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EFFICIENCY AND ECOLOGICAL CHARACTERISTICS OF A VCR DIESEL ENGINE

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ABSTRACT−Compression ratio (CR) is a design parameter with highest influence on efficiency, emission and engine characteristics. In conventional internal combustion (IC) engines, the compression ratio is fixed and their performance is, therefore, a compromise between conflicting requirements. One fundamental problem is that drive units in the vehicles must successfully operate at variable speed and loads and in different ambient conditions. If a diesel engine has a fixed CR, a minimal value must be chosen that can achieve a reliable self-ignition when starting the engine in cold start conditions. In diesel engines, variable compression ratio (VCR) provides control of peak cylinder pressure, improves cold start ability and low load operation, enabling the multi-fuel capability, increase of fuel economy and reduction of emissions. By application of VCR and other mechanisms, the optimal regime fields are extended to the prime requirements: consumption, power, emission, noise, etc., and/or the possibility of the engine to operate with different fuels is extended. An experimental Diesel engine has been developed at the Faculty of Engineering, University of Kragujevac . The changes of CR are realized by changing the piston chamber diameter. Detailed engine tests were performed at the Laboratory for IC engines. Special attention has been given to decrease of fuel consumption and exhaust emissions. An optimal field of CR variation has been determined depending on the given objectives: minimal fuel consumption, minimal nitric oxides, and particulate matter emissions, etc.

KEY WORDS : Diesel engine, Efficiency, Exhaust emission, Variable compression ratio

1. INTRODUCTION

Public discussions often give the impression that the Carbon Dioxide (CO_2) emission problem in the European Union can be solved by just reducing the CO_2 emissions from road traffic. In the EU and in Germany, road traffic contributes about 20% to the overall CO_2 emissions. Although other human activities generate far more CO_2 than road traffic, the automotive industry has been working intensively for years on reducing CO_2 emissions by improving the fuel economy of their vehicles (Gruden, 2005).

It is well known that Diesel engines are one of the best candidates to face the future CO_2 limitations thanks to their high thermal efficiency. In modern diesel engines, the relation between nitric oxides (NOx) and particulate matter (PM) emissions has to be deeply improved, maintaining low CO_2 emission (Pesic, 1994; Milojevic, 2005).

The automobile owes its worldwide spreading mainly to the lucky symbiosis between the existence of crude oil - which still can be considered as the least expensive and the most uncomplicated energy resource in the world - and the invention of the reciprocating piston engine with its Otto and Diesel variants (Gruden, 2005).

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Almost from the beginning, engineers had been looking for alternative concepts to replace the Otto and Diesel power units and more than once, the era of the combustion engine had been said to come to an early end. Nevertheless, both drive concepts have prevailed and are sure to do so also in the near future (Gruden, 2005).

Cars will be powered by Otto and Diesel engines far into this century (Lang *et al*., 2004). Development of Otto and Diesel engines leads to symbiosis of their operating processes into a multi-process Otto-Diesel engine that integrates only their good features. The application of engines with automatic variable compression ratio (VCR) makes this possible (Pesic *et al*., 2003).

Use of retarding the intake valve closing is the other way to reduce pollutant emissions in a diesel engine. Experimental results showed that the retarded intake valve closing could enhance the premixed combustion phase, and thus simultaneously reduce soot and NOx emissions (Benajes *et al*., 2008).

Premixed charge compression ignition (PCCI) is expected to make automobile engines more efficient and cleaner, which will help mitigate environmental problems. As a wishful combination of the conventional spark ignition (Otto) and compression ignition (Diesel) engines, PCCI engines are believed to have higher efficiencies than Otto engines due to their high CR and absence of throttle valves. In comparison with Diesel engines, their NOx emissions are lower because only lean premixed combustion occurs (Jung *et al*., 2012).

The brake thermal efficiency of the engine working cycle is improved when CR rises, and firmly depends on the mechanical efficiency, which decreases when CR rises. However, in view of that fact, it is clear that the brake thermal efficiency depends on both the rate of increase of indicated thermal efficiency and the rate of the decrease of mechanical efficiency. The brake thermal efficiency, when CR rises, first rises at the beginning, then reaches the maximal value for optimal CR value and then subsequently declines (Pesic *et al*., 2010).

The CR value when the brake thermal efficiency reaches the maximal value is the optimal value of CR for that load regime in engine operation.

The key problem is that diesel engines do not run at the same loads. The engine in a truck, for instance, sometimes runs on full power on a highway or up the hill, and sometimes on idle speed at low loads. Diesel engines in general also have to be able to start at any temperature range, for example, below zero.

For conventional diesel engine with a constant CR, the CR has to be set so high that a reliable self-ignition can always be achieved even when starting the engine or when running on very low load with little amount of fuel injected into the cylinder.

There is a limit to very high pressures in the cylinder when diesel engine works on full load. Therefore, a high CR also limits the amount of diesel fuel that can be injected at full load.

With a VCR diesel engine, we could increase the CR at start-up and low power and use it to get stable ignition and lower the CR when full power is wanted in order to be able to burn more fuel and get more power, but still having a reliable ignition. Therefore, the concept of VCR engine is a powerful means for increasing low load engine thermal efficiency and for making it possible to maximize engine power with high pressure-charge (Pesic *et al.*, 2010).

The main objective for these investigations was to understand the impact of CR on the efficiency and emission characteristics of the diesel engine at various loads and engine speeds. The other goals of the paper are to summarize our own research and to obtain the results, which may be used in the development of the new Diesel-Otto engine.

2. EXPERIMENTAL ENGINE AND METHODS

The experiments were carried out at the Laboratory for IC engines at the Faculty of Engineering, University of Kragujevac, on a single-cylinder, four-stroke, and air-cooled diesel engine (model No.: 3LD450, Maker: DMB – Lombardini). Main characteristics of the experimental engine are shown in Table 1 (Pesic, 1994; Milojevic, 2005).

It is well known that by increasing the injection pressure in the appropriate range, smoke and economy can be improved effectively. However, NOx will increase. Under the heavy load conditions, if the injection pressure is too high, the improvement of smoke and economy is not remarkable, while NOx will be obviously increased. Under the low load conditions, too high injection pressure will make a brake specific fuel consumption (BSFC) worse (Tan *et al*., 2012).

The experimental engine has an old fuel injection system with low injection pressure. Since we were not able to get a modern fuel injection system, we decided to do the testing with the existing fuel injection systems. Therefore, all the results have been obtained with a low injection pressure.

The geometric value of CR (ε) is varied from 17.5 to 12.1 by replacing the piston in order to adapt piston chamber volume from 20 mL to 33.4 mL. The changes of CR are realized by changing the piston chamber diameter from 43 mm to 55 mm (Figure 1).

The change of the compression ratio is itself inextricably linked with the changing of the shape of the combustion chamber. It is well known that the piston bowl geometry design affects the air–fuel mixing and the subsequent combustion and pollutant formation processes in a direct

Table 1. Main characteristics of the experimental engine.

Description	Specifications
Type and fuel supply system	Single-cylinder Direct injection Unit pump-Pipe- Injector (Injector with four nozzles)
Injection pressure (MPa)	20
Diameter × Stroke (mm)	80 × 85
Stroke volume (cm^3)	454
Valve train system	DOHC, 2 valves

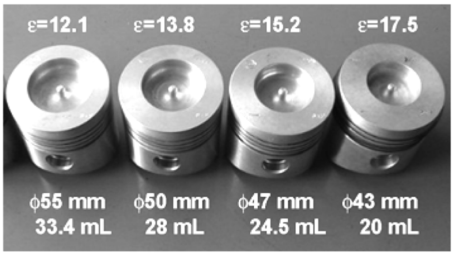

Figure 1. Pistons before experiments.

Table 2. Fuel characteristics.

Description	Specifications
Cetane number (CN)	52
Specific density at 20°C (g/cm^3)	0.839
Kinematic viscosity at 20°C (mm^2/s)	3.964
Sulphur content (%)	0.5

Table 3. Working regimes for combustion analysis.

Engine speed [rpm]	BMEP [MPa]	Mass of fuel per cycle [mg/cycle]
1600	0.12	7
	0.24	10
	0.36	13.5
	0.48	18

injection (DI) diesel engine. In this paper, all investigations results were solely related to the compression ratio.

During the experiments, the engine was operated with diesel fuel which characteristics are shown in Table 2.

The engine is tested on the engine dynamometer (model No.: U1-16/2, Maker: SCHENK). Tests are carried out at compression ratios of 12.1, 13.8, 15.2, and 17.5. Working regimes for the combustion process analysis are defined according Table 3. Working regimes for fuel consumption and exhaust gas analysis are defined according to the ESC (European Stationary Cycle) 13-mode cycle for diesel engines of commercial vehicles (Figure 2). Specific emission of exhaust gases is calculated using the obtained data of exhaust emission and measured engine power at corresponding working point. The final emission results are calculated according to the ESC cycle and expressed in $g{\cdot}kW^{-1}{\cdot}h^{-1}$.

Exhaust emissions are analyzed with suitable measurement equipment (model No.: Dicom 4000, Maker: AVL). PM emissions are determined indirectly through the empirical correlation between the measured values of smoke and PM (Milojevic, 2005). The smoke is measured using a suitable equipment (model No.: 409, Maker: AVL) according to the BOSCH method.

The cylinder pressure is measured using a water-cooled piezoelectric transducer (model No.: QC32D, Maker: AVL). The signal of pressure is amplified with a charge amplifier (model No.: 5007, Maker: Kistler) and processed by an indicating software (model No.: IndiCom, Version 1.2, Maker: AVL) (Figure 3).

The heat release rate and other relevant parameters of the working cycle, which could not be determined by the

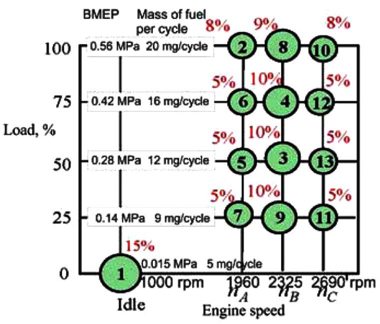

Figure 2. European stationary cycle ESC.

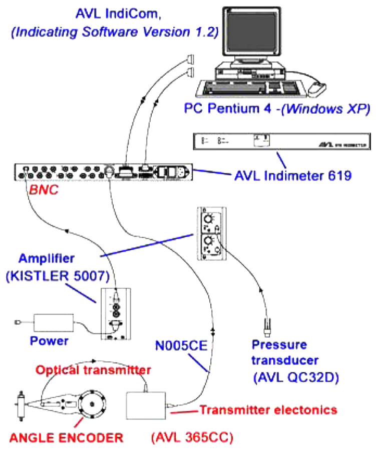

Figure 3. Measuring equipment – instrumentation.

indicating software, are calculated using the software package that is developed at the Laboratory for IC engines of the Faculty of Engineering, University of Kragujevac (Pesic, 1994).

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 4 shows cylinder pressure curves during of the combustion process, for the two different loads and four different compression ratios.

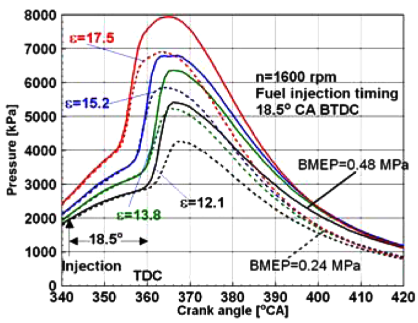

Figure 4. Cylinder pressure vs. crank angle during the combustion process.

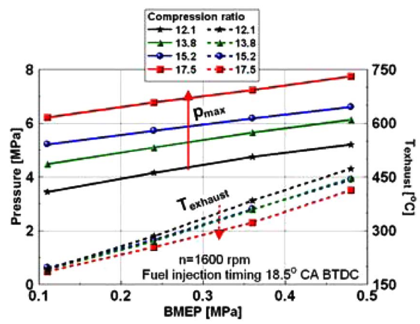

Figure 5. Influence of the CR and engine load on p_{max} and $T_{exhaust}$.

The maximal pressure in cylinder (p_{max}) and the exhaust gas temperature ($T_{exhaust}$) as the functions of engine load (brake mean effective pressure - BMEP) are shown in Figure 5 for different CR values.

When CR and engine load are increased, under the same fuel injection advance time (18.5º BTDC-before top dead centre), the maximum pressure is also increased (Figure 5). This undesirable increase in p_{max} is followed by a relatively improved atomizing of larger amount of fuel in cylinder under higher pressure and engine temperature. Because of improved conditions for combustion process, the entire working process is improved. Moreover, when the CR is increased, the $T_{exhaust}$ value is decreased (Figure 5). Similar results may be found in (Jindal *et al*., 2010).

Figure 6 shows the cylinder temperature curves during the combustion process and Figure 7 shows the influence of the CR on ignition delay. The lower cylinder pressures and temperatures at the time of fuel injection, contributed to delay in auto ignition and to increase in amounts of fuel burned during premixed combustion. Laguitton (Laguitton *et al*., 2007) and Vignesh (Vignesh *et al*., 2012) reached the same conclusions.

When the CR decreases, the increase of the ignition delay causes that more amount of the heat of combustion is releasing after TDC. Therefore, maximal cylinder temperatures decreased, but temperatures in the cylinder during the expansion, and the exhaust gas temperatures increased (Figure 5). The increase of the amount of fuel burned during premixed combustion leads to increase of the maximum value of the Normalized Heat Release Rate (NHRR) (Figure 8) and consequently, the maximal cylinder temperatures are increased. The ignition delay has more influence on the maximal cylinder temperatures than the maximum value of the NHRR at the moderate decrease of CR (from 17.5 to 15.2) at higher loads (BMEP=0.48 MPa). Therefore the decrease of maximal cylinder temperature is occurred. During a further decrease of the CR (from 15.2 to 12.1), the influence of the maximum value of the NHRR becomes more dominant than the ignition delay, and the maximal cylinder temperatures start to increase (Figure 6).

At low loads (BMEP=0.24 MPa), when the compression

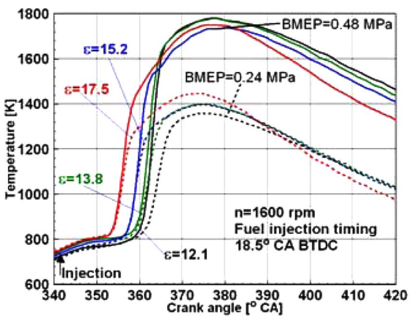

Figure 6. Cylinder temperature vs. crank angle during the combustion process.

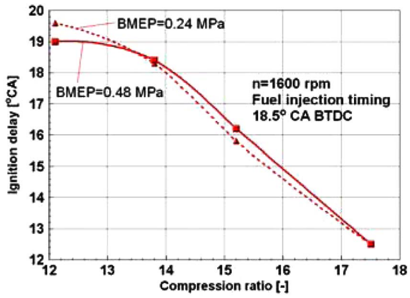

Figure 7. Ignition delay vs. compression ratio.

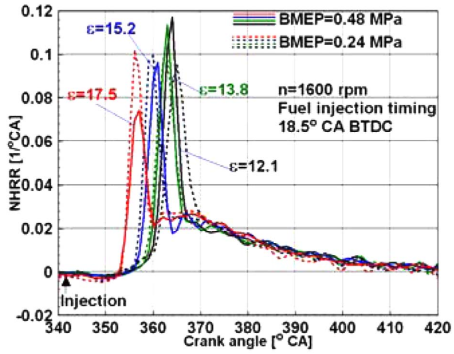

Figure 8. Normalized heat release rate vs. crank angle.

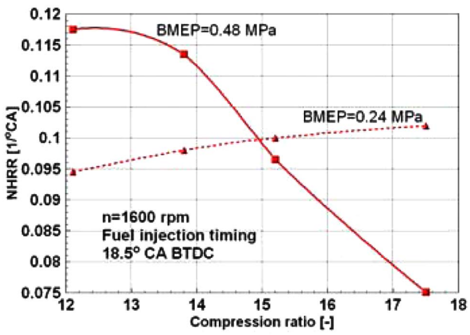

Figure 9. Maximum value of the NHRR vs. CR and engine load.

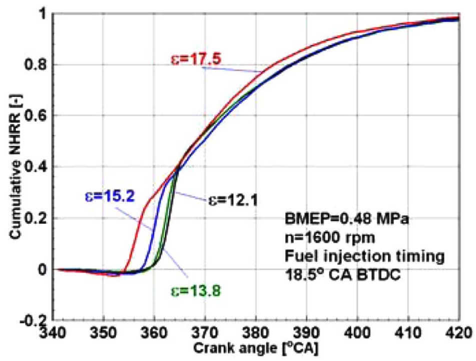

Figure 10. Cumulative NHRR vs. crank angle.

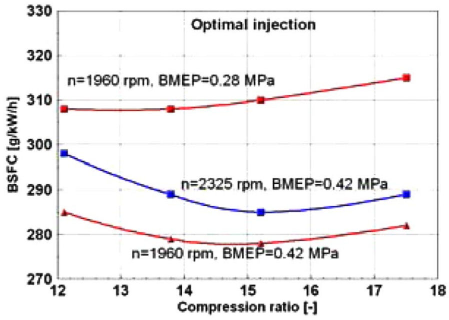

Figure 11. Influence of the CR on BSFC.

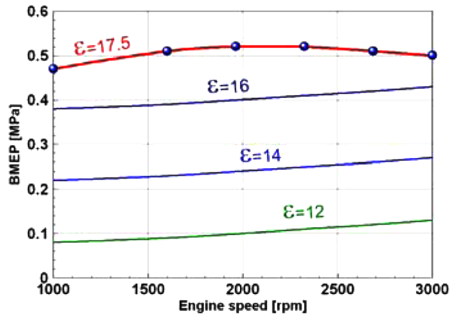

Figure 12. Selection of the optimal CR value for the engine operation with minimal BSFC.

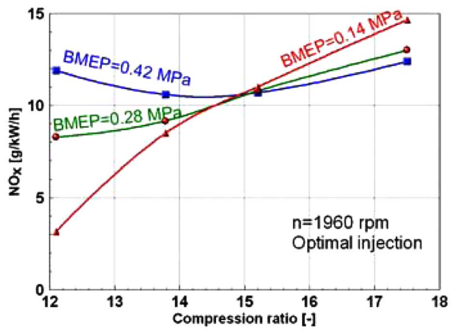

Figure 13. Influence of the CR on NOx emission.

ratio decreases, maximal values of the NHRR continually decrease (Figure 9), which reflects, in the end, in the reduction of maximal cylinder temperatures values (Figure 6).

Influence of the CR on the cumulative NHRR or combustion efficiency is shown on Figure 10. Change of combustion chamber shape, with the decrease of the compression ratio, leads to certain increase of the combustion inefficiency, Figure 10.

Dependence between the BSFC and the CR value is presented in Figure 11, for optimal injection time, at various loads.

The increase of the CR value results in less intensive increase of the BSFC at low load conditions, and then, it more intensively increases for CR values above 14, Figure 11. At high load conditions, the BSFC first decreases and reaches the minimal value for CR value near 15, and then starts to grow again with further increase of the CR value, Figures 11. The increase of the engine speed causes the increase in the mechanical and aerodynamic losses and the increase in fuel consumption (Figure 11).

Performance maps where BSFC contours are plotted on a graph of BMEP versus engine speed are commonly used to describe the effects of load and speed variations (similar diagrams are usually called "performance maps"). In a similar way, the performance maps where the optimal CR values (where the relevant parameters - BSFC or NOx or PM - are reaching the minimum) contours are plotted on a graph of BMEP versus engine speed can be created.

Firstly, it is necessary to determine the optimal CR values according to the relevant parameters (BSFC, NOx or PM) for each regime of loads and engine speeds, with optimal injection. As has already been said, tests are carried out at compression ratios of 12.1, 13.8, 15.2, and 17.5 in all working regimes.

Secondly, the plotted diagrams of previously determined optimal CR value, according to the relevant parameters, for each ESC cycle engine speed (1960 rpm, 2325 rpm and 2690 rpm) and for 1600 rpm as a function of BMEP are necessary.

After that, by processing of these diagrams, it is possible to determine the contours of the optimal CR values according to the relevant parameters that are plotted on a graph of BMEP versus engine speed.

Interpolation and extrapolation are used in the preparation of these diagrams.

The optimal value of the CR at which the engine has minimal BSFC increases with the increase of the engine load (Figure 12). At full load conditions, minimal BSFC is achieved with CR=17.5, while at low load conditions, the minimal BSFC is achieved with CR=12.

At low loads, the NOx emission intensively increases with the increase of the CR value, while at medium load conditions, the intensity of the increase is somewhat smaller (Figure 13). At high load conditions, the NOx emission firstly decreases and then increases with the increase of the CR and reaches its minimal value for CR=15 (Figure 13).

When ignition delay is increasing, then the amount of fuel, during premixed combustion period, also is increased and pre-mixture keeps rich oxygen state. Thus, temperature inside the cylinder rises promptly at the stage of rapid combustion and combustion efficiency is enhanced. At this time, the conditions of high-temperature and oxygen-rich state that are obligatory for the generation of NOx are strengthened and NOx emission increases (Tan *et al.*, 2012). Both the peak of heat release rate and the in-cylinder temperature go up, which contributes to a corresponding increase in NOx emissions (Laguitton *et al.*, 2007).

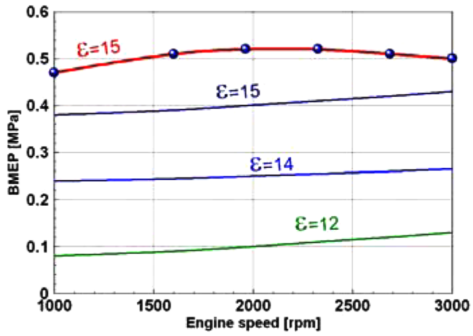

Figure 14. Selection of the optimal CR value for the engine operation with minimal NOx emission.

When diagrams in Figures 8, 9 and 13 are compared, relation between NOx emissions and the maximum value of the NHRR (rapid rate of combustion during premixed-combustion) may be established.

From the aspect of minimal NOx emission, optimal CR at full load has value of 15, while at low load conditions, the minimal NOx emission is achieved with CR=12 (Figure 14).

PM emission is the smallest at medium loads and it increases if the engine is running at low or high load conditions. At the same time, a PM emission increase with the increase of CR value at all loads (Figure 15), so optimal CR value, for all regimes, is 12 (Figure 16).

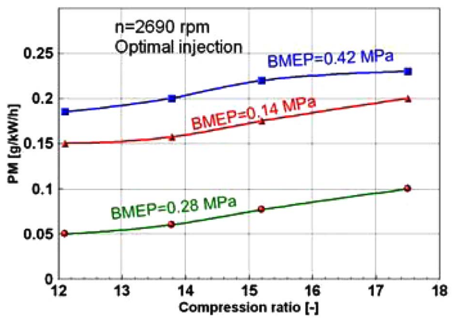

Figure 15. Influence of the CR value on PM emission.

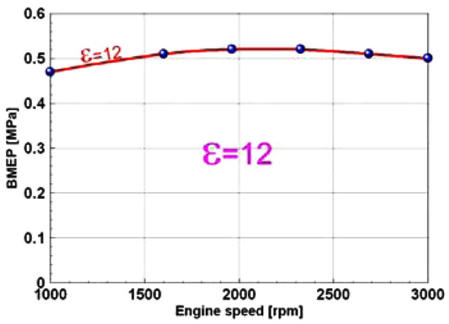

Figure 16. Selection of the optimal CR value for the engine operation with minimal PM emission.

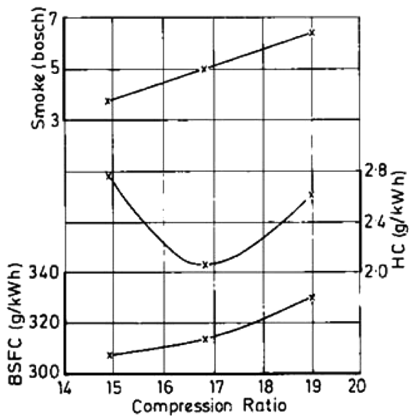

Figure 17. Compression ratio response at 2500 rpm, 25% load (Sobotowski *et al*., 1991).

It is believed that the increased mixing associated with the lower compression ratio suppresses PM formation, eliminating the need for high in-cylinder temperatures for the oxidation process. Temperature and pressure have a strong influence on PM formation, higher pressures and temperatures yielding higher PM formation.

Analysis of universal diagrams shows that the trends of CR variation are almost equal for the same values of fuel consumption and emission.

When compression ratio is decreasing, smoke emission and PM emission are also decreasing. Sobotowski and Ratnakara (Sobotowski *et al*., 1991; GVNSR Ratnakara Rao *et al*., 2008) have reached this conclusion during their research. Relations between fuel consumption rate and NOx emission obtained by the same authors correspond to the results of research presented here (Figure 17).

4. CONCLUSION

A single-cylinder four-stroke experimental engine was operated with various CR values over a sequence of ESC modes. Investigation of the effects of the CR produced the following results regarding the efficiency and ecological characteristics:

The VCR concept is suitable to use in turbocharged diesel engines because of the next advantages: the VCR concept is beneficial only at partial load where efficiency of the diesel engine is higher than that of the gasoline engine, and the diesel engine has better multi-fuel capability.

High CR increases theoretical thermal efficiency, but decreases mechanical efficiency. The maximal pressure within a cylinder and mechanical loses increase with an increase of both engine load and CR.

Value of optimal CR, at which the engine runs with minimal BSFC, increases with the increase of load. At full load, the BSFC is the smallest at maximal CR value of 17.5, while at low loads, minimal BSFC is achieved for minimal value CR of 12.

From the aspect of minimal NOx emission, optimal CR at full load has a value of 15. PM emission is the smallest for medium loads and increases if the engine runs at low or high loads. At the same time, PM emission increases with the increase of the CR, so the optimal CR value is 12.

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