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Ceramic Coating Applications and Research Fields for Internal Combustion Engines

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1. Introduction

Research for decreasing costs and consumed fuel in internal combustion engines and technological innovation studies have been continuing. Engine efficiency improvement efforts via constructional modifications are increased today; for instance, parallel to development of advanced technology ceramics, ceramic coating applications in internal combustion engines grow rapidly. To improve engine performance, fuel energy must be converted to mechanical energy at the most possible rate. Coating combustion chamber with low heat conducting ceramic materials leads to increasing temperature and pressure in internal combustion engine cylinders. Hence, an increase in engine efficiency should be observed.

Ceramic coatings applied to diesel engine combustion chambers are aimed to reduce heat which passes from in-cylinder to engine cooling system. Engine cooling systems are planned to be removed from internal combustion engines by the development of advanced technology ceramics. One can expect that engine power can be increased and engine weight and cost can be decreased by removing cooling system elements (coolant pump, ventilator, water jackets and radiators etc.) (Gataowski, 1990; Schwarz et. al. 1993).

Initiation of the engine can be easier like shortened ignition delay in ceramic coated diesel engines due to increased temperature after compression because of low heat rejection. More silent engine operation can be obtained considering less detonation and noise causing from uncontrolled combustion. Engine can be operated at lower compression ratios due to shortened ignition delay. Thus better mechanical efficiency can be obtained and fuel economy can be improved (Büyükkaya et. al., 1997).

Another important topic from the view point of internal combustion engines is exhaust emissions. Increased combustion chamber temperature of ceramic coated internal combustion engines causes a decrease in soot and carbon monoxide emissions. When increased exhaust gases temperature considered, it is obvious that turbocharging and consequently total thermal efficiency of the engine is increased.

Combustion characteristics is the most important factors which affect exhaust emissions, engine power output, fuel consumption, vibration and noise. In diesel engines, combustion characteristics depended on ignition delay at a high rate (Balcı, 1983). Ignition delay is determined mostly by temperature and pressure of compressed air in combustion chamber. Conventional diesel engines have lower temperature and pressure of compressed air just because engine cooling system soaks considerable heat energy during compression to protect conventional combustion chamber materials. When the lost heat energy, useful work are taken into account, the idea of coating combustion chambers with low heat conduction and high temperature resistant materials leads to thermal barrier coated engines (also known as low heat rejection engines). Thermal barrier coated engines can be thought as a step to adiabatic engines. To achieve this aim, ceramic is a preferred alternative. Thermal barrier coating is mostly done by ceramic coating of combustion chamber, cylinder heads and intake/exhaust valves. If cylinder walls are intended to be coated, a material should be selected which has proper thermal dilatation and wear resistance. Some ceramic materials have self lubrication properties up to 870 ^{0}C (Hocking et. al., 1989).

Exhaust gas temperature changing between 400-600 ^{0}C for conventional diesel engines while it is between 700-900 ^{0}C for thermal barrier coated engine. This temperature value reaches to 1100 ^{0}C in turbocharged engines. When exhaust gas temperatures reaches these high levels, residual hydrocarbons and carbon monoxides in the exhaust gases are oxidized and exhaust emission are become less pollutant regarding hydrocarbons and carbon monoxide. In Figure 1, energy balance diagrams for conventional diesel engine and ceramic coated engine are given (Büyükkaya, 1994). Beside these advantages of ceramic coated low heat rejection engines, mechanical improvements also gained by light weight ceramic materials. By their high temperature resistance and light weight, moving parts of the engine have more duration owing to low inertia and stable geometry of the parts. Bryzik and Kamo (1983) reported 35% reduction in engine dimensions and 17% reduction in fuel consumption with a thermal barrier coated engine design in a military tank.

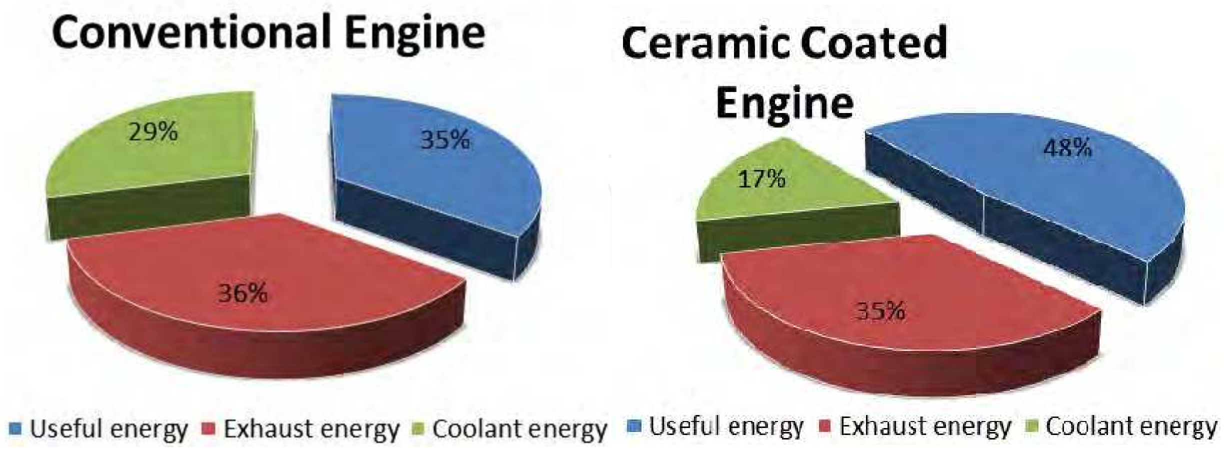


Fig. 1. Energy balance illustration for conventional engine and ceramic coated engine

1.1 Advanced technology ceramics

Ceramics have been used since nearly at the beginning of low heat rejection engines. These materials have lower weight and heat conduction coefficient comparing with materials in conventional engines (Gataowski, 1990). Nowadays, important developments have been achieved in quantity and quality of ceramic materials. Also new materials named as "advanced technology ceramics" have been produced in the last quarter of 20th century. Advantages of advanced technology ceramics can be listed as below;

- Resistant to high temperatures
- High chemical stability
- High hardness values
- Low densities
- Can be found as raw material form in environment
- Resistant to wear
- Low heat conduction coefficient
- High compression strength (Çevik, 1992)

Advanced technology ceramics consist of pure oxides such as alumina (Al_2O_3), Zirconia (ZrO_2), Magnesia (MgO), Berillya (BeO) and non oxide ones. Some advanced technology ceramic properties are given in Table 1.

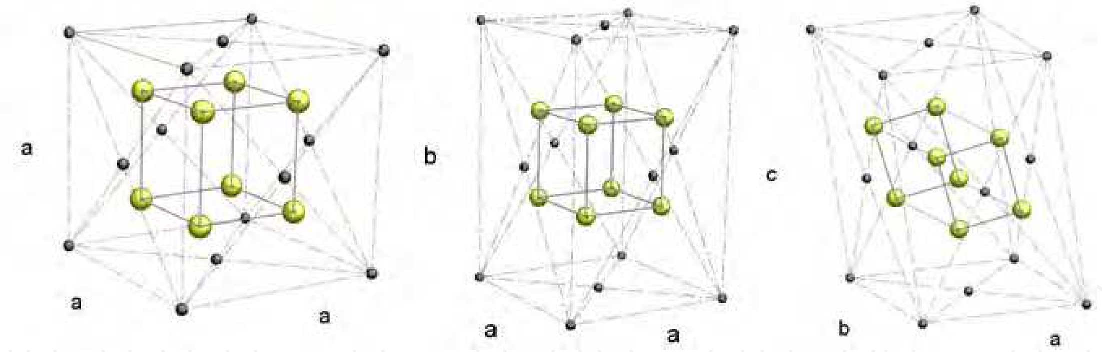
Material	**Melting Tempe-rature (^{0}C)**	**Density (g/cm^3)**	**Strength (MPa)**	**Elasticity Module (GPa)**	**Fracture Toughness (MPa m$^{1/2}$)**	**Hardness (kg/mm^2)**
SiO_2	500	2,2	48	7,2	0,5	650
Al_2O_3	2050	3,96	250-300	36-40	4,5	1300
ZrO_2	2700	5,6	113-130	17-25	6-9	1200
SiC	3000	3,2	310	40-44	3,4	2800
Si_3N_4	1900	3,24	410	30-70	5	1300

Table 1. Some advanced technology ceramic properties

Zirconia has an important place among coating materials with its application areas and properties essential to itself. The most important property of zirconia is its high temperature resistance considering ceramic coating application in internal combustion engines. Ceramics containing zirconia have high melting points and they are durable against thermal shocks. They have also good corrosion and erosion resistances. They are used in diesel engines and turbine blades to reduce heat transfer.

1.1.1. Zirconia (ZrO2)

Zirconia can be found in three crystal structure as it can be seen in Fig. 2. These are monolithic (m), tetragonal (t) and cubic (c) structures. Monolithic structure is stable between room temperature and 1170 ^{0}C while it turns to tetragonal structure above 1170 ^{0}C. Tetragonal structure is stable up to 2379 ^{0}C and above this temperature, the structure turns to cubic structure.



- Cubic - - Tetragonal - - Monolithic, c/a=1,02 -

Fig. 2. Cubic, tetragonal and monolithic zirconia

Usually cracks and fractures are observed during changing phases because of 8% volume difference while transition to tetragonal structure from monolithic structure. To avoid this and make zirconia stable in cubic structure at room temperature, alkaline earth elements such as CaO (calcium oxide), MgO (magnesia), Y_2O_3 (yttria) and oxides of rare elements are added to zirconia. Zirconia based ceramic materials stabilized with yttria have better properties comparing with Zirconia based ceramic materials which are stabilized by magnesia and calcium oxide (Yaşar, 1997; Geçkinli, 1992).

Mechanical properties of cubic structure zirconia are weak. Transition from tetragonal zirconia to monolithic zirconia occurs at lower temperatures between 850-1000 ^{0}C and this transition has some characteristics similar to martensitic transition characteristics which are observed in tempered steels. In practice, partially stabilized cubic zirconia (PSZ) which contains monolithic and tetragonal phases as sediments, is preferred owing to its improved mechanical properties and importance of martensitic transition. Partially stabilized zirconia has been commercially categorized since early 70s. Table 2. contains partially stabilized zirconia types and their properties. Structural properties of these materials are;

- Zt35: Contains 20% (t) phase in cubic matrix. Particle dimensions are about 60-70 µm.
- ZN40: Contains 40-50% (t) phase.
- ZN50: Particle dimensions are about 60-70 µm and a thin film (m) phase lays on the borders of particles.
- ZN20: Is developed for thermal shocks. Contains (m) phase.

Material	**Code**	**Elasticity Module (GPa)**	**Fracture Toughness (MPa $m^{1/2}$)**	**Vickers Hardness (HVat 22 ^{0}C)**	**Expansion Coefficient (22-1000 ^{0}C)**
Ca/Mg-PZS	Zt35	200	4,8	1300	$9{,}8\times10^{-6}$
Mg-PZS	ZN40	200	8,1	1200	9,8
Mg-PZS	ZN50	200	9	900	7
Y-PZS	ZN100	190	9,7	-	9,3
Mg-PZS	ZN20	180	3,5	-	5,5

Table 2. Partially stabilized zirconia types and properties

1.1.2 Yttria (Y_2O_3)

Melting point of yttria is 2410 ^{0}C. It is very stable in the air and cannot be reduced easily. It can be dissolved in acids and absorbs CO_2. It is used in Nerst lambs as filament by alloyed with zirconia and thoria in small quantities. When added to zirconia, it stabilizes the material in cubic structure. Primary yttria minerals are gadolinite, xenotime and fergusonite. Its structure is cubic very refractory.

1.1.3 Magnesia (MgO)

Magnesia is the most abundant one in refractory oxides and its melting point is 2800 ^{0}C. Its thermal expansion rate is very high. It can be reduced easily at high temperatures and evaporate at 2300-2400 ^{0}C. At high temperature levels, magnesia has resistance to mineral acids, acid gases, neutral salts and moisture. When contacted to carbon, it is stable up to 1800 ^{0}C. It rapidly reacts with carbons and carbides over 2000 ^{0}C. The most important minerals of magnesia are magnesite, asbestos, talc, dolomite and spinel.

1.1.4 Alumina (Al_2O_3)

Melting point of alumina is about 2000 ^{0}C. It is the most durable refractory material to mechanical loads and chemical materials at middle temperature levels. Relatively low melting point limits its application. It doesn’t dissolve in water and mineral acids and basis if adequately calcined. Raw alumina can be found as corundum with silicates as well as compounds of bauxide, diaspore, cryolit, silimanite, kyanite, nephelite and many other minerals. As its purety rises, it becomes resistant to temperature, wear and electricity.

1.1.5 Beryllia

Beryllia has a high resistance to reduction and thermal stability and its melting point is 2550 ^{0}C. It is the most resistant oxide to reduction with carbon at higher temperatures. Thermal resistance is very high though its electrical conductivity is very low. Mechanical properties of beryllia are steady till 1600 ^{0}C and it is one of the oxides that has high compression strength at this temperature. An important amount of beryllium oxide acquired from beryl. It is a favourable refractory material for molten metals owing to its resistance to chemical materials (Geçkinli, 1992).

2. Ceramic coating applications in internal combustion engines

Ceramic coatings which are applied to reduce heat transfer are divided into two groups. Generally, up to 0,5 mm coatings named as thin coatings and thick coatings are up to 5-6 mm. Thin ceramic coatings are used in gas turbines, piston tops, cylinder heads and valves of otto and diesel engines. At the beginning of ceramic coatings to low heat rejection engines, thick monolithic ceramic coatings were applied to engine parts. Later, it was understood that these coatings are not appropriate for diesel engine operation conditions. Thus, new approaches were started to develop (Yaşar, 1997; Kamo et. al., 1989).

There are a lot of types and system for ceramic and other material coatings. Most important ones are;

- Thermal spray coating: Plasma spray, wire flame spray and powder flame spray, electrical arc spray, detonation gun technique and high speed oxy fuel system
- Chemical ceramic coating: Sole-gel, slurry, chemical vapour sedimentation, physical vapour sedimentation, hard coating
- Laser coating
- Arc spark alloying
- Ion enrichment method (Yaşar, 1997; Kamo et. al., 1989)

Material conglomerations can be avoided by reducing erosion-corrosion, friction-wear, using ceramics as well as improving heat insulation. Non the less, these methods are proper for very thin coatings except thermal spray coatings. Thin layer coatings are successfully used in gas turbine industry, coating turbine and stator blades and combustion rooms. For thick layer coatings like diesel engines, plasma spray and flame spray coatings are generally utilized (Kamo et. al., 1989).

2.1 Flame spray coatings

Oxy-hydrogen and oxy-acetylene systems are preferred in flame spray coatings and usually refractory oxides which have lower melting point than 2760 ^{0}C are used in coating with these systems. Before ceramic coatings, a binding layer resistant to high temperature like nickel-chromium should be applied to material surface for preventing oxidation as can be seen in Fig. 3. Otherwise, ceramic coating can't adhere to the surface properly. Coating speed in flame spray method is relatively slow and it changes between 4.4x10^{-5} and 1.13x10^{-3} m/s. There are two flame spray method which are wire flame spray method and powder flame spray method (Geçkinli, 1992).

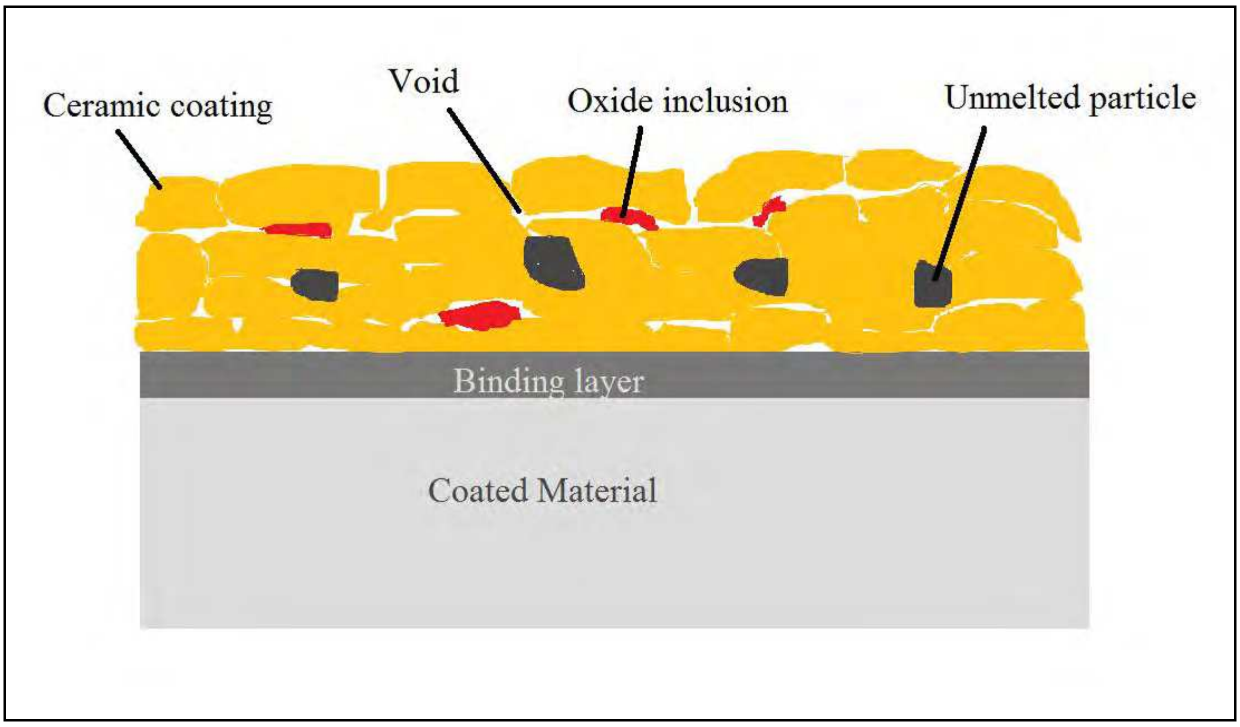


Fig. 3. Ceramic coated material surface, binding layer and coating layer

2.1.1 Powder flame spray coatings

In this method, micro-pulverized powder alloys are sprayed to target surface in oxy-acetylene flame by oxygen vacuum. It is called cold coating because flame temperature is about 3300 ^{0}C and target surface is about 200 ^{0}C during coating process. Adherence is mechanical. Coating layer thickness is changed 0,5 to 2,5 mm according to shape of work piece. Using highly alloyed and self lubricant NiCrBSi materials as coating powder and making materials which are not produced in rod or wire shapes possible for coating are the main advantages of this method. Powder flame spray systems are proper for spraying primarily ceramics and metals and cermets (metals and ceramic oxide alloys) as coating materials. Bearing supports, axle and shaft pivots, compressor pistons, cam shafts, bushes, rings and sleeves, hydraulic cylinders and pistons can be coated by this very method (Yaşar, 1997; Anonymous, 2004).

2.1.2 Wire flame spray coatings

Wire flame spray coating method is applied by spraying a wire shaped metal which has a melting point below flame temperature to coated surface. It can be used for metal spray materials and metal surfaces. Coating material wire is molten by oxygen and gas fuel flame after passing from the coating gun nozzle. Acetylene, propane and hydrogen are used for gas fuel. Relatively low equipment costs, high spray speeds and adjustment property according to wire diameters are the advantages of this system. Lower coating intensity and adherence strength comparing with other methods can be told as disadvantages of the method. Bearing supports, hydraulic piston pins, various bearings, shafts, wearing surfaces of axles, piston segments, synchromesh, crank shafts, clutch pressure plates can be coated with wire flame spray coating systems (Yaşar, 1997; Anonymous, 2004).

2.2 Plasma spray coating

Plasma is a dense gas which has equal number of electron and positive ion and generally named as fourth state of the matter. This method has two primary priorities; It can provide very high temperatures that can melt all known materials and provides better heat transfer than other materials. High operating temperature of plasma spray coating, gives opportunity to operate with metals and alloys having high melting points. Also using plasma spray coating in inert surroundings is another positive side of the method. Oxidation problem of the subject material is reduced due to inert gas usage in plasma spray such as argon, hydrogen and nitrogen. All materials that are produced in powder form and having a specific grain size can be used in this method (Yaşar, 1997; Geçkinli, 1992).

The main objective in plasma spraying is to constitute a thin layer that has high protection value over a non expensive surface. The process is applied as spraying coating material in powder form molten in ionized gas rapidly to coated surface. Plasma spray coating system is shown in Fig. 4. The spraying gun is illustrated in Fig. 5. The system primarily consists of power unit, powder supply unit, gas supply unit, cooling system, spraying gun and control unit.

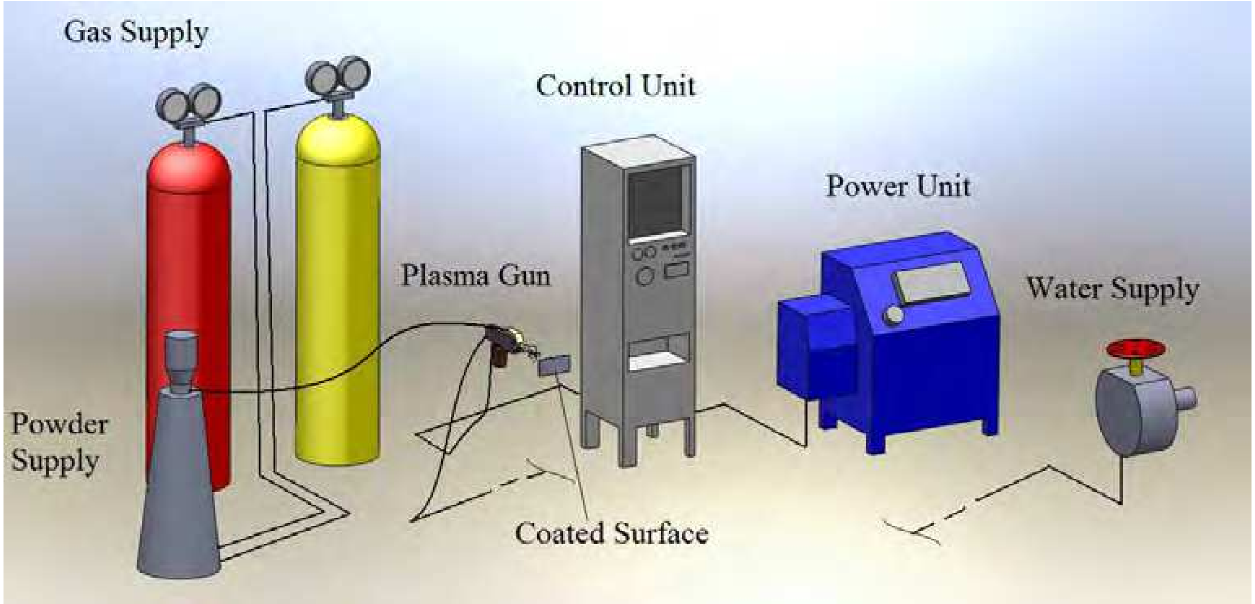


Fig. 4. Plasma spray coating system

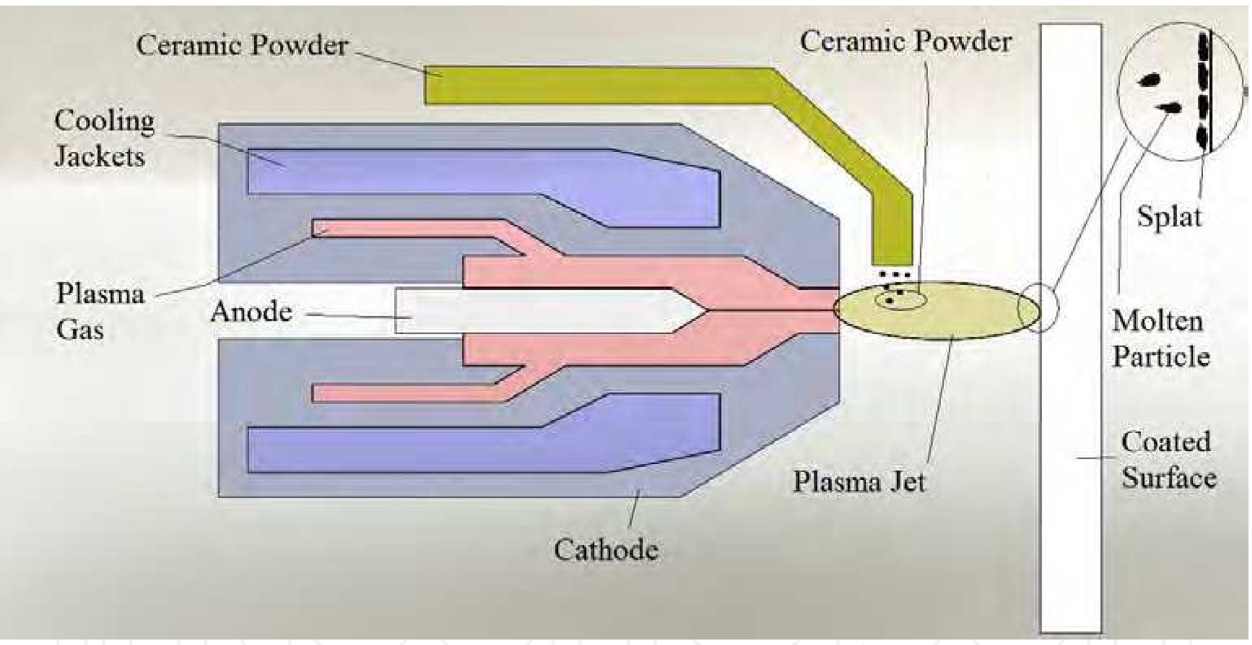


Fig. 5. Plasma spray gun

Direct current electrical arc is formed between electrode and nozzle in plasma spray coating gun. The inert gas (usually argon) and a little amount of hydrogen gas which is used to empower inert gas mixtures are sent to arc area of plasma gun and heated with electrical arc. Gas mixture temperature reaches to 8300 ^{0}C and it becomes ionized. Hence, high temperature plasma beam leaves from gun nozzle. In this system, ceramic grains are supplied to plasma beam as dispersible form. Grains molten by the hot gases are piled up on target surface and hardened. Argon/helium gas mixture increase gas flow and hence ceramic grains speed. Coating layer structure by the plasma spray coating contains equal axial thin solid grains. In some layers, an amorphous structure is attained because of fast solidification (Geçkinli, 1992).

Porosity is a property and a structural indicator of plasma spray coating. By utilizing high viscosity grains and high power plasma units, an intensive coating layer can be attained. Coating layers consisted from brittle and hard ceramic materials have high porosity rates. High porosity negatively affects material hardness which is a mechanical property of the material. While the least porosity layers have about 700 Vickers hardness, porous coating layers have about 300 Vickers hardness. 10 percent of the porosity after plasma spray coating is closed while rest of the porosity is open ones which combined with other defects in the structure because of insufficient fillings of blank areas among settled ceramic grains. Open porosities spoil mechanical properties of substance material by enabling corrosive sediments and gases to diffuse coating layer. On the other hand, spaces parallel to substance surface between layers negatively affect coating adhesion (Yaşar, 1997; Geçkinli, 1992).

Target surface must be rough, cleaned from oxides, oil, dirt and dust for making coating adhere to target surface. Surface roughness usually acquired by spraying an abrasive powder such as dust or alumina to target surface by a pressurized air. By coating base material having its surface prepared with a special binding material, target surface has a proper ground for ceramic coating. In addition to its binding property, binding layers can be used for reducing thermal expansion, protecting base material from effects of corrosion, gases and high temperatures. The most preferred binding material is NiAl. Work pieces which have their surface prepared for coating are placed perpendicular to plasma flame and fixed. Spray powders must hit to target surface perpendicularly to obtain an intensive and good quality ceramic coating (Yaşar, 1997; Geçkinli, 1992).

Another important factor is powder size distribution in the spray. Very small grains in the plasma flame can easily reach plasma flame temperature, big grains however, adhere to target surface without being properly molten and make structure to be porous. Researches show that grain sizes between 60 ±10 μm give good results.

Plasma spray coating can be conducted either in atmospheric conditions or in vacuum conditions. When it is done in vacuum conditions, plasma flame can expand to 20 cm and more intensive coatings can be obtained (Geçkinli, 1992). Fundamental elements and parameters affecting them in plasma spray coating are given in Table 3. One part of the process parameters which are determined for a specific coating application are depended to operator. To eliminate these parameters effecting coating quality, operating plasma gun with a robot arm or making plasma gun to move vertically and horizontally are proposed as solutions and applied.

3. Effects of ceramic coatings to internal combustion engine performance

To reduce damages occurring from high cycle temperatures, high cycle forces, sliding, erosion and corrosion on engine parts, several special techniques have been developed. Water cooling and thick combustion chamber walls had been utilized up to the end of Second World War to transfer excessive heat which material properties of combustion chamber construction materials such as cast iron can't bear. Later on, using low thermal conductivity materials such as glass and its' derivatives were considered. Despite low thermal conductivity, cost and low expansion rate, glass couldn't be used in internal combustion engines due to its' lacking strength. Using glass ceramic materials in engine parts was first seen at 1950s. In those days, ceramics used in spark plugs although low application numbers. Requirements for ceramic coatings for high temperature applications had been started to increase at 1960s. Especially developing gas turbines leaded that requirement because of metals and various alloys that couldn't resist high temperatures. Ceramic coating technology was initially applied to space and aviation areas and then at 1970s it had been started to apply to internal combustion engines, especially diesel engines. Performance increase and specific fuel consumption decrease of aforementioned ceramic coated systems created an interest to the topic.

SPRAYED POWDER PERAMETERS	COATING PARAMETERS	PROCESS PARAMETERS
COATING MATERIAL	COATED MATERIAL	PROCESS
Chemical composition	Mechanical properties	Atmospheric plasma spray
Phase stability	Thermal expansion rate	Inert gas plasma spray
Thermal expansion	Oxidation resistance	Vacuum plasma spray
Melting characteristics	Work piece dimensions	Under water plasma spray
Grain size distribution	Surface quality	Sprayed powder
Grain morphology	SERVICE CONDITIONS AT OPERATION CONDITIONS	Plasma gases
Specific surface area	Wear	Plasma temperature
Fluidity	Wear-wet corrosion	Speeds of sprayed powders
	Wear-oxidation	Powder supply speed
	Wear- gas corrosion	Pre heating and cooling of work piece
	Wear-erosion	Surface cleaning
	COMPOSITE COATING	Spraying environment
	Chemical components	
	Adhesion strength	
	Metallurgical reaction	
	Mechanical properties	
	Physical properties	
	Coating thickness	
	Porosity	
	Residual stresses	
	Coating properties under load	
	QUALITY CONTROL	
	TEST	
	PRODUCTION	

Table 3. Plasma spray coating technology; Components and parameters

Thermal barrier coatings used for reducing heat loss from cylinders and converting engines to low heat rejection engines also prevent coated materials from decomposing under high temperatures. ZrO_2 is the most preferred material in thermal barrier coated internal combustion engines due to its' low thermal conductivity and high thermal expansion rate. To avoid negative effects of phase changes of ZrO_2 at higher temperatures, it should be partially or fully stabilized with a stabilizer material. By this procedure, whole structure is formed with one phase, generally cubic phase. As stabilizer, usually MgO, CaO, CeO_2 and Y_2O_3 oxides are used.

There are a vast number of studies investigating effects of thermal barrier coatings and especially ceramic coatings to internal engine performance and exhaust emission behaviours. Investigated parameters can be summarized as coating material, coated material, coating thickness, engine types and operational conditions such as engine load and speed. Obtained results can be different in dimensions and magnitudes such as volumetric efficiency, thermal efficiency, engine torque, engine power, specific fuel consumption, heat rejection from cylinders, exhaust temperature, exhaust energy and exhaust emissions. Investigations of thermal barrier coating in internal combustion engines are mostly focused on diesel engines because of detonation and knocking problems of spark ignition engines at higher in cylinder temperatures. For diesel engines, studies can be divided into two main categories; turbocharged engines and non-turbocharged engines. For non-turbocharged engines, thermal barrier coating application and thus ceramic coatings of internal combustion engine cylinders generally results negatively due to decreasing volumetric efficiency. In the other hand, turbocharged diesel engines exhibit better performance and exhaust emissions according to improved volumetric efficiency and in cylinder temperatures. This phenomenon's main reason is the increased exhaust gas energy which is converted to mechanical energy and later on to air mass flow rate increase in turbocharger. For instance, Leising and Prohit (1978) suggested that desired results by heat rejection insulation could only be achieved by the utilization of turbocharger and intercooler. They also reported that a diesel engine performance could be increased up to 20% by the addition of a turbocharger. When studies about thermal barrier coated engines without turbochargers are considered, it was observed that most of the studies were conducted on a single cylinder, four stroke diesel engines. Miyairi et. al. (1989), Dickey (1989) and Alkidas (1989) are some of these researchers. Prasad et. al. (2000), Charlton et. al. (1991), Chang et. al. (1983) can be given as examples for researchers that studied on natural aspirated multi-cylinder diesel engines. In the other hand, multi-cylinder diesel engines types were mostly preferred for turbocharged thermal barrier coated engine researches. For instance Woods et. al. (1992), Kimura et. al. (1992), Woschni and Spindler (1988), Hay et. al. (1986) and Ciniviz (2005) performed parametric studies on thermal barrier coated turbocharged multi-cylinder diesel engines. Parlak (2000) and Kamo et. al. (1997) are two studies among limited turbocharged single cylinder thermal barrier coated engine investigations.

Coating materials and methods can be divided into two categories for this book; ceramics and non-ceramics. Coating thickness is usually changes between 100-500 µm. A typical thickness for coating materials is 0,15 mm binding layer and 0,35 mm coating material. Parlak et. al. (2003) and Taymaz et. al. (2003) are two of these studies which used the typical coating thickness. For the researchers that preferred ceramic materials, zirconia is the most seen material among other ceramics. NiCrAl is frequently used as binding materials for those studies. Uzun et. al. (1999), Beg et. al. (1997), Taymaz et. al. (2003), Marks and Boehman (1997), Schwarz et. al. (1993) and Hejwowski (2002) can be referred for these studies. Alternatively, Sun et. al. (1994), proposed silicon nitride (HPSN) piston materials and thick coating layers of plasma sprayed zirconia between 2-7 mm for cylinders. Matsuoka and Kawamura (1993) used Si_3N_4 instead of zirconia.

Specific literature survey was resulted that specific fuel consumption, heat rejection from cylinders and NO_x emissions are the most reported results of experimental and numerical studies for ceramic coated engines. Depending on rising in cylinder temperatures, almost all studies expressed an increase in NO_x emissions. This event can be named as the main side effect of ceramic coating or thermal barrier coating of internal combustion engines. The increase in NO_x emissions is observed between 10-40% from the literature. Gataowski (1990), Osawa et. al. (1991) and Kamo et. al. (1999) some of the papers in which these aforementioned results can be found. However there are some suggestions for reducing this increase by changing injection timing or decreasing advance angle. Winkler and Parker (1993) reported 26% decrease in NO_x emissions of thermal barrier coated engine by changing injection timing. Similarly Afify and Klett (1996), stated that 30% decrease in NO_x emissions was achieved by advance adjustment. When specific fuel consumption is considered, results are varying both negatively and positively. This is particularly the result of volumetric and combustion efficiency. Specific fuel consumption decrease can be observed from the literature between 1-30%. Ramaswamy et. al. (2000), reported 1-2% specific fuel consumption decrease while Bruns et. al. (1989), stated specific fuel consumption decrease between 16-37% by means of ceramic thermal barrier coating. On the contrary, Sun et. al. (1993) and Beg et. al. (1997) expressed 8% increase in specific fuel consumption by the utilization of ceramic thermal barrier coating. Similarly Kimura et. al. (1992), specified that thermal barrier coating resulted 10% increase in specific fuel consumption. As desired, ceramic thermal barrier coatings were resulted as a decrease between 5-70% in heat rejection from cylinders to engine block and cooling system. Vittal et. al. (1997) reported 12% decrease in transferred heat from cylinders and Rasihhan and Wallace (1991) informed that heat rejection rate was decreased between 49,2-66,5% after ceramic coating.

There are several more indicators that show effectiveness of ceramic thermal barrier coatings. Further search can be conducted for specific parameters.

4. A case study: The effects of Y_2O_3 with coatings of combustion chamber surface on performance and emissions in a turbocharged diesel engine

In this study, the effects of ceramic coating of combustion chamber of a turbocharged diesel engine to engine performance and exhaust emissions were investigated. Increasing mechanical energy by preventing heat losses to coolant and reducing cooling load, improving combustion by increasing wall temperatures and decreasing ignition delay, more power attaining in turbocharged engines by increasing exhaust gas temperatures and decreasing carbon monoxide and soot are aimed. For this aim, cylinder head, inlet and exhaust valves and pistons of the engine were coated with 0.5 mm zirconia by plasma spray coating. Then, the engine was tested for different brake loads and speeds at standard, ceramic coated engine one and ceramic coated engine 2 conditions. The results gained from the experimental setup were analyzed with a computer software and presented with comparatively graphics. Briefly, specific fuel consumption was decreased 5-9 percent, carbon monoxide emission was decreased 5 percent, and soot was decreased 28 percent for a specific power output value. Considering these positive results nitrogen oxide however was increased about 10 percent. By the development of exhaust catalysers, increase in nitrogen oxide becomes no more a problem for present day. When results are generally investigated, it was concluded that engine performance was clearly improved by zirconia ceramic coating.

4.1 Experimental setup

Appropriate measurement equipment, their calibration and operational conditions have an important effect on experimental results. Engine specifications are given in Table 4. Experiments were conducted in internal combustion engines workshop in Gazi University Technical Education Faculty Mechanical Education Department Turkey. Cross section view of the engine is shown in Fig. 6 and solid model view of experimental setup is illustrated in Fig. 7.

ENGINE	SPECIFICATIONS
Brand, type and model	Mercedes-Benz/OM364A/1985
Cylinder number/diameter/stroke	4/97.5 mm/133 mm
Total cylinder volume (Combustion room + cylinder)	3972 cm^3
Compression rate	17.25
Nominal revolution rate	2800 rev/min
Engine power	66 kW (2800 rev/min)
Maximum torque	266 Nm (1400 rev/min)
Operation principle	4 stroke diesel engine
Injection sequence	1-3-4-2 (cylinder numbers)

Table 4. Specifications of engine used in experiments

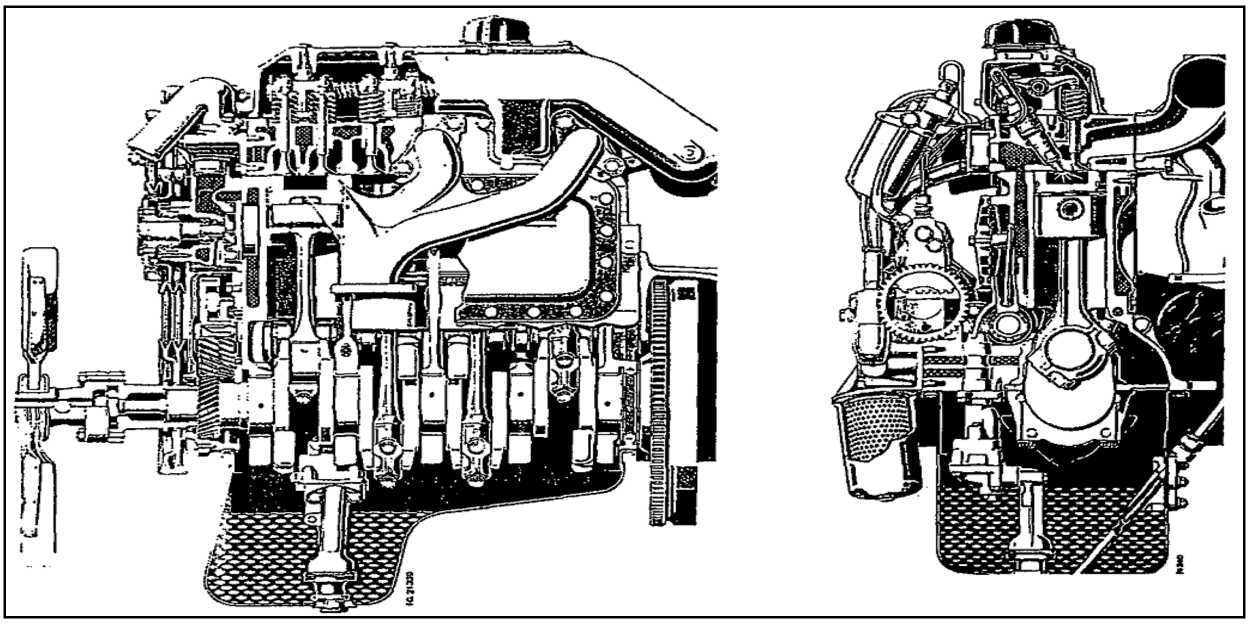


Fig. 6. Cross sectional view of test engine

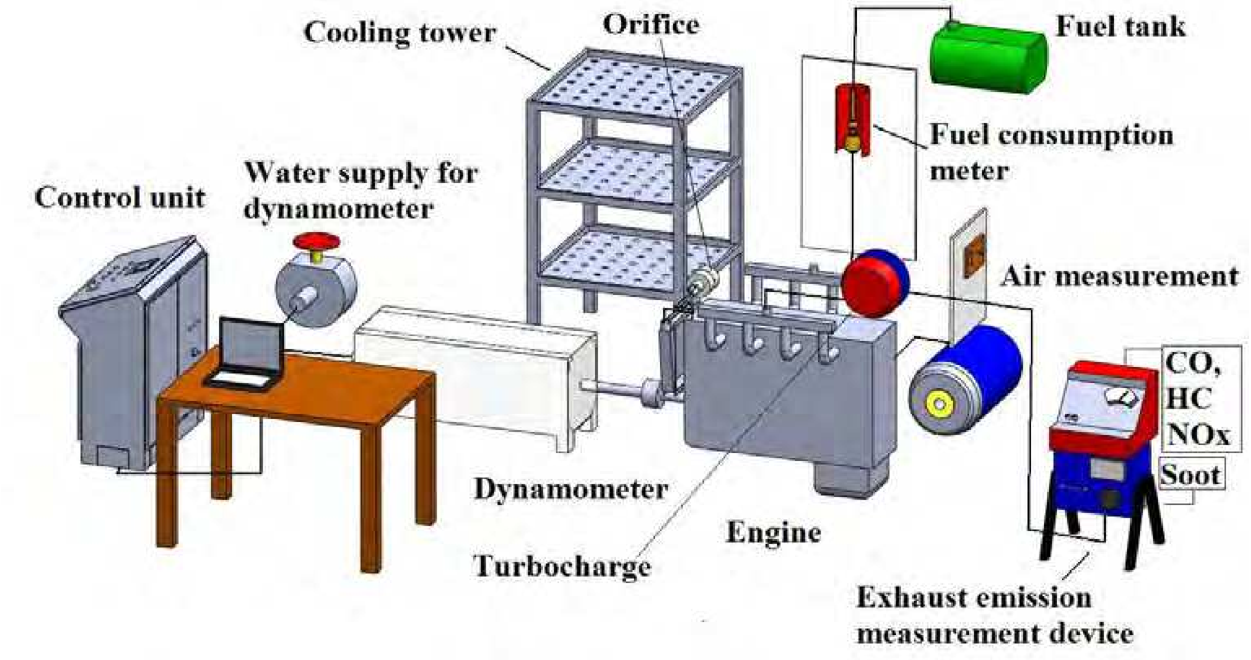


Fig. 7. Solid model view of experimental setup

Measurement devices were used for determining both exhaust emission values and performance characteristics. Photographs of these devices are given in Fig. 8. Experimental setup consist of basic units such as hydraulic brake dynamometer, cooling tower for cooling engine coolant, fuel consumption measurement device, temperature and pressure probes and control panel.

Engine was loaded by hydraulic dynamometer which is connected to engine with a shaft during experiments. Fig. 9 shows test engine in experimental setup. Additionally, flow rate measurement setups were utilized in the system for charge air and coolant.

a) Control panel

b) Charge air flow measurement unit and damper

c) Orifice plate for measuring coolant flow rate

d) Exhaust gas analyser

e) Smoke intensity measurement device

f) Temperature measurement screen

Fig. 8. Measurement devices in experimental setup for determining exhaust emissions and performance characteristics

Air flow measurement device used in the experiments is GO-Power M5000 type. A manometer was placed onto the device and it has a gauge glass of 0-75 mm long. For the conducted experiments, a 2.75 inch nozzle was attached to entrance of damper. Ohaus brand digital mass scale with 0.1 gram sensibility and 8 kg capacity was preferred for determining fuel amount. For exhaust emission, two different exhaust emission measurement devices were used during experiments as it can be seen from Fig. 7 and Fig. 8. For measuring carbon monoxide, carbon dioxide, nitrogen oxides, oxygen and sulphur oxides as ppm (particle per million) and mg/m^3, Gaco-SN branded exhaust gas analyser device was used. It can also calculate combustion efficiency and excess air coefficient. For determining smoke intensity, OVLT-2600 type diesel emission measurement device was used. This device can measure smoke amount as *k* factor and percentage. Measurement range and accuracy of OVLT-2600 are given in Table 5.

Fig. 9. Three different views of the test engine

Measured parameter	Measurement range	Accuracy
k factor	0-10 (m^{-1})	±0.01
Smoke intensity	0-99 (%)	±0.01
Engine revolution	0-9999 rev/min	1 rev/min

Table 5. OVLT-2600 measurement ranges and accuracies

1 ^{0}C accuracy thermometer which have 130 ^{0}C gauge and Precision branded barometer which has measurement range of 710-800 mmHg were used during experiments. A chronometer with 0.01 second resolution was employed while fuel consumption rate was measuring.

4.2. Experimental method

Determining ceramic coating effects on performance and exhaust emissions of turbocharger diesel engine requires standard values for performance indicators. For this purpose, test engine was operated without ceramic coatings according to 1231 numbered Turkish Standards (TS) experimental essentials and results were recorded. Ceramic coatings were applied after those standard tests. Cylinder heads, piston tops and intake exhaust valves were machined at 0.5 mm depth. Machining was done for achieving same compression rate with conventional combustion chamber after ceramic coating. Ceramic coating was applied by plasma spray coating system in Metal & Seramik Kaplama Ltd. Sti. in Turkey.

The most critical coated engine part is pistons due to its thermal expansion rate which is very different from selected ceramic material. In literature, ZrO_2 stabilized with Y_2O_3 and Si_3N_4 ceramic coating materials are told as positive result giving materials. At cylinder heads and intake exhaust valves, ZrO_2 stabilized with MgO can be utilized safely. Another important point in ceramic coatings is the binding layer composition. Coating durability is increased when NiCrAlY is used as binding layer.

Surfaces to be coated were cleaned from lubricants and other unwanted dirt after machining before roughed by sandblasting and prepared for ceramic coating. When surface preparation was done, surface was first coated with binding layer at 0.15mm thickness and then coated with 0.35 mm thick ceramic material layer. Reduction of thermal instability (high heat conduction difference) between coating layer and target surface is aimed by this way. Hence, the failure risk for coating layer is lowered. In Fig. 10, coated piston tops can be seen. Fig. 11 contains two different figures which are illustrating cylinder head and valves before coating and after coating respectively.

Ceramic materials used for coating are;

- Coating sequence for inlet exhaust valves and cylinder head was selected as base material + 0.15 mm thick NiCrAl + 0.35 mm thick Y_2O_3 – ZrO_2.
- Coating sequence for piston heads was selected as base material + 0.15 mm NiCrAlY + 0.35 Y_2O_3 – ZrO_2.

After coating process was done, coated engine parts were mounted to engine. Same circumstances with standard engine test were applied to coated engine tests. Experimental measurements were evaluated via MS Excel and Matlab v6.5 software.

In diesel engines, power output, torque and fuel consumption values according to engine speeds are named as engine characteristics. Differences in these characteristics at different load and engine speeds are illustrated with graphical curves. These curves are called as characteristic curves. Engine characteristic curves provide important information about engine performance at real time operational circumstances. Experimental measurements not always give directly the desired data. These data should be calculated using experimental measurements. Experimental measurements generally consist of torque, engine revolution rate, fuel consumption, charge air flow rate, coolant flow rate, ambient temperature, pressure and humidity, exhaust gases temperatures, coolant entrance and exit temperatures. The most important performance characteristics calculated from these measurements are effective power, torque, mean effective pressure and specific fuel consumption (Ciniviz, 2005).

Fig. 10. Ceramic coated piston tops

a) Cylinder heads and valves without coating b) Ceramic coated cylinder heads and valves

Fig. 11. Cylinder head and valves before coating and after coating

During experiments, intake and exhaust valve adjustments were made according to engine catalogue values and injectors were tested at 200 bar injection pressure. Piston rings were renewed. To measure exhaust gas composition, exhaust pipe was drilled after one meter distance from exhaust pipe entrance and measurement probe was fitted to the hole. Experiments were conducted at ten different engine speeds changing between 1100 rev/min and 2800 rev/min and seven different brake loads changing between 40 Nm and full load.

Measurement points are 1100-1200-1400-1600-1800-2000-2200-2400-2600-2800 rev/min and 40-80-120-160-200-240 Nm and full load. Due to vast number of experimental results, only 40, 120, 200 Nm and full load points are presented in this study.

Two different ceramic coated combustion chambers were compared with standard combustion chamber. In the first one, only cylinder heads and intake exhaust valves were coated. This configuration is represented by SKM1 in graphics. In second one, piston tops also coated with selected ceramic material. So, whole combustion chamber was coated in second configuration. Second configuration is represented as SKM2 in graphics. Three dimensional performance curves obtained in experimental study were evaluated and provided in four different regions. These regions are;

1. Low load, low speed
2. High load, low speed
3. Low load, high speed
4. High load, high speed

An example graphic layout was given in Fig. 12 for previously mentioned regions. In two dimensional graphics, results are provided for 40, 120, 200 Nm and full load points. Before experiments, engine was heated by operating low and medium loads thus steady state was acquired.

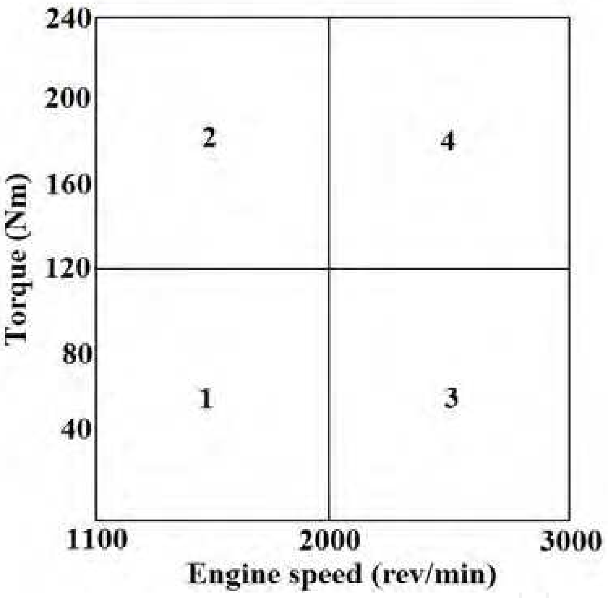


Fig. 12. Three dimensional performance map and regions for evaluation

4.3 Experimental results

In Fig. 13 and Fig. 14, specific fuel consumption comparison of SKM1 and SKM2 with standard engine are provided respectively. Specific fuel consumption changing with engine speed at full load for all engine configurations are given in Fig. 15. For partial load measurement points which are 40, 120 and 200 Nm, similar specific fuel consumption comparison graphics are given for all engine configurations at Fig. 16, 17 and 18 respectively. At first region in three dimensional performance map for specific fuel consumption, SKM1 exhibits 4.5 percent and SKM2 9 percent low specific fuel consumption comparing with standard engine. These figures indicate that there is an important decrease in specific fuel consumption by the utilisation of ceramic thermal barrier coating. This decrease presents continuity at low and medium engine torques. At high torque and high engine speeds, in the other hand, specific fuel consumption decrease continues with a declining trend for ceramic coated engine.

For specific fuel consumption rate, especially second region gives better results. At 1100-1800 rev/min engine speed and 160-200 Nm torque range, standard engine specific fuel consumption is 220 g/kWh while SKM1 has 210 g/kWh and SKM2 has 200 g/kWh.

Fig. 19 and 20 are presented for comparing exhaust gas temperature increase in SKM1 and SKM2 with standard engine respectively. Figures are clearly indicating high exhaust temperatures in ceramic coated engines. In third region, the difference between standard engine exhaust temperatures and ceramic coated engine exhaust temperatures are relatively strong.

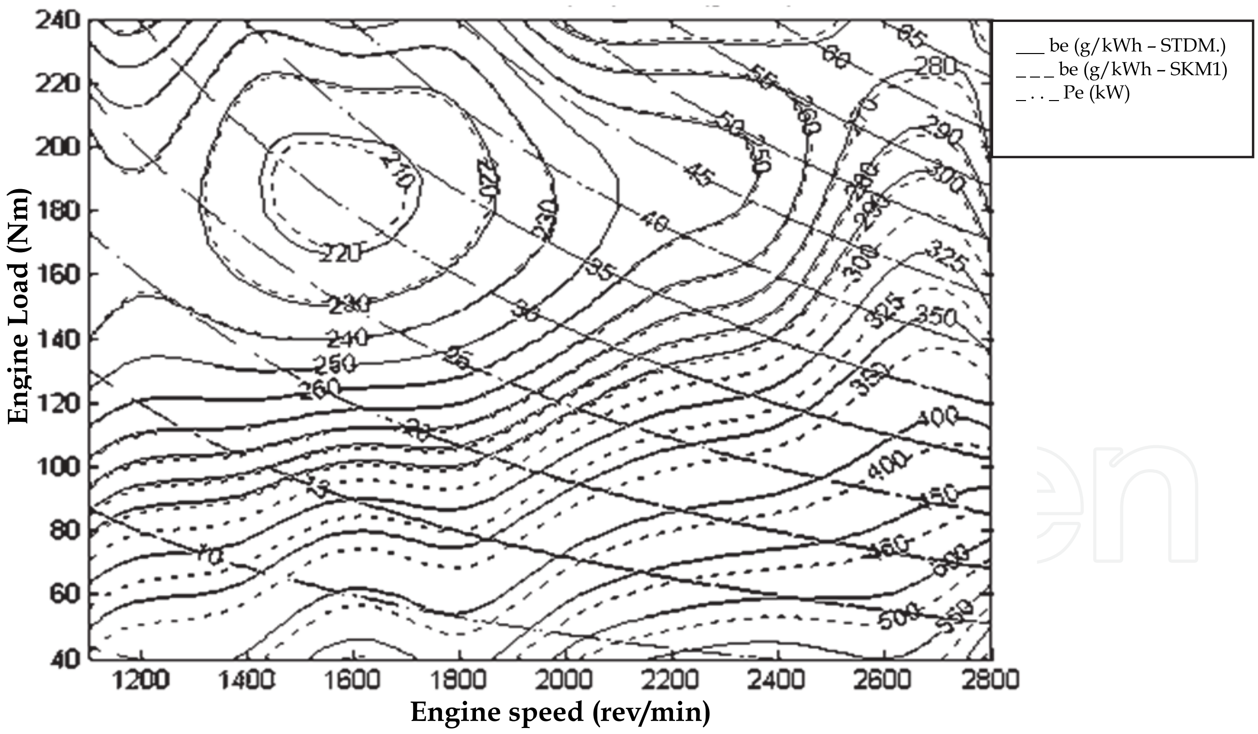


Fig. 13. Three dimensional specific fuel consumption map for SKM1 and standard engine configuration

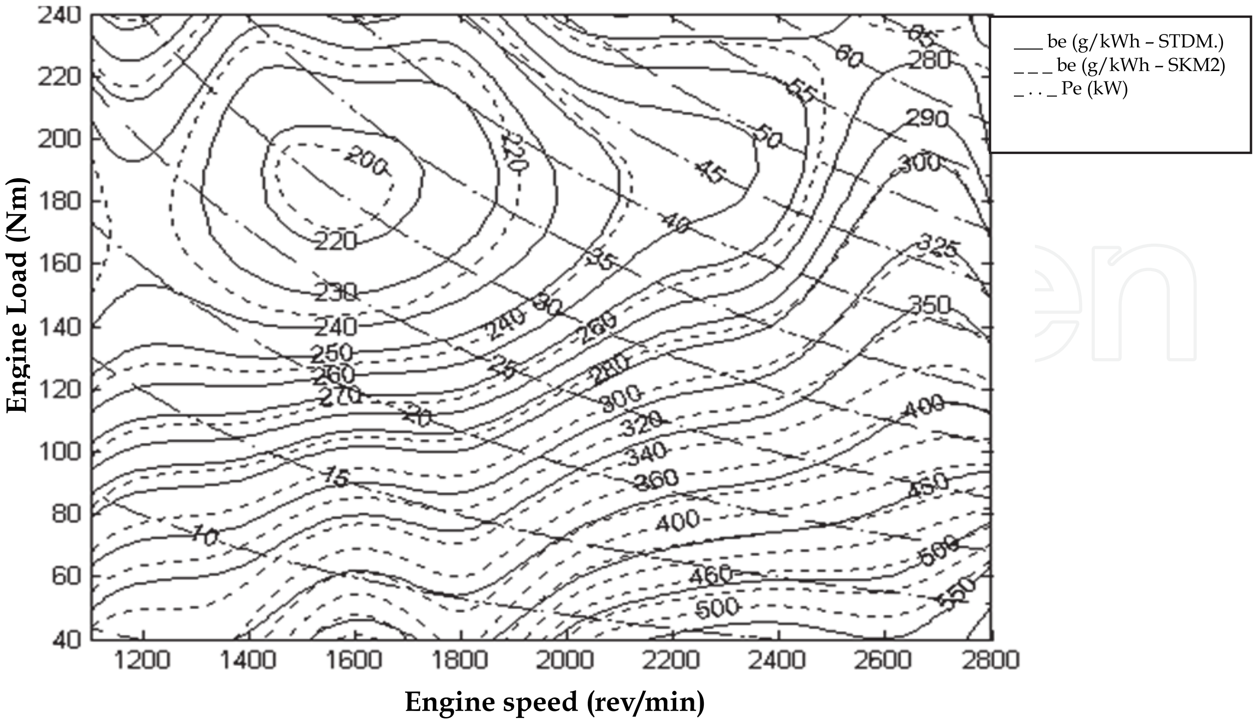


Fig. 14. Three dimensional specific fuel consumption map for SKM2 and standard engine configuration

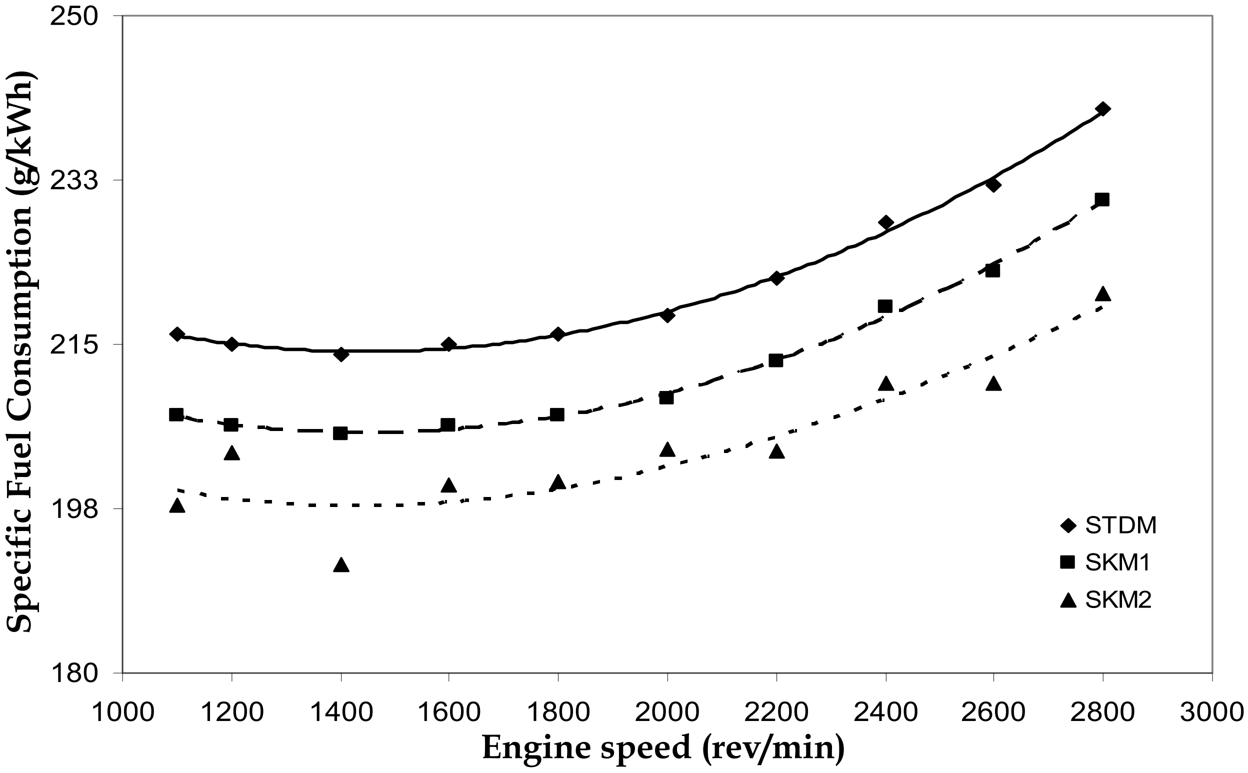


Fig. 15. Specific fuel consumption rate at full load for all engine configurations

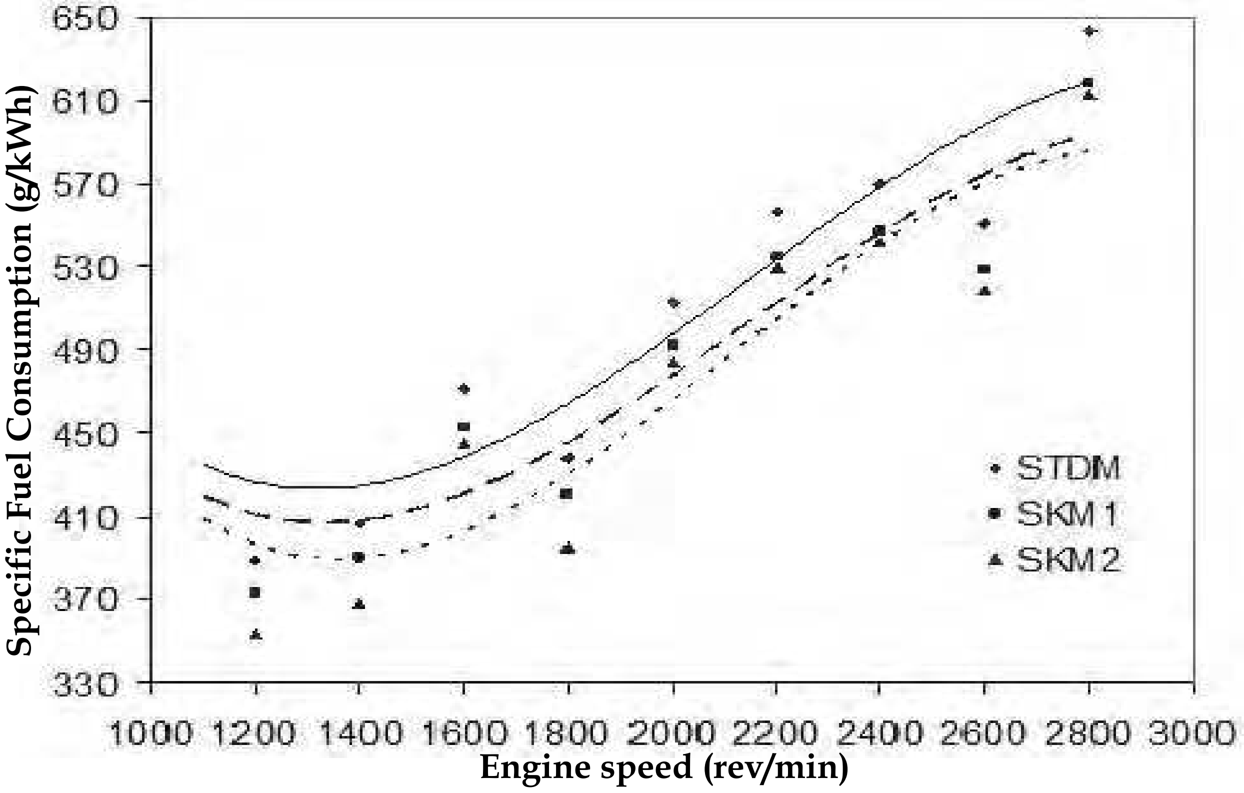


Fig. 16. Specific fuel consumption rate at 40 Nm load for all engine configurations

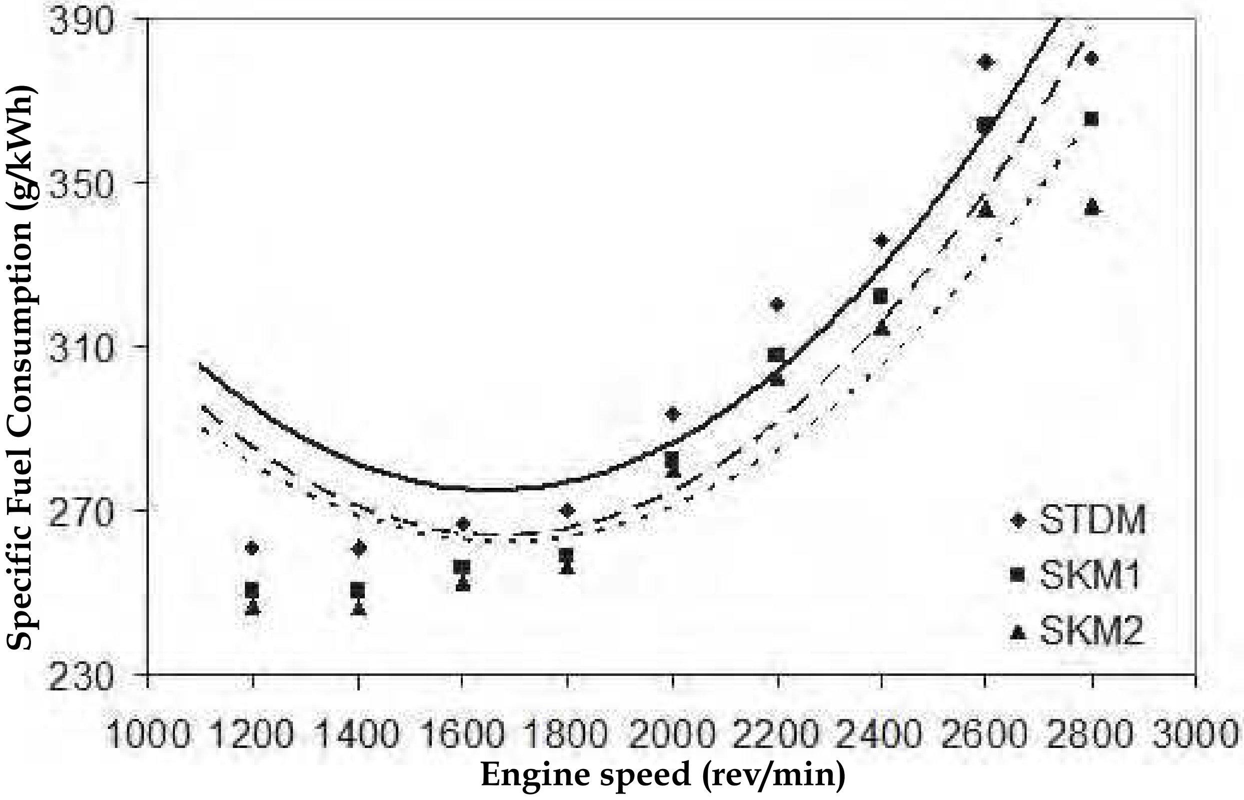


Fig. 17. Specific fuel consumption rate at 120 Nm load for all engine configurations

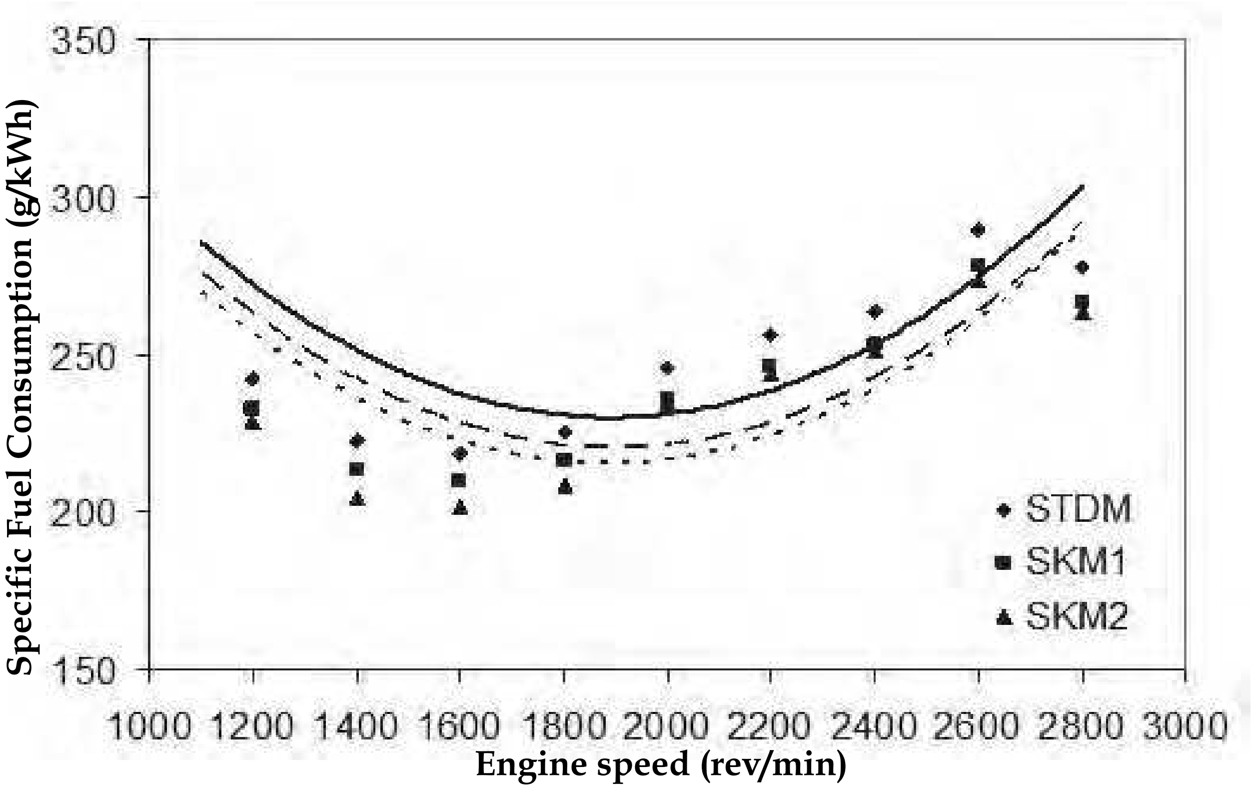


Fig. 18. Specific fuel consumption rate at 200 Nm load for all engine configurations

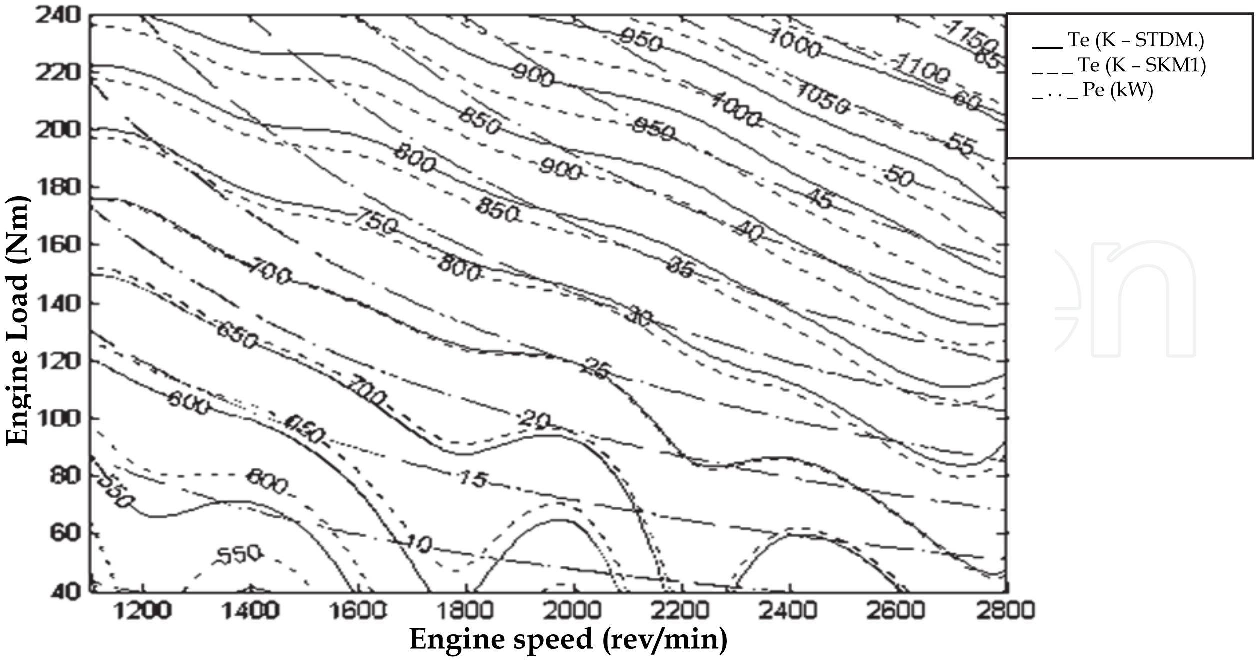


Fig. 19. Three dimensional exhaust temperatures map for SKM1 and standard engine configuration

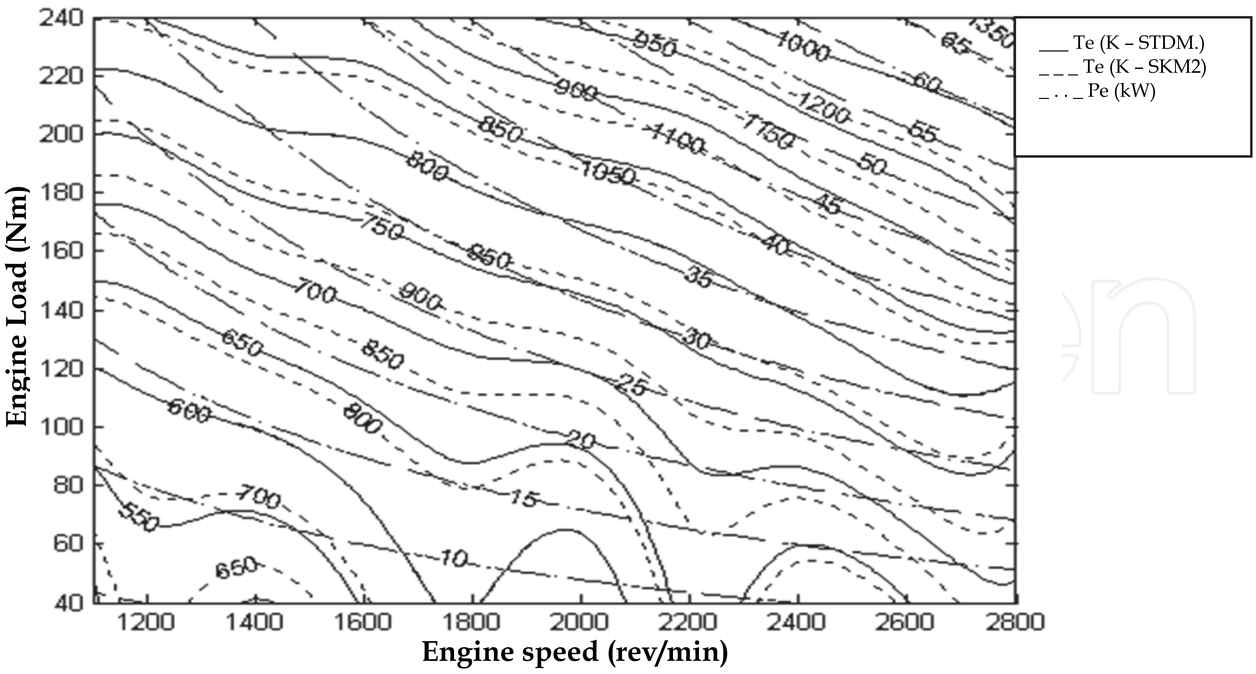


Fig. 20. Three dimensional exhaust temperatures map for SKM2 and standard engine configuration

One can expect that ceramic thermal barrier coating may decrease volumetric efficiency due to increased in-cylinder temperatures. Although exhaust gases and cylinder wall temperatures are high enough to make such effect, turbocharger causes an opposite effect in this study. Fig. 21 illustrates volumetric efficiency change of engine configurations with engine speed at full load. In a same way, Fig. 22, 23 and 24 are presented for 40, 120 and 200 Nm brake loads respectively.

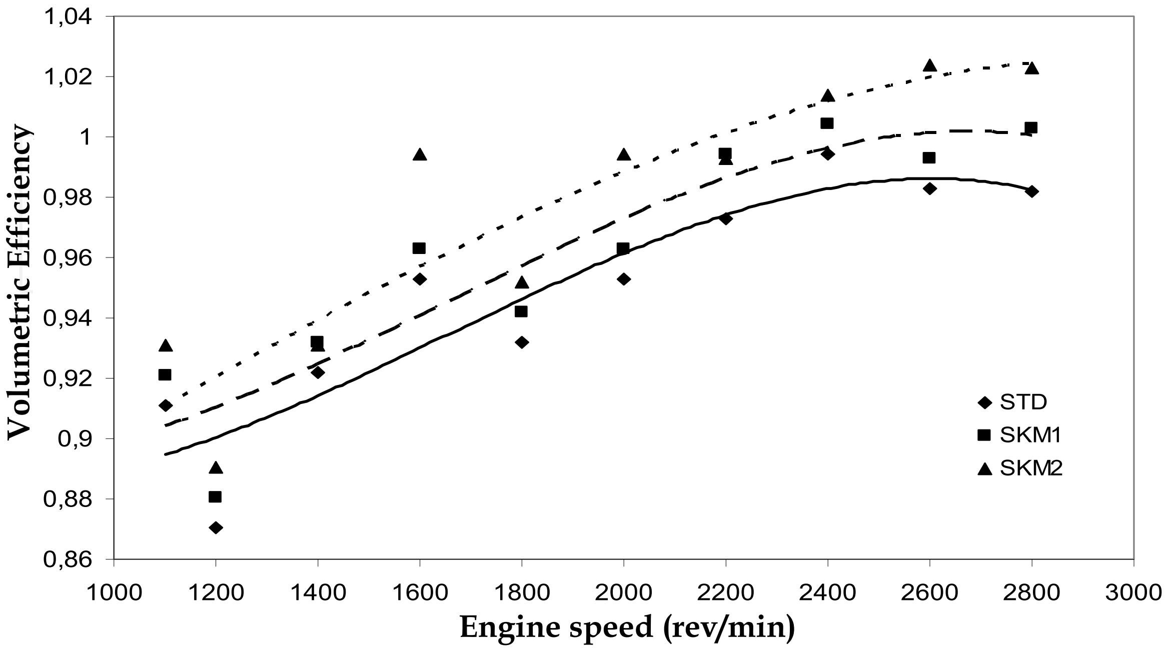


Fig. 21. Volumetric efficiency change at full load for all engine configurations

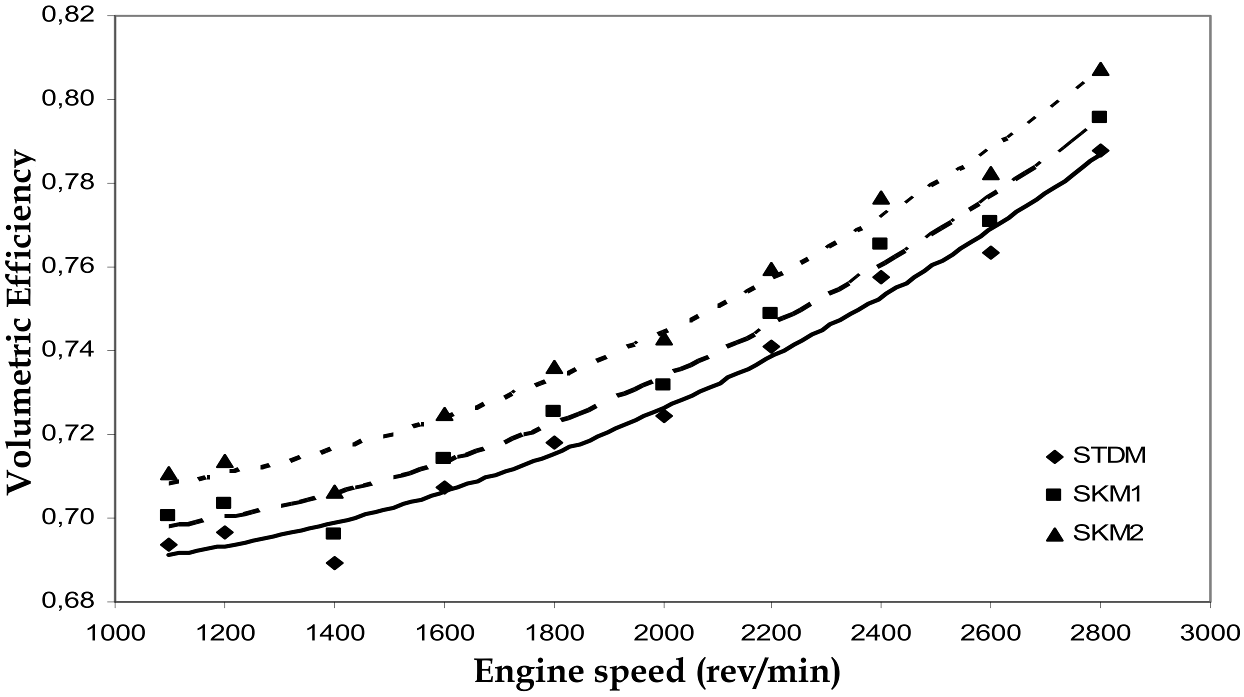


Fig. 22. Volumetric efficiency change at 40 Nm load for all engine configurations

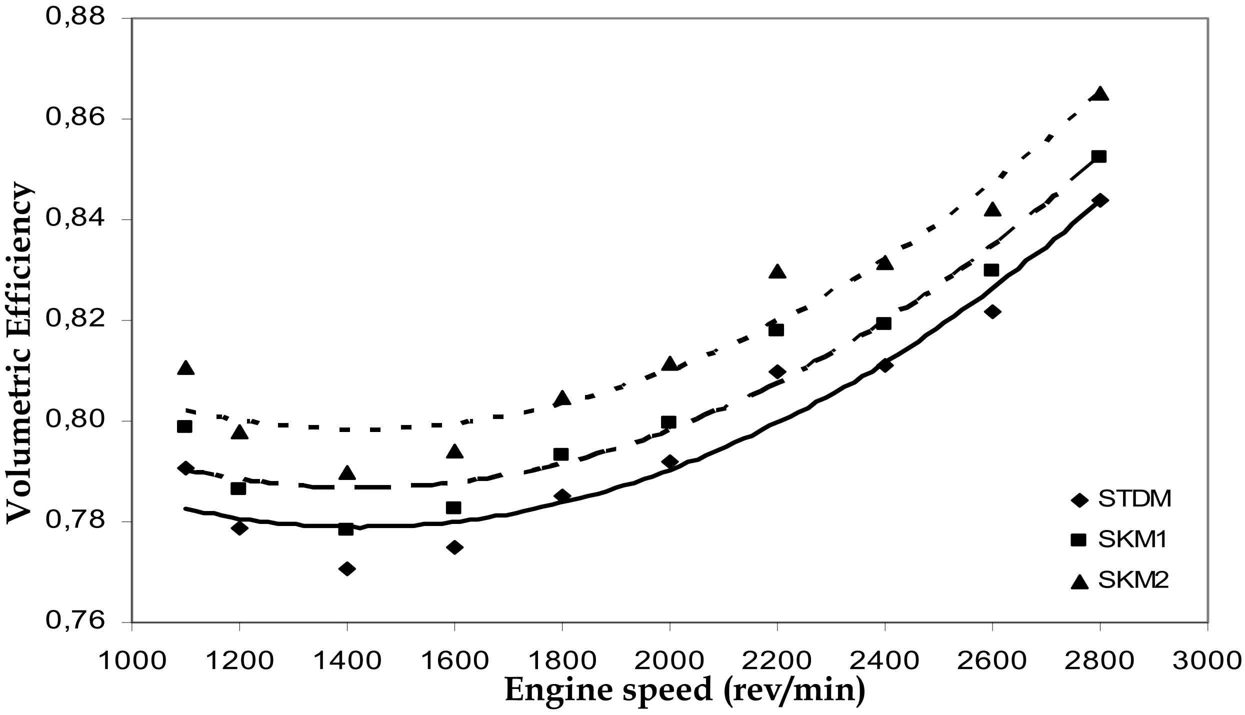


Fig. 23. Volumetric efficiency change at 120 Nm load for all engine configurations

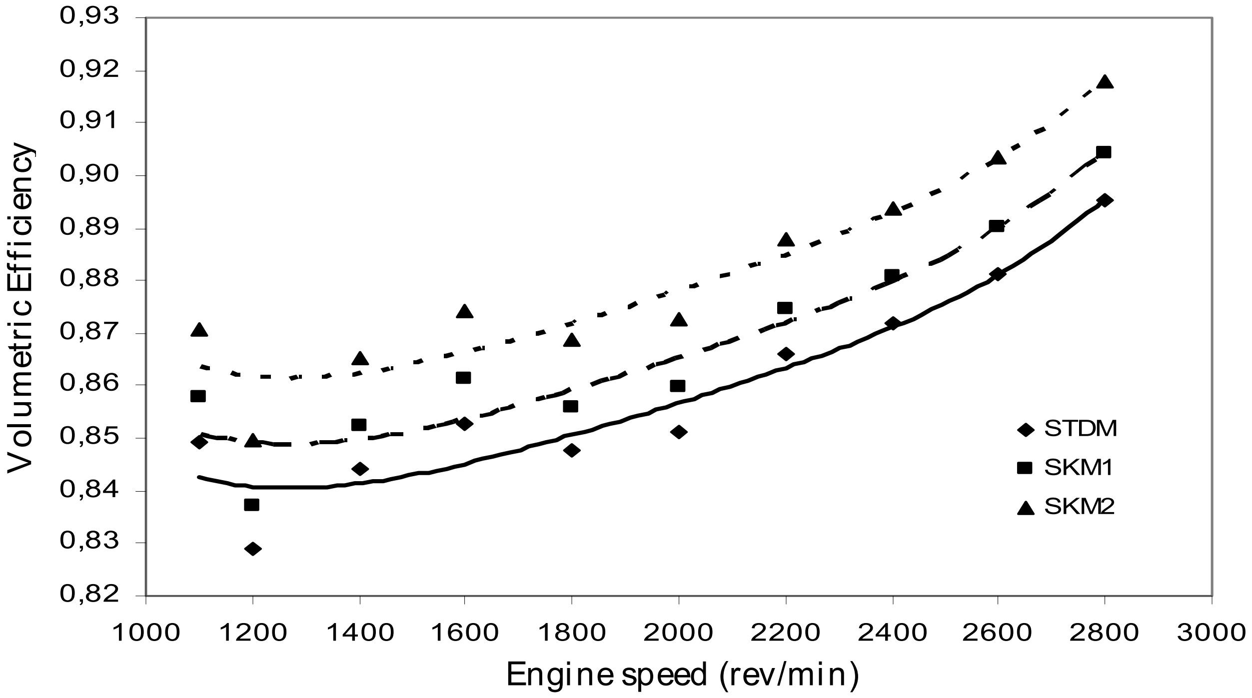


Fig. 24. Volumetric efficiency change at 200 Nm load for all engine configurations

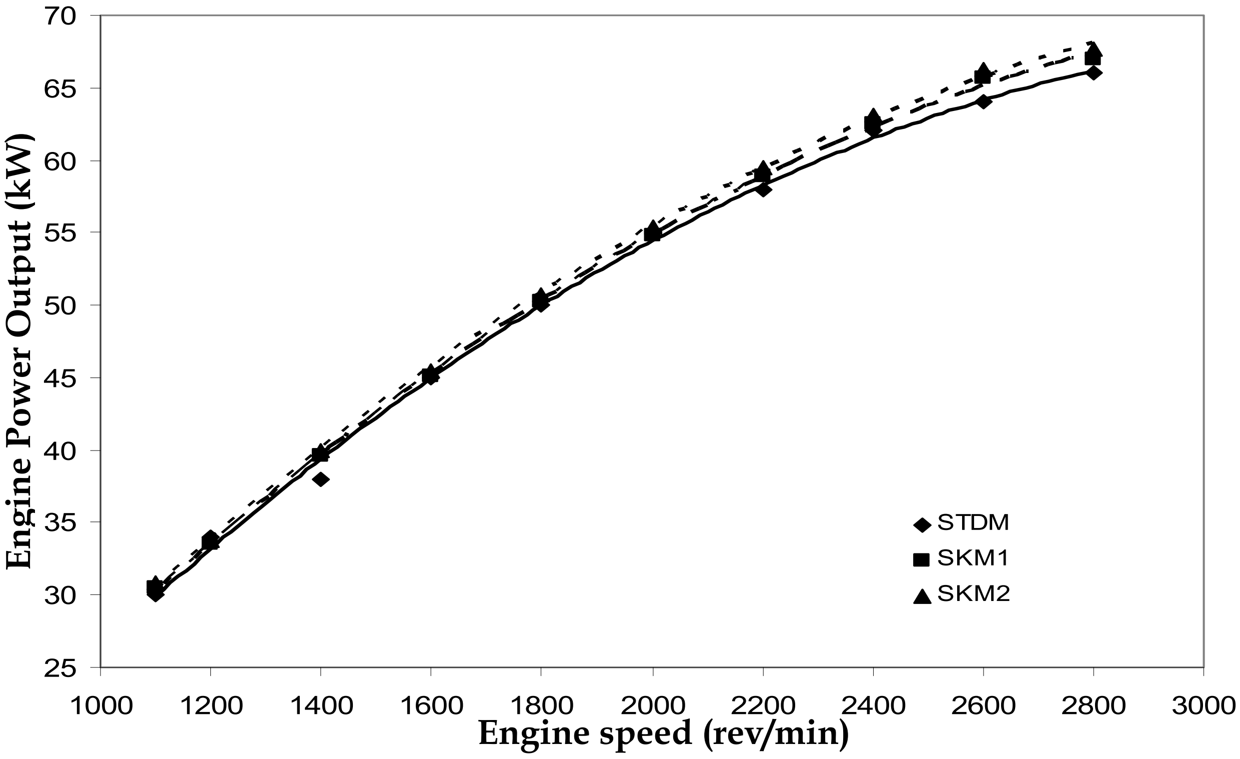


Fig. 25. Engine power output change at full load for all engine configurations

Engine power output is increased between 1-3% and torque increased between 1,5-2,5% by ceramic coating comparing with standard diesel engine. These observations can be chased in Fig. 25 for engine power and in Fig. 26 for torque at full load.

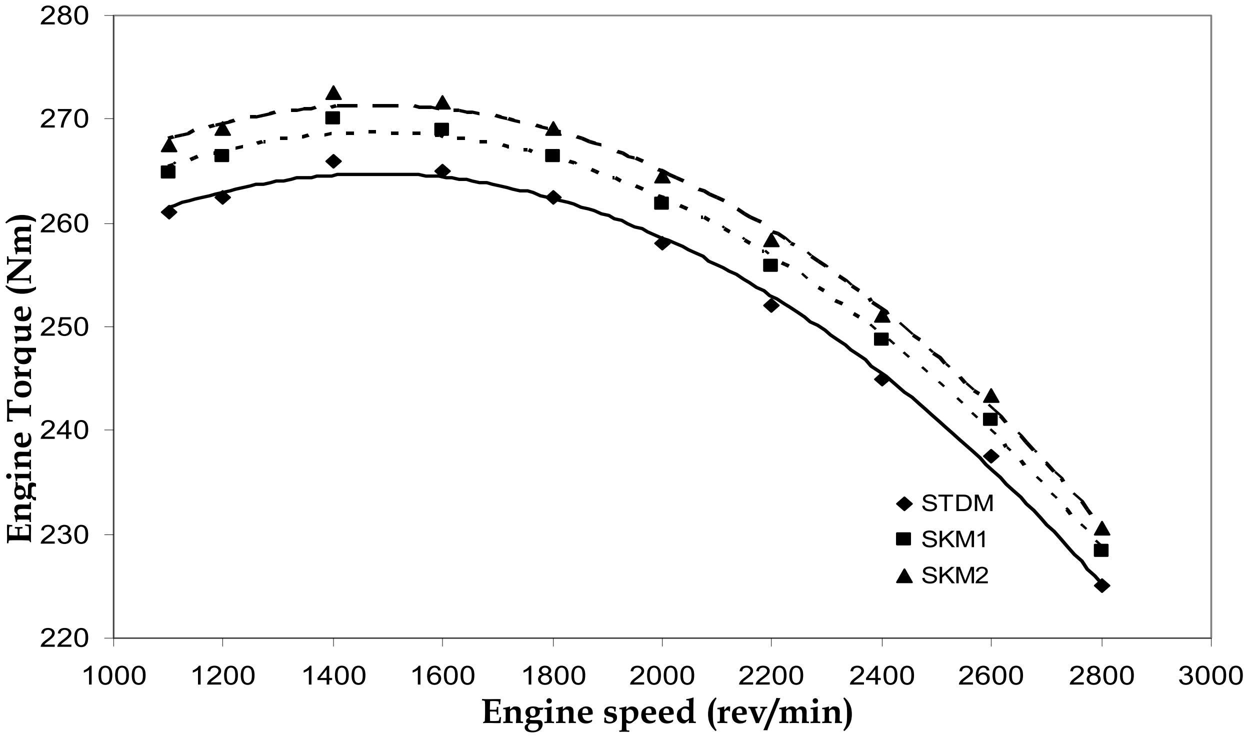


Fig. 26. Engine torque change at full load for all engine configurations

In Fig. 27, heat flux transferred to engine coolant changing with engine speed can be seen at full load for all engine configurations. In Fig. 28, 29 and 30, same graphic was drawn for 40, 120 and 200 Nm loads. In both coated engine configurations and standard engine, heat flux to coolant increase with increasing engine speed however its percentage to total heat is decreasing. These results are compatible with Wallace et. al. (1979; 1984). Experimental results show that heat flux was reduced at a rate of 19 percent by ceramic coating.

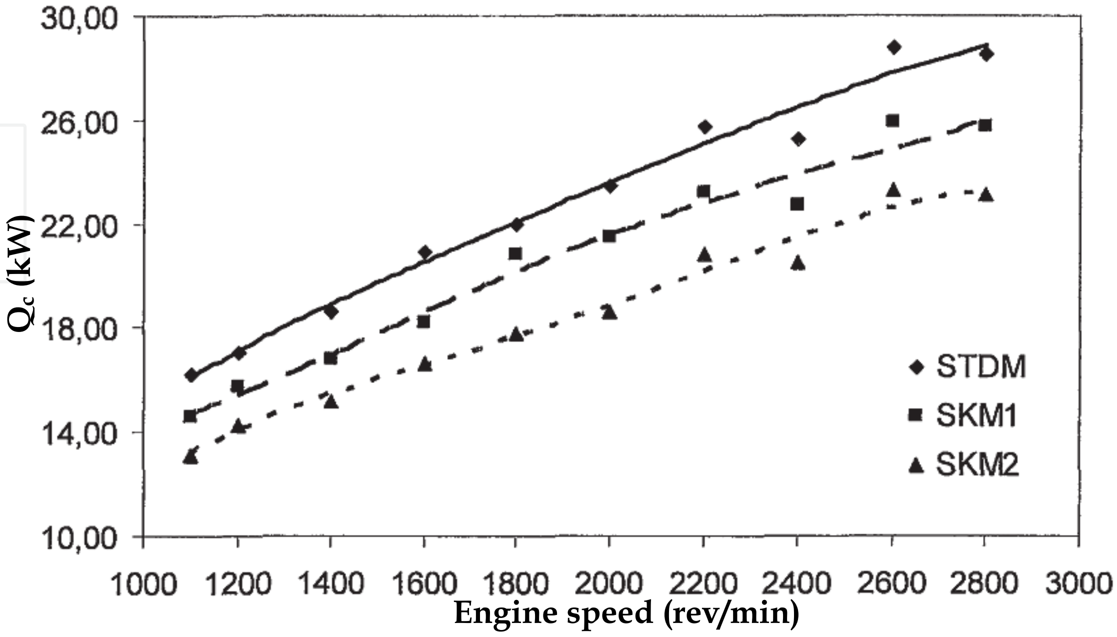


Fig. 27. Heat transfer rate to coolant at full load for all engine configurations

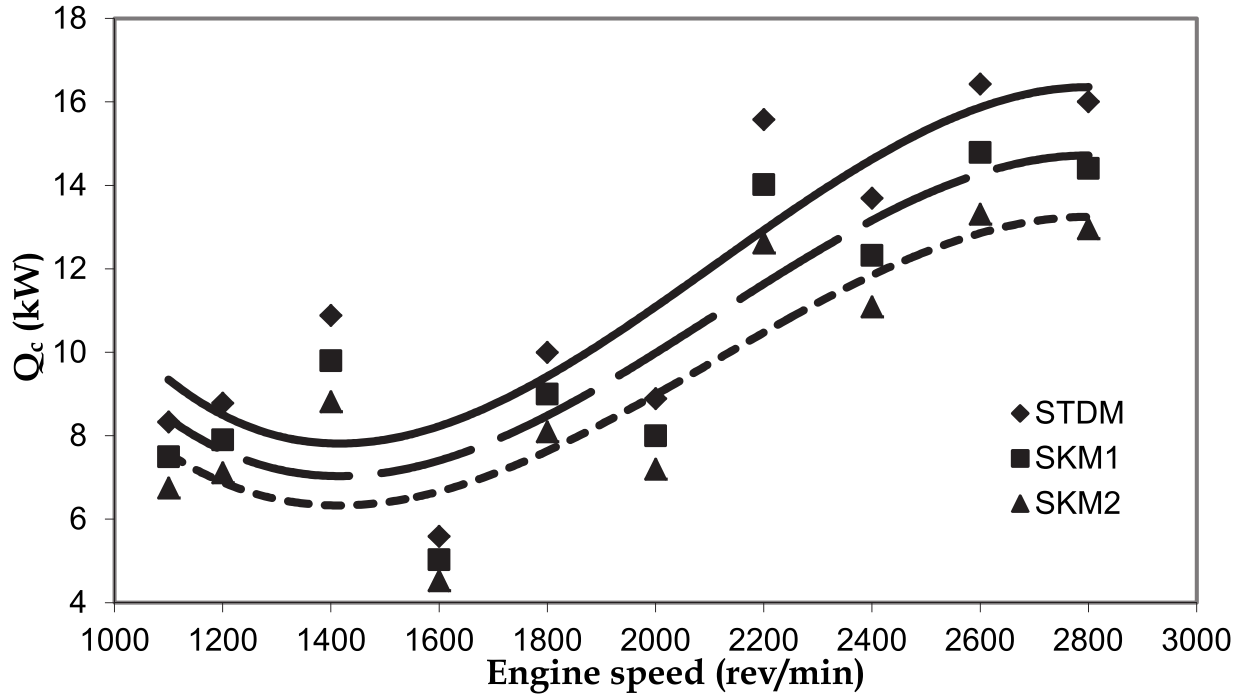


Fig. 28. Heat transfer rate to coolant at 40 Nm load for all engine configurations

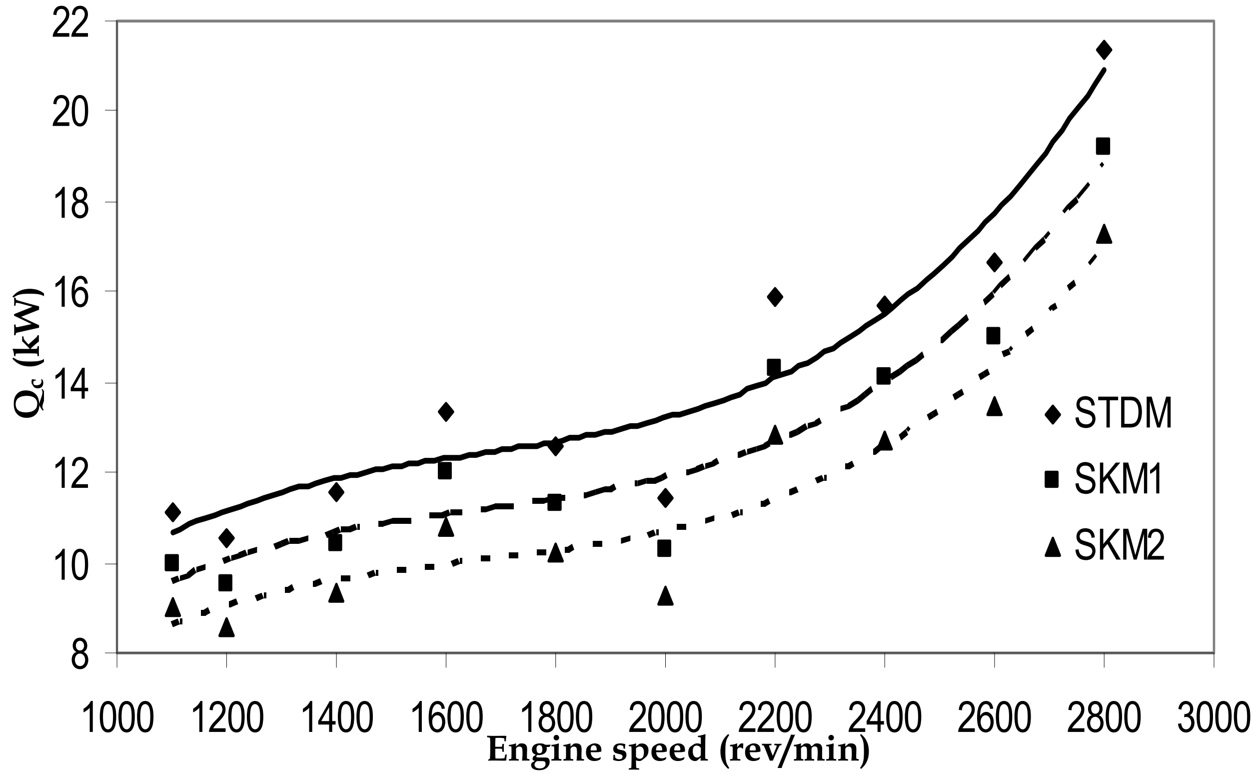


Fig. 29. Heat transfer rate to coolant at 120 Nm load for all engine configurations

Some of the heat after combustion can't be converted into mechanical energy and also it can't be transferred to coolant. This heat portion is carried with exhaust gases. Percentage rate increase of exhaust gas energy is inversely proportional with heat flux to coolant. According to experimental results, about 17.5% increase was observed in the heat energy that passes to exhaust gases. Exhaust heat energy changing with engine speed at full, 40 Nm, 120 Nm and 200 Nm loads for all engine configurations are given in Fig. 31, 32, 33 and 34 respectively.

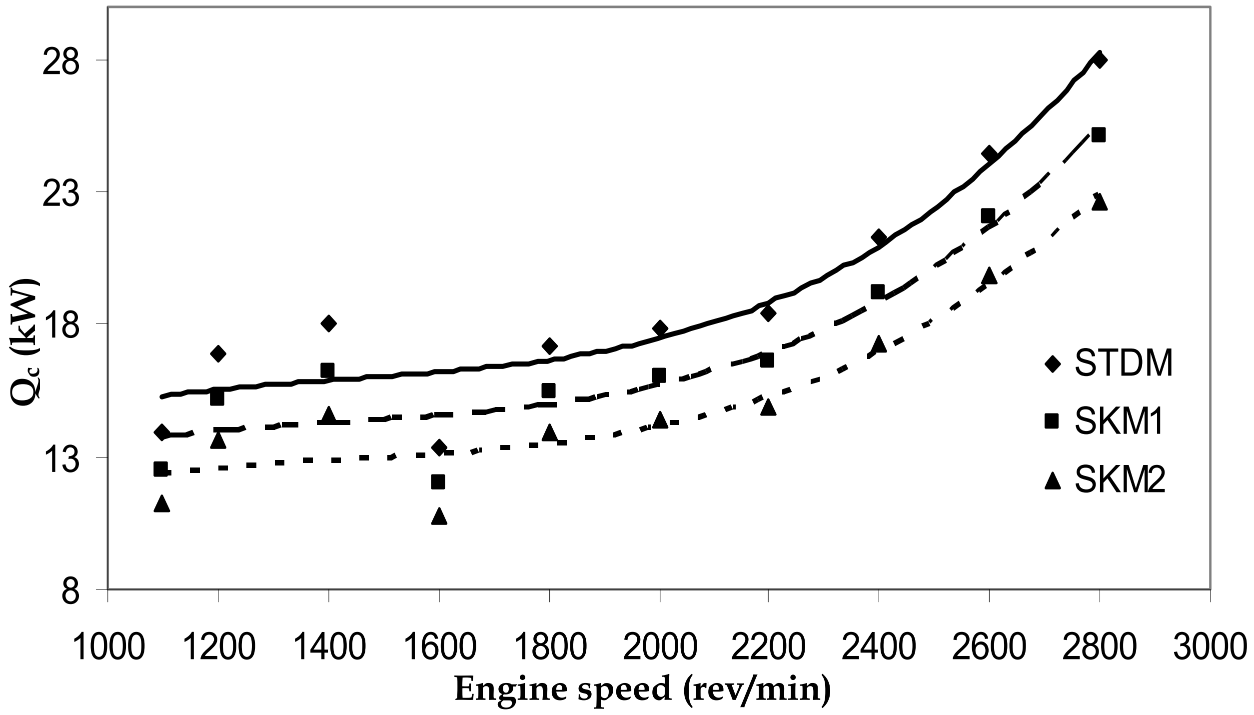


Fig. 30. Heat transfer rate to coolant at 200 Nm load for all engine configurations

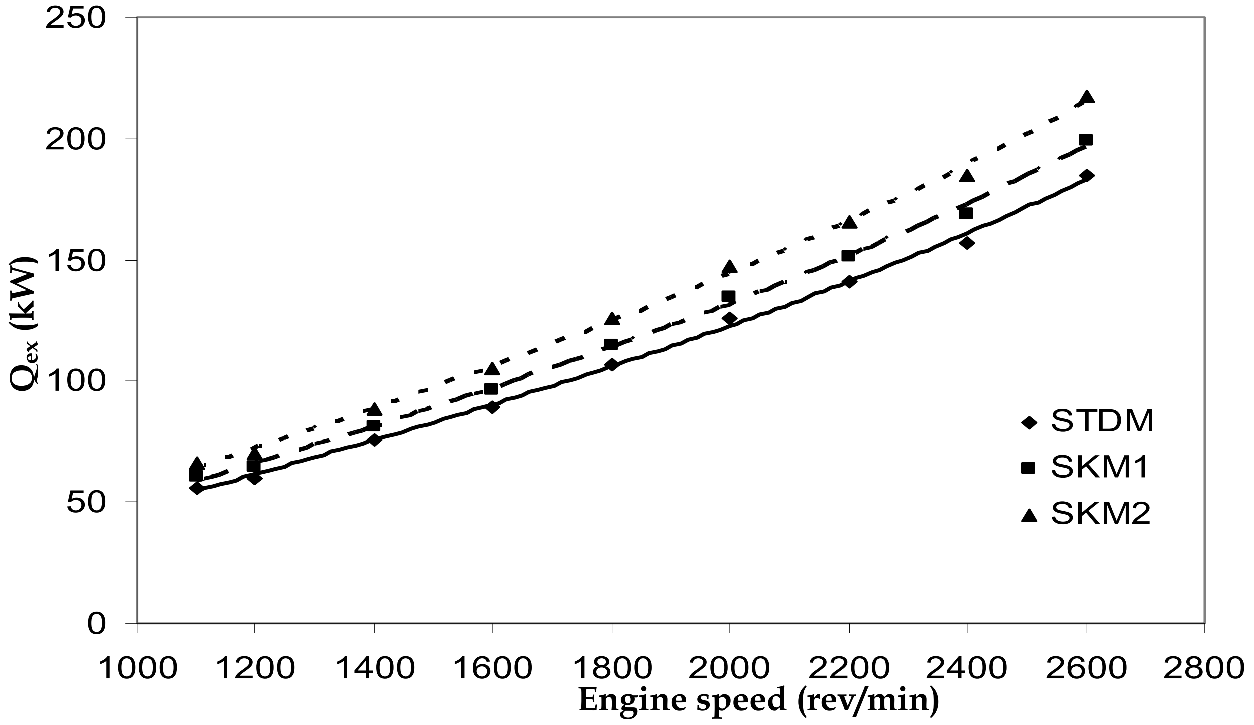


Fig. 31. Heat carried with exhaust gases at full load for all engine configurations

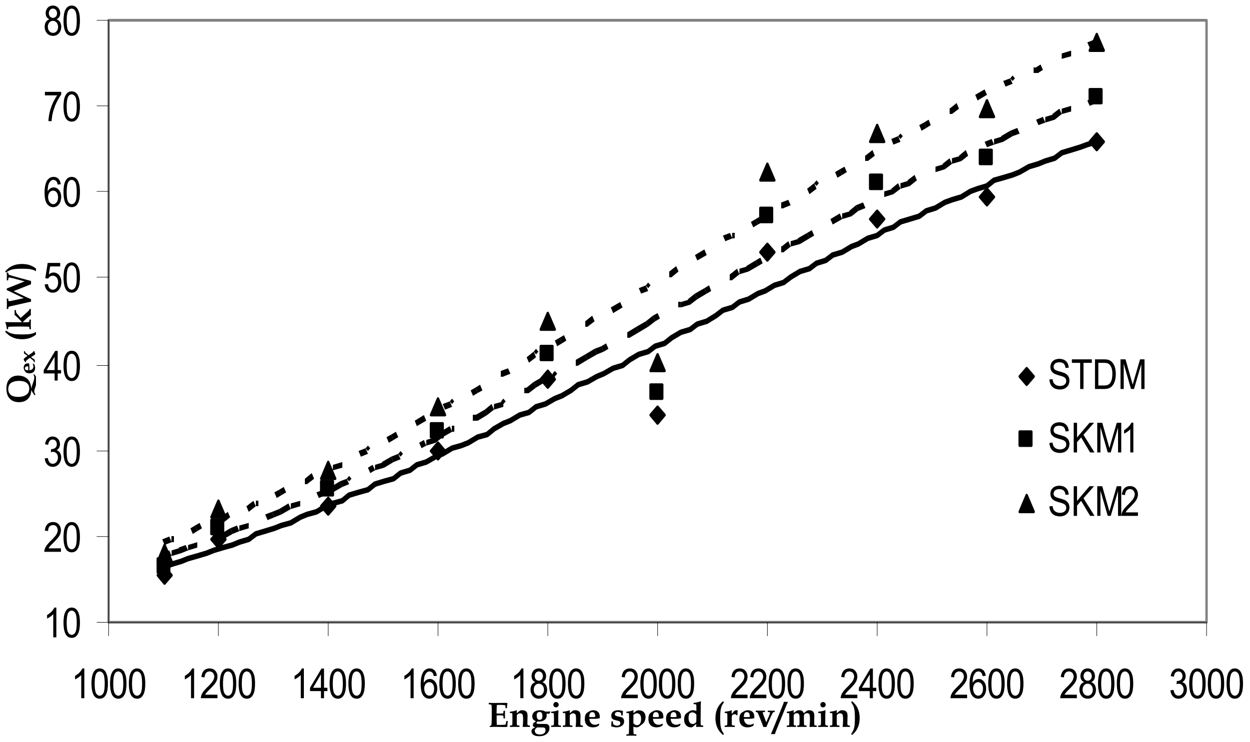


Fig. 32. Heat carried with exhaust gases at 40 Nm load for all engine configurations

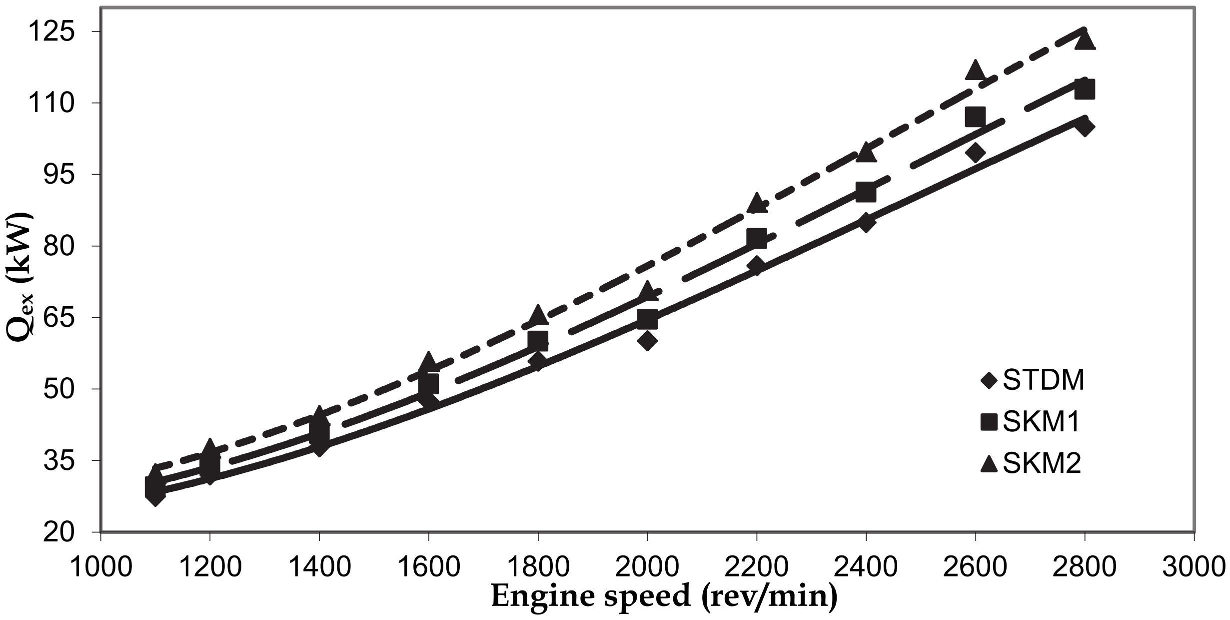


Fig. 33. Heat carried with exhaust gases at 120 Nm load for all engine configurations

One of the most dangerous exhaust emissions is nitrogen oxides in diesel engines. Nitrogen oxide emissions are generally generated over 1800 ^{0}C. Top temperature value during combustion can increase about 150-200 ^{0}C in ceramic thermal barrier coated engines. High in-cylinder temperatures cause an increase in nitrogen oxides emissions about 10% comparing with standard engine operation. Fig. 35 and 36 illustrates nitrogen oxides emissions for SKM1-standard engine and SKM2-standard engine comparisons.

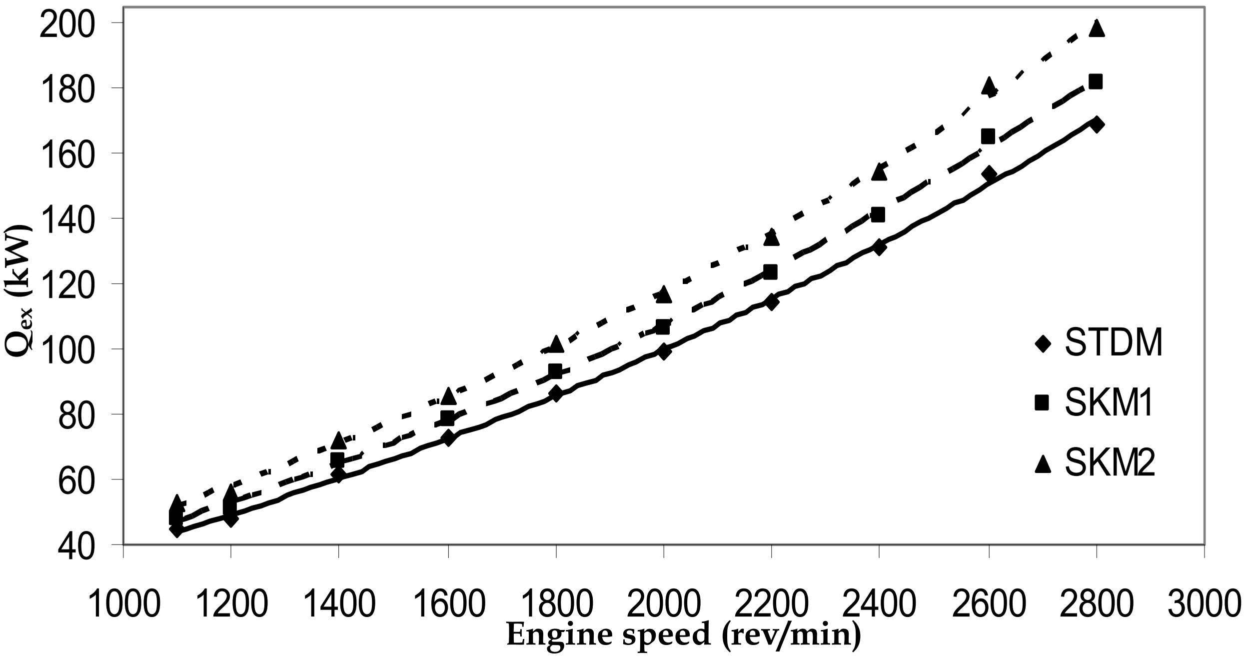


Fig. 34. Heat carried with exhaust gases at 200 Nm load for all engine configurations

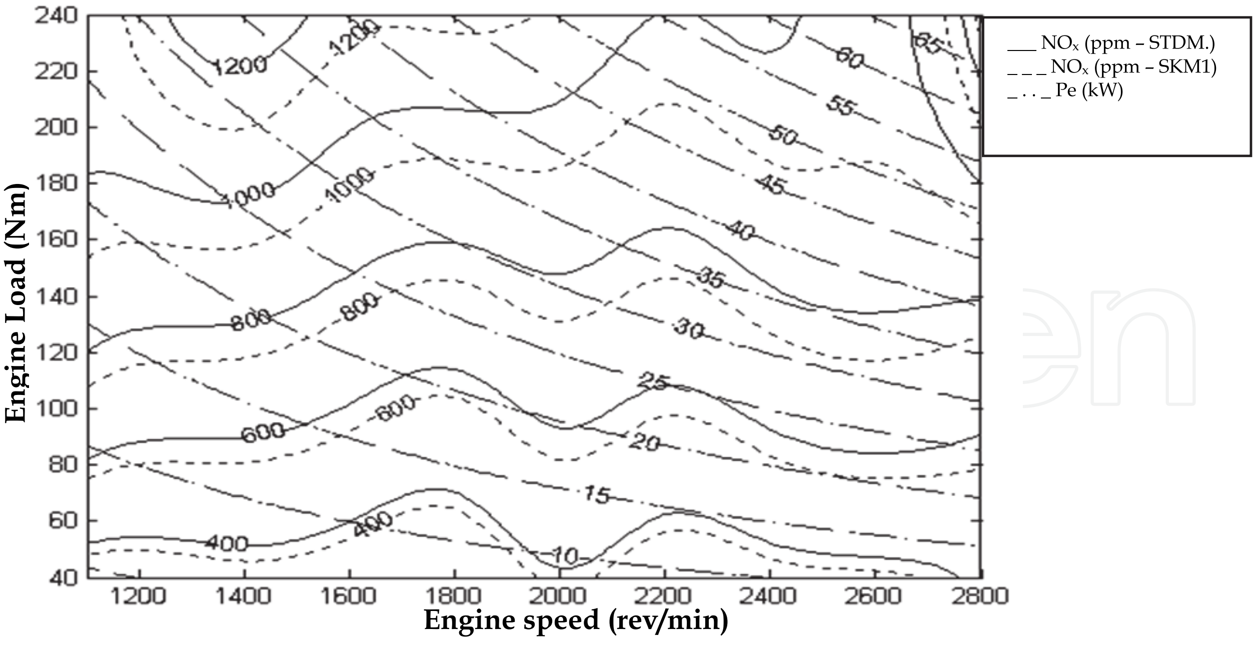


Fig. 35. Three dimensional nitrogen oxides emissions map for SKM1 and standard engine configurations

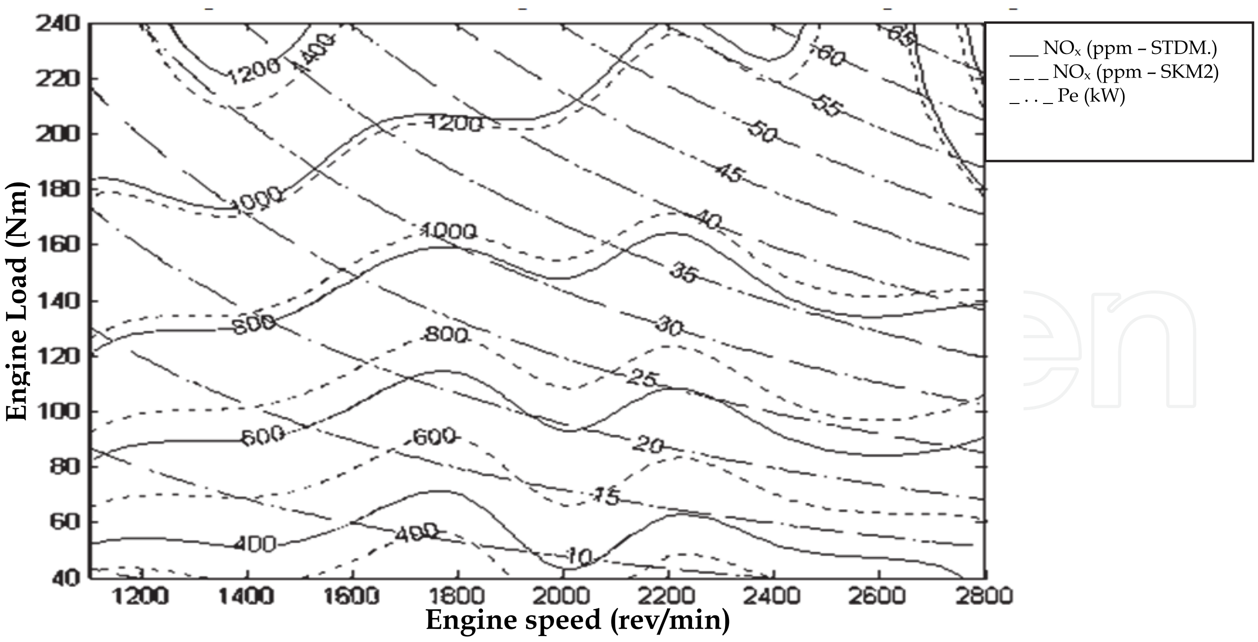


Fig. 36. Three dimensional nitrogen oxides emissions map for SKM2 and standard engine configurations

In standard diesel engines, fuel air mixture ratio is changing with load condition and revolution rate of engine and usually engines are operated at lean fuel air mixture. In this situation, carbon monoxide is converted to carbon dioxide due to sufficient oxygen existence in combustion chamber. However, low combustion temperature, short combustion period and low oxygen content may lead to high carbon monoxide emissions. In ceramic coated engine configurations, carbon monoxide emissions reduced at a rate of 5 to 10% by the increased exhaust temperature. Fig. 37 to 40 show changes in carbon monoxide emissions according to engine speed at full load, 40 Nm load, 120 Nm load and 200 Nm load respectively.

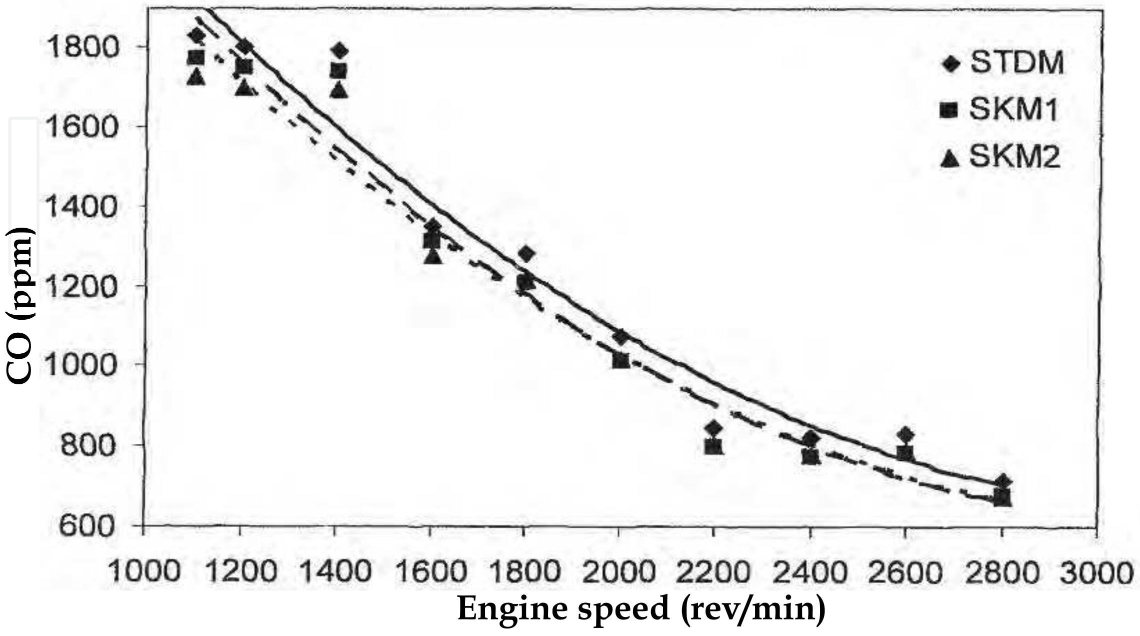


Fig. 37. Carbon monoxide change at full load for all engine configurations

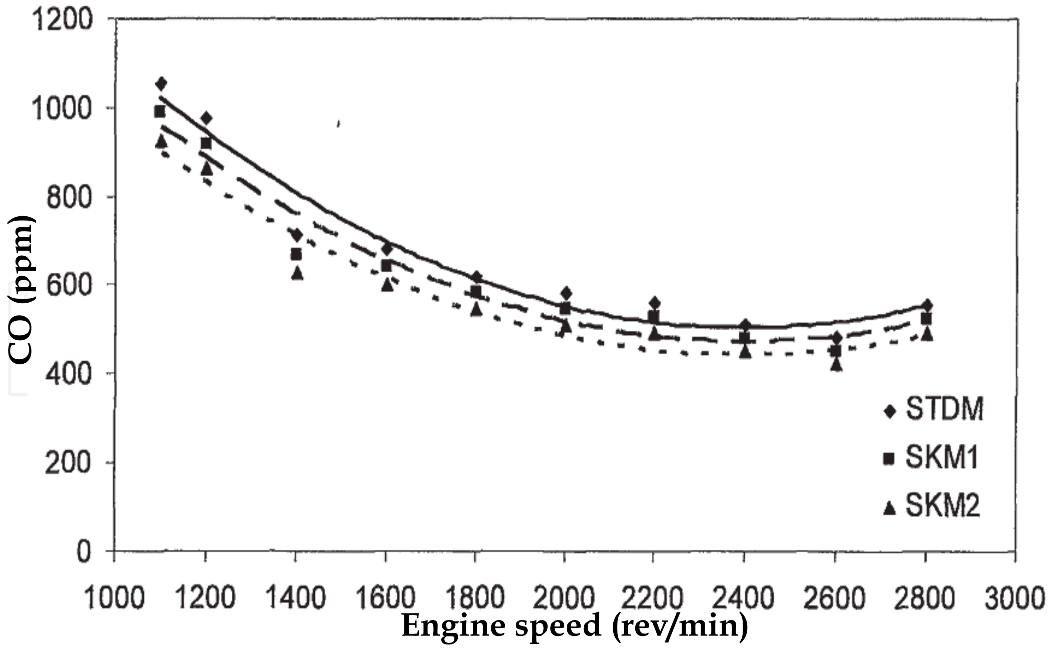


Fig. 38. Carbon monoxide change at 40 Nm load for all engine configurations

Smoke intensity can be evaluated by *k* factor in internal combustion engines. Since diesel engines have a smoke emission problem, the effects of ceramic thermal barrier coating to smoke emissions should be evaluated. Similarly to previous exhaust emission graphics, Fig. 41 to 44 show changes in *k* factor according to engine speed at full load, 40 Nm load, 120 Nm load and 200 Nm load respectively. When figures are investigated, it can be observed that *k* factor decreasing with increasing engine speed. This is due to improved combustion in cylinders owing to increasing temperature. Hence, ceramic coated engine configurations exhibit 18% better smoke emissions.

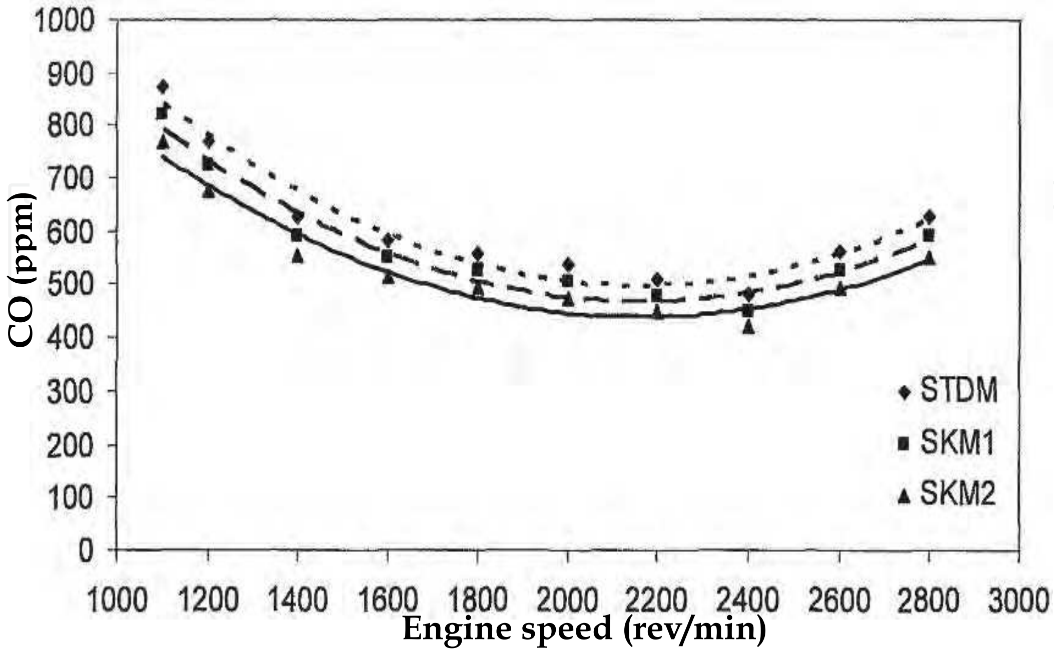


Fig. 39. Carbon monoxide change at 120 Nm load for all engine configurations

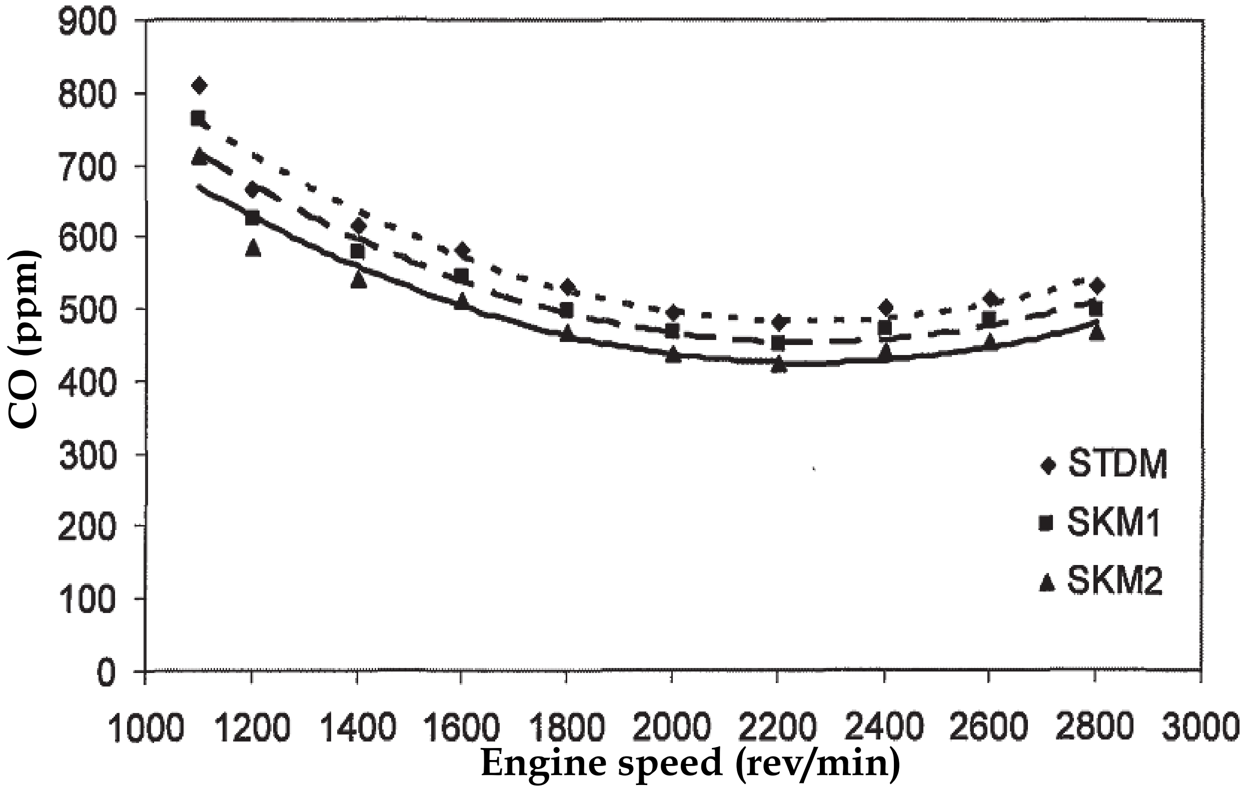


Fig. 40. Carbon monoxide change at 200 Nm load for all engine configurations

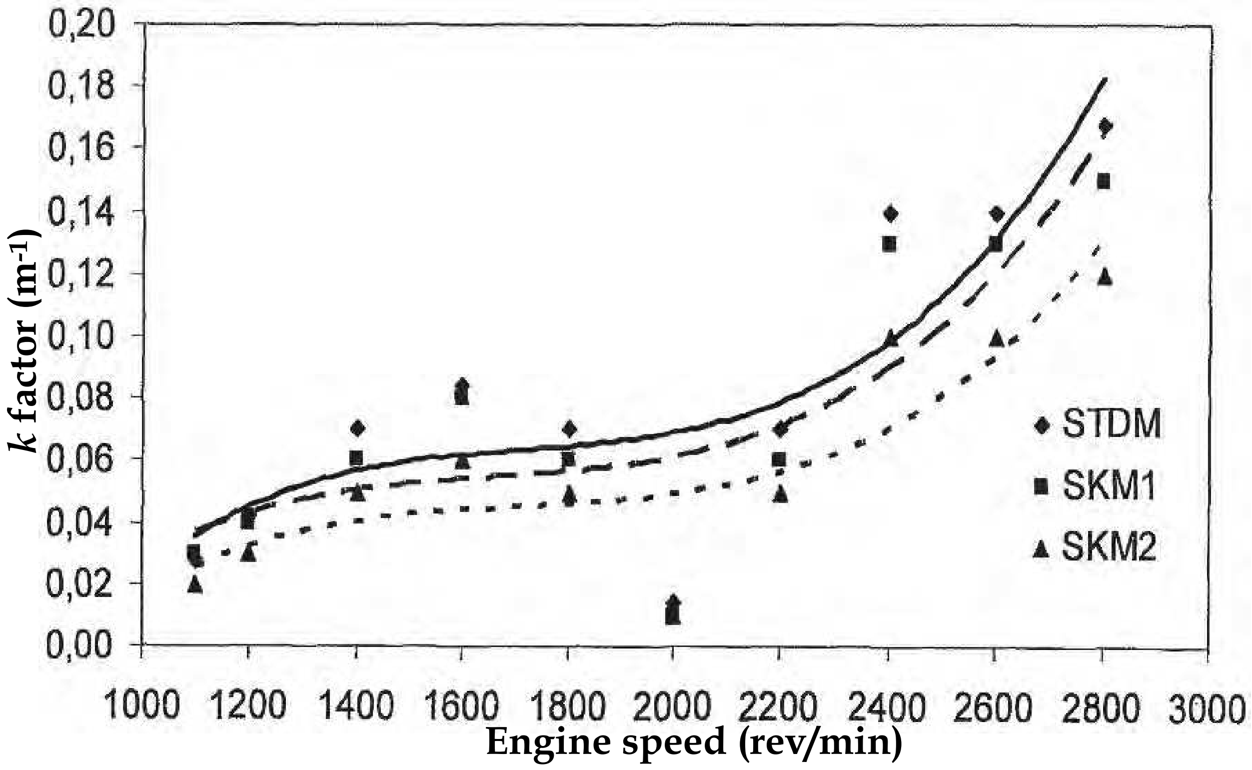


Fig. 41. *k* factor change at full load for all engine configurations

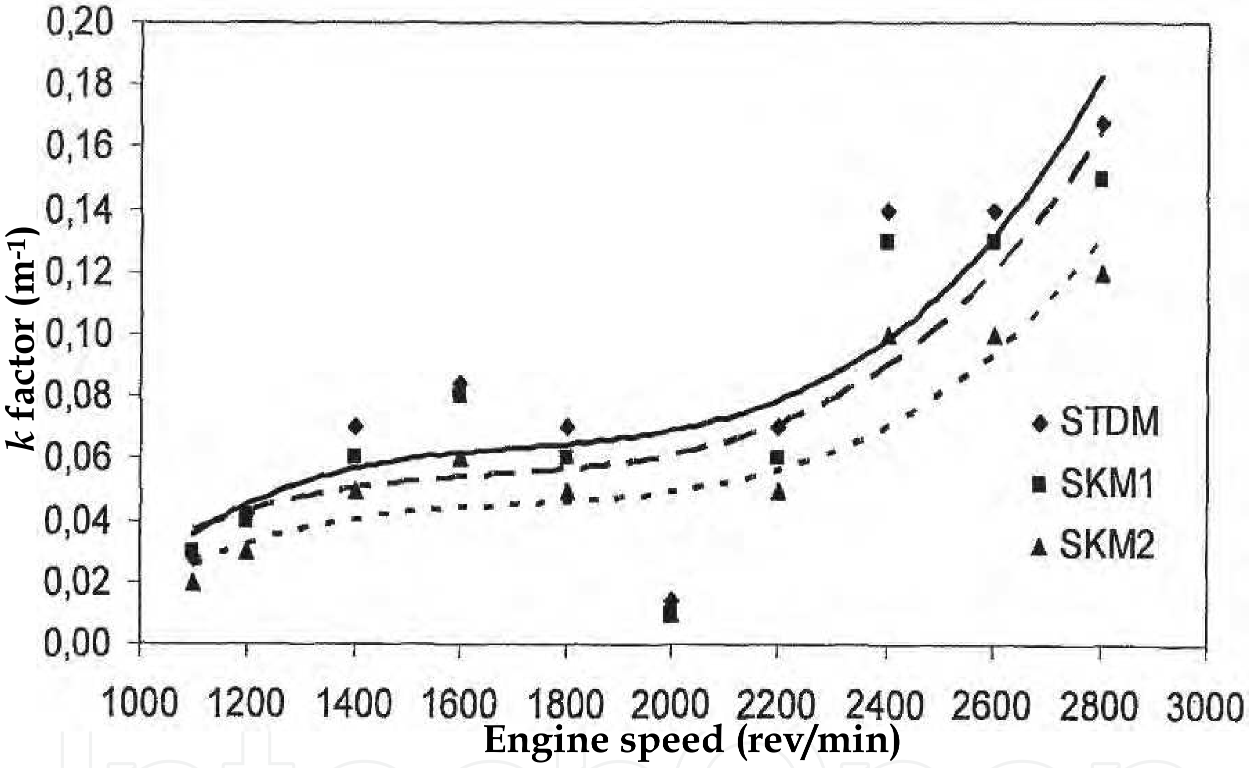


Fig. 42. *k* factor change at 40 Nm load for all engine configurations

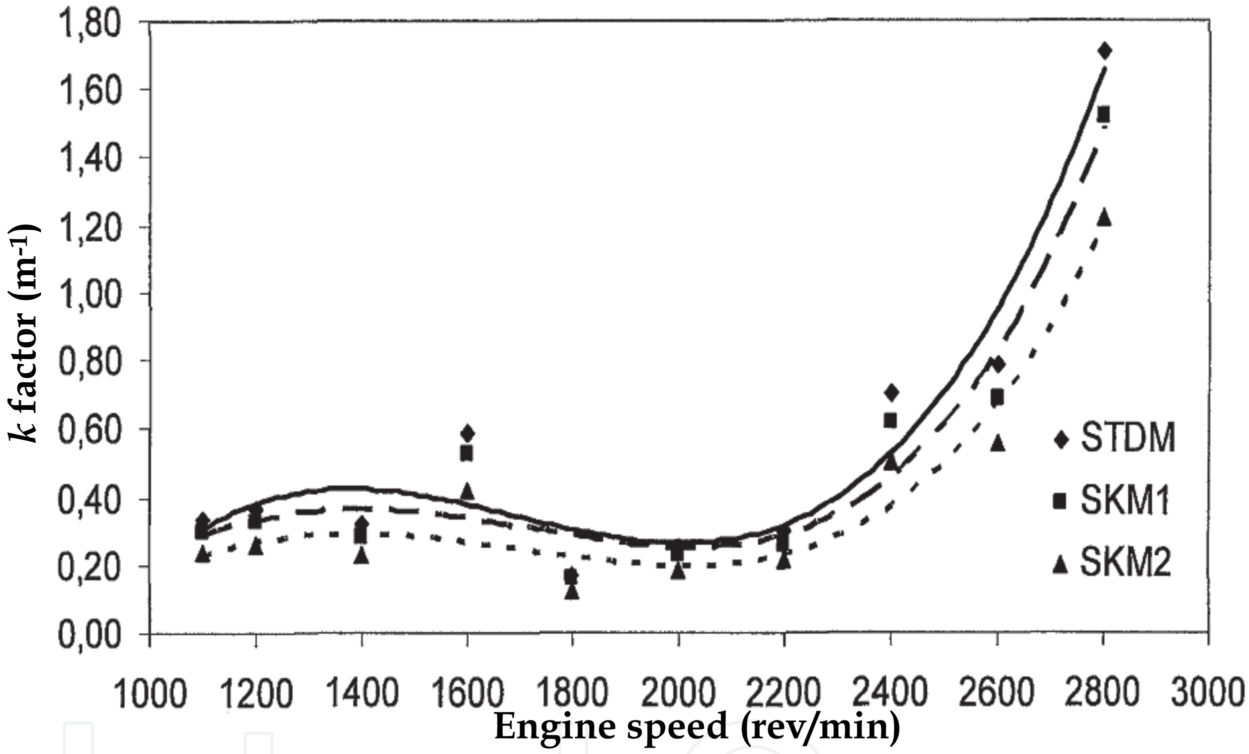


Fig. 43. *k* factor change at 120 Nm load for all engine configurations

4.4 Discussion

In this work, changes in engine performance of a four stroke direct injection four cylinder turbocharged diesel engine were investigated after it was ceramic thermal barrier coated with plasma spray coating method. For study, a specific experimental setup was utilized.

There are some significant problems between coating and coated materials due to thermal expansion ratios in aluminium-silisium alloyed pistons. To avoid these problems, 0.15 mm thick NiCrAlY was coated to base material as binding layer. Zirconia which was stabilized with yttria was used as ceramic coating material for all engine parts.

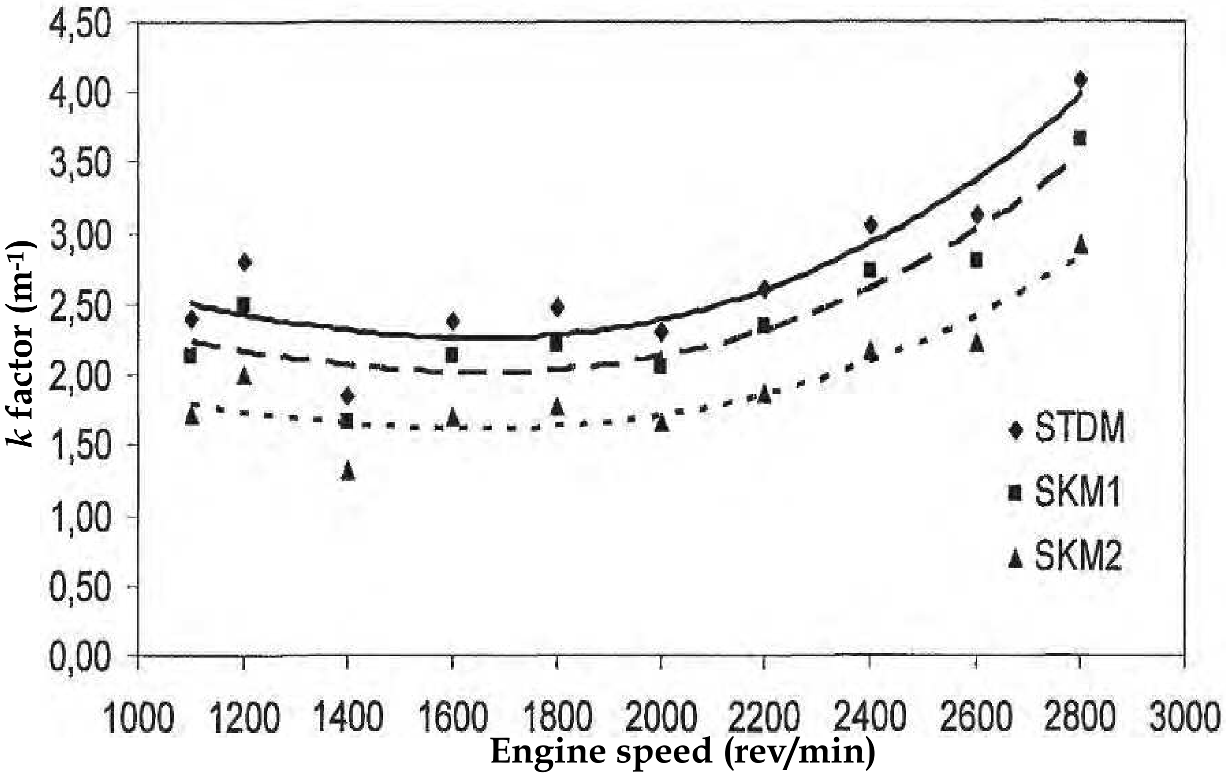


Fig. 44. *k* factor change at 200 Nm load for all engine configurations

A reduction between 4.5 to 9 percent in specific fuel consumption was achieved by ceramic coating in the study. These findings are in accordance with specific literature about ceramic coatings in diesel engines. For instance Coers et. al. (1984) reported 14%, Badgley et. al. (1990) reported 5%, Havstad et. al. (1986) reported 4-9% and Leising et. al. (1978) reported 6% specific fuel consumption reduction in thermal barrier coated engines.

Present experimental study shows that volumetric efficiency was slightly increased at low loads and engine speeds while it was increasing significantly at medium loads and engine speeds. At latter conditions, volumetric efficiency increase reached to 1-2.4%.

Ceramic coating increased exhaust gases temperatures at every operational condition. Exhaust gases temperatures were increased 150 to 200 ^{0}C according to standard engine configuration. This increase corresponds to 7 to 20 percent of standard engine exhaust gases temperatures. When a turbine is combined to the system, aforementioned excess of exhaust energy can be converted to useful mechanical energy.

Heat flux to coolant is also decreased at a rate of 19 percent in present work. This is an important result owing to the possibility of downsizing of cooling system. Reducing sizes of cooling system would be returned as low mechanical energy consume to pumping mechanisms and low weight.

Carbon monoxide emission was decreased 12%, and soot was decreased about 28% in present experimental work. However nitrogen oxides were increased at a rate of 20%. In thermal barrier coating literature for internal combustion engines, reduction of carbon monoxide and soot was emphasized by a lot of researchers. Sudhakar (1984), Toyama et. al. (1989), Assanis et. al. (1991), Amann (1988), Bryzik et. al. (1983) and Matsuoka et. al. (1993) are some of these researchers. Assanis et. al. (1991) reported 30-60% reduction in carbon monoxide emission.

According to present study;

- ZrO_2 stabilized with Y_2O_3 over NiCrAlY binding layer as a coating material gives good results for aluminium alloyed pistons.
- As ceramic coating material, ZrO_2 stabilized with Y_2O_3 is expensive for practical usage. More research should be performed to reduce its cost.
- Cylinder walls also can be coated to reduce heat rejection.
- Injection systems may be tuned for a proper operation in ceramic coated engines. Thus, improvements can be enhanced.
- Alternative fuels can be tested in ceramic coated engines since combustion temperature is increased. Some fuels react positively to this temperature increase as they can be burned more efficiently.

5. References

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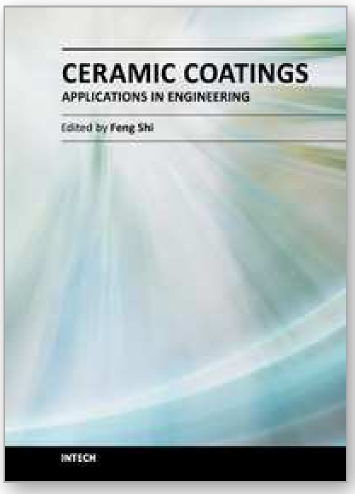

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