ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)

https://doi.org/10.17559/TV-20211220232130
Original scientific paper

Correlation between Emission and Combustion Characteristics with the Compression Ratio and Fuel Injection Timing in Tribologically Optimized Diesel Engine

Saša MILOJEVIĆ*, Slobodan SAVIĆ, Dejan MARIĆ*, Ondrej STOPKA, Božidar KRSTIĆ, Blaža STOJANOVIĆ

Abstract: Diesel engines are economical thanks to their combustion process characteristics, which is why they have a high noise emission level as well as exhaust emissions of nitrogen oxide and particulate matters. By continuously changing the value of compression ratio, it is possible to control the power and emissions. Implementation of variable compression ratio has many benefits, such as being able to work with different types of fuel. In this way, it is possible to optimize the combustion process for operation with minimum fuel consumption and emission generation, so that diesel engines can be applied to the framework of future hybrid vehicle concepts, and so forth. As far as the crucial objective of the manuscript is concerned, experimental diesel engine investigation was performed on a roller test-bench by using zero-dimensional computer model (specifically AVL IndiCom Indicate Software). Engine indication was executed with the factory compression ratio value and with three lower values. During our examination, the change in the compression ratio value was achieved by changing the volume of a combustion chamber at a piston-bowl. The results of laboratory research on the experimental engine are presented in the paper when discussing a series of specific parameters (characteristics), such as compression ratio, fuel injection timing, engine speed, as well as load influence on combustion process and exhaust emissions.

Keywords: combustion characteristics; diesel engine; emission; fuel injection timing; variable compression ratio

1 INTRODUCTION

Parallel to other sources of toxic gas emissions, such as energy sector, increasing the road transport volume has partially negative impacts on the environment, as well as on society and human health [1-4]. In this regard, appropriate types of new vehicles were introduced in the European Union, as well as around the world, and the emission limit values for vehicles were prescribed [5, 6]. As an example, according to environmental strategy in Germany, green city plans of municipalities exist [7, 8].

Diesel vehicles are considered as being most responsible for the increased levels of toxic gas emissions in city centers. As a result, the use of trucks and buses powered by compression ignition engines (hereinafter referred to as diesel engines) in the inner city centers is increasingly restricted. Also, strict regulations were put in place to control emissions from vehicles during operation, as well as rules for measuring emissions [9, 10]. Due to low fuel consumption and thus carbon dioxide (CO_2) emissions, diesel engines have a perspective in vehicles with alternative powertrains, such as hybrid vehicles. Depending on the mode of operation within the hybrid vehicles, very low fuel consumption has been achieved, while the emissions of nitrogen oxides (NO_X) and solid particles or particulate matters (PM) have been regulated by the application of modern technologies [7, 11, 12].

Based on theoretical calculations, the thermal efficiency of reciprocating internal combustion (IC) engines can be increased. The best petrol engines, where the Otto cycle occurs as an idealized thermodynamic cycle, have an efficiency of 40% while the best diesel engines (with the diesel cycle with the highest thermal efficiency under higher compression ratio value) have the thermal efficiency of up to 50%. Efficiency over 50% can only be achieved with two-stroke marine diesel engines −55%. Low-speed diesel engines (as used in ships and other applications where overall engine weight is relatively unimportant) often have the thermal efficiency which exceed 50% [13, 14]. Generally, average efficiency of IC engines under the ideal working regime is about 30% in automotive application and around 45% for watercraft [15, 16].

Therefore, there are many opportunities to improve fuel economy and optimize IC engines [17, 18]. Technologies for optimization on the engine and transmission, introduction of the start-stop system, reduction of resistance to movement of vehicles, and application of variable drive for the peripheral equipment on engine and vehicle, have the most influence on reduction of fuel consumption (Fig. 1) [19, 20].

Optimization of the combustion process was successfully resolved by combining the benefits of Otto and diesel combustion principle during the working regime of IC engines [21]. This requires the mandatory application of variable mechanisms on the IC engines and logical control of work processes [22, 23]. One of examples for logical control of work process is the engine with mixed-mode combustion, starting from low-temperature combustion or homogeneous charge compression ignition (HCCI) process via partly pre-mixed compression ignition (PPCI) also known as partly pre-mixed combustion (PPC) and compression ignition (CI) [24, 25]. Such a combustion process was carried out with the support of new technologies and modern engine equipment, such as VVT-variable valve timing and VVA-variable valve actuation [26, 27], EGR-exhaust gas recirculation [28], turbocharger, multiple (split) and late injections and afterburning [29].

In line with the measures on the engine, exhaust emission from the vehicle was reduced by the application of catalytic treatment of raw combustion products [30]. Selective Catalytic Reduction (SCR) is regarded as one of important technology for reducing NO_X emission by up to 80% in real-world driving conditions, including cold-start, and up to 100% when the engine is warm [31, 32].

Application of modern technologies with the solved combustion process optimization and tribological problems regarding friction and wear resulted in lower fuel consumption and exhaust emission [33, 34]. The subject of research is to deal with the combustion process in a diesel engine with a variable compression ratio (VCR). Variable compression ratio is one of technologies for simultaneous transition between the combustion modes in modern engines as described above [33, 35].

The use of the engine with VCR is one of the methods to control the maximum pressure in a diesel engine cylinder, depending on the load or brake mean effective pressure (BMEP). On the other hand, by applying this technology, the compression ratio (CR) of the gasoline engine at low loads could be increased simultaneously during operation, which contributes to reduction of pump losses and fuel consumption [36, 37]. In this way, by automatically changing the CR, the engine is less sensitive to fuel quality, i.e. it can work with different kinds of fuel. Multi-fuel engines are very useful in military vehicles, primarily due to the limited supply of fuels [38, 39].

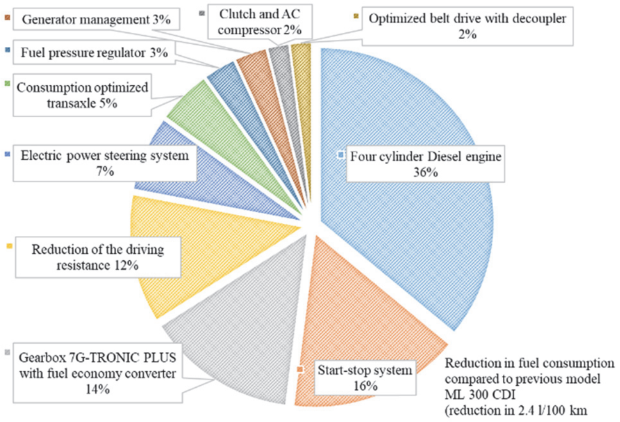

Figure 1 Share of equipment in fuel consumption reduction of optimized vehicle Mercedes-Benz ML 250 BlueTEC

The above facts are considered the starting points for researchers in this field [39]. The ensuing sections of the paper implicate research outcomes of our experimental measurement of diesel engine on a testing bench while utilizing zero-dimensional computer model (AVL IndiCom Indicate Software). First of all, a literature review is elaborated encompassing a wide array of research studies related to the similar subject being addressed in this article. Thereafter, data and methods of investigation applied in our research are briefly summarized. As for the very findings, engine indication was made with a specific value of compression ratio and with several lower values. When investigating, the change in a compression ratio value was obtained by varying the combustion chamber volume at the piston-bowl. The laboratory outcomes regarding the experimental engine characteristics are discussed in the text when presenting several engine attributes (i.e. compression ratio, fuel injection timing, engine speed, load influence on combustion process and exhaust emissions). Following the literature review compiled as well as research outcomes obtained, it can be stated that no analogous research study dealing with our topic has been published yet.

2 PREVIOUS RESEARCH

The subject of testing CR in IC engines has been dealt with in a number of scientific-research publications. For example, the issue of CR investigation in terms of assessing various characteristics of spark ignition engines is discussed in [40, 41]. Hotta et al. (2020) examined ignition timing and CR in terms of improving the operating characteristics of a biogas fueled spark ignition engine, wherein individual findings were obtained through series of experiments while putting an emphasis on effects of the engine performance and combustion characteristics [40]. On the other hand, Oh et al. (2019) dealt with performing spark ignition (SI) engine experiments in order to measure the combustion characteristics of a high CR related to single-cylinder engine with hydrogen-rich gas mixture [41]. Their findings proved that high-temperature combustion is the crucial factor to the reducing efficiency at engine high-load conditions, whereby the gas-exchange process and elongated burn duration were the largest contributors at engine low-load conditions.

The research study [42] is focused on experiments regarding changes in the spark plug vertical location and its impact on performance and emission characteristics of a 100% raw biogas fuelled SI engine when varying CR. In regard to this examination, quicker combustion process leading to early and higher pressure of peak cylinder as well as higher temperature of combusted gas (2 mm) protrusion location of the spark plug for all the CR was proved to be optimal while lower emissions were achieved. The authors Ahmed et al. (2018) intended to search for the optimal CR of single cylinder SI engine so that monitored performance characteristics of such an engine are enhanced including improvement of brake thermal efficiency and reduction in brake specific fuel consumption (BSFC) [43].

Whereas the literature [44] discusses the development of a novel VCR mechanism and its implementation in a small and relatively large-size single-cylinder SI engines, the objective of the publication [45] is to present an examination of impacts of mechanical CR modification in terms of SI engine when utilizing ethanol-water fuel mixture containing specific quantity of water in ethanol.

In line with aforementioned, numerous studies dealing with examination and experimental activities aimed at evaluation of different characteristics of CI engines have been elaborated as well. For instance, the literature [46] addresses multiple performance characteristics of CI engine with raw oil (Jatropha and coconut oil) fuel mixtures at fixed CR, wherein analysis of the performance of pure diesel fuel compared to several fuel mixtures of Jatropha-biodiesel and coconut-biodiesel at a fixed compression ratio is carried out. Or, the paper [47] tests a single cylinder direct injection engine under various CR of (18, 17 and 16:1) while differing in loads. As far as key findings are concerned, the combustion and performance characteristics' distinctions depending on the CR values were proved conclusively. On the other hand, Xu et al. (2019) took into consideration both VCR and VVT scenarios regarding a heavy-duty (HD) diesel engine. The aim of this study was to systematically evaluate such two scenarios on the basis of reactivity-controlled CI engine under a wide-load range with respect to fuel efficiency, as well as combustion process control [48]. Even the publication [49] deals with assessing the influences of CR on performance and combustion characteristics of CI engine. Nevertheless, in this literature, a special emphasis is placed on testing the different mixtures of jojoba methyl ester used in a diesel engine, in which a number of experiments related to impact of CR on using neat jojoba methyl ester are executed.

Another study [50], written by Krishnamoorthi and Malayalamurthi (2017), presents an experimental testing realized on light-duty single-cylinder CI naturally-aspirated multi-fuel engine with VCR, where three input attributes, i.e. CR, injection pressure and injection timing, are taken into account. The very rehearsal confirmed that the specific models designed within this manuscript when using response surface methodology were appropriate in terms of the impact analysis of monitored attributes on certain tested characteristics. Similar topic is discussed in the publication [51], where the authors measure the capabilities of low-temperature combustion concept in the operation of a medium-duty CI engine suggesting scenarios to address its major challenges. In view of these experiments, an enlarging to high load of this concept without exceeding mechanical stress and reducing the amount of (CO_2) as well as unburned hydrocarbons (HC) emissions at low load along with a fuel-consumption penalty were detected to be the crucial reactivity-controlled CI deficiencies.

The specific issue related to the examining the influence of CR in different IC engines on the emission quantities has also been discussed in multiple literature. For example, the publication [52] investigates the amount of emissions in Otto cycle engine working with hydrous and wet ethanol when taking into consideration several distinct CR. In particular, a comparative analysis was conducted among individual outcomes of hydrous ethanol and wet ethanol in an Otto cycle engine, working under a uniform speed in order to search for the maximum brake torque in each examination. Biofuels were investigated under distinct CR to measure the overall engine efficiency and the effect of such a variable on the amount of emissions, namely carbon-monoxide (CO), NO_X and HC. Or, in the scientific study [53] dedicated to the topic of testing a high CR engine, the authors designed a new experimental approach, in which the liquefied natural gas is first purified into liquefied methane gas and then fueled to the engine itself. In the literature, the thermal-balance examinations were executed, and thereafter the combustion, emissions and thermal balances of such a liquefied-methane gas engine were evaluated. Last but not least, Gnanamoorthi and Devaradjane (2015), in their experimental work [54], analyze the effect of CR degrees on combustion, performance as well as emission characteristics of a four-stroke direct injection (DI) naturally-aspirated diesel engine fueled with ethanol e-diesel mixtures. Specifically, examinations were carried out with various mixtures of ethanol (E0, E10, E20, E30 and E40), while varying CR values and piston bowl parameters were taken into consideration.

3 EXPERIMENTAL SETUP AND METHODS

The tests were performed in the laboratory, on a test bench, with an experimental IC engine manufactured by DMB Lombardini, type 3LD450, Fig. 2. The tested engine is air-cooled, four-stroke, single-cylinder with DI of diesel fuel in the cylinder and with the technology of two valves per cylinder and overhead camshaft (OHC valve train). The fuel injection system is classic, pump-pipe-injector type, with four nozzle openings in the injector head and with mechanical load regulator (manufacturer IPM Belgrade). The tests were carried out with an injection pressure value of 20 MPa.

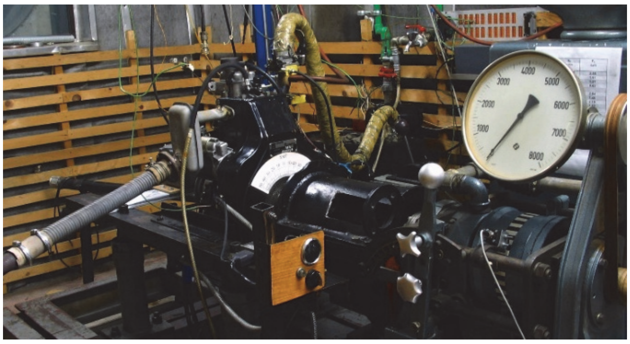

Figure 2 Laboratory with test bench and dynamometer for the examinations of experimental IC engine

The test rig is equipped with the measuring and data acquisition system, (Fig. 3). Various sensors are mounted on the engine to measure different parameters. A thermocouple was installed on the surface of high pressure fuel pipe. A precision crank angle (CA) encoder was coupled with the crankshaft of the engine. The software stores the data of pressures and volumes corresponding to a particular CA location for plotting the indicator diagram curves.

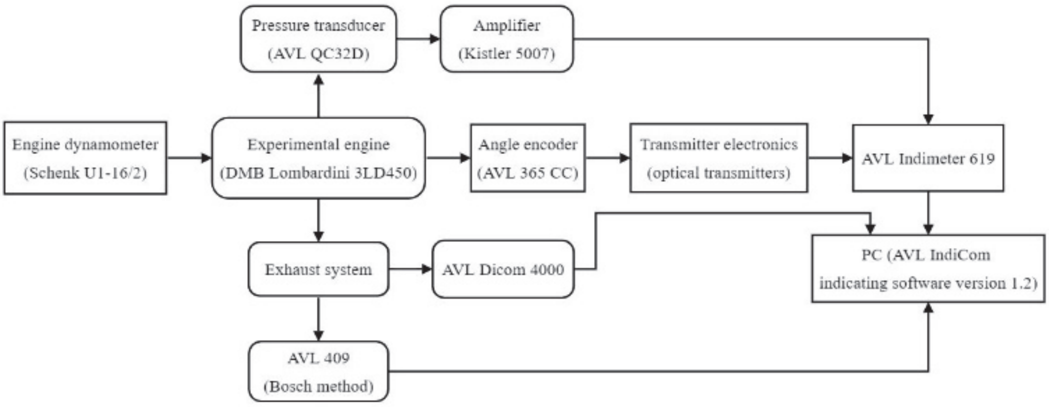

Figure 3 Test rig with the measuring and data acquisition system

The cylinder pressure is measured using the (AVL QC32D) water-cooled piezoelectric transducer. The signal of pressure (during engine indicating) is amplified with the (Kistler type 5007) charge amplifier and it was processed by using the (AVL IndiCom Indicate Software Version 1.2). The software provides the facility of analyzing the combustion data such as the rate of heat release, ignition delay, combustion timing in degrees and peak pressure and stores them separately for analysis in the acquisition system [39]. The geometric value of CR is varied from 17.5 to 12.1:1 by replacing the pistons with different piston bowl volume, conducted by changing the piston bowl diameter from 43 to 55 mm, see Fig. 4.

The base version of the engine is with piston bowl diameter of 43 mm and a volume of 20 ml, which corresponds to CR of 17.5:1 and fixed fuel injection advance angle or start of injection (SOI) timings of 18.5 cad BTDC (crank angle degree before top dead center).

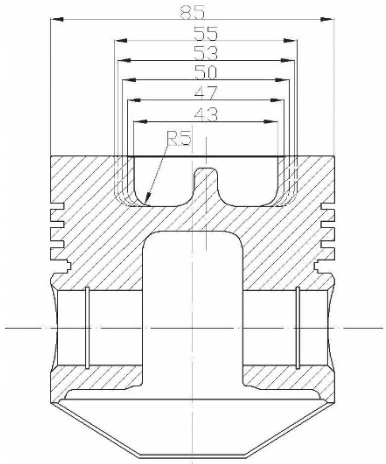

Figure 4 Cross-section drawing of the piston with combustion chamber (piston bowl)

Rated engine power is 6 kW @ 3000rpm according to (DIN 6270) and torque is 28 Nm. Base engine displacement or stroke volume is 454 ccm, which corresponds to the ratio between piston bore and stroke of 80/85 mm/mm, Fig. 5[39].

The experimental engine is examined on the engine dynamometer (maker and type SCHENK U1-16/2) over a steady-state modes, Fig. 2. The investigations are carried out at CR of 12.1, 13.8, 15.2 and 17.5:1. Operating modes for fuel consumption and exhaust gas analysis are defined according to the European Stationary Cycle (ESC) 13 mode cycle, Fig 5. Analysis of the combustion process is processed under maximal load and higher speed.

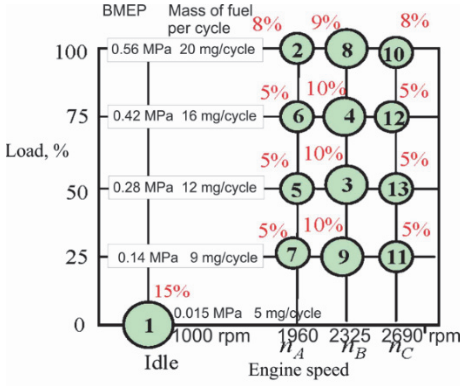

Figure 5 Operating modes in European stationary cycle ESC

Exhaust gasses are analyzed with measurement equipment type (AVL Dicom 4000). Particulate matter emissions are determined indirectly through the empirical correlation between the measured values of smoke and PM. The smoke is measured using the (AVL 409) equipment according to method BOSCH. Specific emission values of exhaust gases are calculated using the obtained data of exhaust emissions and measured engine power at corresponding operating mode, Fig. 5. The final emission results are calculated according to the ESC cycle and expressed in g/kWh.

During experiments the engine was operated with standard diesel fuel with characteristics as specified in Table 1. The engine lubrication oil gradation is SAE 30, manufacturer is Oil Refinery Modriča, trade mark Maxima Super.

Table 1 Fuel characteristics during investigation (manufacturer Oil Refinery Pančevo), trade mark D2

Description	Values
Cetane number / CN	52
Specific density / 20°C, g/cm^3	0.84
Kinematic viscosity / 20°C, mm^2/s	3.96
Sulphur content, %	0.5

4 EXPERIMENTAL FINDINGS

Effect of CR and SOI timings on mean maximum pressure ($P_{\max}$) inside the engine cylinder while operating at constant engine speed of n_e = 2325 rpm as well as full or 100% load (maximum BMEP) are illustrated in Fig. 6.

When CR and SOI timings are increased, under the constant load and speed, $P_{\max}$ is also increased. This undesirable increase in $P_{\max}$ is followed by relatively improved atomizing of larger amount of fuel in cylinder under higher pressure and temperature.

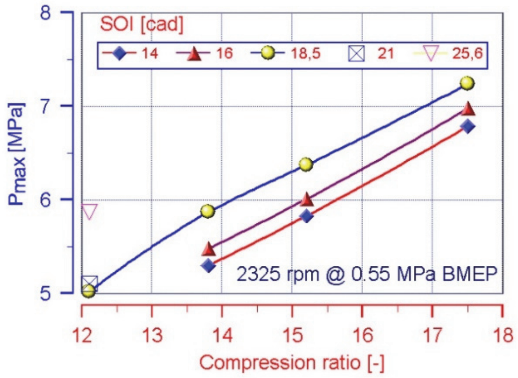

Figure 6 Changes of $P_{\max}$ under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings

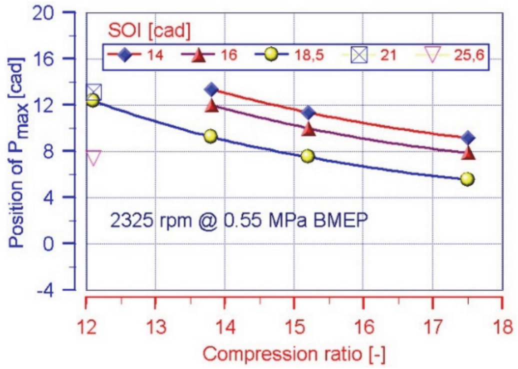

Figure 7 *Positi*ons of $P_{\max}$ under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings

On the contrary, with a decrease in CR, under the same SOI timings, $P_{\max}$ within, the cylinder decreases. As a consequence, the positions of $P_{\max}$ are far from optimum for this regime (near TDC position). That is more evident at simultaneous decrease in SOI timings; see Fig. 7.

When the CR is decreased, under the same SOI timings, the values of maximal pressure rise decrease $(\mathrm{d}P/\mathrm{d}\alpha)_{\max}$, see Fig. 8. Thereby, their positions are moved forward from TDC, that is as well evident with simultaneous decrease in CR and SOI timings; Fig. 9.

During the very examination, the engine operated with a high degree of detonation (knock) at high values of SOI timings (21 and 25.6) and low CR (12.1:1) so that no emission measurement was performed in that mode, see Fig. 8. In this mode, engine starting was only possible with heated intake air. Engine operation was also not possible at other CR values under these higher SOI timings.

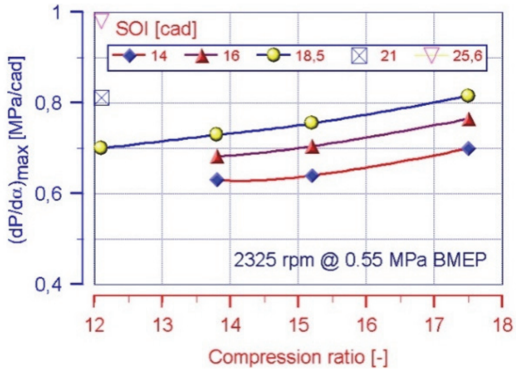

Figure 8 Maximum cylinder pressure rise under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings

In reality the SOI timing is related to the CA position at which combustion starts and where there is (0%) combusted fuel, see Fig. 10. Changes in the ignition delay occur because the compressed air temperature and pressure within the cylinder are different for different SOI timings. Generally, the ignition delay period shortens with increasing air temperature and pressure [38, 50].

Decrease in CR, under the same SOI timings, results in stretched auto-ignition delay period, Fig. 10. The major reason for this is relatively low $P_{\max}$, see Fig. 5 and maximum temperature $T_{\max}$ during this period, Fig. 11.

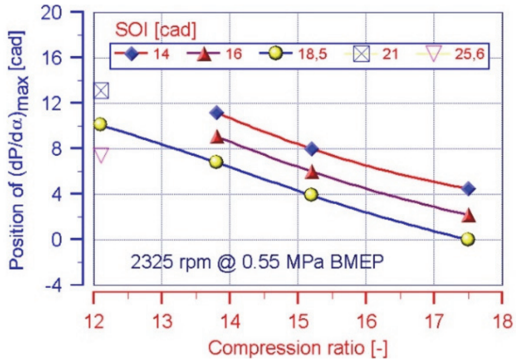

Figure 9 Positions of maximum cylinder pressure rise under (n_e = 2325 rpm, BMEP = 0.55 MPa) depending on CR value and SOI timings

Because of unfavorable conditions, the combustion process is far from TDC i.e., the center of combustion process or CA position where the (50%) of combusted fuel in cylinder was far from optimal position for this regime; see Fig. 10. End of the combustion process is related to the CA position when there is (90%) of combusted fuel. When CR decreases, the increase of the ignition delay causes that more amount of the heat of combustion is releasing after TDC position.

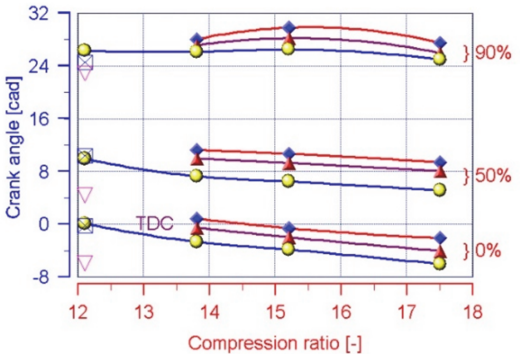

Figure 10 Combustion process characteristics under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings

Therefore, $T_{\max}$ decreased when CR decreases, but during the expansion, temperature in the cylinder, and in exhaust system increased, which is confirmed during researches in [39].

Consequently, it was verified that earlier SOI timing is an effective means of increasing combustion efficiency. Similar results may be found in literature [39, 49]. If injection starts early (well before TDC), the ignition delay period will be longer. This will result in high rates of $P_{\max}$ rise and high $P_{\max}$ in cylinder, see Fig. 6 and Fig. 8. If injection starts late (close to TDC), burning will continue well into the expansion, resulting in hot exhaust gases, worse fuel economy, Fig. 12, and higher emissions of particles and smoke, Fig. 14 and Fig. 15. Therefore, optimal injection timing can be found in between these two extremes.

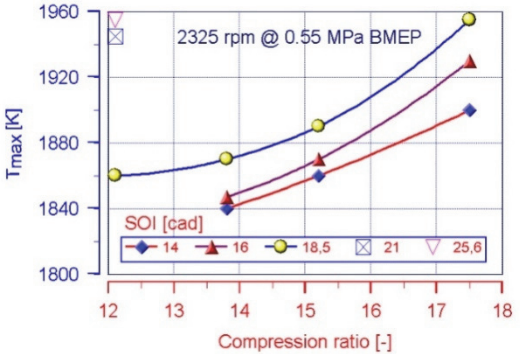

Figure 11 Changes of $T_{\max}$ under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings

Intensive decrease of the $T_{\max}$ in the cylinder, see Fig. 11, with a decrease in the CR is also the consequence of the increase in the diameter and volume of the combustion chamber or piston bowl, Fig. 4. This is due to the lower speed of the airflow into the bowl, as well as the slower extrusion of combustion products from the chamber, which extinguishes the flame and lowers the $T_{\max}$. In these conditions, the heat exchange with the cylinder walls is slower as well. Similar conclusions may be found in literature [47, 58].

With decreasing CR and SOI timings, BSFC drops in the beginning, but at a later stage, tendency to increase is recorded, see Fig. 12. The combustion process is responsible for attenuated fuel economy Fig. 10. When the CR value is about 16:1, a minimum BSFC is achieved, see Fig. 12. A further increase in the value of the CR, behind 16:1 results in an increase in BSFC, which is mainly contributed by the higher engine speed and $P_{\max}$, when both mechanical and aerodynamic losses in the engine are higher, as concluded in the literature [55].

According to the above, as a consequence of the lower temperature in the cylinder at lower values of the CR, the process of auto-ignition of fuel in the cylinder takes longer, due to which a larger amount of fuel burns in the initial (premixed) phase of combustion. Similar conclusions can be found in the literature [56]. As a consequence of that, the losses become greater and that can be followed by dropping the fuel economy, see Fig. 12. This is obvious in the case of a combined application of low CR and retarded SOI timings, when the auto-ignition delay period becomes longer, and given that, the combustion process was prolonged on expansion stroke (the afterburning).

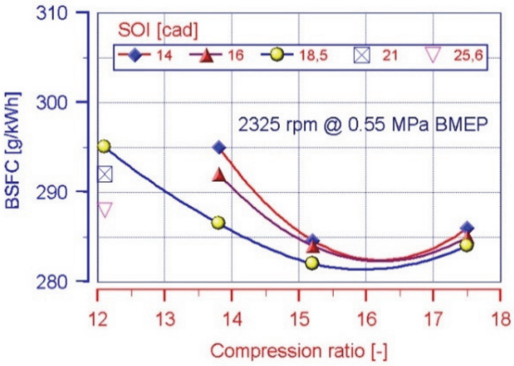

Figure 12 Changes of BSFC under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings

Under full load conditions, mainly due to the high $T_{\max}$ reached during fuel combustion, produced high NO_X emission with CR increase, Fig. 13.

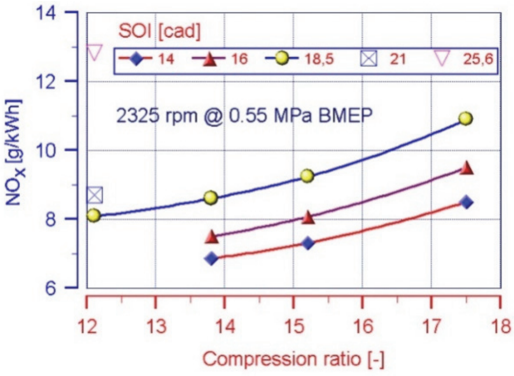

Figure 13 Changes of NO_X emission under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings

The tendency to increase in NO_X emissions is followed with the value of air-fuel ratio coefficient (the presence of excess air), and increase in the SOI timings, see Fig. 17. This is due to better combustion conditions in the cylinder (oxygen-rich state) and high-temperature in the cylinder. Similar results can be found in the literature [57]. The changes of air-fuel ratio λ depending of CR and fuel injection advance angle changes are shown in Fig. 17.

On the other side, the PM emissions decreased with increasing SOI timings and with decreasing CR, (please see Fig. 14). The excess of fresh intake air in the combustion chamber (lean fuel mixture) is one of the reasons for this. It is believed that increased mixing associated with the lower CR suppresses PM formation, eliminating the need for high in-cylinder temperatures for the fuel oxidation process. Temperature and pressure have a strong influence on PM formation, higher pressures and temperatures yielding higher PM formation. Similar conclusions were reached by researchers in the literature [58]. Smoke emissions follow the flow of PM emissions expressed in filter smoke number (FSN). FSN increases with CR and lowering SOI timings, Fig. 15.

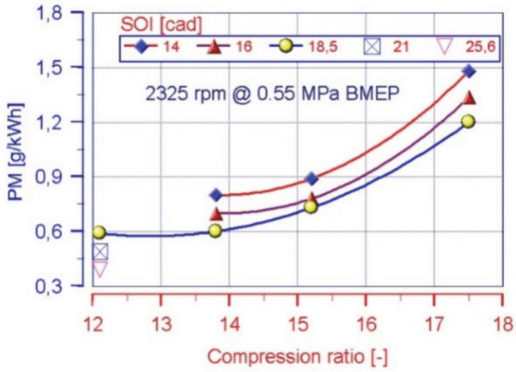

Figure 14 Changes of PM emissions under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings

Increase in PM emissions at lower SOI timings and with an increase in the CR is accompanied by a decrease in HC emissions, see Fig. 16. This can be explained by the fact that soot particles (which mainly consist of carbon spherules) bind to themselves heavier HC molecules in the combustion chamber (adsorb them during adsorption and condensation process) [51, 56].

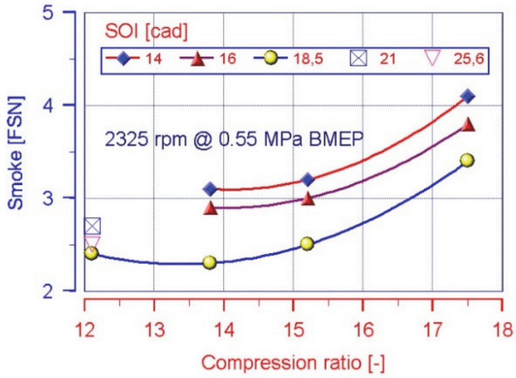

Figure 15 Changes of smoke emissions under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings

Lower HC emissions with increasing CR are partly due to the optimal positioning of the injector (nozzle) to the shape of combustion chamber (eccentric position regarding to piston bowl and cylinder axle). The test modes (under full load and high speed) has, among other things, a positive effect on reducing HC emissions. This is mainly due to better preparation of the mixture of fuel and air (as example, the process of air vortex is better).

In this way the formation of an incomplete mixture is avoided, as well as the fuel condensation on the walls of the combustion chamber, which would otherwise lead to the increase in non-burned hydrocarbons (HC) emissions, see Fig. 16. In general, late SOI timings resulted in this case in lower HC emissions, which is also one way to reduce NO_X emissions, Fig. 14.

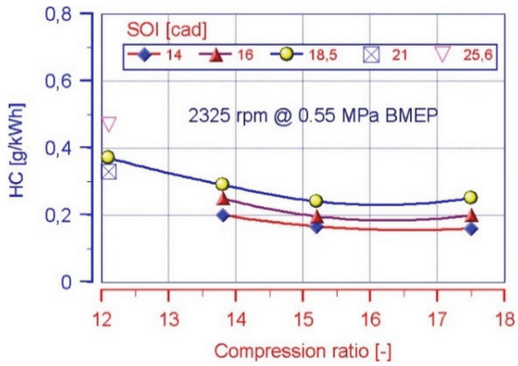

Figure 16 Changes of HC emissions under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings

Other researches showed similar results and conclusions about the trend of HC emission, depending on the changes of CR value [56].

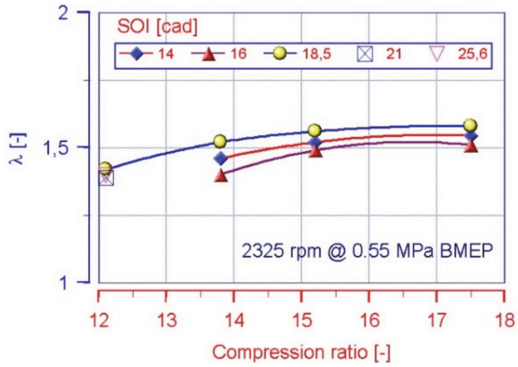

Figure 17 Changes of air-fuel ratio *λ* (lambda) under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings

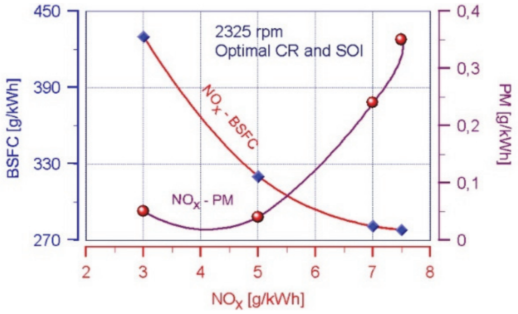

Figure 18 Trade-offs between BSFC, NO_X and PM emissions under n_e = 2325 rpm, BMEP = 0.55 MPa for optimal CR value and SOI timing

In general, simultaneous changes in SOI timings and CR value are necessary for achieving reductions in exhaust emissions. Trade-offs between fuel consumption and PM emission vs. NO_X emissions under optimal values of CR and SOI timing are presented in Fig. 18.

Generally during the research it was confirmed that the used retarded SOI timing is an effective way for NO_X reduction in relation to the smoke limit and minimal fuel consumption.

Injection timing has a strong effect on NO_X emission, as well as maximal cylinder temperature. Retarding the SOI timings can result in a substantial reduction in NO_X emission with only a moderate BSFC penalty.

In Fig. 19, compression ratio response under n_e = 2500 rpm, 25% load is depicted.

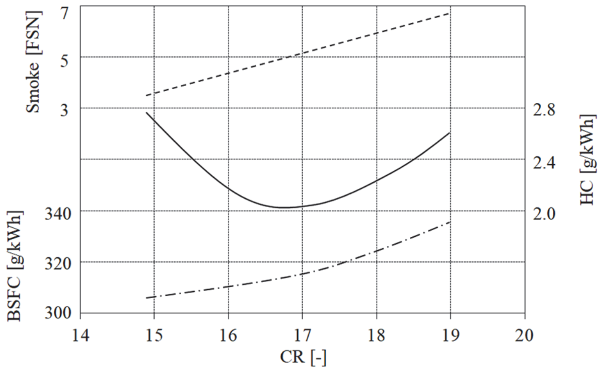

Figure 19 CR response under n_e = 2500 rpm, 25% load

If CR decreases, smoke emissions and PM emissions also decrease. Soot-contaminated oils have significant impact on engine wear [58]. This conclusion was reached also during analogous research studies of other authors [59]. The same authors obtained dependence between BSFC and NO_X emissions which corresponds to the results presented above (Fig. 19).

5 DISCUSSION

Our research findings comprise experimental investigation of compression ignition (diesel) engine conducted on a roller dynamometer (test-bench) when applying zero-dimensional computer model; i.e. AVL IndiCom Indicate Software. First, a literature review was elaborated embracing the whole spectrum of literature sources dealing with the topic similar to our in this manuscript. Subsequently, relevant data and particular methods of investigation implemented in our research were briefly summarized. Concerning the results themselves, a specific value of compression ratio was used, followed by several lower values. During conducting the research, a change in the compression ratio value was achieved while the combustion chamber volume at the piston-bowl was varying. The very findings in terms of different engine characteristics (such as compression ratio, fuel injection timing, engine speed, load influence on combustion process and exhaust emissions) are summarized in the most imperative part of the article. Namely, the following aspects were examined and then illustrated:

- changes of $P_{\max}$ under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings,
- positions of $P_{\max}$ under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings,
- changes of maximum cylinder pressure rise under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings,
- positions of maximum cylinder pressure rise under (n_e = 2325 rpm, BMEP = 0.55 MPa) depending on CR value and SOI timings,

- combustion process characteristics under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings,
- changes of $T_{\max}$ under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings,
- changes of BSFC under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings,
- changes of NO_X emission under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings,
- changes of PM emissions under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings,
- changes of smoke emissions under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings,
- changes of HC emissions under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings,
- changes of air-fuel ratio λ under n_e = 2325 rpm, BMEP = 0.55 MPa depending on CR value and SOI timings,
- trade-offs between BSFC, NO_X and PM emissions under n_e = 2325 rpm, BMEP = 0.55 MPa for optimal CR value and SOI timing,
- CR response under n_e = 2500 rpm, 25% load (comparative results of other authors).

In accordance with the data from the literature (see section 2) and with the obtained research results, it can be concluded that such trade-offs can be satisfied by applying modern systems and equipment on engines. Annulment of deterioration in fuel consumption due to the later fuel injection or SOI timings can be achieved by reducing the period of ignition delay of diesel fuel by simultaneous increase of CR value during engine operation.

Accordingly VCR method with other additional measures on the IC engine such as reductions in friction losses, increases in fuel injection pressure and split injections, turbocharging *etc.* can be taken to control trade-offs between BSFC and PM emission vs. NO_X emissions or increases of BSFC and PM emissions under lower NO_X emission.

6 CONCLUSION

Diesel engines are economically efficient especially due to their combustion process characteristics, which is one of the reasons why they have a high noise emission level and exhaust emissions of NO_x and PM. When changing the compression ratio value continuously, we can monitor and manage the power and emission values. Involving variable compression ratio in terms of compression ignition engines has many pros including an option of working with various fuel types. In this light, we may streamline the entire combustion process of engine operation with minimum fuel consumption and emission production in order to install diesel engine in further concepts of hybrid vehicles and so on.

The development of vehicle powertrains is increasingly challenged by emission legislation and by the end-users' fuel-economy demands. Direct injection diesel engines are excellent in fuel economy and are advantageous in reducing CO_2 emissions, but still have the problems in reduction of NO_X and PM emissions.

The control of maximum in-cylinder pressure, as well as optimal management of exhaust emissions and fuel consumption can be achieved by the simultaneous compression ratio change during combustion process in modern diesel engines. If the CR value is about 16:1, a minimum BSFC is achieved. A further increase in the value of the CR, behind 16:1 results in an increase in BSFC, mainly because of higher engine speed and maximum pressure, when both mechanical and aerodynamic losses in the engine are higher. Under full load conditions, due to higher maximal temperature in-cylinder produced high NO_X emission with CR increase, PM, similarly to smoke emissions decreasing during SOI timings increase and with decreasing CR value. An increase in PM emissions at lower SOI timings and with an increase in the CR is accompanied by a decrease in HC emissions.

As aforementioned, by automatically changing the compression ratio, the diesel engine emission can be adjusted to optimal values depending on the load and fuel quality. The application of other variable mechanisms on the engine, such as a variable fuel injection time, depending on the operating mode of the engine, also contributes to this. Based on the elaborated literature review and achieved research findings, we can conclude that no analogous research study dealing with the identical issue discussed in this manuscript has been published yet.

Acknowledgements

The paper is a result of the research within the project TR 35041 financed by the Ministry of Science and Technological Development of the Republic of Serbia.

7 REFERENCES

[1] Xue, Y., Guan, H., Corey, J., Zhang, B., Yan, H., Han, Y., & Qin, H. (2017). Transport Emissions and Energy Consumption Impacts of Private Capital Investment in Public Transport. *Sustainability*, 9, 1760. https://doi.org/10.3390/su9101760

[2] Patil, L. N. & Khairnar, H. P. (2021). Investigation of Perceived Risk Encountered by Electric Vehicle Drivers in Distinct Contexts.*Appl. Eng. Lett.*, *6*(2), 69-79. https://doi.org/10.18485/aeletters.2021.6.2.4

[3] Liu, J.-Y., Liu, S.-F., & Gong, D.-Q. (2021). Electric Vehicle Charging Station Layout Based on Particle Swarm Simulation. International Journal of Simulation Modelling, 20(4), 754-765. https://doi.org/10.2507/IJSIMM20-4-CO17

[4] Huang, A.Q., Zhang, Y.Q., He, Z.F., Hua, G.W., & Shi, X.L. (2021). Recharging and transportation scheduling for electric vehicle battery under the swapping mode, Advances in Production Engineering & Management,16(3), 359-371. https://doi.org/10.14743/apem2021.3.406

[5] Jette, K., Christian, T., Dimitrios, T., Zissis, S., Christian, R., Andy, W., Peter, P., Thierry, C., Stephan, N., & Wim, V. (2020). EU road vehicle energy consumption and CO2 emissions by 2050-Expert-based scenarios.*Energy Policy*, *138*. https://doi.org/10.1016/j.enpol.2019.111224

[6] Giechaskiel, B., Gioria, R., Carriero, M., Lähde, T., Forloni, F., Perujo, A., Martini, G., Bissi, L. M., & Terenghi, R. (2019). Emission Factors of a Euro VI Heavy-duty Diesel Refuse Collection Vehicle. *Sustainability*, *11*, 1067. https://doi.org/10.3390/su11041067

[7] Skrúcaný, T., Kendra, M., Stopka, O., Milojević, S., Figlus, T., & Csiszár, C. (2019). Impact of the Electric Mobility Implementation on the Greenhouse Gases Production in Central European Countries. *Sustainability*, *11*, 4948. https://doi.org/10.3390/su11184948

[8] Johnsen, D., Vorholt, F., Gieschen, J. H., Müller, B., & Randhahn, A. (2019). Electric Mobility and Smart Mobility Concepts-Restrained Uptake in German Cities. *World Electric Vehicle Journal*, *10*, 81. https://doi.org/10.3390/wevj10040081

[9] Jelica, P., Amara, L. H., & Tiffany, L. B. Y. (2015). Effects of Aftermarket Control Technologies on Gas and Particle Phase Oxidative Potential from Diesel Engine Emissions. *Environmental Science & Technology*, *49*(17), 10544-10552. https://doi.org/10.1021/acs.est.5b01487

[10] Shammut, M., Cao, M., Zhangc, Y., Papaix, C., Liu, Y., & Gao, X. (2019). Banning Diesel Vehicles in London: Is 2040 Too Late? *Energies*, *12*(18), 3495. https://doi.org/10.3390/en12183495

[11] Kiseleva, E., Kaminskiy, N., & Presnykov, V. (2020). Study of Fuel Efficiency of Hybrid Vehicles. *IOP Conference Series: Earth and Environmental Science*. 459. 022086. 086. https://doi.org/10.1088/1755-1315/459/2/022086

[12] Joschka, S., Korbinian, V., Matthias, K., Thomas, K., Katharina, K., Giovanni, V., & Benjamin, K. (2018). Diesel hybrid powertrains-enabling lowest emissions, minimum CO2 and fun-to-drive. *Internationaler Motorenkongress*, 197-219. https://doi.org/10.1007/978-3-658-21015-1_13

[13] Caton, J. A. (2018). Maximum efficiencies for internal combustion engines: Thermodynamic limitations. *International Journal of Engine Research*, *19*(10), 1005-1023. https://doi.org/10.1177/1468087417737700

[14] Liu, H., Ma, J., Tong, L., Ma, G., Zheng, Z., & Yao, M. (2018). Investigation on the Potential of High Efficiency for Internal Combustion Engines. *Energies*, *11*, 513. https://doi.org/10.3390/en11030513

[15] Dumböck, O., Schutting, E., Eichlseder, H., & Walter, H. (2018). Increasing the Efficiency of the Internal Combustion Engine through Extended Expansion. *MTZ Worldw*, *79*, 7479. https://doi.org/10.1007/s38313-018-0108-3

[16] Frigge, P., Affolter, S., Bachmann, D., & de Jong, R. (2011). New Two-Stroke Marine Diesel Engines from Wärtsilä. *MTZ Worldw*, *72*, 10-17. https://doi.org/10.1365/s38313-011-0105-2

[17] Knauder, C., Allmaier, H., Sander, D. E., & Sams, T. (2019). Investigations of the Friction Losses of Different Engine Concepts. Part 1: A Combined Approach for Applying Subassembly-Resolved Friction Loss Analysis on a Modern Passenger-Car Diesel Engine. *Lubricants*, *7*(5), 39. https://doi.org/10.3390/lubricants7050039

[18] Meiser, J., Deuß, T., Ehnis, H., & Künzel, r.(2017). Friction Power Measurements of a Fired Gasoline Engine Influence of Piston Pin Bore. *MTZ Worldw*, *78*, 58-62. https://doi.org/10.1007/s38313-016-0152-9

[19] Skrucany, T., Stopkova, M., Stopka, O., & Milojević, S. (2020). Design of a Daily-User Methodology to Detect Fuel Consumption in Cars with Spark Ignition Engine. *Appl. Eng. Lett.*, *5*(3), 80-86. https://doi.org/10.18485/aeletters.2020.5.3.2

[20] Gruden, D. (2008).Umweltschutz in der Automobilindustrie. Vieweg+Teubner-GWV Fachverlage GmbH, Wiesbaden.

[21] Singh, A. & Agarwal, A. (2014). Combustion characteristics of diesel HCCI engine: An experimental investigation using external mixture formation technique. *Applied Energy*., *99*. 116-125. https://doi.org/10.1016/j.apenergy.2012.03.060

[22] Neubauer, M., Kapus, P., & Fraidl, G. (2019). Efficiency and Emission Measures for Future High-performance Engines. *MTZ MotortechnischeZeitschrift*, *80*, 54-58. https://doi.org/10.1007/s38313-018-0120-7

[23] Mofijur, M., Hasan, M., Mahlia, T., Rahman, S. A., Silitonga, A., & Ong, H. C. (2019). Performance and Emission Parameters of Homogeneous Charge Compression Ignition (HCCI) Engine: A Review. *Energies*, *12*(18), 3557. https://doi.org/10.3390/en12183557

[24] Kalghatgi, G., Zhang, F., & Xu, H., Rezaei, S. Z., & Shuai, S. (2012). Combustion and Emission Characteristics of a PPCI Engine Fuelled with Dieseline. *SAE Paper* 2. https://doi.org/10.4271/2012-01-1138

[25] Sang, W., Cheng, W., & Maria, A. (2014). The Nature of Heat Release in Gasoline PPCI Engines. *SAE Technical Paper*. https://doi.org/10.4271/2014-01-1295

[26] De Ojeda, W. (2010). Effect of Variable Valve Timing on Diesel Combustion Characteristics. *SAE Technical Paper*. https://doi.org/10.4271/2010-01-1124

[27] Lou, Z. & Zhu, G. (2020). Review of Advancement in Variable Valve Actuation of Internal Combustion Engines. *Applied Sciences*, *10*(4), 1216. https://doi.org/10.3390/app10041216

[28] Jungsoo, P. & Kyo, S. L. (2013). Optimization of Diesel Engine with Dual-Loop EGR by Using DOE Method, Diesel Engine - Combustion, Emissions and Condition Monitoring, Saiful Bari. *IntechOpen*, https://doi.org/10.5772/55861

[29] Shi, H., Tang, Q., An, Y., Raman, V., Sim, J., Chang, J., & Johansson, B. (2020). Study of spray/wall interaction in transition zones from HCCI via PPC to CI combustion modes. *Fuel*, *268*, 117341. https://doi.org/10.1016/j.fuel.2020.117341

[30] Carlo, B., Natale, R., Di Blasio, G., Athanasios, G. K., Eleni, P., & Abdurrahman, I. (2016).Impact of Emerging Engine and After-Treatment Technologies for Improved Fuel Efficiency and Emission Reduction for the Future Rail Diesel Engines. Emiss. *Control Sci. Technol.*, *2*, 99-112. https://doi.org/10.1007/s40825-016-0035-1

[31] Latha, H. S., Prakash, K. V., Veerangouda, M., Devanand, M., & Ramappa, K. T. (2019). A Review on SCR System for NOx Reduction in Diesel Engine. *Int. J. Curr.Microbiol.App.Sci.*, *8*(4), 1553-1559. https://doi.org/10.20546/ijcmas.2019.804.180

[32] Kim, H. S., Kasipandi, S., Kim, J., Kang, S. H., Kim, J. H., Ryu, J. H., & Bae, J. W. (2020). Current Catalyst Technology of Selective Catalytic Reduction (SCR) for NOx Removal in South Korea. *Catalysts*, *10*(1), 52. https://doi.org/10.3390/catal10010052

[33] Pesic, R. & Milojevic, S. (2013). Efficiency and ecological characteristics of a VCR diesel engine. *Int.JAutomot. Technol.*, *14*, 675-681. https://doi.org/10.1007/s12239-013-0073-4

[34] Milojević, S. & Stojanović, B. (2018). Determination of tribological properties of aluminum cylinder by application of Taguchi method and ANN-based model. *J Braz. Soc. Mech. Sci. Eng.*, 40, 571. https://doi.org/10.1007/s40430-018-1495-8

[35] Gérard, D., Besson, M., Hardy, J., Croguennec, S., Marc, T., Shunichi A., & Masayuki, T. (2008). HCCI Combustion on a Diesel VCR Engine. *SAE Technical Paper*. https://doi.org/10.4271/2008-01-1187

[36] Naveen, K., Ankit, S., & Harveer, S. P. (2018). *Alternative Fuels for Diesel Engines: New Frontiers, Diesel and Gasoline Engines*. Diesel Engines.

[37] Boretti, A. (2012). Novel Engine Concepts for Multi Fuel Military Vehicles. *SAE Technical Paper*. https://doi.org/10.4271/2012-01-1514

[38] Milojevic, S., Skrucany, T., Miloševic, H., Stanojevic, D., Pantic, M., & Stojanovic, B. (2018). Alternative drive systems and environmentally friendly public passengers transport. *Appl. Eng. Lett. 3*, 105-113. https://doi.org/10.18485/aeletters.2018.3.3.4

[39] Milojevic, S. (2005).*Analyzing the Impact of Variable Compression Ratio on Combustion Process in Diesel Engines*. PhD Thesis, University of Kragujevac Faculty of Mechanical Engineering.

[40] Hotta, S. K., Sahoo, N., Mohanty, K., & Kulkarni, V. (2020). Ignition timing and compression ratio as effective means for the improvement in the operating characteristics of a biogas fueled spark ignition engine. *Renewable Energy*, *150*, 854-867. https://doi.org/10.1016/j.renene.2019.12.145

[41] Oh, S., Kim, C., Lee, Y., Yoon, S., Lee, J., & Kim, J. (2019). Experimental investigation of the hydrogen-rich off gas spark ignition engine under the various compression ratios. *Energy Conversion and Management*, *201*, 112136. https://doi.org/10.1016/j.enconman.2019.112136

[42] Chaudhari, A. J., Hotta, S. K., Sahoo, N., & Kulkarni, V. (2019). Effect of vertical location of the spark plug on the performance of a raw biogas-fueled variable compression ratio spark ignition engine. *Energy and Environment*, 3*0*(7), 1313-1338. https://doi.org/10.1177/0958305X19841270

[43] Ahmed, A. N., Obeid, Z. H., & Jasim, A. H. (2018). Experimental investigation for optimum compression ratio of single cylinder spark ignition engine. *IOP Conference Series: Materials Science and Engineering*, *454*(1), 012003. https://doi.org/10.1088/1757-899X/454/1/012003

[44] Chaudhari, A. J., Kulkarni, V., & Sahoo, N. (2018). State-of-the-art technology in variable compression ratio mechanism for spark ignition engine. *Sadhana-Academy Proceedings in Engineering Sciences*, *43*(12), 211. https://doi.org/10.1007/s12046-018-0987-7

[45] Sari, R. L., Golke, D., Enzweiler, H. J., Santos, K. F., Salau, N. P. G., Martins, M. E. S., &Pereira, F. M. (2017). Investigation of compression ratio effect on wet ethanol use in spark ignition engines. *SAE Technical Papers*, In: 26th SAE BRASIL International Congress and Display, BRASILCONG 2017, Sao Paulo, Brazil. https://doi.org/10.4271/2017-36-0208

[46] Rathore, Y., Ramchandani, D., & Pandey, R. K. (2019). Experimental investigation of performance characteristics of compression-ignition engine with biodiesel blends of Jatropha oil & coconut oil at fixed compression ratio. *Heliyon*, *5*(11). https://doi.org/10.1016/j.heliyon.2019.e02717

[47] Hariram, V. & Vagesh, S. R. (2015). Influence of compression ratio on combustion and performance characteristics of direct injection compression ignition engine. *Alexandria Engineering Journal*, *54*(4), 807-814. https://doi.org/10.1016/j.aej.2015.06.007

[48] Xu, G., Jia, M., Li, Y., Chang, Y., Liu, H., & Wang, T. (2019). Evaluation of variable compression ratio (VCR) and variable valve timing (VVT) strategies in a heavy-duty diesel engine with reactivity controlled compression ignition (RCCI) combustion under a wide load range. *Fuel*, *253*, 114-128. https://doi.org/10.1016/j.fuel.2019.05.020

[49] Hawi, M., Elwardany, A., Ookawara, S., & Ahmed, M. (2019). Effect of compression ratio on performance, combustion and emissions characteristics of compression ignition engine fueled with jojoba methyl ester. *Renewable Energy*, *141*, 632-645. https://doi.org/10.1016/j.renene.2019.04.041

[50] Krishnamoorthi, M. & Malayalamurthi, R. (2017) Combined effect of compression ratio, injection pressure, and injection timing on performance and emission of a di compression ignition engine fueled with diesel-aeglemarmelos oil-diethyl ether blends using response surface methodology. *Energy and Fuels*, *31*(10), 11362-11376. https://doi.org/10.1021/acs.energyfuels.7b01515

[51] Benajes, J., Pastor, J. V., García, A., & Boronat, V. (2016). A RCCI operational limits assessment in a medium duty compression ignition engine using an adapted compression ratio. *Energy Conversion and Management*, *126*, 497-508. https://doi.org/10.1016/j.enconman.2016.08.023

[52] Fagundez, J. L. S., Sari, R. L., Martins, M. E. S., & Salau, N. P. G. (2018). Experimental evaluation of the emissions in an Otto cycle engine operating with hydrous and wet ethanol under different compression ratios. *SAE Technical Papers*, 27th SAE BRASIL International Mobility Technology Congress and Exhibition, BRASILCONG 2018, Sao Paulo, Brazil. https://doi.org/10.4271/2018-36-0277

[53] Zhou, F., Fu, J., Li, D., Liu, J., Lee, C. F., & Yin, Y. (2019). Experimental study on combustion, emissions and thermal balance of high compression ratio engine fueled with liquefied methane gas. *Applied Thermal Engineering*, *161*. https://doi.org/10.1016/j.applthermaleng.2019.114125

[54] Gnanamoorthi, V. & Devaradjane, G. (2015). Effect of compression ratio on the performance, combustion and emission of di diesel engine fueled with ethanol e diesel blend. *Journal of the Energy Institute*, *88*(1), 19-26. https://doi.org/10.1016/j.joei.2014.06.001

[55] Devendra, S., Fengshou, G., John, D. F., Nishan, S., & Singal, S. K. (2014). Prediction and Analysis of Engine Friction Power of a Diesel Engine Influenced by Engine Speed, Load, and Lubricant Viscosity.*Advances in Tribology*, *2014*. https://doi.org/10.1155/2014/928015

[56] Laguitton, O., Crua, C., Cowell, T., Heikal, M. R., & Gold, M. R. (2007). The effect of compression ratio on exhaust emissions from a PCCI diesel engine. *Energy Conversion and Management*, *48*(11), 2918-2924. https://doi.org/10.1016/j.enconman.2007.07.016

[57] Sivaramakrishnan, K. & Ravikumar, P. (2014). Optimization of operational parameters on performance and emissions of a diesel engine using biodiesel. *Int. J. Environ. Sci. Technol. 11*, 949-958. https://doi.org/10.1007/s13762-013-0273-5

[58] Ašonja, A., Mikić, D., Stojanović, B., Gligorić, R., Savin, L., & Tomić, M. (2013).Examination of Motor-Oils in Exploitation at AgriculturalTractors in Process of Basic Treatment of Plot. *Journal of the Balkan Tribological Association*, *19*(2), 314-322.

[59] Sobotowski, R., Porter, B., & Pilley, A. (1991). The Development of a Novel Variable Compression Ratio, Direct Injection Diesel Engine. *SAE Transactions*, *100*, 776-792.

Contact information:

Saša MILOJEVIĆ, expert advisor
(Corresponding author)
University of Kragujevac,
Faculty of Engineering,
Department for Motor Vehicles and Engines,
Kragujevac 34000, Sestre Janjić 6, Serbia
E-mail: sasa.milojevic@kg.ac.rs

Slobodan SAVIĆ, prof.
University of Kragujevac,
Faculty of Engineering,
Department for Applied Mechanics and Automatic Control,
Kragujevac 34000, Sestre Janjić 6, Serbia
E-mail: ssavic@kg.ac.rs

Dejan MARIĆ, PhD
(Corresponding author)
University of Slavonski Brod,
Mechanical Engineering Faculty in Slavonski Brod,
Trg Ivane Brlić Mažuranić 2, HR-35000 Slavonski Brod, Croatia
E-mail: dmaric@unisb.hr

Ondrej STOPKA, prof.
Institute of Technology and Business in České Budějovice,
Faculty of Technology,
Department of Transport and Logistics, Czech Republic
E-mail: stopka@mail.vstecb.cz

Božidar KRSTIĆ, prof.
University of Kragujevac,
Faculty of Engineering,
Department for Motor Vehicles and Engines,
Kragujevac 34000, Sestre Janjić 6, Serbia
E-mail: bkrstic@kg.ac.rs

Blaža STOJANOVIĆ, prof.
University of Kragujevac,
Faculty of Engineering,
Department for Mechanical Constructions and Mechanization,
Kragujevac 34000, Sestre Janjić 6, Serbia
E-mail: blaza@kg.ac.rs