FUNDAMENTAL UNDERSTANDING OF HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE

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Abstract: *Low temperature combustion in homogeneous charge compression ignition (HCCI) engines is an alternative combustion technique to existing automotive spark ignition and diesel engines. The present study is aimed at fundamental understanding of phenomena affecting combustion and emissions of gasoline fuelled HCCI engines with internal gas re-circulation. The experiments that yielded the results were performed using dedicated engine test stand with single cylinder research engine. Different control parameter sweeps were accomplished to provide comprehensive data on engine operating parameters, combustion evolutions and emissions under variable conditions. Experimental analysis was also supported by engine cycle simulation to provide more comprehensive data on in-cylinder processes.*

Keywords: ENGINES , LOW TEMPERATURE COMBUSTION, HOMOGENEOUS CHARGE COMPRESSION IGNITION

1. Introduction

Homogeneous charge compression ignition (HCCI) is nowadays emerging technology in the field of piston combustion engines. In the light of future emissions regulations, it appears to be the most promising solution for automotive propulsion systems fuelled with gasoline. This novel combustion technique provides significant reduction of fuel consumption and engine-out nitrogen oxides (NOX) emissions at low and medium engine load/speed conditions. HCCI combustion system utilizes auto-ignition of homogeneous in-cylinder charge, thus it is a combination of two acknowledged principles of internal combustion engines operation. The cylinder is fed with a homogeneous mixture, typical of spark ignition engines, and combustion is initiated by compression temperature, typical of diesel engines.

One of the first efforts in HCCI combustion implemented in a 2-stroke engine was reported by Onishi et al.[1]. Large amounts of residuals in the cylinder of 2-stroke engine provided end of compression temperature high enough to invoke the auto-ignition of gasoline. Najt and Foster[2] presented the first results of a 4-stroke gasoline HCCI engine. Additional energy for gasoline auto-ignition under low compression ratio of the engine was provided by heating-up of the air-fuel mixture in the engine intake system. These initial research demonstrated reduction of cylinder-out NOX emissions by 98% in comparison to spark ignition engines.

During the last decade, the more production feasible HCCI approach was developed. It utilizes internal exhaust gas re-circulation (EGR) obtained by a negative valve overlap (NVO). The NVO technique allows auto-ignition of high octane number fuels (gasoline like) at compression ratios typical of spark ignition engines[3-5]. In order to trap a sufficient amount of exhaust in the cylinder, an exhaust valve is closed before top dead center (TDC) in the exhaust stroke. The trapped residuals are then compressed and expanded after TDC. To avoid excessive backflows into the intake port, the opening of an intake valve is retarded. This technique is also referred to as controlled auto-ignition (CAI)[3]. Example traces of in-cylinder pressure, temperature and valve lifts during engine operation in the NVO mode are shown in Fig. 1.

Combustion process in an HCCI engine is initiated by increase in temperature inside the combustion chamber and starts at multiple sites simultaneously. In contrast to spark ignition and diesel engines, combustion process is very rapid and results in realization of the close to ideal Otto cycle. It increases thermal efficiency of the engine. Due to volumetric combustion of the mixture, temperature in the combustion chamber is uniform, and considerably lower than maximum temperatures in case of other combustion systems. Additionally, high EGR rates are provided, which further contribute towards temperature reduction. Thus, low temperature combustion is realized which produces extremely low NO_X emissions and smokeless exhaust[6, 7].

Ignition and combustion processes in HCCI engines are governed primarily by chemical kinetics of hydrocarbons oxidation. Auto-ignition timing is primarily controlled by compression temperature histories. It is also affected by mixture composition and its ignitability[8]. However, it should be noted that aforementioned parameters cannot be separately and directly controlled in practical engines.

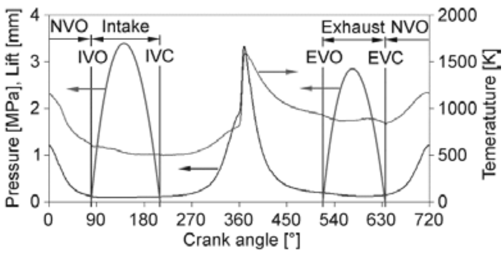

Fig. 1 *In-cylinder pressure, temperature and valve lifts during HCCI engine operation using NVO technique.*

Thus, successful implementation of such engines will depend on fundamental understanding of the in-cylinder processes and development of control technologies. The most crucial challenges for development of HCCI engines are: control of combustion timing under variable operating conditions, expansion of operating range in the HCCI mode and engine operation under transient conditions[9].

This study presents achievements of combustion engine group from Lublin University of Technology in the field of understanding of fundamental phenomena of HCCI engine operation. The presented results were collected during the past few years at a dedicated laboratory with a single cylinder engine. The purpose of this study was not to optimize engine operation to achieve the best operating parameters. Rather, it was intended to demonstrate the effects of different control strategies on combustion and exhaust emissions.

2. Experimental equipment

The experiments that yielded results presented in this study were carried out using dedicated single cylinder research engine. The engine was built in-house using special hydraulic engine head, which enabled fluent regulation of valve timings and valve lifts. Fully variable valvetrain was set to achieve NVO, and thus HCCI combustion. Swept volume of the cylinder was 489 cm3 and geometric compression ratio was 11.7. Fuel was directly injected into the combustion chamber with the use of solenoid swirl-type injector. The engine was fuelled with a pump-grade European Euro Super gasoline (95 research octane number). The engine was fitted with electrically driven vane compressor to increase intake pressure. Thus, it was able to be operated as naturally aspirated or boosted. The engine was installed on a test bench equipped with direct current dynamometer governed by an automation system. Fig. 2 shows appearance of the experimental engine.

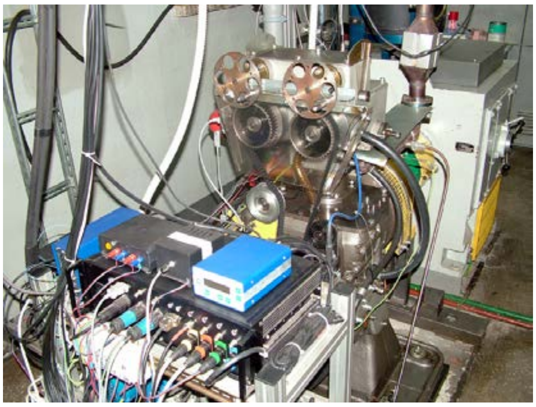

Fig. 2 *Appearance of the experimental test stand.*

The engine test bench was equipped with all necessary measurement and control instruments. Fuel consumption was measured using a fuel balance and intake air flow was measured with a thermal mass flow meter. The engine was also equipped with a set of pressure and temperature transducers in order to control the thermodynamic conditions of all media; intake, exhaust, cooling liquid, etc. In-cylinder pressure was measured with the use of a miniature pressure transducer installed directly in the engine head. Pressure and other crank angle (CA) based parameters were recorded with a constant angular resolution of 0.1 °CA, where analog-digital converter was triggered by optical encoder. The composition of exhaust gas was measured with a Fourier transform infrared (FTIR) multi-compound analytical system. Additionally, oxygen content in exhaust gas and excess air ratio (λ) were provided by wide-band oxygen probe installed in the exhaust runner. Detailed descriptions of the experimental test stand can be found in[10, 11].

3. Experimental results

Effects of valve timing

Valve timings are basic control parameters of the HCCI engines operated in the NVO mode. Valvetrain settings enable regulation of the quantity of exhaust gas trapped on the cylinder as well as amount of intake air. However, these two parameters are coupled and cannot be controlled separately. During the intake process the cylinder is partially filled with trapped exhaust. Thus, amount of aspirated air is affected by amount of internally re-circulated exhaust and its temperature[12].

To demonstrate these complex effects, intake and exhaust valve timings were varied independently. Exhaust valve closing (EVC) was varied in a range from 627 °CA to 646 °CA, whereas intake valve opening (IVO) was varied between 77 °CA and 99 °CA. All valvetrain timings are expressed in domain of crank angle as shown in Fig. 1. This experiment was performed at constant engine speed of 1500 rev/min. Fuel was injected into the cylinder in a single dose during exhaust expansion, during the NVO period. Excess air ratio was maintained nearly stoichiometric.

(a) (b)

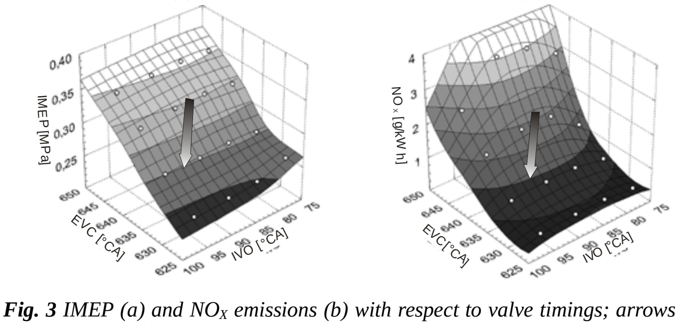

Fig. 3 *IMEP (a) and NO_X emissions (b) with respect to valve timings; arrows show direction of NVO angle increase.*

Fig. 3a shows that engine load expressed as IMEP is controlled solely by exhaust valve timing. Delay of EVC by 19 °CA resulted in change in IMEP from approx. 0.24 MPa to 0.35 MPa. Primarily this change was a result of variable amounts of aspirated air. At constant air excess, quantity of fuel was varied too, thus amount of chemical energy introduced to the cylinder was reduced at EVC advance. Additionally, engine load was affected by variable thermal efficiency. Thermal efficiency increased for increasing engine load, as lower was contribution of thermal losses to energy balance of the engine. It should be also noted that for constant exhaust valve timing, intake valve timing affected thermal efficiency. For all conditions, the highest efficiency was observed for moderate intake valve timings. While engine load was not strongly influenced by IVO, NO_X emissions appeared to be affected by the intake valve timing to the high extent, as shown in Fig. 3b.

(a)

(b)

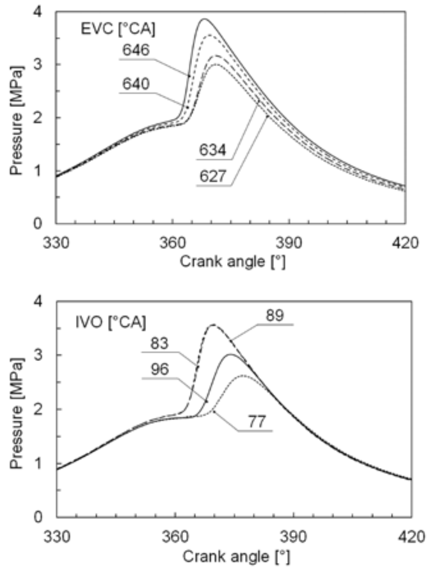

Fig. 4 *In-cylinder pressure for variable EVC at IVO = 89 °CA (a) and for variable IVO at EVC = 640 °CA (b).*

To provide more insight into the effects of valve timings on combustion, Fig. 4 shows in-cylinder pressure for variable EVC and variable IVO. It can be noted from Fig. 4a that the change in engine load as a result of variable EVC does not affect auto-ignition timing. Obviously peak pressure decreased for lower loads. In contrast, at constant load, variable IVO modified start of combustion timing, as shown in Fig. 4b. Both early and late IVOs resulted in combustion delay. Later combustion reduced peak in-cylinder pressure and temperature, which was reflected in the NO_X emissions, shown in Fig. 3b. The delay of combustion was attributed to the cooling effects of early and late backflows through the intake valve. The pressure traces explain drop in thermal efficiency at extreme intake valve timings. Trivially, slower combustion reduced work produced by the engine cycle.

Effects of excess air

The previous section showed that load control of the engine using solely variable valve timings under constant λ enabled engine operation in a very narrow range of IMEP. Thus, to expand engine operation range it is necessary to combine variable valvetrain settings with variable λ. Experiments at variable λ were performed for four NVO angles. The configurations of EVCs and IVOs were set to provide maximum thermal efficiency under desired engine load. For EVC varied from 627 °CA to 646 °CA, IVO was varied from 89 °Ca to 83 °CA accordingly. Fuel was injected in a single dose during exhaust expansion during the NVO period.

Fig. 5a shows the results for IMEP with respect to λ values, which were varied from stoichiometric to maximum attainable level, where limitation came from occurrence of misfires. It can be noted that even small increase in air excess resulted in relatively high drop in IMEP. This effect was attributed to variation in EGR rate. Increase in λ results in a decrease in exhaust temperature. When colder exhaust gasses are trapped, their amount increases, thus reducing amount of aspirated air. As a result, overall effect of λ on engine load is much stronger than one resulting from air excess itself. One conclusion can be drawn from the above analysis that λ is an effective parameter for controlling of the engine load. Fig. 5b demonstrates how NOX emissions are sensitive to engine load and air excess. For stoichiometric mixture, where IMEP was varied from approx. 0.25 MPa to 0.35 MPa NO_X emissions were increased 8 times, showing EGR impact on emission. In this range, EGR rate varied between 0.49 and 0.54, resulting in drop in peak temperature from 1708 K to 1510 K. It should be noted that emission levels of spark ignition engines under comparable operating conditions are approx. 12 g/kW h. The NO_X emissions increased at slight λ increase above stoichiometric level, as a result of higher oxygen availability. Further increase in λ resulted in substantial drop in emissions due to increasing fuel dilution by air and re-circulated exhaust.

(a)

(b)

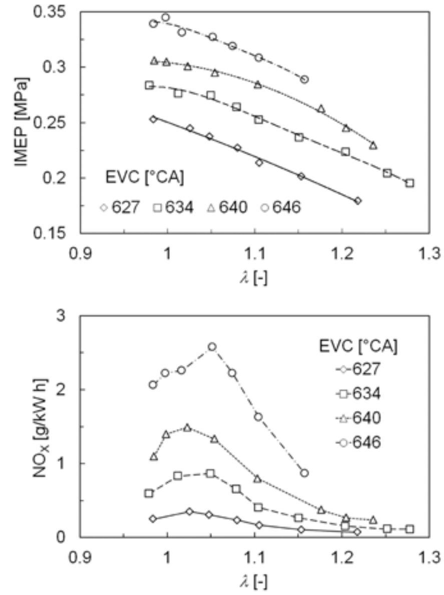

Fig. 5 *IMEP (a) and NOX emissions (b) with respect to λ at variable valve timings.*

(a)

(b)

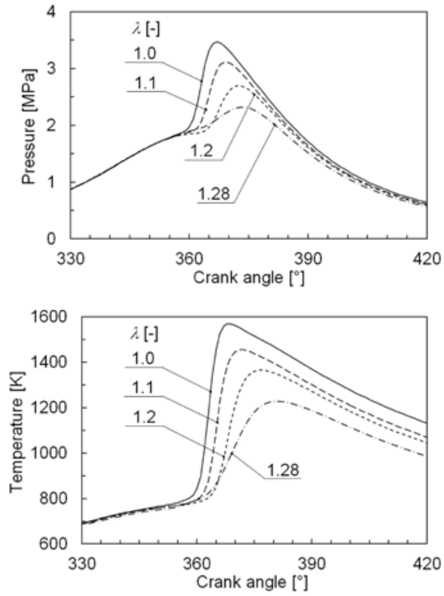

Fig. 6 *In-cylinder pressure (a) and temperature (b) for variable λ; EVC = 634 °CA.*

Limitations of applicable λ values during HCCI operation result from delay of auto-ignition, as shown in Fig. 6a. When fuel chemical reactions are not commenced before piston top position, combustion will not take place due to dropping in-cylinder temperature.

It should be noted, that temperature of gasoline auto-ignition is not sensitive to λ; thus, combustion timing is controlled solely by compression temperature histories[8]. Fig. 6b shows that end of compression temperature decreases for leaner mixtures, indeed. Substantial drop in peak temperatures clearly accounts for the reduction in NOX emissions.

Effects of boost

Meaningful effect of air excess on NO_X emissions and combustion, shown in the previous subsection, reveals another possibility to further reduce emissions and control heat release by using boost. Additionally, application of boost enables increase of quantity of aspirated air and can be utilized in HCCI engines for extension of operating regime[11, 13].

Tests that yielded results presented in this section were performed at 1500 rev/min. Likewise in previous experiments, fuel was injected during the NVO period. Valve timings were set at 640 °CA for EVC and 82 °CA for IVO. Boost pressure sweeps were applied at different amounts of fuel. In the first case 13.3 mg of fuel was injected, which provided stoichiometric mixture at naturally aspirated conditions. Boost pressure was increased from atmospheric to approx. 150 kPa absolute, providing variable air excess at constant fuelling. In the second case mass of fuel was increased to 18 mg in order to explore engine operation above limit resulting from insufficient amount of air under naturally aspirated conditions. At this condition, minimum boost pressure was increased to provide stoichiometric mixture. It was found that thermal efficiency at constant fuelling and variable intake pressure was nearly constant, thus achieved IMEP values were approx. 0.35 MPa and 0.5 MPa, accordingly. Values of λ were varied from slightly lean to 1.5 for less fuel injected and to 1.3 for more fuel injected.

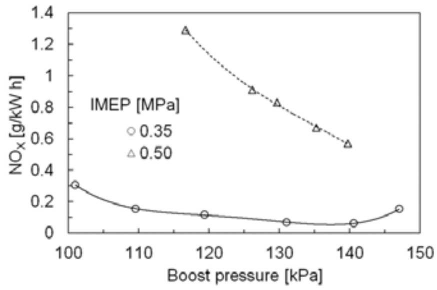

Fig. 7 *NO_X emissions with respect to boost pressure.*

(a)

(b)

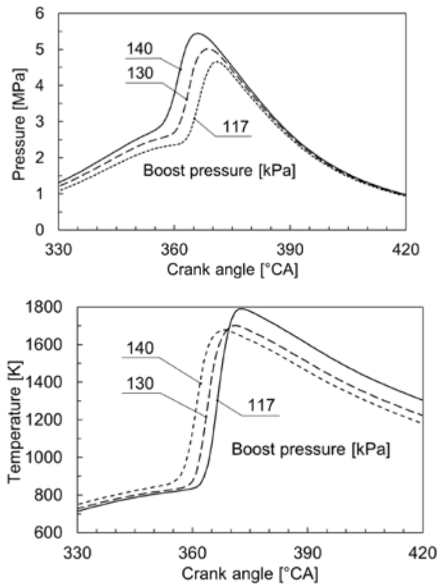

Fig. 8 *In-cylinder pressure (a) and temperature (b) for variable boost pressure; IMEP ~ 0.5 MPa.*

Fig. 7 shows NO_X emissions at variable boost pressure for two applied fuel doses. For less fuel injected, increase in boost pressure from atmospheric to 140 kPa enabled reduction in NO_X emissions by factor of 5. For the highest boost pressure increase in the emissions was noted, however, it was attributed to unstable combustion at very lean mixture. Likewise, in the case of higher fuel dose, increase in boost pressure appeared to be an effective method for reduction of NO_X emissions. Narrower range of applicable boost pressures resulted from increase in combustion harshness. It was found that increase in boost pressure advanced auto-ignition, as shown in Fig. 8a. Additionally, higher peak pressures were noted, which increased combustion noise and mechanical loads of the combustion chamber. Fig. 8b shows that advance in combustion resulted from increase in end of compression temperatures. At the same time, peak temperatures were reduced, justifying drop in NO_X emissions.

4. Engine cycle modelling

Analysis of auto-ignition timing at variable boost pressures reveal a peculiar effect. Considering changes in the amounts of fresh air and retained residuals, as well as exhaust temperature, it was expected that boost application will result in drop of start of compression temperature and auto-ignition retard. However, experimental results provided relationships opposite to expected ones, as shown in Fig. 8. Increase of amount of aspirated air at constant fueling increased end of compression temperature and thus, resulted in advance of auto-ignition.

To provide detailed data on gas exchange and thermal balance between trapped residuals and aspirated air, experiments were complemented by zero-dimensional modelling of the engine cycle. Boost software from AVL was used for simulation. Computations were done at the same conditions as during experiments. The obtained results confirmed experimental observations that increase of intake pressure increased compression temperature, besides reduction of the EGR rate at elevated amounts of fresh air in the cylinder. Temperature at IVC event increased by 10 K approximately for intake pressure change from atmospheric to 150 kPa, as shown in Fig. 9. The results also clarified the reason for the delay of auto-ignition for increase of air excess under constant fueling conditions, shown in Fig. 6 Increase of excess air reduces temperature as well, besides compensation by EGR rate.

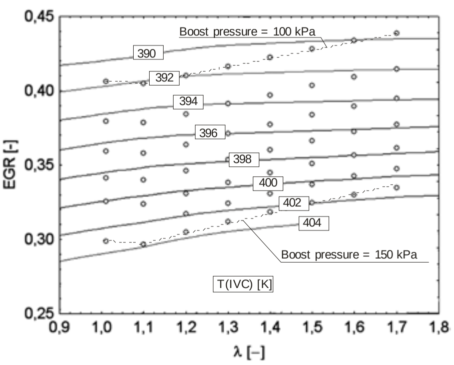

Fig. 9 *Calculated temperature at intake valve closing (IVC) versus air excess ratio and EGR rate at variable intake pressure.*

5. Conclusions

Low temperature combustion of gasoline in an HCCI engine operated in the NVO mode was studied using variable control methods. Variable valve timings, air excess ratio and boost pressure were accomplished to provide experimental end modeling data on their effects on combustion and emissions. The collected data show fundamental principles of residual effected HCCI engine operation. The findings of the study can be summarized as follows:

1) At regulation of the engine via valvetrain settings exhaust valve timing determined fresh air intake, whereas intake valve timing had much smaller effect. However, intake valve timing had an impact on heat release rate, and therefore influenced thermal efficiency and emissions of nitrogen oxides.

2) Amount of fuel and resulting excess air ratio are effective methods for engine load control. Lean mixture boundary of the engine operation resulted from drop in compression temperature, which caused delay of auto-ignition. However, lean combustion produced extremely low NO_X emissions.

3) Application of boost enabled extension of permissible engine load range. Additionally, increase in boost pressure and resulting fuel dilution further reduced NO_X emissions.

4) Auto-ignition timing and boundaries of engine operation in an HCCI mode are resulting primarily from temperature of the mixture at the end of compression. The thermal state of the mixture is mainly affected by thermal balance of the gas exchange process.

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References

1. Onishi S., Jo S., Shoda K., Jo P., Kato S., Active thermo-atmosphere combustion (ATAC) – a new combustion process for internal combustion engines, SAE Technical Paper 790501, 1979.
2. Najt P.M., Foster D.E., Compression-ignited homogeneous charge combustion, SAE Technical Paper 830264, 1983.
3. Lavy J., Dabadie J.Ch., Angelberger Ch., Duret P. et al., Innovative ultra-low NOX controlled auto-ignition combustion process for gasoline engines: the 4-SPACE project, SAE Technical Paper 2000-01-1837, 2000.
4. Zhao H., Li J., Ma T., Ladommatos N., Performance and analysis of a 4-stroke multi-cylinder gasoline engine with CAI combustion, SAE Technical Paper 2002-01-0420, 2002.
5. Yap D., Karlovsky J., Megaritis A., Wyszynski M.L., Xu H., An investigation into propane homogeneous charge compression ignition (HCCI) engine operation with residual gas trapping, Fuel 84, 2005, 2372-2379.
6. Yao M., Zheng, Z., Liu H., Progress and recent trends in homogeneous charge compression ignition (HCCI) engines, Progress in Energy and Combustion Science 35, 2009, 398–437.
7. Najafabadi M.I., Aziz N.A., Homogeneous charge compression ignition combustion: challenges and proposed solutions, Journal of Combustion, article ID 783789, 2013.
8. Dec J.E., Yang Y., Dronniou N., Boosted HCCI – controlling pressure-rise rates for performance improvements using partial fuel stratification with conventional gasoline, SAE International Journal of Engines 4, 2011, 1169–1189.
9. Saxena S., Bedoya I.D., Fundamental phenomena affecting low temperature combustion and HCCI engines, high load limits and strategies for extending these limits, Progress in Energy and Combustion Science 39, 2013, 457–488.
10. Hunicz J., An experimental study of negative valve overlap injection effects and their impact on combustion in a gasoline HCCI engine, Fuel 117, 2014, 236–250,
11. Hunicz J., Gęca M.S., Kordos P., Komsta H., An experimental study on a boosted gasoline HCCI engine under different direct fuel injection strategies, Experimental Thermal and Fluid Science 62, 2015, 151-16.
12. Shaver G.M., Roelle M.J., Caton P.A., Kaahaaina N.B., et al., A physics-based approach to the control of homogeneous charge compression ignition engines with variable valve actuation, International Journal of Engine Research 6, 2005, 361–374.
13. Canakci M., Combustion characteristics of a DI-HCCI gasoline engine running at different boost pressures, Fuel 96, 2012, 546–555.