Application of thermal isolation to the combustion chamber of a single cylinder diesel engine and its effects on performance and emission

Uğur Öztürk *

*Department of Automotive Engineering, Technology Faculty, Firat University, Elazig 23119, Turkey

(ugurozturk@msn.com)

‡ Department of Automotive Engineering, Technology Faculty, Firat University, Elazig 23119, Turkey

Tel: +90 424 2370000, ugurozturk@msn.com

Received: 21.06.2019 Accepted:08.05.2019

Abstract- In this study, the effects of boron based thermal barrier coating (Fe2B and NiCrBSi) on the performance and emission of a single cylinder diesel engine were investigated. In the coating process of the engine parts, two difference methods were used. Cylinder liner and valves were coated with solid boronizing and the top surface of the piston is coated with plasma spray method. Boron layer (Fe2B) and NiCrBSi have low thermal conductivity and high thermal resistance. So that, the combustion chamber of diesel engine was converted in to insulated form. Tests were carried out under 5 speeds (1800-2100-2400-2700-3000 rpm) of diesel engine. commercial D-2 was used as test fuel. Coated (CE) and standard engine (SE) test results were compared. Comprehensive analyses have shown that brake specific fuel consumption (BSFC) was reduced by 11 %, in the CE. On the other hand, CO and HC emissions of the CE decreased by 33-17 %, respectively. And NOx emission increased by 14 % .

Keywords Boronizing, thermal barrier, engine, performance, emission.

1. Introduction

Environmental pollution caused by exhaust gas remains a major risk. Developed countries are taking preventive measures in this regard. On the other hand, demand for petroleum-based fuels is increasing day by day. The environmental pollution caused by the vehicles and the increased fuel consumption costs drive automotive manufacturers to new researches [1-3]. Boronizing is a thermochemical surface hardening process which is carried out by diffusion of boron to the metallic surface at high temperatures. During the application of the boronizing process, boron atoms diffuse to the metal surface by the effect of heat. The characteristic feature of the boron layer is that it has a tooth-like structure [4-6]. Depending on the mechanical properties of the ceramics and the progress in ceramic design technology, these materials are used as structural parts in engines. Ceramics are materials that do not require cooling and have higher thermal durability than conventional metals. Also, they can reduce the heat transfer in the cylinder walls when they are used on the inner surfaces of the cylinders where the temperature and fluid density change rapidly. These materials make it easier to control the temperature distribution and the heat flow within the engines [7]. According to the second law of thermodynamics, the thermal efficiency of the engines can be increased, and the fuel consumption can be reduced by using thermal barrier coating. In the low heat rejection engine concept, combustion chamber components such as piston, valve, cylinder top, cylinder liner, exhaust port are coated with high temperature resistant materials. In the lhr engines, the thermal energy lost by the cooling water and the exhaust gas convert into beneficial power. In such engines, the heat that goes to the cooling system is prevented by the thermal barrier. Due to the thermal insulation of the combustion chamber, total heat dissipation of the LHR engines is higher than conventional engines. By this insulation the total combustion time increases, and the combustion continues at the exhaust time [8-10].

In recent years, researchers have done many studies about coating of the conventional engines. High velocity oxy fuel spraying, atmospheric plasma spraying, flames spraying were used as coating methods. After the coating of the engines, conventional engines gained superior aspects such as low fuel consumption and lower exhaust emissions. Some of the researchers have reported that thermally coating of the combustion chamber elements improved the thermal efficiency of engines with better brake specific fuel consumption and lower exhaust emissions, except NOx. Also the researchers attributed the reduction in emissions to the elevated temperature in the combustion chamber [11-13]. Differ from other coating methods', boronizing offers superior aspects to improve mechanical properties significantly. Some of the superior aspects of boronizing are having diffusion mechanism, high temperature oxidation resistance, low thermal conductivity, high thermal durability [14-16].

Thermal barrier coatings are mostly applied to the cylinder top, piston top surface and valves using plasma spray method. Unlike the others in this study, boronizing was applied to cylinder liners and valves. A coating layer (Fe2B) with a high thermal resistance and a low heat transfer was obtained on the surfaces of these parts. In addition, plasma spray coating (NiCrBSi) was applied to the upper surface of the piston. Coated and standard engines were subjected to performance and emission tests under the same conditions. The obtained results are compared with each other.

2. Material and Method

2.1. Coating Procedures

Two different methods were used for coating operations. For the coating process of cylinder liners and valves, the solid boronizing method is used. Stainless steel boxes were manufactured to place the boronized samples into the furnace. Boronizing was carried out in a PID controlled high temperature furnace. Ekabor-2® was used for the boronizing agent and Ekrit® was used as the deoxidizing material. After the coating of the cylinder liner surface, a honing process with a precision of 0.01 mm was carried out. Boronizing parameters are shown in Table 1.

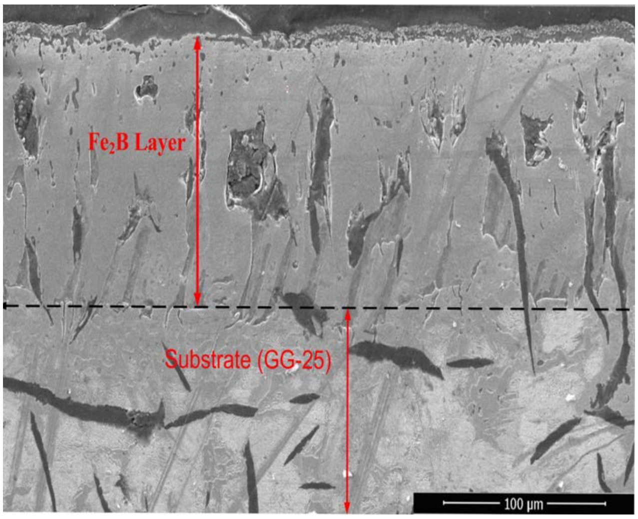

Fig. 1. SEM image of coated cylinder liner (150 µm).

Since the piston material is containing Al-Si, the melting temperature is about 900 °C. For this reason, boronizing is not a suitable coating method for piston. Therefore, the plasma spray method is preferred in consideration of these characteristics when piston coating is performed. So, the upper part of the piston is coated by plasma spray method. Coating operations were performed with a Sulzer-Metco Type 3 MB atmospheric plasma arc device. The plasma arc spray parameters applied in the coating process are shown in Table 2. At the end of the plasma spraying process, a layer (CoNiCrAlYttra + NiCrBSi) with a thermal barrier property of 300 µm in thickness was introduced on the piston top surface.

Table 1. After the boronizing

After the boronizing process, the surface of the cylinder liner was subjected to scanning electron microscope (SEM) analysis. Figure 1 shows SEM image of coated cylinder liner 150 microns (µm) thick Fe2B layer on the surface.

Treatment	Boronizing Agent	Deoksidant	Temperature	Time
Pre-heating	EKabor®2	EKrit®	0-950 C°	3 hours
Boronizing	EKabor®2	EKrit®	950 C°	4 hours
Cooling in furnace	EKabor®2	EKrit®	950-25C°	8 hours

Table 2. Plasma arc spray parameters.

Plasma gun	Sulzer-Metco 3 MB
Current (Ampere)	500
Voltage (Volt)	62
Spray distance (mm)	70
Gas pressure (psi) (Ar/H_2)	80/15
Applied coating thickness (µm)	250µm (NiCrBSi)+50µm (CoNiCrAlYttra)=300µm

As a result of the entire coating process, the surface of the combustion chamber elements has achieved a low heat transfer capacity. Coated parts are seen in Figure 2. Thus, the combustion chamber is transformed into thermally insulated and adiabatic form. The heat transfer coefficients of the coating layers are shown in Table 3.

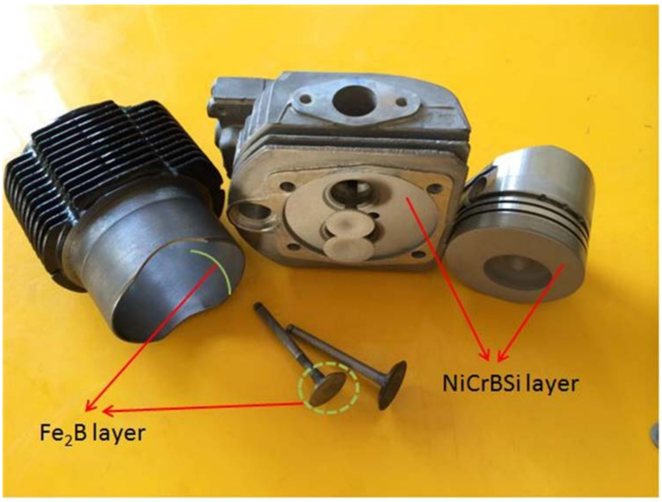

Figure 2. Coated parts of diesel engine.

2.2. Performance and emission tests

The single-cylinder, 4-stroke, air-cooled diesel engine (lombardini 6LD400) was used as the test engine. The technical specifications of the test engine are shown in Table 4. Performance tests were carried out on a Cusson P8160 electric dynamometer. The image of the test setup is shown in Figure 3. The engine was run for 15 minutes to stabilize before the tests were run. Each experiment period lasted approximately 10 minutes. The tests were carried out in 5 periods under half load, at 1800-3000 rpm. The engine speed is increased by 300 rpm for each period. The exhaust gas temperature was measured with a K-type thermocouple. Commercial D-2 fuel was used as test fuel. Physicochemical properties of test fuel are shown in Table 5. A special device was prepared using a 100 ml burette to measure the engine fuel consumption. Each 10 ml fuel consumption time is recorded with a stopwatch. Emissions measurements were performed with the Bosch BEA-350 exhaust emission device. Technical specifications of the device are shown in Table 6.

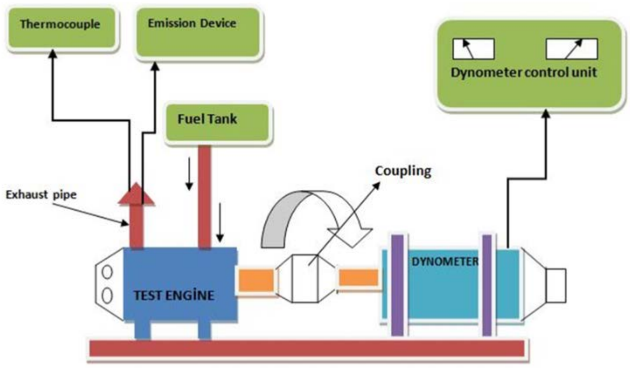

Figure 3. The image of the test set up.

Table 3. The heat transfer coefficients of the coating layers.

Material	**GG-25**	**Fe_2B**	**AlSi12CuNi**	**NiCrBSi**
Coefficient of thermal conductivity (W/m. K)	53,3	20-30	151-220	7-17

Table 4. Technical specifications of test engine.

Make/model	Lombardini /6ld400
Engine type	DI-Diesel engine, naturel aspirated, air cooled
Cylinder number	1
Bore x stroke (mm)	86x68
Displacement (cm^3)	395
Compression ratio	18:1
Maximum power (kW)	5.4 @3000 rpm
Maximum torque (Nm)	19.6@2200 rpm
Fuel type	diesel
Lubricating	Full pressure

Table 5. Physicochemical properties of test fuel.

Properties	**Diesel (ASTM-D:2)**	**Standard**
Density (kg/m^3)	850	ASTM D 1798
Kinematic viscosity at 40 °C (cst)	3,05	ASTM 445
Calorific value (kJ/kg)	42,800	ASTM D 240
Flash point (°C)	56	ASTM D 93
Cetane number	49-55	ASTM D 613-84

Table 6. Technical specifications of the Bosch BEA-350 exhaust emission device.

Component	**Measurement Range**	**Resolution**
CO	0.00 – 10.00 % Vol.	0.001 % Vol.
CO_2	0.00 – 18.00 % Vol.	0.01 % Vol.
HC	0 – 9999 ppm .	1 ppm .
O_2	0.00 – 22.00 % Vol.	0.01 % Vol.
Lambda	0.500 – 9.999	0.001
NO	0 – 5000 ppm ppm.	≤ 1 ppm .
Smoke Opacity (Degree of opacity)	0-100%	0.1%

3. Results and discussions

3.1. Carbon monoxide (CO)

CO is a harmful reaction product resulting from incomplete combustion. The amount of CO depends on the in-cylinder temperature, the air-fuel mixture ratio, the local conditions of the combustion chamber and its physical properties [17]. Variations of CO emission for both engines is showed in Figure 4.

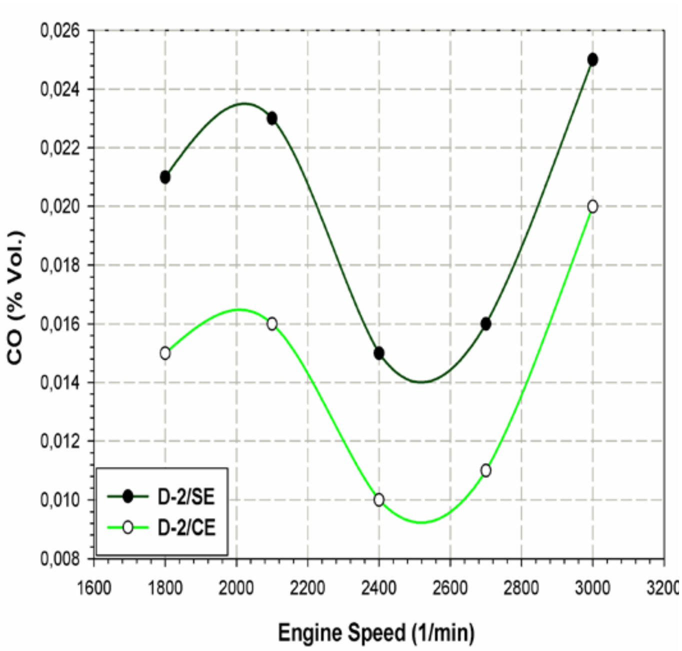

Figure 4. Variations of CO emission for SE and CE.

Similar curves appeared in both engines as shown. The only difference is that CE produces lower CO for all speeds. The CO emission produced by the diesel engine is related to the fuel and combustion characteristics. High CO emissions have occurred for both engines at low speeds. This is due to the low end-of-combustion temperature and poor combustion. At medium speeds, the combustion improves because the mixture is enriched and the combustion efficiency is high because of the sufficient time for the complete combustion of the fuel, so that the CO emission is low. At high speeds, CO emission showed an increasing. This can be explained by the increase in engine speed and the lack of time to burn the fuel [18]. At 2400 rpm, CE produced 33 % less CO than SE. Due to the thermal insulation layer, the heat transfer is reduced. The post combustion heat is trapped into the adiabatic chamber. Increased burning pressure raises the temperature of the combustion chamber. The reduction of the premixed combustion level scale-downs the formation of initial CO emission and then CO oxidation accelerates by helping the subsequent high temperature during the diffusive combustion process. In addition, the high temperature advances the burning of fuel throughout the expansion stroke. Thermal insulation improves heat dissipation and affects the combustion process positively. Thus, CO emissions are reduced compared to SE [19].

3.2. Hydrocarbon (HC)

HC emission occurs as a result of incomplete or partial combustion of the fuel. The amount of HC varies according to the operating conditions of the engine and fuel. In addition, the physical structures (surface roughness, porosity) of the combustion chamber also affect the amount of HC remaining on the surface [20]. Figure 5 shows the variations of HC emission of both engines. Both engines exhibited higher HC emission at low speeds, minimal HC emission at medium speeds, and increased HC emissions at higher speeds. This is a classic emission behavior seen in diesel engines. The most important difference is that CE produces lower emission than SE. When taken as a reference at 2400 rpm, CE produced 17 % lower HC emissions than SE.

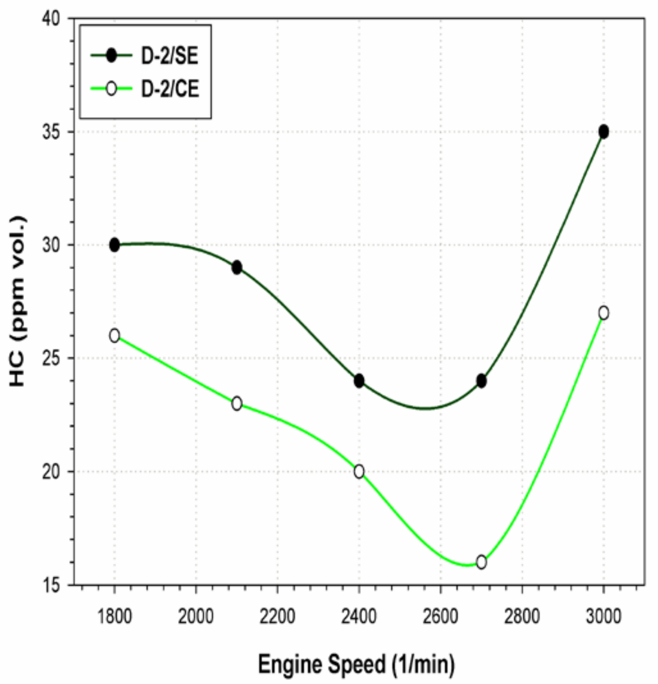

Figure 5. Variations of HC emissions for SE and CE

The decrease in heat losses causes an increase in wall temperature. As a result, while the gas temperature increases, high compression causes intense vortices in the combustion chamber. These intense vortices contribute to unburned HC's participate into the combustion. So that a more uniform burning takes place in combustion chamber. As a result of the insulation of the combustion chamber and the smoother surface structure, the combustion end temperature and pressure increased, and the combustion process improved. On the other hand, HC emissions have decreased because the burning of the fuel continues during the expansion (exhaust) time. In LHR engines, it has been reported that thermal barrier coating improves local conditions, increases end-of-burn temperature and pressures, and consequently HC emissions tend to decrease [21, 22].

3.3. Nitrogen oxide (NOx)

NOx is a very dangerous emission type that occurs as a result of oxidation with atmospheric nitrogen at adequate temperature. The most important parameters in NOx formation are stoichiometry and flame temperature [23]. Figure 6 shows the NOx variation in the CE and SE under different speeds. As it is understood from the figure, the NOx emission in CE is higher than in SE. When taken as a reference at 2400 rpm, CE produced 14 % higher NOx emissions than SE. Higher NOx emissions are expected in coated engines. Increase of NOx formation due to temperature increase and long burning process. However, engine load, speed, combustion chamber content, homogeneity and mixture density are also important parameters affecting NOx formation [24, 25].

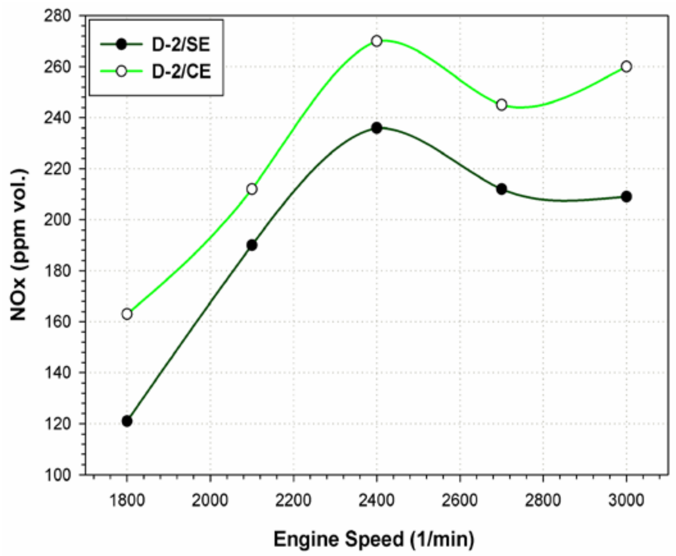

Figure 6. Variations of NOx emissions for SE and CE

On the other hand, at high engine speeds, the NOx is low despite the high temperature. This situation is explained as not having enough time for NOx formation. NOx emissions can be reduced by measures such as setting the injection time, slower burn rates [26-28].

3.4. Brake Specific Fuel Consumption (BSFC)

Figure 7 shows the measured BSFC values in CE and SE. Both engines have similarly showed an increasing in BSFC values at low speeds and decrease at medium speeds. Main reasons for decreasing in medium speed are sufficient time, proper mixture formation and high combustion efficiency in combustion chamber. When taken as a reference at 2400 rpm, CE showed 11 % lower BSFC value than SE.

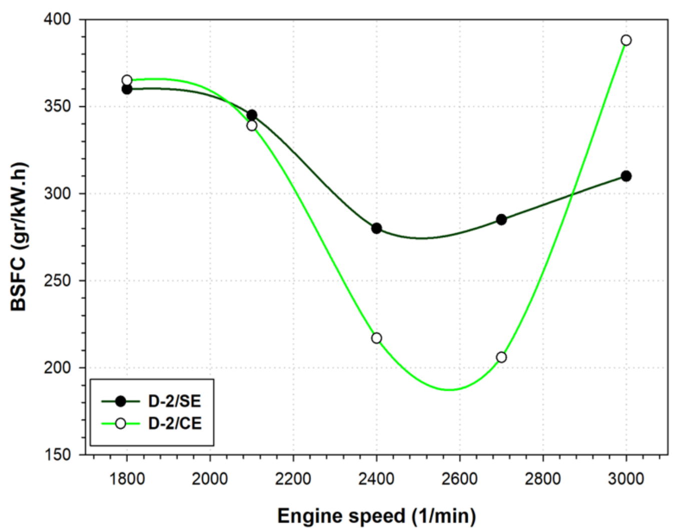

Figure 7. Variations of BSFC for SE and CE

During the spraying, the fuel is atomized and mixed with the air. This causes physical delays in the combustion process. Simultaneously, the chemical reaction slows down and chemical lagging occurs. If the total ignition delay period including these two processes is longer, more fuel is sent to the combustion chamber and thus fuel consumption increase. One of the foremost features of the LHR engines is a shorter ignition delay period. Thanks to these features, the physical and chemical period shorten, and fuel consumption improves in the positive direction. Similarly, it has been reported that LHR engines show a reduction in BSFC values compared to normal engines[22, 24, 29]. When the engine is at high speeds, volumetric efficiency decreases, so the combustion process becomes weaker and the coated engine shows higher fuel consumption value.

3.5. Exhaust Gas Temperature (EGT)

By the increasing of speed, the rate of burning and hence the heat dissipation rate increases. As seen in Figure 8, EGT has showed a raising in both engines with increasing speed. Exhaust gas temperature difference between CE and SE is 10 % under 2400 rpm. In LHR engines, the adiabatic medium heat, which can not find its way out, follows the exhaust path and is released to the atmosphere. It is thought that the higher EGT values seen in CE are due to this situation [30, 31].

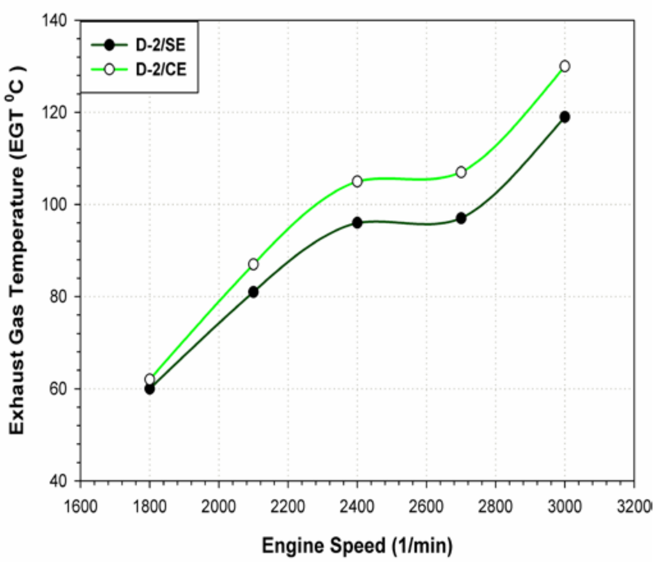

Figure 8. Variations of EGT for SE and CE

4. Conclusions

In this study, boronizing was carried out to the combustion chamber, the heat transfer was prevented, in this way the heat was returned to the combustion chamber again and the combustion temperature was increased in a short time. The ignition delay was shortened and the physical and chemical reactions in the combustion chamber were positively affected. The results of the coated engine showed that there is an improve on performance and a decrease on emission values by the thermal insulation of combustion chamber. According to the results it has been understood that boronizing of the combustion chambers is an effective, sustainable and economical method for automotive industry and manufacturing eco-friendly engines.

References

1.Awad, O.I., et al., "The effect of adding fusel oil to diesel on the performance and the emissions characteristics in a single cylinder CI engine." Journal of the energy Institute, 2017. 90(3): p. 382-396.

2.İscan, B., "Application of ceramic coating for improving the usage of cottonseed oil in a diesel engine." Journal of the Energy Institute, 2016. 89(1): p. 150-157.

3.Sharma, A. and S. Murugan, "Combustion, performance and emission characteristics of a DI diesel engine fuelled with non-petroleum fuel: a study on the role of fuel injection timing." Journal of the Energy Institute, 2015. 88(4): p. 364-375.

4.Meric, C., Sahin S., and Uzkut M., "Investigation of effect of boronising on welding zone." Science and technology of welding and joining, 2002. 7(2): p. 107-110.

5.Carbucicchio, M. and G. Palombarini, "Effects of alloying elements on the growth of iron boride coatings." Journal of Materials Science Letters, 1987. 6(10): p. 1147-1149.

6.Meric, C., Sahin S., and Yilmaz S.S., "Investigation of the effect on boride layer of powder particle size used in boronizing with solid boron-yielding substances." Materials Research Bulletin, 2000. 35(13): p. 2165-2172.

7.Alkidas, A., "Performance and emissions achievements with an uncooled heavy-duty, single-cylinder diesel engine." 1989, SAE Technical Paper.

8.Parlak, A., H. Yasar, and Sahin B., "Performance and exhaust emission characteristics of a lower compression ratio LHR Diesel engine." Energy Conversion and Management, 2003. 44(1): p. 163-175.

9.Hejwowski, T. and A. Weroński, "The effect of thermal barrier coatings on diesel engine performance." Vacuum, 2002. 65(3-4): p. 427-432.

10.Altin, R., Cetinkaya S., and Yucesu H.S., "The potential of using vegetable oil fuels as fuel for diesel engines." Energy conversion and management, 2001. 42(5): p. 529-538.

11.Garud, V., et al., "Performance and CombustionCharacteristics of Thermal Barrier Coated (YSZ) Low Heat Rejection Diesel Engine." Materials Today: Proceedings, 2017. 4(2): p. 188-194.

12.Karthikeyan, B. and K. Srithar, "Performance characteristics of a glowplug assisted low heat rejection diesel engine using ethanol." Applied Energy, 2011. 88(1): p. 323-329.

13.Musthafa, M.M., "Development of performance and emission characteristics on coated diesel engine fuelled by biodiesel with cetane number enhancing additive." Energy, 2017. 134: p. 234-239.

14.Fu, J., et al., "A comparative study on various turbocharging approaches based on IC engine exhaust gas energy recovery." Applied Energy, 2014. 113: p. 248-257.

15.Hazar, H., Ozturk U., and Gul H., "Characterization and effect of using peanut seed oil methyl Ester as a fuel in a low heat rejection diesel engine." Energy & Fuels, 2016. 30(10): p. 8425-8431.

16.Ozturk, U., Hazar H., and Yılmaz F., "Comparative performance and emission characteristics of peanut seed oil methyl ester (PSME) on a thermal isolated diesel engine." Energy, 2019. 167: p. 260-268.

17.Karabektas, M., "The effects of turbocharger on the performance and exhaust emissions of a diesel engine fuelled with biodiesel." Renewable Energy, 2009. 34(4): p. 989-993.

18.Mittal, N., et al., "Study of performance and emission characteristics of a partially coated LHR SI engine blended with n-butanol and gasoline." Alexandria Engineering Journal, 2013. 52(3): p. 285-293.

19.Buyukkaya, E., "Thermal analysis of functionally graded coating AlSi alloy and steel pistons." Surface and coatings technology, 2008. 202(16): p. 3856-3865.

20.Wentworth, J., "More on Origins of Exhaust Hydrocarbons-Effects of Zero Oil Consumption, Deposit Location, and Surface Roughness." 1972, SAE Technical Paper.

21.Musthafa, M.M., Sivapirakasam S., and Udayakumar M., "Comparative studies on fly ash coated low heat rejection diesel engine on performance and emission characteristics fueled by rice bran and pongamia methyl ester and their blend with diesel." Energy, 2011. 36(5): p. 2343-2351.

22.Modi, A. and D. Gosai, "Experimental study on thermal barrier coated diesel engine performance with blends of diesel and palm biodiesel." SAE International Journal of Fuels and Lubricants, 2010. 3(2): p. 246-259.

23.Buyukkaya, E. and M. Cerit, "Experimental study of NOx emissions and injection timing of a low heat rejection diesel engine." International journal of thermal sciences, 2008. 47(8): p. 1096-1106.

24.Haşimoğlu, C., et al., "Performance characteristics of a low heat rejection diesel engine operating with biodiesel." Renewable energy, 2008. 33(7): p. 1709-1715.

25.Prasath, B.R., P. Tamilporai, and M.F. Shabir, "Analysis of combustion, performance and emission characteristics of low heat rejection engine using biodiesel." International Journal of Thermal Sciences, 2010. 49(12): p. 2483-2490.

26.Palash, S., et al., "State of the art of NOx mitigation technologies and their effect on the performance and emission characteristics of biodiesel-fueled Compression Ignition engines." Energy conversion and management, 2013. 76: p. 400-420.

27.Aydin, H., "Combined effects of thermal barrier coating and blending with diesel fuel on usability of vegetable oils in diesel engines." Applied thermal engineering, 2013. 51(1-2): p. 623-629.

28.İşcan, B. and H. Aydın, "Improving the usability of vegetable oils as a fuel in a low heat rejection diesel engine." Fuel processing technology, 2012. 98: p. 59-64.

29.Hazar, H. and U. Ozturk, "The effects of Al2O3–TiO2 coating in a diesel engine on performance and emission of corn oil methyl ester." Renewable Energy, 2010. 35(10): p. 2211-2216.

30.Musthafa, M.M., et al.," Effects of Al2O3 coating on diesel engine performance, combustion, and emission characteristics fueled by pongamia methyl ester and its blends with diesel." Environmental Progress & Sustainable Energy, 2012. 31(1): p. 147-156.

31.Reddy, T.R., et al., "Comparative performance of different versions of low heat rejection diesel engines with Mohr oil based bio-diesel." Int J Res Rev Appl Sci, 2012. 13: p. 73-87.