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Wojciech BUESCHKE
Maciej SKOWRON
Krzysztof WISŁOCKI
Filip SZWAJCA

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Comparative study on combustion characteristics of lean premixed CH_4/air mixtures in RCM using spark ignition and turbulent jet ignition in terms of orifices angular position change

The increase in ignitability consist a main aim of implementation of the turbulent jet ignition (TJI) in relation to the combustion of diluted charges. Such an ignition system has been introduced to the lean-burn CNG engine in the scope of GasOn-Project (Gas Only Internal Combustion Engines). In this study the impact of TJI application on the main combustion indexes has been investigated using RCM and analyzed on the bases of the indicating and optical observations data. The images have been recorded using LaVision HSS5 camera and post-processed with Davis software. Second part of the study based on indicating measurements consist the analysis of combustion regarding the variation in the geometry of pre-chamber nozzles. It has been noted, that combustion with TJI indicates significantly bigger flame luminescence and simultaneously – faster flame front development, than the combustion initiated with conventional SI. The positive impact of nozzles angular position on engine operational data has been found in the static charge movement conditions, regarding the combustion stability.

Key words: *CNG, turbulent jet ignition, pre-chamber, optical analysis, flame development, heat release rate*

1. Introduction

GasOn project was aimed to develop the monovalent engines fuelled with CNG. Methane-rich CNG, as a low carbon fuel, is alternative and environment-friendly chemical energy source for automotive powertrains. Poznan University of Technology participated in the GasOn work package 5, which was focused on lean burn combustion system indicating potential to increase the efficiency and emission indexes.

The potential in methane-based fuelling of the spark ignition engines (SI) is emphasized among others with its high octane number (up to 120) and therefore high knock resistance [1]. This determines the possibility to significant increase the compression ratio (CR), according to various investigations up to 15.6, what affects positively the combustion thermal efficiency and the engine brake efficiency [9, 10, 13]. Further increase of engine efficiency provides the implementation of lean-mixture combustion by means of excessive oxidizer content in the supplied mixture. With increase in dilution of the combusted mixtures, the thermal efficiency is being increased [22]. Also the combustion of lean charges generates smaller in-cylinder temperature resulting in smaller temperature-dependent emission of NO_x [8]. Both effects correlate positively on increase in air-fuel equivalence ratio, which is however significantly limited due to the inflammation capability of spark ignition [2, 7].For the specific NO_x emission, the introduction of TJI to the gas engine results in reduced THC and CO emission [23].

As mentioned, one of the biggest challenges in lean-mixture combustion is the demand on ignition energy, which is rising along the λ increase. In case of methane combustion in model conditions, the minimal ignition energy (MIE) for stoichiometric process equals 0.35 mJ, while for $\emptyset = \frac{1}{\lambda} = 0.5$ the MIE increases up to approximately 10 mJ [11].

The air-fuel stoichiometry is not the only factor influencing the inflammation capability, what the author of this paper has already studied [4], so the MIE demand in real engine conditions is in fact much bigger. Some studies rate the ignition energy generated from TJI on 10^4–10^5 bigger as this achieved with conventional ignition system [19], what makes it interesting for lean-burn applications. Also another ignition mechanism (multipoint type) makes the TJI beneficial in terms of mixture inflammation capability [3].

As the studies deliver, two main approaches are known: jet ignition and flame ignition. In first approach the flame from pre-combustion is being quenched when passing the orifices. The main combustion process is being started with hot combustion products. When the orifice diameter is being increased, the on-ignition is tending to the second approach – flame ignition.

The studies on combustion of diluted charges applied to the full engine confirmed positive results related to the thermal efficiency [18]. The air dilution of the mixture indicated in another study 2% greater increase in thermal efficiency, than dilution with EGR, combined with 2-times better THC emission, however with some NO_x emission drawback [20]. This can be covered with further mixture dilution, which cannot be achieved with recirculated exhaust gasses.

The challenges of CNG fuelled engines consist both the conversion of unburned methane in the exhaust aftertreatment systems and the low exhaust gas temperature affecting negatively the activity of catalyst. There are known however measures from the side of engine control [12] and aftertreatment systems as alternative catalytic materials [15], reducing this issue significantly, what is the important fact intensifying the research activities on CNG lean combustion.

The TJI initiated combustion is being influenced by system constructional factors and operational parameters. The control strategies indicate top and bottom limitations, which are sourced in boarder parameters and determine ignitability and the flame propagation in pre-chamber [6, 21]. Kotzagianni et al. investigated SOI using RCM and found increase in cyclic variation, when ignition is being retarded [17]. Roethlisberger and Farvat conducted research into pre-chamber volume and its internal shape [24], using the 6-cylinder CNG fuelled engine with CR = 12.0 and pre-chamber consisting 2–3% of main chamber volume. In lean conditions (λ = 1.61–1.67) the ignition chamber with smaller volume caused 2 deg CA advance in main chamber heat release, 0.3 bar bigger Δp and reduced concentrations of THC and CO for up to 100 mg/m^3. Another investigations discovered positive correlation between the brake specific emission of NO_x and the pre-chamber volume fraction [26].

Tanoue compared the single orifice prechamber to double-nozzle system, regarding the knock combustion, based on the optical data recorded on RCM [25]. The shift of the knock source position has been noted. Double nozzle system caused the move of knock source to the away from the pre-chamber tip. Kawabata noted that the larger number of pre-chamber orifices impacts positively HRR and promotes therefore faster combustion in the main chamber [16].

The analysis of flame propagation in terms of orifice diameter has been studied by Gholamisheeri et al. [14]. The orifices with diameters of 2.0, 2.5 and 3.0 mm have been introduced to the RCM and investigated at Ø = 1.0, 0.8, 0.67. The strict dependency of jet tip penetration speed on orifice diameter and fuel stoichiometry has been proven. The increase in orifices diameter results in the jets speed reduction. The same tendency is valid also for air-fuel stoichiometry – increased λ causes reduced flame development speed. However, the calculated Reynolds numbers indicate the turbulent character of the flow in all investigated cases, which is affecting positively the mixing in the main chamber, heat exchange between jet and unburned fraction and, in consequence, promoting faster inflammation of main charge.

This study has been conducted to complement insufficient state of knowledge regarding the prechamber nozzles angularity.

2. Investigations methodology

2.1. Test bench

Investigations have been performed using the rapid compression machine (RCM) executing the single combustion cycles, equipped with CNG fuelling system and spark/spark-jet ignition (Fig. 1).

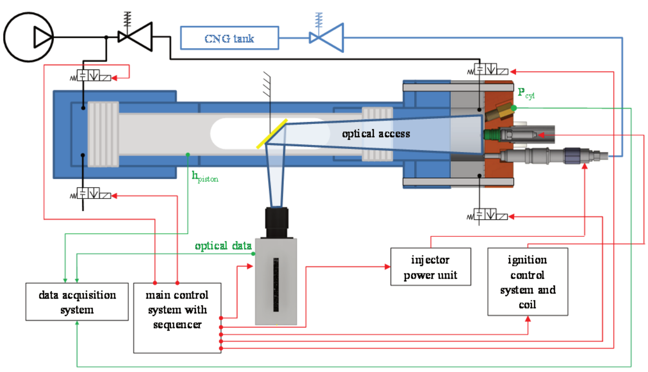

Fig. 1. RCM Test bench

The RCM has pneumatic piston activation (pressure chamber in the bottom of piston connected to fast solenoids) with air pressure delivered from the compressor, which has been designed to driving pressure p_d < 80 bars. However, in this study p_d = 38 bars has been applied and provided requested piston velocity, which has also the connection to the crank mechanism. The crank mechanism makes the piston movement independent from driving parameters. In the middle part of the piston, the flat mirror has been fixed to redirect the optical view from combustion chamber (quartz glass window with g = 50 mm assembled in piston crown) to the camera system – LaVision HSS5. The recorded images have been processed using Davis software.

The ignition energy has been delivered from the dedicated adjustable ignition control module with variable time of coil loading (regulation of ignition energy) and its phase. Both, for SI and for TJI, the e_{DIS} = 34 mJ has been applied.

The dimensional parameters of RCM used in this study have been collected in the Tab. 1. Methane N35 has been used as a fuel to the measurements.

Tab. 1. Main data of the Rapid Compression Machine (RCM)

Parameter	Value	Unit
Cylinder displacement	438	cm^3
Compression ratio	15.0 (SI) / 14.2 (TJI)	–
D_{OA}	Ø48	mm
Driving pressure	< 80	bar
Pressure sensor – main chamber	AVL GM11D	–
Pressure sensor – prechamber	FOS CPS 2000	–

2.2. Investigated combustion systems

The modular construction of used RCM provides the implementation of spark ignition and spark-jet ignition system, which are replaceable in the cylinder head (Fig. 2).

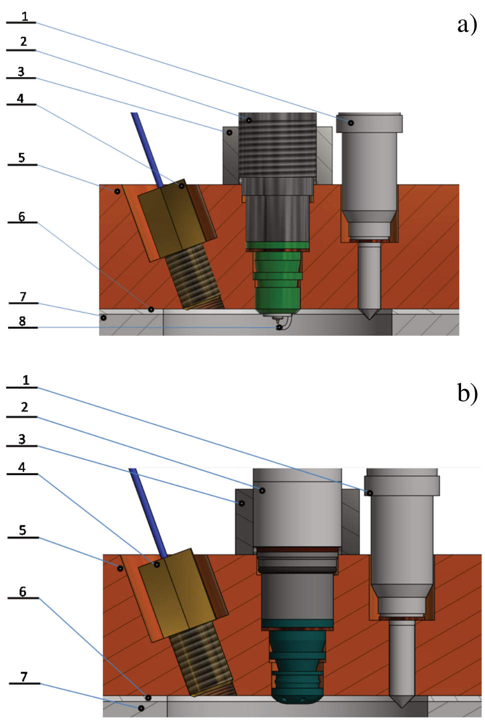

Fig. 2. SI (a) and TJI (b) assembled in the RCM body

The RCM in both configurations (Fig. 2) – with SI and with TJI – has got the Bosch electromagnetic CNG nozzle (1) to direct CNG injection assembled in the cylinder head (5), separated with head gasket (6) from cylinder (7). The cylinder head consists also the pressure transducer (4) and ignition system fixed with adapter (3). In the SI configuration (Fig. 2a) the spark plug (8) has been mounted in the adapter (marked with green) and fixed with sleeve (2). The TJI-setup (Fig. 2b) consist the pre-combustion chamber (marked with blue), which is fixed with adapter (dark gray) consisting fuel supply channel and pressure transducer. Abovementioned components are immobilized with sleeve (light gray).

2.3. Scope of investigations

The measurements have been divided in two campaigns:
- comparison of SI and TJI with tangential nozzles,
- comparison of tangential and tilted nozzles in TJI.

Both SI and TJI systems have been compared (a) at constant λ = 1.5. The λ value has been calculated according the equation:

$$\lambda = \frac{m_{air}}{m_{fuel} \cdot L_t} = \frac{m_{air}}{(q_{0\_PC} + q_{0\_MC}) \cdot L_t} \tag{1}$$

The air mass has been calculated based on the total volume of combustion chamber. Because of its scavenging with fresh charge, which is preceding the start of sequence, no significant residual content has been assumed. In case of SI application, the m_{fuel} injected directly to the combustion chamber has been considered in the λ calculation, while with TJI it was the sum of $q_{0_PC}$and q_{0_MC}. The comparison of SI and TJI has been performed based on the optical signal from MC. Based on this signal share of flame exposition A_f in the optically accessible part of combustion chamber A_{oa} has been calculated:

$$r = \frac{A_f}{A_{oa}} = \frac{4 \cdot A_f}{\pi \cdot D_{oa}^2} \tag{2}$$

The intensity of the flame at the defined time instances has been assessed relative to the maximal value:

$$c = \frac{I}{I_{max}} \tag{3}$$

The combustion nozzles angularity (b) has been assessed for following conditions:
- λ = 1.5, q_{0tot} = 20 mg/cycle,
- λ = 1.3, q_{0tot} = 23 mg/cycle.

The analysis concerns:
- maximal cylinder pressure Pmax(t_{pmax}),
- maximal rate of heat release HRR(t_{HRRmax}).

The HRR has been calculated according the formula presented in [27].

3. Comparison of spark ignition and turbulent jet ignition

The combustion process (for TJI: combustion of main charge) indicates changes in its course, when replacing the conventional spark ignition system with TJI. The analysis contains the flame propagation investigation providing qualitative information about intensity distribution based on recorded chemiluminescent combustion signal (Fig. 3). In the further steps, images have been parameterized regarding the flame intensity and area of its exposition at the defined time instances (Fig. 4).

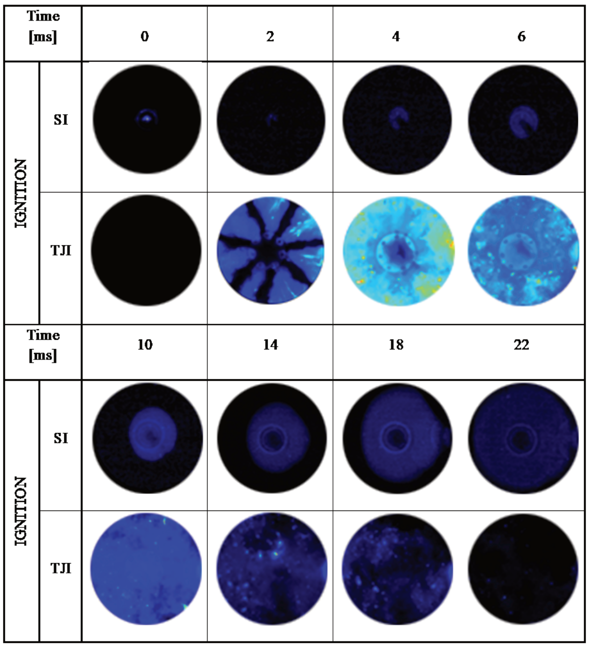

Fig. 3. Flame propagation for λ = 1.5 for SI and TJI

The images (Fig. 3) represent the flame development over the time for SI (top) and TJI (bottom) in the optically accessible part of combustion chamber ($Ø_{OA}$ = 48 mm) at λ = 1.5. First pictures, marked as 0, represent the view from combustion chamber at the moment of ignition(SOI) and the spark plug discharge visible in the undivided combustion chamber (Fig. 3, top, 0 ms). Further pictures captured for SI indicate typical premixed flame characteristic for well homogenized mixture with tangential development from the ignition source to the auxiliary regions of combustion chamber. In case of combustion initiated with TJI, 2 ms after SOI the igniting jets already developed throughout the optically accessible part of combustion chamber. This, and also conical shape of captured jets expositions with expanded jets tips (generated from cylindrical nozzles) suggests significant contribution of jets interaction with walls of combustion chamber in the flame development. Next time steps indicate bigger flame luminescence in the auxiliary parts of combustion chamber, while the combustion intensity is getting significantly lower, from the time of 4 ms after SOI. Based on the optical signal it can be stated, that TJI provides significant more intensive and faster combustion.

The parameterized optical data (Fig. 4) indicates significant differences in the character of flame development. For the conventionally initiated combustion, 1.6 ms after SOI flame luminescence achieve approximately 50% of its maximal value, which has been reached 14 ms after SOI, and reduced to 80% during next 8 ms. The maximal value of flames intensity for TJI has been achieved much earlier, 4 ms after SOI, dropped intensively within next 6 ms to 23%, then has been slowly quenched. As the peak flame luminescence intensity has been achieved 4 ms after SOI, also the large increase in the area of flame occurs in first 4 ms, when the flame area covers almost entire (98%) combustion chamber.

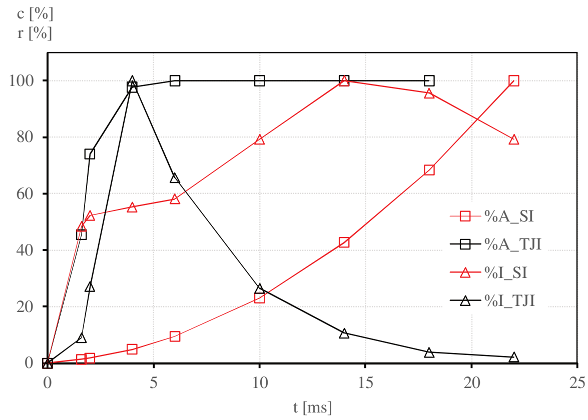

Fig. 4. Share of the flame (square points) and intensity (triangular points) in the optically accessible part of combustion chamber for SI (red line) and TJI (black line)

The impact of ignition type on cylinder pressure has been analyzed using the indicating approach based on the cylinder pressure to investigate more generalized, quantitative effect (Fig. 5).

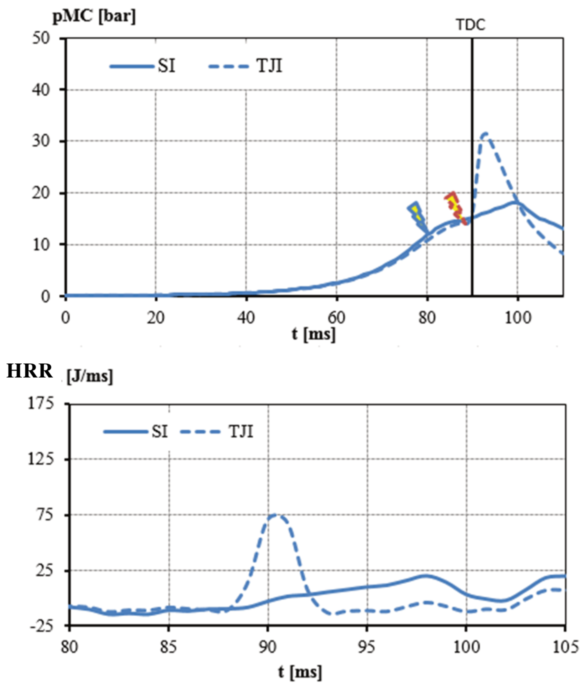

Fig. 5. Cylinder pressure (a) and HRR (b) for SI (solid line) and TJI (dashed line)

The traces of PMC indicate smaller cylinder pressure during the compression stroke for TJI, what is caused with smaller geometrical CR due to additional volume introduced to the combustion chamber. The SOI has been adjusted adequately to the ignition – retarded for 18 ms when TJI used. The pressure and HRR curves have been presented for abovementioned single operation cycle. Using the SI, cylinder pressure has been increased for 6 bars from the SOI to time instance, when maximal value has been achieved (time period of approximately 20 ms), while with use of TJI, the pressure has been increased for 16 bars within 5 ms. The HRR curves show increase in HRR to the maximal values in 18 ms and 4 ms with magnitudes of 25 J/ms and 75 J/ms, respectively for SI and TJI.

Based on the results, it has been noted, that during the combustion of defined fuel quantity heat is being released much more intensive, when TJI introduced, then with use of conventional ignition system. The different on-ignition mechanism is here important. TJI generates hot jets, which are developing both downstream the flow from pre-chambers nozzle and perpendicularly to the flow. This takes place due to the areal mixing the hot gasses with unburned fraction on the jets surface and makes the inflammation source decentralized. The combustion initiated parallel from the multiple hot surfaces indicates faster flame development, which covers bigger volume and provides bigger value of heat release rate.

4. Impact of TJI nozzles angularity on combustion

The angularity of pre-chamber nozzles has been particularly investigated within the scope of another authorship study, using the optical measurement approach [5]. The combustion, at λ = 1.3 with tangential nozzles TJI and without introduced charge motion, indicated bigger intensity then in case of tilted nozzles. In this study, the combustion in bigger λ range and using the pressure based on indicating investigation approach (Fig. 6, Fig. 7).

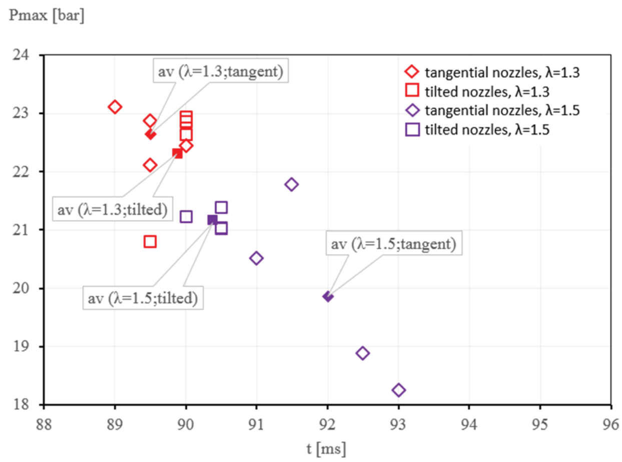

Fig. 6. Pmax for tangential and tilted nozzles

The Pmax values over their occurrence time at λ = 1.3 and λ = 1.5 (red and violet color respectively) for tangential (rotated squares) and tilted (squares) nozzles have been indicated for the single combustion cycles (Fig. 6). All mentioned cycles have been performed for the constant ignition advance. It can be noted, that combustion at λ = 1.5 indicates bigger spread of maximal pressures – an obvious effect of worse combustion stability, which is typically being found when increasing mixture dilution. When the charge with λ = 1.5 has been combusted, the tilted nozzles caused in average 7% increase in Pmax, which has been advanced for 1.6 ms. This increase has been caused by the better mixing the lean charge, what consists an critical factor by such a conditions to the inflammation capability. In contrast to this, at more rich conditions (λ = 1.3) the differences are very small (ca. 0.4 bar and 0.4 ms of advance) and beneficial effect achieved tangential nozzles.

In general, along the increase in maximal cylinder pressure, the occurrence of this value is being advanced. This effect is better visible for more diluted mixtures.

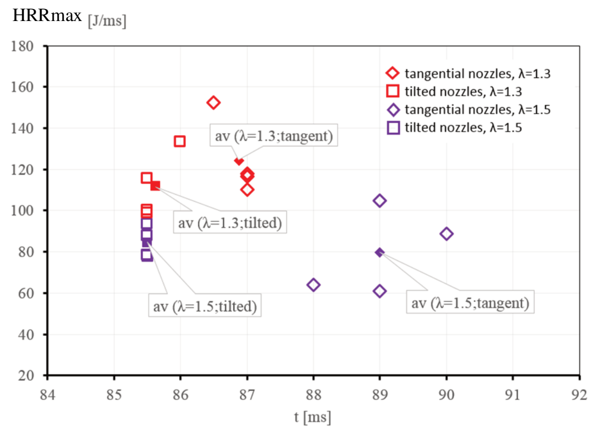

Fig. 7. HRRmax for tangential and tilted nozzles

Based on the cylinder pressure signal, the HRR values over their occurrence time at λ = 1.3 and λ = 1.5 (red and violet color respectively) for tangential (rotated squares) and tilted (squares) nozzles have been indicated for the single combustion cycles (Fig. 7). At high load points (λ = = 1.3), tangential nozzles provided approximately 9% bigger average value of HRRmax, which has been however retarded for 1.2 ms. At low load points (λ = 1.5), the tilted nozzles caused 4% bigger HRRmax. However, for both investigated λ, the occurrence of HRRmax indicates much smaller spread, when the tilted nozzles have been used. The better mixing characteristic with use of tilted nozzles results in smaller cyclic variability of Pmax and HRRmax.

5. Summary and conclusions

The combined optical and indicating RCM measurement approaches have been employed into the comparative investigation on ignition type and nozzles angularity modification of advanced ignition. The TJI has been related to the SI regarding the flame development in lean conditions – at λ = 1.5. Based on the recorded images, when the centralized ignition energy source applied, the flame develops from the source to the auxiliary chamber regions tangentially, while the igniting jets generated from TJI achieved the walls of combustion chamber within 2 ms and intensively develop perpendicularly to the flow. The maximal flame luminescence intensity and almost complete cover of combustion chamber with flame in 4 ms after SOI using the TJI. The flame of combustion initiated with SI reaches the optical access area in 22 ms. The cylinder pressure measurements indicated faster increase, despite SOI retarded for 8 ms and Pmax bigger for 15 bars. The calculated HRR indicates rapid and earlier heat release with HRRmax bigger for 50 J/ms. The combustion initiated with TJI is advanced in phase, intensified and faster.

The pre-chamber consisting 7 tangential nozzles has been compared to the pre-chamber with 7 tilted nozzles. It has been noted, that combustion cycles performed at λ = 1.5 indicate bigger cyclic variation of Pmax, regarding both their values and the occurrence time instance. The tangential nozzles achieved worse results in these points. For bigger mixture dilution, the nozzles rotation influencing the mixing inside pre-chamber and generating additional charge motion in the main combustion chamber. In contrast to the high load point (λ = 1.3), prechamber with tangential nozzles provided slightly bigger Pmax and HRRmax. However, the application of tilted nozzles resulted in earlier occurrence of HRRmax, confirming therefore improved prechamber mixing and positive results from introduced charge movement inside main combustion chamber.

Acknowledgements

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Nomenclature

A area
av average point
CNG compressed natural gas
CR compression ratio
D diameter
e energy
g thickness
HRR heat release rate
IMEP indicated mean effective pressure
MC main chamber
m mass
n engine speed
NO_x nitrogen oxides
p pressure
PC pre-chamber
q_o fuel dose
RCM rapid compression machine
SI spark ignition
SOI start of ignition
TJI turbulent jet ignition
V volume
λ air fuel equivalence ratio
Ø fuel air equivalence ratio

Indexes

d driving (start)
DIS discharge
MC main chamber
o overall
OA optical access
PC pre-chamber
t thermal
tot total
V volume

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Wojciech Bueschke, DEng. – Faculty of Transport Engineering, Poznan University of Technology.
e-mail: *Wojciech.Bueschke@put.poznan.pl*

Maciej Skowron, MEng. – Faculty of Transport Engineering, Poznan University of Technology.
e-mail: *Maciej. Skowron@put.poznan.pl*

Prof. Krzysztof Wislocki, DSc. DEng. – Faculty of Transport Engineering, Poznan University of Technology.
e-mail: *Krzysztof.Wislocki@put.poznan.pl*

Filip Szwajca, MEng. – Faculty of Transport Engineering, Poznan University of Technology.
e-mail: *Filip.Szwajca@put.poznan.pl*