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DETECTION OF KNOCKING COMBUSTION IN A SPARK IGNITION ENGINE USING OPTICAL SIGNAL FROM THE COMBUSTION CHAMBER

DETEKCJA SPALANIA STUKOWEGO W SILNIKU O ZAPŁONIE ISKROWYM ZA POMOCĄ SYGNAŁU OPTYCZNEGO Z KOMORY SPALANIA

The aim of the presented research was to investigate spectral properties of the combustion flame with special regard to the detection and estimation of intensity of knocking combustion. Research was made using modified single cylinder test engine with spark ignition (SI) equipped with an optical sensor having direct access to the combustion chamber. Measurements were based on wideband intensity of optical radiation and chemiluminescence phenomena occurring in the combustion flame under the influence of high temperature and pressure. Spectral recordings were done for wavelengths typical for emission of intermediate products, covering the range from 250 nm to 625 nm, including typically investigated radicals like C_2, CH, CN, OH. Obtained results confirmed, that occurrence and intensity of knock can be determined on the basis of further signal analysis. Comparison with in parallel recorded indicated pressure have shown that characteristics of emitted spectra is more sensitive to the changing of engine operating conditions.

Keywords: *knocking combustion, optical measurements, spectral flame properties, chemiluminescence, fiber optics.*

Celem prezentowanych badań było zbadanie widmowych własności płomienia w komorze spalania ze specjalnym uwzględnieniem możliwości detekcji i oceny intensywnosci spalania stukowego. Badania zostały wykonane na zmodyfikowanym jednocylindrowym silniku o zapłonie iskrowym (ZI), wyposażonym w optyczny czujnik z bezpośrednim dostępem do komory spalania. W pomiarach wykorzystano zjawiska szerokopasmowej emisji optycznej oraz chemiluminescencji towarzyszące spalaniu mieszanki paliwowo-powietrznej. Sygnał optyczny poddawano filtracji, wyodrębniając długości fal typowe dla emsji produktów przejściowych, w zakresie od 250 do 625 nm, obejmującym typowe rodniki takie jak C_2, CH, CN oraz OH. Uzyskane rezultaty potwierdziły, że pojawienie się i intensywność spalania stukowego mogą zostać ocenione na podstawie dalszej analizy sygnału zarejestrowanego zarówno w szerokim paśmie promieniowania jak i dla widma chemiluminescencji poszczególnych rodników. Porównanie z rejestrowanym równocześnie przebiegiem ciśnienia pokazało, że emitowane widmo jest bardziej wrażliwe na zmiany warunków pracy silnika.

Słowa kluczowe: *spalanie stukowe, szerokopasmowy sygnał optyczny, rodniki, chemiluminescencja.*

1. Introduction

An abnormal combustion resulting with knock phenomenon can occur in cylinders of both, spark ignition and compression ignition engines. Resulting pressure oscillations lead to deterioration of engine cycle efficiency, dramatic increase of exhaust emissions, as well as provide engine noise. Severe knock results in substantial reduction of engine lifetime and, in extreme cases can lead to damage of the engine. Typical engine damages caused by knock are cracks and fractures of the piston crown and piston-rings grooves as a result of shock wave action. Intensive knock occurring for a long period can even lead to piston seizure and melting of its edges [13]. Considering the recent trends in spark ignition engines development, i.e. downsizing, turbo- or supercharging and increase of compression ratios, knocking combustion poses a challenge for numerous researchers. Without exception, all actually being developed solutions for spark ignition engines are in favor of increasing knock risk [1, 5, 31].

Although a huge effort was done to understand knocking combustion, what can be confirmed by many scientific publications [11, 23], knock is yet not completely understood phenomena accompanying combustion in spark-ignition gasoline engines.

In general, scientific sources distinguish two mechanisms leading to knock: self-ignition and detonation [13, 24, 28]. Theory of self-ignition assumes spontaneous initiation of combustion in the part of the combustion chamber which lies usually in the most distant location from the spark-plug. Self-ignition zone is defined as end-gas region containing unburned charge. When temperature and charge pressure reach boundary conditions, a spontaneous self-ignition takes place in one or more points simultaneously. A very violent explosion follows, resulting in pressure waves, which oscillating, create typical sound effects. Theory of detonation in turn assumes initiation of knocking as a result of flame front propagation, which accelerates with supersonic speed from the spark-plug towards surrounding end-gas and peripheries of the combustion chamber. This creates shock wave (detonation), which reflects from the combustion chamber walls with its resonant frequency. Resulting momentary pressure changes but have high amplitude and cause typical knocking sounds.

Describing different types of knocking combustion occurring during vehicle operation, one can also distinguish knock related to the acceleration and knock at constant rotational speed of the engine [19]. It is accepted, that knock taking place during acceleration is mainly a burdensome effect for the driver and his passengers. Knocking combustion occurring at the constant rotational speed of the engine (high speed driving) is usually hard to recognize, but can lead to the heavy engine damage.

There are two main reasons why knock should be avoided. First is the sound emitted by the engine during knocking combustion. Sounds emitted from the engine compartment can be nuisance for the driver, but the can be efficiently limited by improvement of the acoustic insulation. More serious problem is the fact, that self-ignition in the combustion chamber can lead to the engine damage. It is the reason, why engine manufacturers have introduced many countermeasures aimed at elimination of the knocking phenomena, as soon as it appears.

Detection and control of knocking combustion have become essential components of control systems in modern engines. Nowadays all contemporary SI engines are controlled on the border of knock limit in case of full load or higher partial load operation, what allows for reaching maximum fuel efficiency. In this context, precise recognition of knock occurrence and definition of its intensity are of great importance. In the series engines the most commonly knock detection method is based on the application of vibration sensors (accelerometers, knock sensors), which transmit vibration of engine components (usually engine block) [4]. Typically in the 4 cylinder engines, a pair of knock sensors is used. Knock detection is based on the analysis of time or frequency representations of the gathered vibration signal, however available specifications of signal properties recorded during knocking combustion are of low coherence. The most significant weakness of this method is very low signal-to-noise ratio, especially at higher engine speeds, resulting from high background noise level. In consequence, close-loop engine control is either impossible or retarded ignition is used as countermeasure what decreases engine efficiency and power [4].

Knock identification using pressure transducers inherits most of weaknesses mentioned above. However, in extreme situations pressure sensor cannot record any oscillations, as it can be located directly in the vibration's node of the combustion chamber. Moreover, misinterpretations of the self-ignition phenomena on the basis of the pressure signal can arise from the fact, that self-ignition has cyclic variability, even with the same in-cylinder pressures [3], e.g. due to variability of fuel concentration in the combustion chamber [8].

2. Knock detection using optical methods

As it was stated above, the main problem of knock detection is related to the exact separation of knock signal, according to the engine operating conditions. Frequency analysis of the engine block vibrations permits only rough estimation of knock intensity. Objective evaluation of knock intensity is possible, but it requires precise separation of knock signal from the primary signal of engine operation using band-pass filtering.

Optical and optoelectronic methods have become commonly used tool in the combustion research, what is confirmed by many publications [7, 22, 27]. Application of optical combustion sensors has some significant advantages in comparison to vibration knock sensors or pressure measurements. Their operation is not influenced by any mechanical or electrical disturbances, and they offer high speed of data processing with relatively low invasiveness in the process course (comparable with pressure sensors).

Intensity of optical radiation varies with crankshaft position and engine load, there is also randomness of the signal resulting from variability of consecutive combustion cycles. In case of wide-band optical radiation intensity, identification of knocking combustion can be done using some numerical or functional features of the signal, like peak values of the radiation intensity, mean value of total optical radiation or changes in radiation intensity during combustion. Furthermore, application of optical-fiber methods can be used for identification of the self-ignition location in the combustion chamber [10, 29]. Occurrence of knock creates also changes in the spectrally measured intensity of optical radiation – i.e. at wavelengths corresponding to the optical emission of certain radicals existing in the combustion flame [25].

3. Spectrophotometry in combustion research

One of the promising techniques used in combustion diagnostics is based on estimation of concentrations of radicals existing in the flame. Investigation of radicals emission has many applications in the combustion diagnostics, like estimation of air-fuel ratio or local flame temperature, detection of knock or/and misfire [12, 17, 24, 27, 32, 33].

Concentration of radicals can be estimated using gas chromatography, mass spectrometry, electron paramagnetic resonance, laser induced fluorescence, ion current measurement [18] as well as spectrophotometric methods [6, 30]. Measured must be made only in the flame zone directly in the combustion chamber – it is not possible to isolate gases to make chemical analysis. Most reliable and relatively inexpensive methods used to acquire information about concentration of radicals are luminescence methods [25, 26] based on the measurement of spontaneous optical emission accompanying combustion process, recorded in a narrow bandwidth enabling evaluation of radicals' concentration in the reaction zone of the combustion flame.

In the flames of internal combustion engine there is constant thermal emission and linear emission resulting from transitions of molecules from higher to lower electron states. Simplifying, total radiation L is a sum of thermal radiation of combustion products $L_{\text{therm-prod}}$, thermal radiation of intermediate products $L_{\text{therm-int}}$ and chemiluminescence L_{chlum} of radicals $L = L_{\text{therm-prod}} + L_{\text{therm-int}} + L_{\text{chlum}}$.

Depending on which component of the emission is dominant, the course of the optical emission curve will alter. If the source of the radiation were chemiluminescence only, values of the optical emission signal would be proportional to the speed of heat generation. Mechanisms governing the existence of molecules are not completely recognized, but main chemical reactions are identified [10, 12]. The strongest source of chemiluminescence of hydrocarbon flames are radicals OH, CH and C_2 formed in the electron-excited states [32]. CH and C_2 radicals are present mostly in the reaction zone. Other relatively strong emission sources are radicals of HCHO, HCO, CN and NH [2, 20]. Fig. 1. presents main emission lines of molecules existing in the hydrocarbon flames. Emission cannot be however unequivocally identified with concentration of radicals. Resultant luminescence is a product of radicals' concentration and transition probability between excited and basic state.

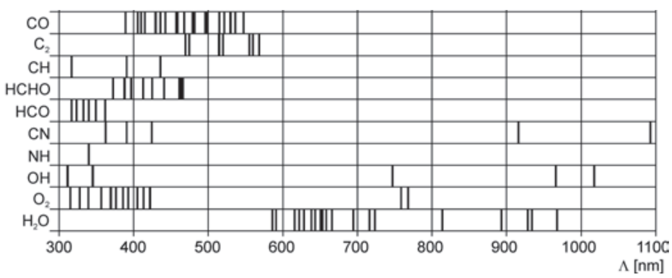

Fig. 1. Emission lines of some radicals existing in the hydrocarbon flames of IC engines [9]

Intensity of chemiluminescence is strongly correlated with combustion parameters, such as pressure, temperature and mixture composition [6]. It can be also modified by phenomena of abnormal combustion, for example engine knock. Development of optical combustion sensors, measurement methods and consecutive research of SI engines are in the scope of research activities of the authors [16], and considers detection of abnormal combustion [21, 22], measurements of flame kernel development [14] as well as identification of diffusion flames in a partially stratified controlled auto-ignition engine [15].

4. Experimental research

Aim of the research. Presented experimental research was aimed at more comprehensive understanding of unwanted phenomena like knock occurrence. Research and further signal analysis were also supposed to settle the question, whether it is possible to use similar signal processing procedures which are used in knock detection algorithms based on the pressure analysis in relation to the signal of optical radiation. Results shown in this paper illustrate usage of autocorrelation function of the wide-band optical radiation intensity signal for the detection of knock and estimation of its intensity. The scope of described research is related to the characteristics of optical radiation recorded within several wavelengths, in conditions of normal and knocking combustion.

Research engine and measurement system. Research was done using modified Honda GX390 one-cylinder, air-cooled SI engine. Engine was retrofitted with specially designed electronic ignition and fuel injection systems controlled by the dedicated PC software. Table 1 shows main technical parameters of the modified Honda GX390 engine. The test stand and measurement system as well as complete description of the measurement system, its components and procedures regarding calibration techniques of the sensor can be found in previous publications of the authors [17, 21, 22, 23].

Table 1. Modified Honda GX390 test engine – main technical characteristics

Engine displacement	$V_s = 0.390$ dm^3
Cylinder diameter x piston stroke	D x S = 88 x 64 mm
Compression ratio	$\varepsilon = 8.0$
Maximum power	N_e = 8.7 kW (11.8 KM) at 3600 rpm
Maximum torque	M_o = 26 N·m at 2500 rpm

Measurement system was based on the optical combustion sensor recording intensity of optical radiation emitted from the combustion chamber. Sensor was mounted in the engine head and had direct access to the combustion chamber. System consisted of the optical combustion sensor with direct access to the combustion chamber coupled to the transmission fiber-optic bundle (lightguides), monochromator, photodetector and A-D acquisition card installed in a PC computer which recorded gathered data. Fig. 2 presents general set-up of the measurement system.

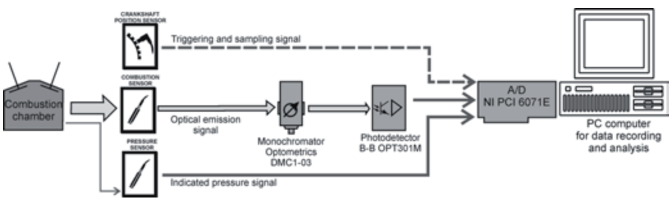

Fig. 2. General scheme of measurement system used for recording optical radiation from the combustion chamber

Panchromatic optical radiation was recorded using transducer with transmission band from 200 to 800 nm and peak sensitivity at 750 nm, then amplified. Emission spectrum from the combustion chamber war recorded using reticular monochromator with measurement range from 200 to 1100 nm. Operating frequency was set manually with accuracy 0.2 nm. Width of entry and exit slots is 600 μm, what gives in result band-pass of 4.4 nm.

During the whole cycle of experiments spectral measurements were done for 12 wavelengths, typical for emission of intermediate products (table 2). They are chemiluminescence traces of various radicals existing in the flame which are most commonly used in the spectrophotometric engine research. For every wavelength 100 consecutive engine cycles were recorded. Triggering and sampling signals were supplied by crankshaft position sensor, and instantaneous optical signal was recorded with resolution of 0.1°CA (crankshaft angle).

Table 2. Wavelengths of intermediate radical emissions and their measurement codes

Compound symbol	Characteristic wavelength [nm]	Measurement code
OH	282.9	**L01**
CH	314	**L02**
CH	431.4	**L03**
NH	336	**L04**
C_2	473	**L05**
HCO	318.6	**L06**
OH	306.4	**L07**
CH	387.1	**L08**
CN	388.3	**L09**
HCHO	395.2	**L10**
C_2	516.5	**L11**
HCO	329.8	**L12**

Research was done for different engine operating conditions: engine speed (n): 1600, 2500, 3500 rpm; throttle positions (a_p): 30, 60, 90%, ignition advance (i_a): 25–65°CA BTDC (crankshaft angle before top dead center). Mixture composition was always set manually by the operator to stoichiometric on the basis of readouts from wide-band lambda probe and exhaust gas analyzer. For comparative analysis a pressure signal was simultaneously recorded using miniature piezoelectric pressure transducer mounted in the spark-plug (AVL GU13Z-24).

5. Data processing and analysis

Onset of knock results in rapid increase in intensity of optical radiation I_{opt}, next it changes in accordance with indicated pressure p_i. Changes of intensity of optical radiation can be associated with high frequency pressure waves which reinitialize luminescence of burned gasses as a result of adiabatic heating. In case of boundary conditions – i.e. at knock limit – pressure traces would not indicate occurrence of knock, whereas optical signal shows rapid growth in value resulting from the presence of auto-ignition centers. This phenomena was confirmed by other researchers [25, 32]. Fig. 3 presents examples of traces of intensity of wide band optical radiation (I_{opt}) and indicated pressure (p_i) recorded for two different engine operation conditions. Knocking combustion was present at n = 3500 rpm, a_p = 90%, i_a = 55ºCA BTDC, whereas at ignition advance of 40ºCA BTDC normal combustion was identified. Magnitude of wide band optical radiation intensity in knock conditions has greater span of changes.

Autocorrelation analysis of the wide-band optical radiation intensity signal I_{opt} obtained from the combustion chamber in different engine operating conditions (rotational speed – load – ignition advance) has shown that it has much higher dynamics of changes resulting from different engine operating conditions. This confirms previous observations regarding higher influence of engine operating conditions on the changes of optical signal in comparison to the indicated pressure [22, 23].

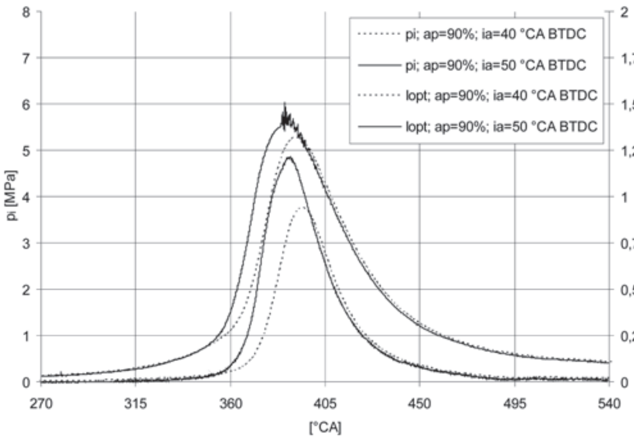

Fig. 3. *Comparison of indicated pressure (p_i) and intensity of wide band optical radiation (I_{opt}) for normal and knocking combustion as a function of crankshaft position*

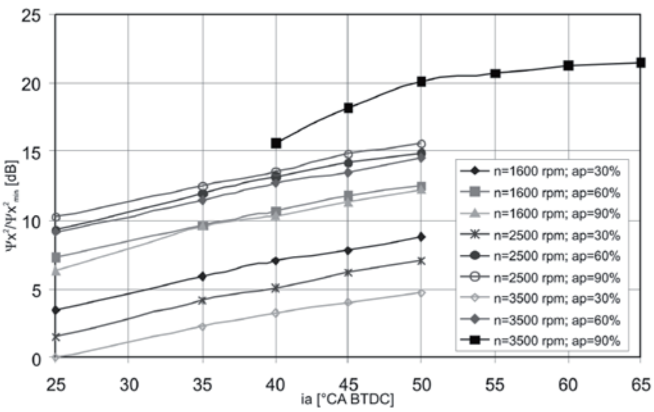

Fig. 5. *Relative root mean square rms ($\Psi_x^2/\Psi_{x\,min}^2$) of the I_{opt} signal for different engine operating conditions and different ignition advances (averaged from 100 consecutive cycles)[23]*

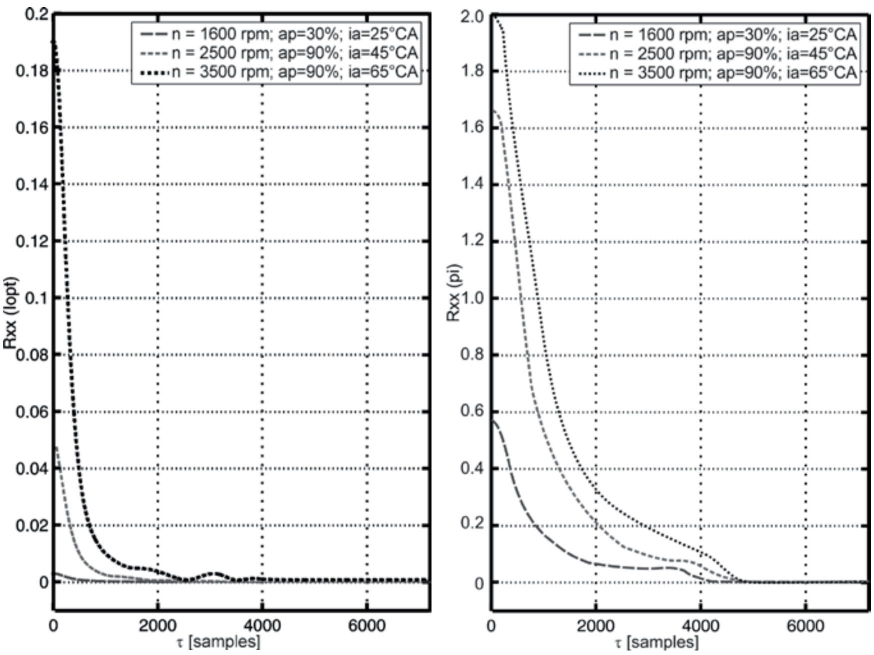

Fig. 4. *Autocorrelation function of I_{opt} (left) and p_i (right) signals obtained for single engine cycle averaged from 100 consecutive runs, at different engine operating as a function of time shift*

Such dependence can be observed on the charts shown on fig. 4. There is much higher dynamics of span changes of the autocorrelation function calculated for the intensity of optical radiation in relation to the indicated pressure: 11.3 and 18.0 dB for $R_{xx}(I_{opt})$ whereas for $R_{xx}(p_i)$ correspondingly it is only 4.6 and 5.5 dB. Autocorrelation function of indicated pressure p_i approaches zero significantly slower than it is in case of I_{opt}. It can point to the fact, that optical signal can be characterized by higher speed of changes and presence of quick-changing components in the analyzed courses, especially that graphs presented on fig. 4 were averaged from 100 consecutive runs.

For the time shift $\tau = 0$ autocorrelation function equals to root mean square (rms) Ψ_x^2 which is a common measure of signal energy. Fig. 5 shows rms values of I_{opt} signal for all investigated engine operating conditions. So as to make comparisons easier, individual values are represented in relative values, referred to minimum value of $\Psi_{x\,min}^2$.

Onset of knocking combustion is accompanied by the increase of transmitted energy, which is visible as an increase of its root mean square value. This phenomena can be clearly observed for the engine rotational speed n = 3500 rpm, throttle position a_p = 90% and ignition timings i_a equal to 50, 55, 60 and 65°CA BTDC. Relative changes of signal rms values ($\Psi_x^2/\Psi_{x\,min}^2$) calculated for combustion without knock phenomena, independent from engine operating conditions were contained in the range <1÷20>. Increase of engine load and ignition advance leading to knock resulted in the increase of relative Ψ_x^2 values – maximum value calculated during the research was 141.77.

So as to more precisely describe characteristic features of autocorrelation function resulting from the presence of knocking combustion, it was necessary to analyze filtered combustion courses. Slow changing component related to cyclic combustion was removed.

Detailed data analysis has shown, that in all cases of researched engine operating conditions au-

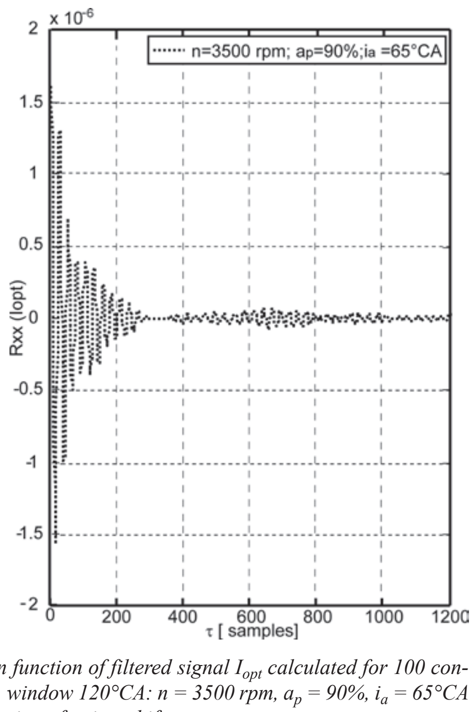

Fig. 6. *Autocorrelation function of filtered signal I_{opt} calculated for 100 consecutive cycles, window 120°CA: n = 3500 rpm, a_p = 90%, i_a = 65°CA BTDC as a function of a time shift*

tocorrelation function of filtered data decreases relatively quickly, and for higher values of shift τ, a Gaussian noise was observed. However, for operating conditions with presence of knocking combustion, periodic components were are clearly visible (fig. 6). Presence of these components should be therefore related to the knock phenomena.

Onset of knock results in much slower decrease of autocorrelation function, moreover its values in case of knock are higher even by one order of magnitude. Observed dependence can result from simultaneous existence of many, superimposing combustion spots, which increase intensity of recorded optical radiation signal. More detailed discussion of optical measurements within the visible light range (wide-band) can be found in [21].

In the described experiments acquired optical radiation was spectrally filtered so as to obtain chemiluminescence traces of the commonly used radicals existing in the flame (see table 2). Further signal analysis was done in a function of angular crankshaft position. Fig. 7 presents emission traces of all measured radicals recorded in full load conditions of engine operation. Significant high frequency noise is visible in all bands, which results from electrical interference generated by the spark discharge. It can be assumed, that location of the optical probe in the combustion chamber allowed for recording of initial phase of combustion – clearly visible are local peaks of radiation in the range 310-320°CA following the ignition which took place at 310°CA. Relatively high level of radiation corresponds to the emission in bands L03 (CH, 431.4 nm), L11 (C_2, 515.5 nm), L10 (HCHO, 395.2 nm), L05 (C_2, 473 nm), L09 (CN, 388.3 nm) and L08 (CH, 387.1 nm), whereas bands L02 (CH, 314 nm), L06 (HCO, 318.6 nm) L12 (HCO, 329.8 nm) and L04 (NH, 336.4 nm) are up to 15 times smaller in magnitude. A good conformity between emission peaks and maximum of the indicated pressure can be also observed.

Fig. 8 shows emission traces of some of the radicals recorded at engine operating conditions without knocking combustion. The highest level of radiation corresponds to the emission in bands L03 (CH, 431.4 nm), L11 (C_2, 515.5 nm), L09 (CN, 388.3 nm) and L08 (CH, 387.1 nm). In comparison with results shown on fig. 7, obtained for the full load operation conditions, traces of the bands L10 (HCHO, 395.2 nm) and L05 (C_2, 473 nm) remained at very low level. It is also noteworthy that at low engine load and low rotational speed (fig. 8), optical power of the emission corresponding to the L03 band (CH, 431.4 nm) was approx. 20% higher than power generated at full load and high engine speed (fig. 7). This probably can be associated with more stable course of combustion. Knocking combustion shown on fig. 8 resulted in significant increase of the measured optical power – for the “strongest” band L03 it was approx 2.7 times higher relative to non-knocking conditions presented on fig. 7. Is should be also noted that in case of regular (i.e. without knock) combustion emission peaks were retarded 3–5°CA relatively to the maximum of the indicated pressure (fig. 7), whereas in case of knock (fig. 8) no shift was observed.

Fig. 9 presents emission traces of the CH (L03 – 431.4 nm) recorded at different engine operating conditions at different engine speeds (1600, 2500 and 3500 rpm), loads (a_p = 30% and 90%) and ignition advances (i_a) of 30°CA BTDC (fig. 8, upper) and 50°CA BTDC (fig. 8, lower). It can be observed, that conditions which can lead to the knocking combustion – i.e. low rotational speed and high load – result in high levels of recorded emission power. Early ignition – i.e. ignition advance – significantly increases emission power. In case of CH emission (431.4 nm) at 1600 rpm and a_p = 90%, the difference in spectral power is up to 80% for two ignition advances.

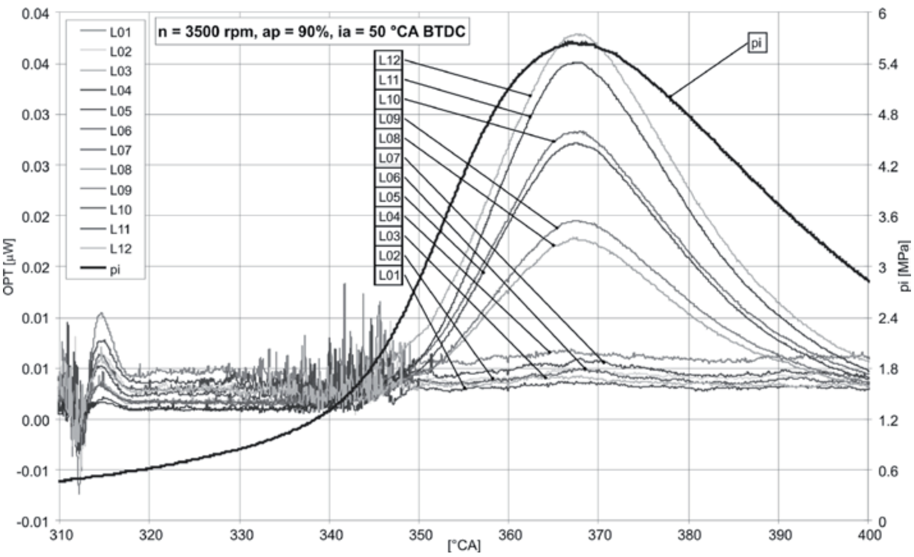

Fig. 7. Emission lines of all measured radicals and indicated pressure p_i for full load operating conditions as a function of crankshaft position

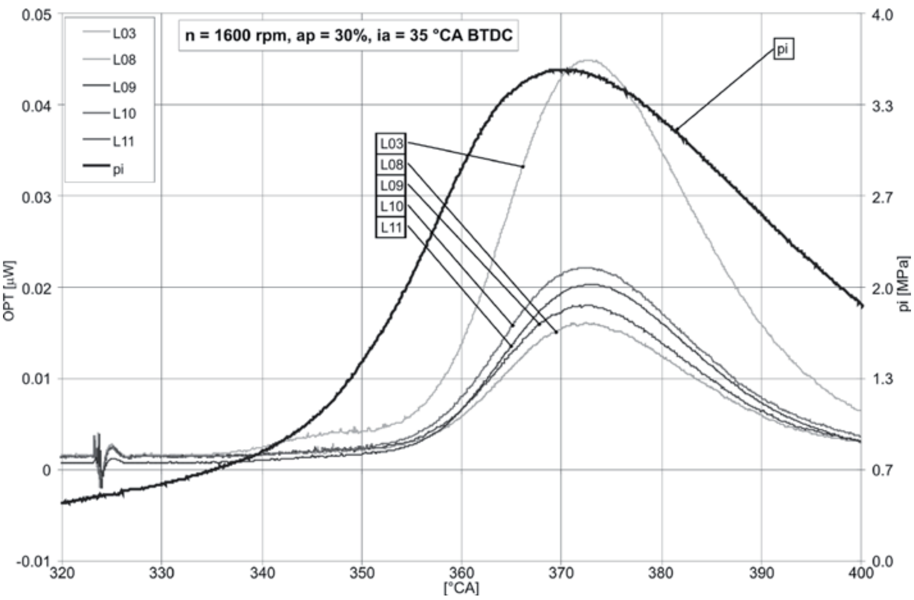

Fig. 8. Emission lines of radicals L03 – CH, L08 – CH, L09 – CN, L10 – HCHO, L11 – C_2 and indicated pressure p_i for engine operating conditions without knocking combustion as a function of crankshaft position

6. Conclusions

Analysis of the results shows, that resultant wide-band optical radiation is more sensitive to the changing engine operating conditions in a wide-band region and less susceptible to the external interferences in comparison to the indicated pressure. A higher dynamics of span changes of the autocorrelation function calcu-

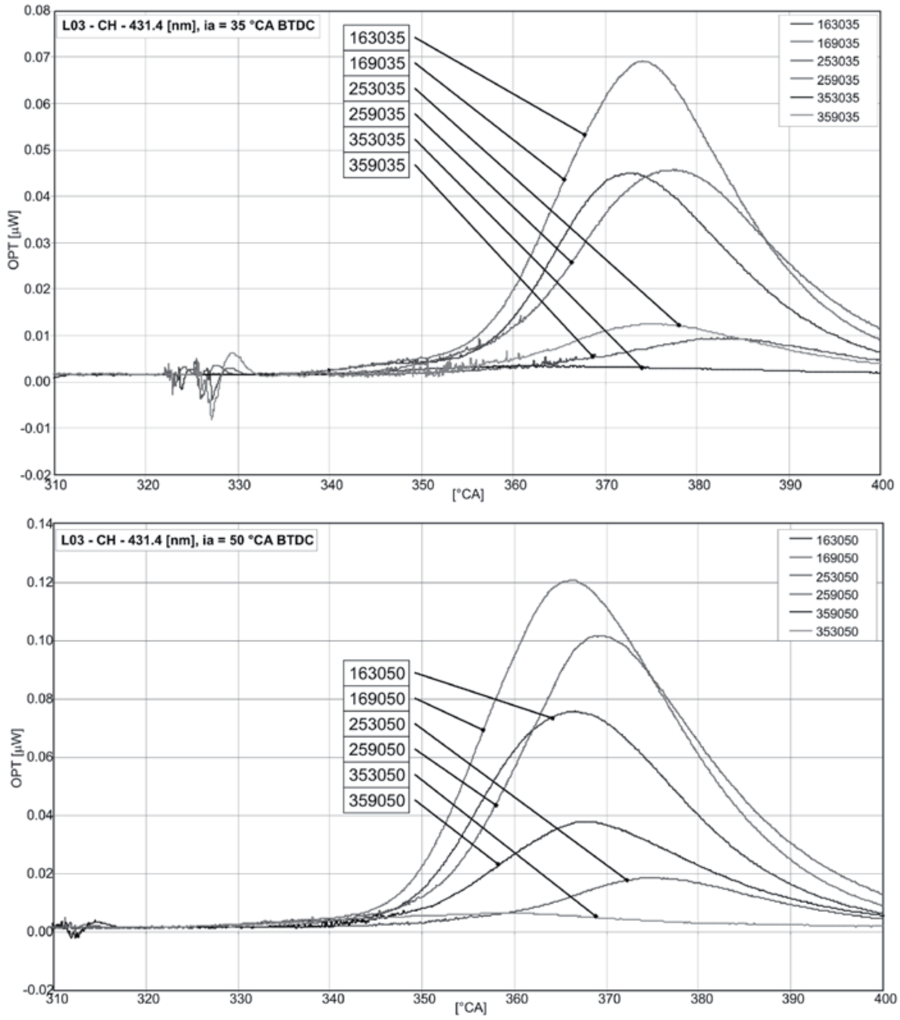

Fig. 9. Emission of CH radicals measured at 431.4 nm at different engine speeds (1600, 2500 and 3500 rpm), loads (a_p = 30% and 90%) and ignition advances (i_a) of 30°CA BTDC (upper) and 50°CA BTDC (lower) as a function of crankshaft position

lated for the intensity of optical radiation can be also observed. Detailed analysis of results presented in this paper shows that autocorrelation function calculated for the intensity of optical radiation during knocking combustion shows periodic components.

Onset of knock results in much slower decrease of autocorrelation function, moreover its values in case of knock are higher even by one order of magnitude. Knock results also in a significant increase of the root mean square calculated for the signal. This can result from simultaneous existence of many, superimposing combustion spots. Violent increase of energy transmitted by the signal directly influences intensity of recorded optical radiation signal.

Recorded flame spectrum had very strong levels of emission lines of OH, CH and C_2 radicals typical of homogenous mixtures. In all recorded cases the strongest emission levels were obtained for CH at 431.4 nm (L03) and C_2 at 516.5 nm (L11), their magnitude varied depending on engine operating conditions. In knocking conditions relatively strong emission of HCHO (395.2 nm – L10) was observed – a radical typical of cold flames emerging in self-ignition centers.

Further and more detailed data analysis is required, including estimation of heat release and detailed quantitative and qualitative analysis of recorded emissions.

References

1. Alkidas AC. Combustion advancements in gasoline engines. Energy Conversion and Management 2007; 48: 2751–2761.
2. Arias L, Torres S, Sbarbaro D, Ngendakumana P. On the spectral bands measurements for combustion monitoring. Combustion and Flame 2011; 158: 423–433.
3. Ballais R, Gallardo-Riuz JM, Merola SS. Optical diagnostics of the cycle-to-cycle variation in the kernel development and abnormal combustion SI. Journal of KONES Powertrain and Transport 2010; 17(2): 17–25.
4. Brecq G, Bellettre J, Tazerout M. A new indicator for knock detection in gas SI engines. International Journal of Thermal Sciences 2002; 42: 523–532.
5. Brewster S. Initial Development of a Turbo-charged Direct Injection E100 Combustion System. SAE Technical Paper 2007; 2007-01-3625.
6. Chang C, Clasen E, Song K, Campbell S, Rhee KT, Jiang H. Quantitative imaging of in-cylinder processes by multispectral methods. SAE Technical Paper 1997; 970872.
7. Docquier N, Candel S. Combustion Control and Sensors a Review. Progress in Energy and Combustion Science 2002; 28: 107–150.
8. Fansler TD, Drake MC, Stojkovic B, Rosalik ME. Local Fuel Concentration, Ignition and Combustion in a Stratified Charge Spark Ignited Direct-Injection Engine Spectroscopic, Imaging and Pressure-Based Measurements. International Journal of Engine Research 2003; 4(2): 61–87.
9. Fischer J, Kubach H, Tribulowski J, Spicher U. Analyse der Zylinderinnerströmung und des Verbrennungsverhaltes bei Ottomotoren mit Direktteinspritzung. 5. Internationales Symposium für Verbrennungsdiagnostik 2002: 177–192.
10. Gaydon AG, Wolfhard HG. Flames Their Structure, Radiation and Temperature. London: 1979.
11. Griffiths JF., Whitaker BJ. Thermokinetic interactions leading to knock during homogenous charge compression ignition. Combustion and Flame 2002; 131: 386–399.
12. Hardalupas Y, Orain M. Local measurements of the time-dependent heat release rate and equivalence ratio using chemiluminescent emission from a flame. Combustion and Flame 2004; 139: 188–207.
13. Heywood JB. Internal combustion engine fundamentals. McGraw–Hill, New York: 1988.

14. Hunicz J. Experimental research of flame kernel development and its relation to cycle-to-cycle variability of homogenous charge spark ignition engine. Archivum Combustionis 2009; 29 (1-2): 28–37.
15. Hunicz J, Kordos P. An experimental study of fuel injection strategies in CAI gasoline engine. Experimental Thermal and Fluid Science. 2011; 35(1): 243–252.
16. Hunicz J, Piernikarski D. Investigation of combustion in a gasoline engine using spectrophotometric methods. Proceedings of SPIE 2001; 4516: 307–314.
17. Hunicz J, Piernikarski D. Transient in-cylinder AFR management based on optical emission signals. SAE Technical Paper 2004; 2004-01-0516.
18. Kinoshita M, Saito A, Mogi K, Nakata K. Study on ion current and pressure behaviour with knocking in engine cylinder. JSAE Review 2000; 21: 483–488.
19. Leppard WR. Individual cylinder knock occurrence and intensity in multicylinder engine. SAE Technical Paper 1982: 820074.
20. Merola SS, Vaglieco BM. Knock investigation by flame and radical species detection in spark ignition engine for different fuels. Energy Conversion and Management 2007; 48: 2897–2910.
21. Piernikarski D. Statistic evaluation of usability of optical radiation intensity for the knock detection. Archivum Combustionis 2006; 26(3-4): 103–120.
22. Piernikarski D, Hunicz J. Diagnostics of abnormal combustion in a SI automotive engine using in-cylinder optical combustion sensor. Proceedings of SPIE 2004; 5566: 211–217.
23. Piernikarski D. Funkcja autokorelacji szerokopasmowej emisji optycznej w detekcji spalania stukowego. Silniki Spalinowe (Combustion Engines) 2009; 1(136): 44-51.
24. Saminy B, Rizzoni G. Engine knock analysis and detection using time-frequency analysis. SAE Technical Paper 1996; 960618.
25. Shoji H, Shimizu T, Nishizawa T, Yoshida K, Saima A. Spectroscopic Measurement of Radical Behavior Under Knocking Operation. SAE Technical Paper 1996; 962104.
26. Smith G, Luque G, Park C, Jeffries JB, Crosley DR. Low Pressure Determinations of Rate Constants for OH(A) and CH(A) Chemiluminescence. Combustion and Flame 2002; 131: 59–69.
27. Sohma K., Yukitake Y, Azuhata Y, Takaku Y. Application of Rapid Optical Measurement to Detect the Fluctuations of the Air-Fuel Ratio and Temperature of a Spark Ignition Engine. SAE Technical Paper 191; 910499.
28. Sun Z, Blackshear PL, Kittelson DB. Spark Ignition Engine Knock Detection Using In-Cylinder Optical Probes. SAE Technical Paper 1996; 962103.
29. Töpfer G, Reissing J,Weimar HJ, Spicher U. Optical Investigation of Knocking Location on S.I.-Engines with Direct-Injection. SAE Technical Paper 2000; 2000-01-0252.
30. Tosaka Y, Shoji H, Saima A. A study of the influence of intermediate combustion products on knocking. JSAE Review 1995; 16: 233–238.
31. Wildman C, Scaringe RJ, Cheng WK. On the maximum pressure rise rate in boosted HCCI operation. SAE Technical Paper 2009; 2009-01-2727.
32. Yang J, Plee S, Remboski D. Relationship Between Monochromatic Gas Radiation Characteristics and SI Engine Combustion Parameters. SAE Technical Paper 1993; 930216.

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