources [19]. Numerous researchers [18,20,21] have reported that FT diesel can be used directly in CI engines without significant modifications to engine structure or systems, while also contributing to emission reduction [18,20,22,23].

Recent experimental studies have supported these findings. Geng et al. [19] investigated the spray and combustion characteristics of FT and petro-diesel, reporting superior vaporization properties for FT diesel. Song et al. [24] examined emission results according to the European Stationary Cycle (ESC) test and found that as the FT diesel ratio increased, brake-specific CO_2 emissions decreased. Cai et al. [25] observed that soot emissions were significantly reduced with FT–diesel blends.

Several researchers [26–28] have examined the effects of FT diesel on particulate matter (PM) and NOx emissions, reporting reductions when FT diesel was used either neat or blended. Zhang et al. [28] studied combustion and emission characteristics of FT diesel/gasoline blends and observed that FT100 exhibited higher brake thermal efficiency under high-load conditions than pure petroleum diesel. Bermúdez et al. [29] investigated the exhaust emissions of FT diesel and ultra-low sulfur diesel (ULSD) in a EURO IV-compliant four-cylinder light-duty diesel engine and reported lower emissions and fuel consumption with FT diesel. Torregrosa et al. [30] analyzed the performance and emissions of FT diesel and biodiesel, reporting increased NOx emissions and specific fuel consumption but reduced soot formation. Pei et al. [31] compared the spray, combustion, and emission characteristics of coal-derived FT diesel and fossil diesel, finding that FT diesel use led to reductions in NOx, unburned hydrocarbons (UHC), CO, and soot emissions.

The reviewed studies show that the use of FT diesel has positive effects on engine emissions. Geng et al. [18] investigated the effects of injection timing and injection line pressure on NOx, soot, and ultrafine particle (UFP) emissions of FT diesel under different operating conditions. As a result of the study, it was stated that reasonable injection timing for FT diesel is recommended in order to obtain the lowest UFP emissions. It was also observed that advancing the injection timing for both fuels increased NOx emissions and decreased smoke emissions. Shi et al. [32] investigated the effects of injection parameters on the performance of a 4-cylinder diesel engine running on FT fuel synthesized from coal and observed that advancing the main injection timing by 6°KA reduced soot emissions by 52.2%, and advancing the main injection timing by 6°KA reduced NOx emissions by 171 ppm. Rahman et al. [33] examined the effects of injection timing on engine emissions through a literature review and found that advancing the injection timing reduces peak cylinder pressure and, consequently, peak temperatures, which in turn reduces NOx emissions. Advancing injection timing, on the other hand, increases cylinder temperatures, facilitating the oxidation process between carbon and oxy-gen molecules, thereby reducing HC and CO emissions.

It is a fact that controlling greenhouse gas emissions plays a significant role in global warming. There is a growing need to find solutions to mitigate the negative impact of internal combustion engine exhaust emissions on greenhouse gas concentrations. One of the objectives of this study is to expand the use of FT diesel's emission reduction potential. It is expected that FT fuel will be more widely adopted in Turkey as a sustainable and environmentally friendly alternative to conventional diesel fuels.

As previously mentioned, diesel engines are widely used in transportation thanks to their high efficiency and reliability. To meet the fuel demand due to the increasing number of diesel vehicles, researchers are intensively working to find alternative fuels to fossil diesel. At the same time, reducing harmful emissions from diesel engines, particularly PM and NOx, is crucial. The aim of this study is to determine the combustion parameters of FT diesel fuel produced from domestic lignite in a diesel engine. An important outcome of the study is that it provides data on a local energy source in Turkey. Fuel injection timing was chosen as the key parameter in the engine tests. FT diesel test results were interpreted in comparison with petroleum-based diesel.

2. Materials and Methods

2.1. Fuel Properties

A petroleum-based diesel fuel conforming to the EN 590 standard (denoted as D100 in tables and figures) was obtained from a local fuel station in Türkiye. The domestically produced FT diesel derived from Turkish lignite (denoted as FT100) was supplied from a pilot-scale facility at TÜBİTAK Marmara Research Center. D100 was used as the reference fuel under all test conditions for comparison with FT diesel. The main properties of the test fuels are presented in Table 1.

Table 1. Properties of the test fuels

Property	**EN 590:2014 limits**	**D100**	**FT100**
Density (kg/m^3, 20°C)	820 – 845	842.8	784.8
Kinematic viscosity (mm^2/s, 40°C)	2.00 – 4.50	2.84	2.12
Flash point (°C)	> 55	69.5	85.5
Distillation at 205°C (%)	< 65	35.6	51.5
Distillation at 350°C (%)	> 85	95.8	100
Water content (mg/kg)	200	60	30
Sulfur content (mg/kg)	< 10	7.6	14.3
Cetane number	> 51	51.7	> 65
Aromatic HC (%)	< 8	–	1.8
Lower heating value (MJ/kg)	–	42.612	43.247

The characteristics of liquid diesel fuels synthesized from coal via the FT process vary depending on the chemical composition of the coal, the process conditions (pressure and tem-perature), and the type of catalyst used [16, 34, 35].

Zhang et al. [28] reported for coal-based FT diesel a cetane number of 75.4, a lower heating value of 44.0 MJ/kg, a density of 754 kg/m^3 at 20 °C, and a kinematic viscosity of 2.225 mm^2/s at 20 °C.

Another study [18] measured for coal-based FT diesel a density of 750 kg/m^3, a kinematic viscosity of 2.46 mm^2/s, a lower heating value of 44.3 MJ/kg, and a cetane number of 78.

Compared with D100, FT100 generally exhibits a higher H/C ratio, greater cetane number, higher heating value, lower sulfur and aromatic content [20, 25, 36].

Its lower density and viscosity provide better atomization and more homogeneous air–fuel mixing [37]. Kinematic viscosity and sulfur content are critical for the durability of fuel-injection system components (e.g., pump and injector). Although the kinematic viscosity of FT diesel meets the EN 590 limits, its sulfur content slightly exceeds the specification. Despite this, no malfunctions were observed in the injection system or fuel lines during the experiments, suggesting acceptable compatibility of FT diesel with convention-al diesel hardware.

2.2. Experimental Setup

The experiments were carried out on a single-cylinder research diesel engine equipped with a common-rail direct-injection system, electronic control unit (ECU), and in-cylinder pressure transducers. Tests were performed at engine speeds of 1400, 1800, and 2200 rpm under a constant throttle position corresponding to 50 % of full load. Injection timing was advanced or retarded by 10 °CA (crank angle) for each operating condition and monitored in real time.

A schematic of the experimental setup is shown in Figure 1. The test engine was coupled to an active AC dynamometer; oil and coolant pumps were integrated into the dynamometer to eliminate parasitic losses. Lubricant and coolant temperatures were controlled via a dedicated control panel and maintained at 90 °C and 70 °C, respectively, through-out all tests.

Fuel conditioning was achieved using an AVL 735C unit to stabilize fuel temperature at 25 °C. Table 2 lists the instruments employed and their corresponding measurement accuracies.

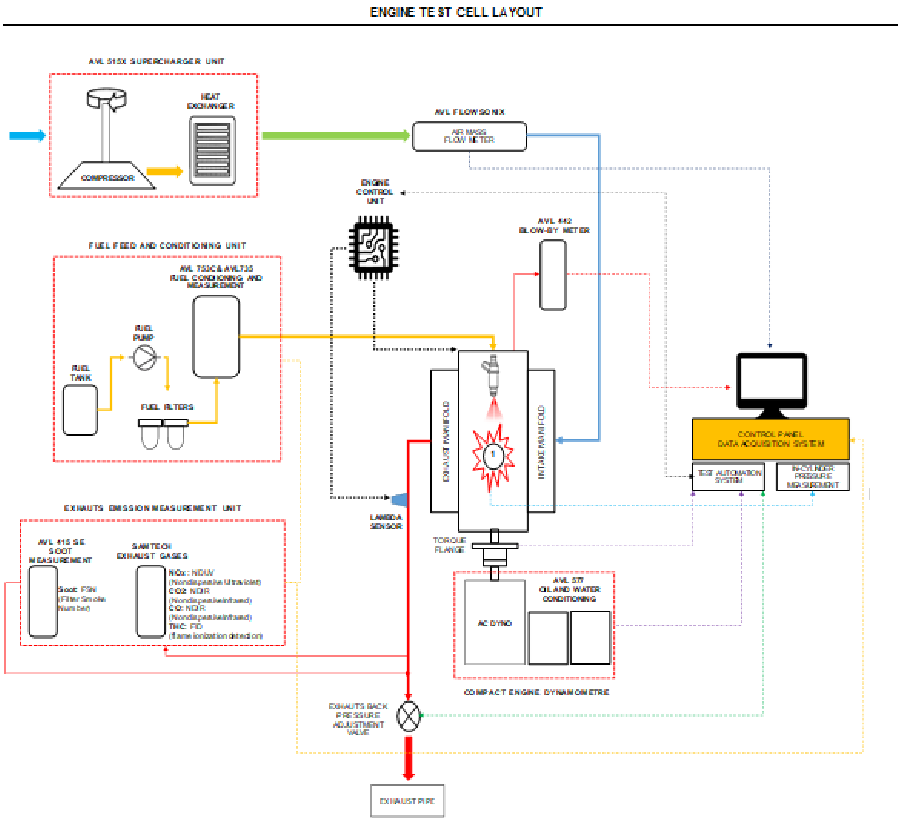

Figure 1. Schematic diagram of the experimental setup

Table 2. Test cell instrumentation and measurement accuracies

Measured Parameter	Instrument	Accuracy
Torque	HBM T40B Torque Flange	± 0.05 Nm (± 0.1 %)
Engine speed	Dynamometer	± 2.2 rpm (0.1 %)
Ambient humidity & temperature	Vaisala HMT 330	± 1 % RH; ± 0.2 °C
Injection timing	AVL Angle Encoder	± 0.05 °CA
Intake air temperature	AVL 515X	± 1 K
Intake air pressure	AVL 515X	± 10 mbar
Coolant & oil temperature	AVL 577	± 1 K
Fuel consumption	AVL 735	< ± 0.15 %
Temperature sensors	PT100 (K-type)	± 1 %

2.3. Exhaust Gas Measurement and Conversion

NO_x, CO, CO_2, and HC emissions were measured using a Samtech DS Plus analyzer, while soot emissions were determined by an AVL 415 SE device. The Samtech system reports gas concentrations in ppm, whereas the AVL device outputs Filter Smoke Number (FSN). For comparison, all data were converted to specific emission units (g/kWh) fol-lowing ISO 8178-1 and manufacturer guidelines [38,39]. Soot values were first converted from FSN to mg/m³ using Eq. (1), then to g/kWh using Eq. (2).

$$\text{Soot}=\frac{1}{0.405}*4.95*\text{FSN}*\exp(0.38*\text{FSN}) \qquad (1)$$

$$\text{Soot}=\frac{\text{Soot (mg/m}^3)}{1000}*\frac{(m_{air}*m_{fuel})*3.6}{\rho_{is}*N_i} \qquad (2)$$

where N_i is indicated power (kW), ṁ_air is air mass flow (kg/h), ṁ_fuel is fuel mass flow (kg/h), and ρ_soot is the soot density

(1.165 kg/m³). Other emission components (NOx, HC, CO, CO₂) were converted from ppm to g/kWh using Eq. (3)–(6):

$$\mathrm{ISNO_x} = \mathrm{NO_x}\ (\mathrm{ppm}) * \frac{(\mathrm{m_{air}} + \mathrm{m_{fuel}}) * 1.587}{1000 * \mathrm{N_i}} \tag{3}$$

$$\mathrm{ISCO} = \mathrm{CO}\ (\mathrm{ppm}) * \frac{(\mathrm{m_{air}} + \mathrm{m_{fuel}}) * 0.966}{1000 * \mathrm{N_i}} \tag{4}$$

$$\mathrm{ISHC} = \mathrm{HC}\ (\mathrm{ppm}) * \frac{(\mathrm{m_{air}} + \mathrm{m_{fuel}}) * 0.479}{1000 * \mathrm{N_i}} \tag{5}$$

$$\mathrm{ISCO_2} = \mathrm{CO_2}\ (\mathrm{ppm}) * \frac{(\mathrm{m_{air}} + \mathrm{m_{fuel}}) * 1.518}{1000 * \mathrm{N_i}} \tag{6}$$

The constants 1.587, 0.966, 0.479, and 1.518 represent the respective molecular weights of NO_x, CO, HC, and CO_2.

2.4. Uncertainty Analysis

Uncertainty analysis was performed to quantify the accuracy of the measured parameters in engine testing. For each emission variable (X), N consecutive readings were taken, and the mean value and standard deviation were calculated using Eq. (7) and Eq. (8) [40]. The calculated STD values were presented as error bars in the exhaust-emission graphs.

$$\bar{X} = \frac{1}{N}\sum_{\mathrm{i}=1}^{N} X_{\mathrm{i}} \tag{7}$$

$$STD = \left[\frac{1}{N-1}\sum_{\mathrm{i}=1}^{N}(X_{\mathrm{i}} - \bar{X})^2\right]^{1/2} \tag{8}$$

3. Results and Discussion

In this study, the effects of different start of injection (SOI) timings on exhaust emissions were examined using FT diesel (FT100) and conventional petroleum diesel (D100).

The SOI is one of the most critical parameters for minimizing exhaust emissions. Fuel injection timing was monitored via current-clamp measurement, and baseline SOI values were determined as 13.15°CA before TDC at 1400 rpm, 16.15°CA before TDC at 1800 rpm, and 18.35°CA before TDC at 2200 rpm.

3.1. Hydrocarbon (HC) Emissions

HC emissions originate from unburned fuel that escapes in-to the exhaust due to incomplete combustion. Regions of low in-cylinder temperature or poor air–fuel mixing tend to in-crease HC formation. Figure 2 illustrates HC emissions for various SOI timings. Overall, FT100 produced lower HC emissions compared to D100. This can be attributed to the higher cetane number of FT100, which results in shorter ignition delay and less time for mixture formation. Retarding SOI increased HC emissions due to shorter combustion duration and a higher proportion of unburned fuel.

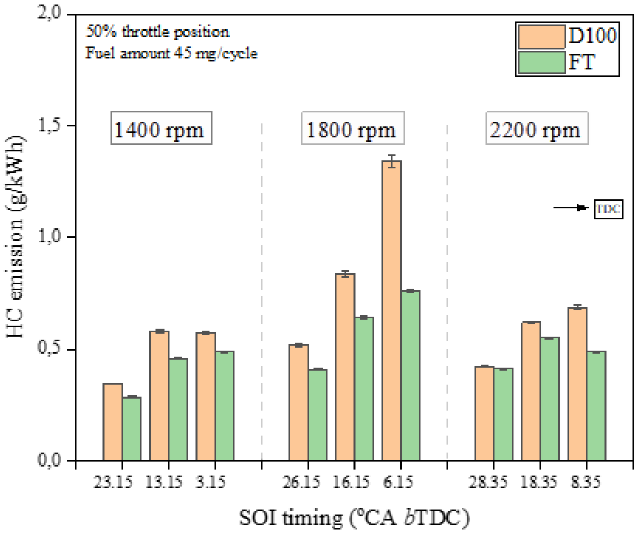

Figure 2. HC emissions with fuel type and injection timing

3.2. Carbon Monoxide (CO) Emissions

Carbon monoxide is generated when combustion occurs under oxygen-deficient or low-temperature conditions. As shown in Figure 3, FT100 exhibited lower CO emissions than D100 at all test conditions. This reduction can be explained by improved atomization and more homogeneous mixture formation of FT100. Advancing the injection timing provided more time for oxidation, leading to lower CO emissions.

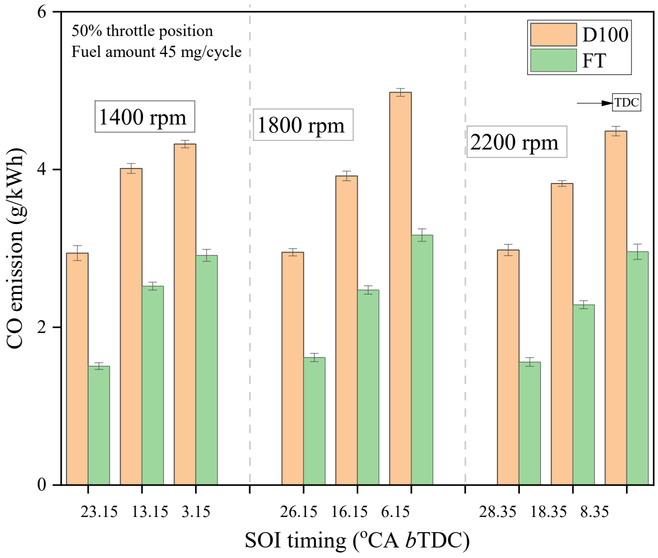

Figure 3. CO emissions with fuel type and injection timing

3.3. Carbon Dioxide (CO_2) Emissions

Carbon dioxide (CO_2) is a product of complete combustion and serves as an indicator of combustion efficiency. Figure 4 shows that FT100 produced slightly lower CO_2 emissions than D100. This is primarily due to the lower density of FT100, which results in a smaller mass of fuel injected per cycle. Advancing SOI increased CO_2 emissions, indicating more complete combustion.

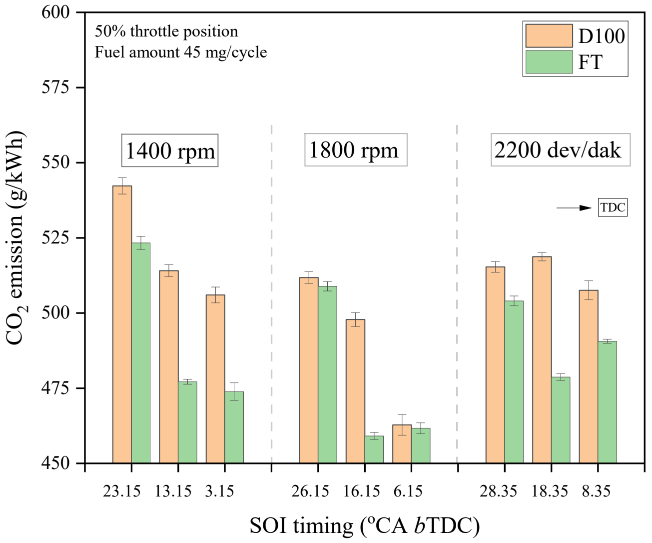

Figure 4. Variation of CO_2 emissions with fuel type and injection timing

3.4. Nitrogen Oxides (NO_x) Emissions

NOx emissions are mainly formed at high temperatures in oxygen-rich regions during combustion. As shown in Figure 5, FT100 generated lower NOx emissions than D100 under all test conditions. This is attributed to the lower aromatic content and cleaner combustion of FT diesel. Advancing SOI increased NOx emissions due to higher peak in-cylinder temperatures.

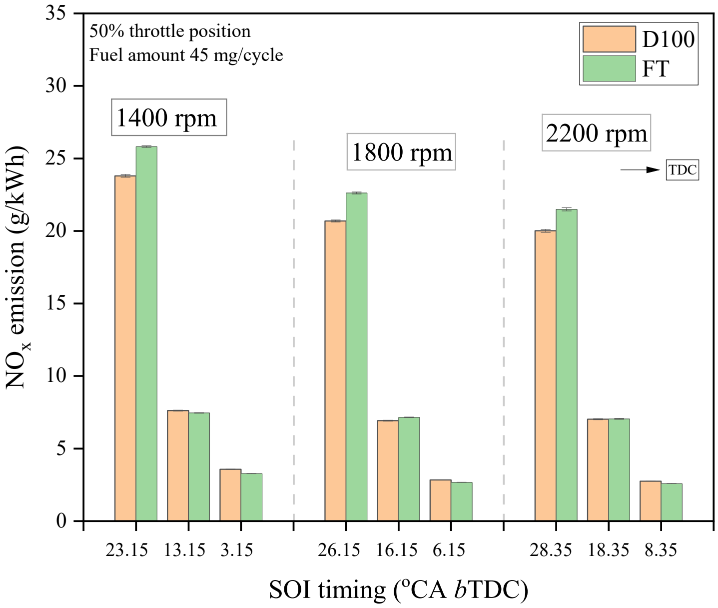

Figure **5**. Variation of NO_x emissions with fuel type and injection timing

3.5. Soot (Particulate) Emissions

Soot emissions are typically produced in fuel-rich regions and under oxygen-deficient conditions. As presented in Figure 6, FT100 produced significantly lower soot emissions than D100 across all engine speeds. This reduction is due to FT100's lower sulfur and aromatic content and its superior atomization behavior. Advancing SOI reduced soot emissions, whereas retarding SOI increased them.

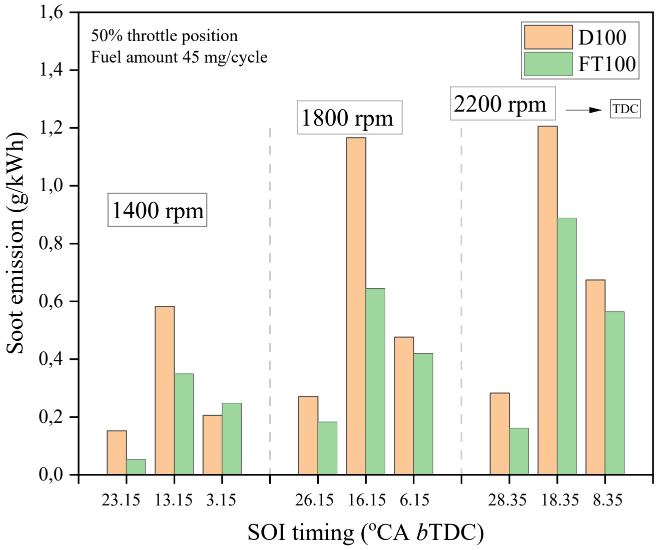

Figure 6**.** Soot emissions with fuel type and injection timing

During the experiments, FT diesel produced from Turkish lignite via the Fischer–Tropsch process was tested in a single-cylinder diesel engine and compared with petroleum-based EN 590 diesel fuel. The injection timing was varied, and the corresponding emission characteristics were analyzed.

The main findings of the study can be summarized as follows:

- Fuel properties: FT100 exhibited a higher cetane number and lower density than D100.
- Combustion phasing: Combustion started and ended earlier with FT100, mainly due to its high cetane number.
- Emission behavior:
  - HC emissions decreased by approximately 50%,
  - CO emissions decreased by 48.7%,
  - CO_2 emissions decreased by 7.8%,
  - Soot emissions decreased by up to 50%,

compared to conventional diesel.

- NO_x emissions: FT100 produced slightly lower NOx emissions than D100 under equivalent conditions.

Overall, FT diesel synthesized from lignite can be considered a viable alternative fuel for use in diesel engines without requiring any hardware modifications. Moreover, fine-tuning the injection timing can further reduce emissions when operating with FT diesel.

Acknowledgment

The author expresses sincere gratitude to the researchers of TÜBİTAK RUTE and the Energy Institute of the Marmara Research Center for providing the FT diesel fuel used in this study under the TÜBİTAK-supported project "Production of Liquid Fuel from Biomass and Coal – 108G043"; and to Prof. Dr. Ahmet Necati ÖZSEZEN for the guidance.

References

[1] R.D. Reitz, Directions in internal combustion engine research, Combust. Flame. 160 (2013). https://doi.org/10.1016/j.combustflame.2012.11.002.

[2] T. Johnson, A. Joshi, Review of Vehicle Engine Efficiency and Emissions, SAE Int. J. Engines. 11 (2018). https://doi.org/10.4271/2018-01-0329.

[3] M. Hürpekli, A. Necati Özsezen, Determination of combustion and emission characteristics of liquid Fischer-Tropsch diesel fuel synthesized from coal in a diesel engine, Energy Convers. Manag. 292 (2023). https://doi.org/10.1016/j.enconman.2023.117351.

[4] Emerging Fuel Technologies and Policies Impacting These Tech-nologies, in: Sustain. Nucl. Power, 2007. https://doi.org/10.1016/b978-012370602-7/50021-1.

[5] D. Moodley, J. Potgieter, P. Moodley, R. Crous, P. van Helden, L. van Zyl, R. Cunningham, J. Gauché, K. Visagie, T. Botha, M. Claeys, E. van Steen, Tuning the active sites of supported cobalt Fischer-Tropsch catalysts to enhance efficiency for hard wax pro-duction, Catal. Today. 454 (2025). https://doi.org/10.1016/j.cattod.2025.115282.

[6] V.S. Sikarwar, M. Zhao, P.S. Fennell, N. Shah, E.J. Anthony, Progress in biofuel production from gasification, Prog. Energy Combust. Sci. 61 (2017). https://doi.org/10.1016/j.pecs.2017.04.001.

[7] A. Smolinski, S. Wochna, N. Howaniec, Gasification of lignite from Polish coal mine to hydrogen-rich gas, Int. J. Coal Sci. Technol. 9 (2022). https://doi.org/10.1007/s40789-022-00550-9.

[8] Y. Li, X. Liang, J. Liang, An overview of the Chinese UCG pro-gram, Data Sci. J. 6 (2007). https://doi.org/10.2481/dsj.6.S460.

[9] Q. Zhang, J. Kang, Y. Wang, Development of Novel Catalysts for Fischer-Tropsch Synthesis: Tuning the Product Selectivity, ChemCatChem. 2 (2010). https://doi.org/10.1002/cctc.201000071.

[10] M. Ostadi, K. Dalane, E. Rytter, M. Hillestad, Conceptual design of an autonomous once-through gas-to-liquid process Comparison between fixed bed and microchannel reactors, Fuel Process. Technol. 139 (2015). https://doi.org/10.1016/j.fuproc.2015.07.022.

[11] S.S. Bharadwaj, L.D. Schmidt, Catalytic partial oxidation of natural gas to syngas, Fuel Process. Technol. 42 (1995). https://doi.org/10.1016/0378-3820(94)00098-E.

[12] L. Yang, X. Ge, C. Wan, F. Yu, Y. Li, Progress and perspectives in converting biogas to transportation fuels, Renew. Sustain. En-ergy Rev. 40 (2014). https://doi.org/10.1016/j.rser.2014.08.008.

[13] X. Zhao, A. Naqi, D.M. Walker, T. Roberge, M. Kastelic, B. Joseph, J.N. Kuhn, Conversion of landfill gas to liquid fuels through a TriFTS (tri-reforming and Fischer-Tropsch synthesis) process: A feasibility study, Sustain. Energy Fuels. 3 (2019). https://doi.org/10.1039/c8se00344k.

[14] A.P. Steynberg, H.G. Nel, Clean coal conversion options using Fischer-Tropsch technology, in: Fuel, 2004. https://doi.org/10.1016/j.fuel.2003.09.023.

[15] J. Xu, Y. Yang, Y.W. Li, Recent development in converting coal to clean fuels in China, Fuel. 152 (2015). https://doi.org/10.1016/j.fuel.2014.11.059.

[16] P. Basu, Production of synthetic fuels and chemicals from bio-mass, in: Biomass Gasification, Pyrolysis Torrefac-tion Pract. Des. Theory, 2018. https://doi.org/10.1016/B978-0-12-812992-0.00012-1.

[17] H. Yuan, T. Tsukuda, Y. Yang, G. Shibata, Y. Kobashi, H. Og-awa, Effects of Chemical Compositions and Cetane Number of Fischer–Tropsch Fuels on Diesel Engine Performance, Energies. 15 (2022). https://doi.org/10.3390/en15114047.

[18] L. Geng, Y. Xiao, S. Li, H. Chen, X. Chen, Effects of injection timing and rail pressure on particulate size-number distribution of a common rail DI engine fueled with fischer-tropsch diesel syn-thesized from coal, J. Energy Inst. 95 (2021). https://doi.org/10.1016/j.joei.2020.08.008.

[19] L. Geng, Y. Zhao, S. Shan, B. Kang, N. Gao, H. Chen, Study on spray and combustion characteristics of Fischer-Tropsch die-sel/biodiesel blends in a constant volume chamber, J. Energy Inst. 111 (2023) 101422. https://doi.org/10.1016/j.joei.2023.101422.

[20] S.S. Gill, A. Tsolakis, K.D. Dearn, J. Rodríguez-Fernández, Combustion characteristics and emissions of Fischer-Tropsch die-sel fuels in IC engines, Prog. Energy Combust. Sci. 37 (2011). https://doi.org/10.1016/j.pecs.2010.09.001.

[21] T.L. Alleman, R.L. McCormick, Fischer-tropsch diesel fuels - Properties and exhaust emissions: A literature review,

in: SAE Tech. Pap., 2003. https://doi.org/10.4271/2003-01-0763.

[22] W. Sun, Y. Sun, L. Guo, H. Zhang, Y. Yan, W. Zeng, S. Lin, Comparative assessment of n-butanol addition in CTL on perfor-mance and exhaust emissions of a CI engine, Fuel. 303 (2021). https://doi.org/10.1016/j.fuel.2021.121223.

[23] Z. Liang, Z. Yu, H. Liu, L. Chen, X. Huang, Combustion and emission characteristics of a compression ignition engine burning a wide range of conventional hydrocarbon and alternative fuels, Energy. 250 (2022). https://doi.org/10.1016/j.energy.2022.123717.

[24] C. Song, G. Gong, J. Song, G. Lv, X. Cao, L. Liu, Y. Pei, Po-tential for reduction of exhaust emissions in a common-rail direct-injection diesel engine by fueling with Fischer-Tropsch diesel fuel synthesized from coal, in: Energy and Fuels, 2012. https://doi.org/10.1021/ef201378r.

[25] P. Cai, C. Zhang, Z. Jing, Y. Peng, J. Jing, H. Sun, Effects of Fischer-Tropsch diesel blending in petrochemical diesel on com-bustion and emissions of a common-rail diesel engine, Fuel. 305 (2021). https://doi.org/10.1016/j.fuel.2021.121587.

[26] J. Huang, Y. Wang, S. Li, A.P. Roskilly, H. Yu, H. Li, Experi-mental investigation on the performance and emis-sions of a diesel engine fuelled with ethanol-diesel blends, Appl. Therm. Eng. 29 (2009). https://doi.org/10.1016/j.applthermaleng.2008.12.016.

[27] M.H. McMillian, M. Gautam, Consideration for fischer-tropsch derived liquid fuels as a fuel injection emission control parameter, in: SAE Tech. Pap., 1998. https://doi.org/10.4271/982489.

[28] C. Zhang, Z. Jing, P. Cai, Y. Li, H. Sun, W. Huang, J. Jing, H. Wang, X. Yu, Experimental investigation on combustion and emission characteristics of Fischer-Tropsch diesel/gasoline in a multi-cylinder heavy-duty diesel engine under different loads, Fuel. 324 (2022) 124504. https://doi.org/10.1016/j.fuel.2022.124504.

[29] V. Bermúdez Vicente, J.M. Lujan, B. Pla, W.G. Linares, Com-parative study of regulated and unregulated gaseous emissions during NEDC in a light-duty diesel engine fuelled with Fischer Tropsch and biodiesel fuels, Biomass and Bioenergy. 35 (2011). https://doi.org/10.1016/j.biombioe.2010.10.034.

[30] A.J. Torregrosa, A. Broatch, B. Plá, L.F. Mónico, Impact of Fischer-Tropsch and biodiesel fuels on trade-offs be-tween pollu-tant emissions and combustion noise in diesel engines, Biomass and Bioenergy. 52 (2013). https://doi.org/10.1016/j.biombioe.2013.03.004.

[31] Y. Pei, J. Qin, Y. Dai, K. Wang, Investigation on the spray de-velopment, the combustion characteristics and the emissions of Fischer-Tropsch fuel and diesel fuel from direct coal liquefaction, Proc. Inst. Mech. Eng. Part D J. Automob. Eng. 231 (2017). https://doi.org/10.1177/0954407016687861.

[32] J. Shi, T. Wang, Z. Zhao, T. Yang, Z. Zhang, Experimental study of injection parameters on the performance of a diesel engine with Fischer–Tropsch fuel synthesized from coal, Energies. 11 (2018). https://doi.org/10.3390/en11123280.

[33] S.M.A. Rahman, H.H. Masjuki, M.A. Kalam, A. Sanjid, M.J. Abedin, Assessment of emission and performance of compression ignition engine with varying injection timing, Renew. Sustain. En-ergy Rev. 35 (2014) 221–230. https://doi.org/10.1016/j.rser.2014.03.049.

[34] C. Knottenbelt, Mossgas " gas-to-liquid " diesel fuels—an environmentally friendly option, Catal. Today. 71 (2002).

[35] O. Doustdar, M.L. Wyszynski, H. Mahmoudi, A. Tsolakis, En-hancing the properties of Fischer-Tropsch fuel produced from syngas over Co/SiO2 catalyst: Lubricity and Calorific Value, in: IOP Conf. Ser. Mater. Sci. Eng., 2016. https://doi.org/10.1088/1757-899X/148/1/012092.

[36] Z. Zhang, C. Zhang, P. Cai, Z. Jing, J. Wen, Y. Li, H. Wang, L. An, J. Zhang, The potential of coal-to-liquid as an alternative fuel for diesel engines: A review, J. Energy Inst. 109 (2023). https://doi.org/10.1016/j.joei.2023.101306.

[37] S. Liu, R. Chen, Y. Wang, Y. Chen, X. Guo, H. Huang, Spray and Combustion Characteristics of CTL-Diesel Fuel Blends in a Constant-Volume Combustion Chamber, ACS Omega. 8 (2023). https://doi.org/10.1021/acsomega.3c00942.

[38] J. Benajes, J. V. Pastor, A. García, V. Boronat, A RCCI opera-tional limits assessment in a medium duty compres-sion ignition engine using an adapted compression ratio, Energy Convers. Manag. 126 (2016). https://doi.org/10.1016/j.enconman.2016.08.023.

[39] International Organization for Standardization, ISO 8178-1 - Reciprocating internal combustion engines -- Ex-haust emission measurement -- Part 1: Test-bed measurement systems of gaseous and particulate emissions, ISO Stand. Cat. (2017).

[40] H.W. Coleman, W.G. Steele, M. Buzhuga, Experimentation, Validation, and Uncertainty Analysis for Engineers, Noise Con-trol Eng. J. 58 (2010). https://doi.org/10.3397/1.3383084.

[41] J.B. Heywood, Internal combustion engine fundamentals / John B. Heywood., Intern. Combust. Engine Fundam. (1988).

[42] A.N. Özsezen, Effects of E-diesel on the combustion characteris-tics of a diesel engine operating at different boost pressures, J. Brazilian Soc. Mech. Sci. Eng. 45 (2023). https://doi.org/10.1007/s40430-023-04401-9.

[43] F. Ponti, V. Ravaglioli, D. Moro, G. Serra, Combustion control using a model-based MFB50 estimation methodol-ogy, IFAC Proc. Vol. 43 (2010) 282–287. https://doi.org/10.3182/20100712-3-DE-2013.00122.

[44] A. Roubaud, R. Minetti, L.R. Sochet, Oxidation and combustion of low alkylbenzenes at high pressure: Compara-tive reactivity and auto-ignition, Combust. Flame. 121 (2000). https://doi.org/10.1016/S0010-2180(99)00169-8.

[45] A. Abu-Jrai, A. Tsolakis, K. Theinnoi, R. Cracknell, A. Megari-tis, M.L. Wyszynski, S.E. Golunski, Effect of gas-to-liquid diesel fuels on combustion characteristics, engine emissions, and exhaust gas fuel reforming. Comparative study, Energy and Fuels. 20 (2006) 2377–2384. https://doi.org/10.1021/ef060332a.

[46] P. Rounce, A. Tsolakis, J. Rodríguez-Fernández, A.P.E. York, R.F. Cracknell, R.H. Clark, Diesel engine perfor-mance and emis-sions when first generation meets next generation biodiesel, SAE Tech. Pap. 4970 (2009) 1–10. https://doi.org/10.4271/2009-01-1935.

[47] P. Schaberg, J. Botha, M. Schnell, H.O. Hermann, N. Pelz, R. Maly, Emissions performance of GTL diesel fuel and blends with optimized engine calibrations, SAE Tech. Pap. (2005). https://doi.org/10.4271/2005-01-2187.

[48] L.L. Stavinoha, E.S. Alfaro, H.H. Dobbs, L.A. Villahermosa, J.B. Heywood, Alternative fuels: Gas to liquids as potential 21st century truck fuels, SAE Tech. Pap. (2000). https://doi.org/10.4271/2000-01-3422.