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KNOCK DETECTION USING SPECTRAL EMISSION OF FLAMES

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Abstract

Introduction of spectrophotometric methods into engine research considerably expands diagnostic possibilities of the work cycle in the internal combustion engine. Spectral analysis enables to determine concentrations of chemically active compounds – radicals, which are temporary present in the flame and do not constitute final products of the combustion. 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 si test engine equipped with an optical sensor having direct access to the combustion chamber. The sensor enabled on-line transmission of the transient optical signal during the combustion through the bundle of optical wave-guides. Measurements were based on the chemiluminescence phenomena occurring in the combustion flame under the influence of high temperature and pressure. Gathered signal was passed to the monochromator. Spectral recordings were done for wavelengths typical of emission of intermediate products, covering the range from 250 nm to 625 nm, including investigated radicals like C_2, CH, CN, OH. Obtained results confirmed, that occurrence of knock can be precisely detected on the basis of signal analysis which was recorded for chemiluminescence traces of different radicals. Comparison with in parallel recorded indicated pressure have shown that characteristics of emitted spectra remain in good conformity and are more sensitive to the changing of engine operating conditions.

Keywords: *knocking combustion, radicals, chemiluminescence, optical research*

1. Introduction

Research results and thermodynamic analysis of the working cycle of the automotive internal combustion engine show, that there is still unexploited potential related to the improvement of combustion systems used so far. Widely applied laboratory research methods, like combustion pressure measurement (engine indicating) are reliable source of information however, increasing variety of components used in engine design requires introduction of new, faster and better research procedures [2, 4]. Credibility of these methods must be supported by the deepened knowledge about the course of the single working cycle and its interactions with surrounding engine components.

Precise understanding of phenomena related to the combustion in the engine is of great importance, considering more stringent emission regulations, which force search of new design solutions, capable of fulfilling these requirements. A good example is constant development of engines with direct gasoline injection or introduction of new combustion systems, like lean burn with stratified charge or engines with variable compression ratio. Similar task is fulfilled by advanced diagnostic systems monitoring correct engine operation, which are already formulated within obligatory norms in the form of on-board diagnostics (EOBD). So as to correctly diagnose and in full extent understand course of gasoline combustion, and in parallel to widen knowledge regarding flame properties, it becomes necessary to develop new – including optical – methods of combustion research and diagnostics.

2. Spectrophotometry in combustion research

Optical and optoelectronic methods have become a commonly used tool in the combustion research in automotive engines, offering minimum invasiveness and high speed of data processing [18-21, 23]. 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, and is a very rich source of information [7, 10, 13, 20]. Concentration of radicals can be estimated using gas chromatography, mass spectrometry, electron paramagnetic resonance, laser induced fluorescence, ion current measurement [9] as well as spectrophotometric methods [1, 23]. 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 [10, 22] 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.

Chemiluminescence is a result of chemical processes, it is generated by excited atoms or molecules. Constant excitation of molecules results in their emission at typical wavelengths. Linear emission spectra at the ultraviolet and visible light bandwidth correspond to the reactions forming molecules in the electron-excited states. Gaseous products of combustion existing in the post-reaction zone are in thermodynamic equilibrium and have rotation-vibration bands in the red and infrared band. Soot particles emit constant thermal radiation. So, 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:

$$L = L_{therm-prod} + L_{therm-\text{int}} + L_{chlum} . \quad (1)$$

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 [6, 8]. The strongest source of chemiluminescence of hydrocarbon flames are radicals OH, CH and C_2 formed in the electron-excited states. 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. 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.

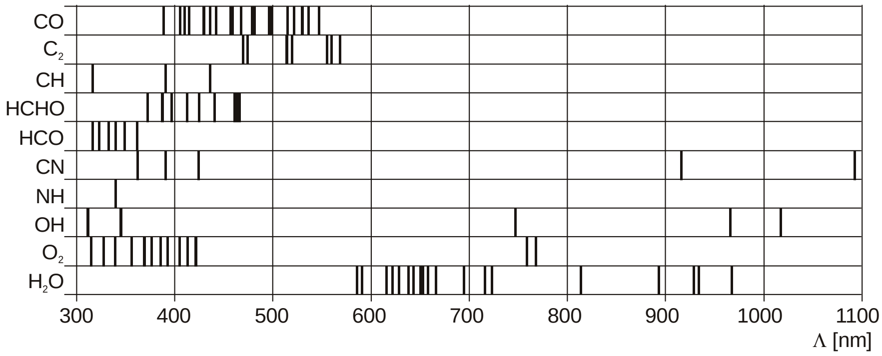

Fig. 1. Emission lines of some radicals existing in the hydrocarbon flames of IC engines [8]

For homogenous mixtures flame spectrum consists mostly of emission lines of OH, CH and C_2 radicals, and blue glow resulting from CO-O recombination in the range from 350 to 550 nm. Presence of excited particles of formaldehyde HCHO (strongest radiation at 395.2 nm) and HCO (318.6 nm and 329.8 nm) is typical of cold flames which emerging in self-ignition centers. Soot thermal emission is of minor importance. Such types of spectrum are typical of spark ignition engines fuelled with homogenous air-fuel mixture, with gasoline injection into the inlet manifold and for gas fueled engines. Intensity of chemiluminescence is strongly correlated with combustion parameters, such as pressure, temperature and mixture composition [4]. It can be also modified by phenomena of abnormal combustion, for example engine knock.

3. Knock detection using optical methods

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. Available specifications of signal properties recorded during knocking combustion are of low coherence, both in case of time and frequency domain interpretation. Knock detection is based mainly on the analysis of time or frequency representations of the accompanying processes. The most commonly used method is based on the application of vibration sensors [2, 3, 12], but its significant weakness 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 decreases engine efficiency and power. 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. The main problem of knock detection is related to the exact separation of knock signal from the primary signal and its frequency properties, according to the engine operating conditions.

In general, spectrofotometric knock detection using optical combustion sensor is based on the measurement of intensity of optical radiation during combustion, converting it to the electrical signal, and then analysis by the knock control system. Mentioned optical radiation can be measured either within wide-band spectra or at wavelengths corresponding to the chemiluminescence emission of certain radicals existing in a flame. Identification of knocking combustion can be done on the basis of peak values of the radiation intensity, mean value of total optical radiation or changes in radiation intensity during combustion. 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. Knock detection algorithms usually use the fact, that occurrence of knock creates significant changes in the intensity of optical radiation and increase of peak values and increasing output voltage of the detector.

4. Research engine and scope of measurements

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 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, detailed description of the engine and its modifications can be found in previous publications of the author [14, 15].

Measurement system was based on the set of optical combustion sensors recording intensity of optical radiation emitted from the combustion chamber. System consisted of the following components:

- optical combustion sensors with direct access to the combustion chamber,
- transmission fiber-optic bundle (lightguides),

- monochromator,
- photodetector,
- A-D acquisition card,
- PC microcomputer recording gathered data.

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

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

Complete description of the measurement system, its components as well as procedures regarding calibration techniques of the sensor can be found in previous publications of the author [13-17]. Fig. 2 presents general set-up of optical measurement system.

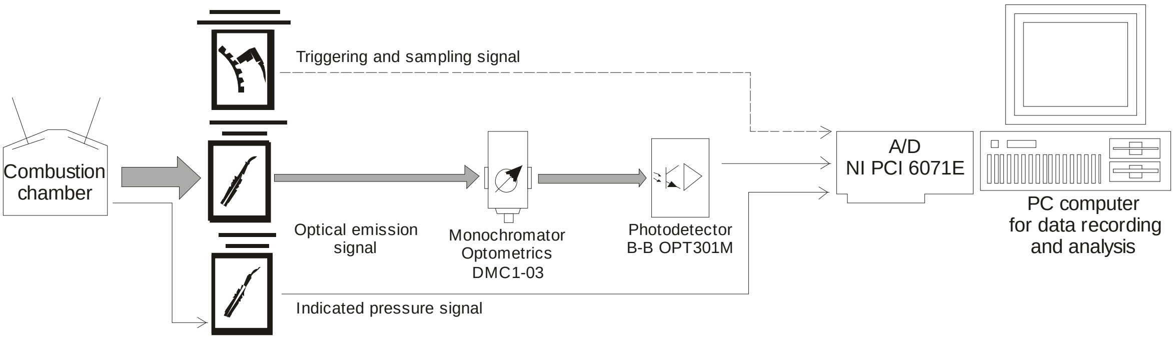

Fig. 2. General scheme of measurement system used for recording optical radiation from the combustion chamber

Recording emission spectrum from the combustion chamber as well as determination of attenuation curves of the sensor was done using reticular monochromator Optometrics DMC1-03 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.

In case of spectrophotometric measurements spectral attenuation characteristics of the whole optical measurement path is of great importance. The composition and intensity of deposits gathering on the sensor's tip depend on conditions of engine operation and its regulating parameters – mostly on the mixture composition. During preliminary engine research spectral characteristics of the complete optical measurement path was made (Fig. 3). So as to compensate for different sensitivities at different wavelengths, it was necessary to calculate gain coefficients corresponding to the different wavelengths used in the research. Later on, these coefficients were used to normalize measured power of spectral radiation.

During the whole cycle of experiments spectral measurements were done every 10 nm, however additional wavelengths were added, typical of emission of intermediate products. In this paper recordings obtained for 12 wavelengths are discussed (Tab. 2). They are chemiluminescence traces of various radicals existing in the flame which are most commonly used in the spectrophotometric engine research, and were chosen according to the literature research. For every wavelength 100 consecutive engine cycles were recorded. Filtered signals were passed to photodiodes integrated with amplifiers (Burr-Brown OPT301M) and then to instrumental amplifiers (Analog Devices AD210).

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 wideband lambda probe and exhaust gas analyzer.

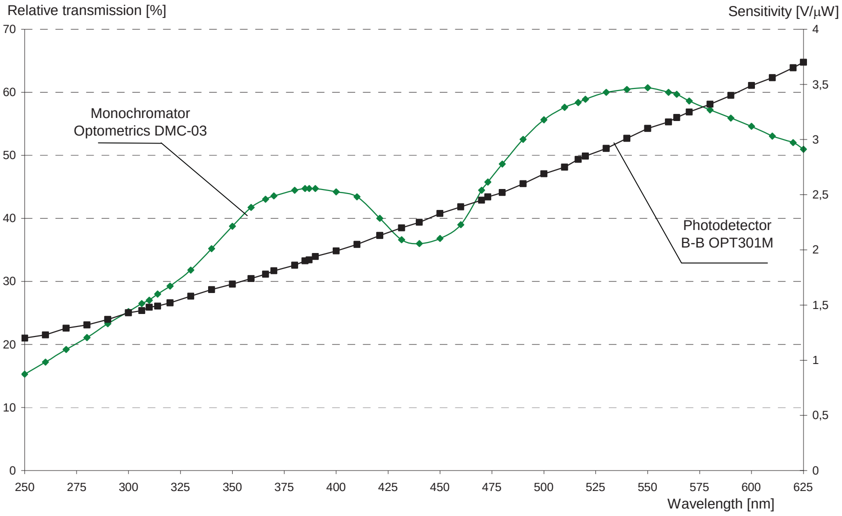

Fig. 3. Photodetector sensitivity and monochromator relative transmission as a function of measured wavelength

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

Compound symbol	Characteristic wavelength [nm]	Measurement code	Compound symbol	Characteristic wavelength [nm]	Measurement code
OH	282.9	01	OH	306.4	07
CH	314.0	02	CH	387.1	08
CH	431.4	03	CN	388.3	09
NH	336.0	04	HCHO	395.2	10
C_2	473.0	05	C_2	516.5	11
HCO	318.6	06	HCO	329.8	12

5. Data analysis

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 Tab. 2). Further signal analysis was done in a function of angular crankshaft position. Data processing was done using averaged emission traces obtained from 100 consecutive cycles. It should be stated, that presented results are of preliminary type and constitute only part of the research.

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 phenomenon was confirmed by other researchers [18, 21]. Figure 4 presents some 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, $a_{\text{p}} = 90\%$, $i_{\text{a}} = 55$ °CA BTDC, whereas at ignition advance of 40 °CA BTDC normal combustion was identified. Magnitude of wide band optical radiation intensity in knock conditions has greater span of changes. More detailed discussion of optical measurements within the visible light range (wideband) can be found in [16, 17].

Figure 5 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.

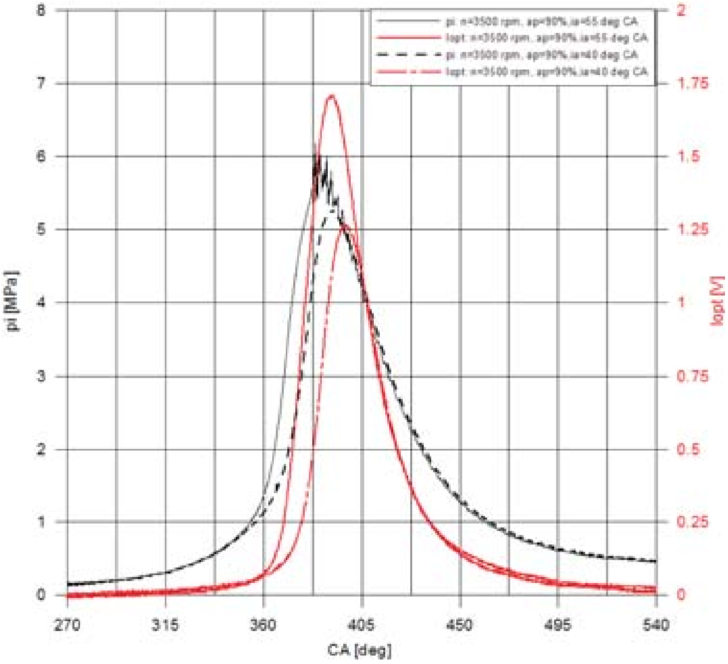

Fig. 4. Comparison of indicated pressure (p_i) and intensity of wide band optical radiation (I_{opt}) for normal and knocking combustion

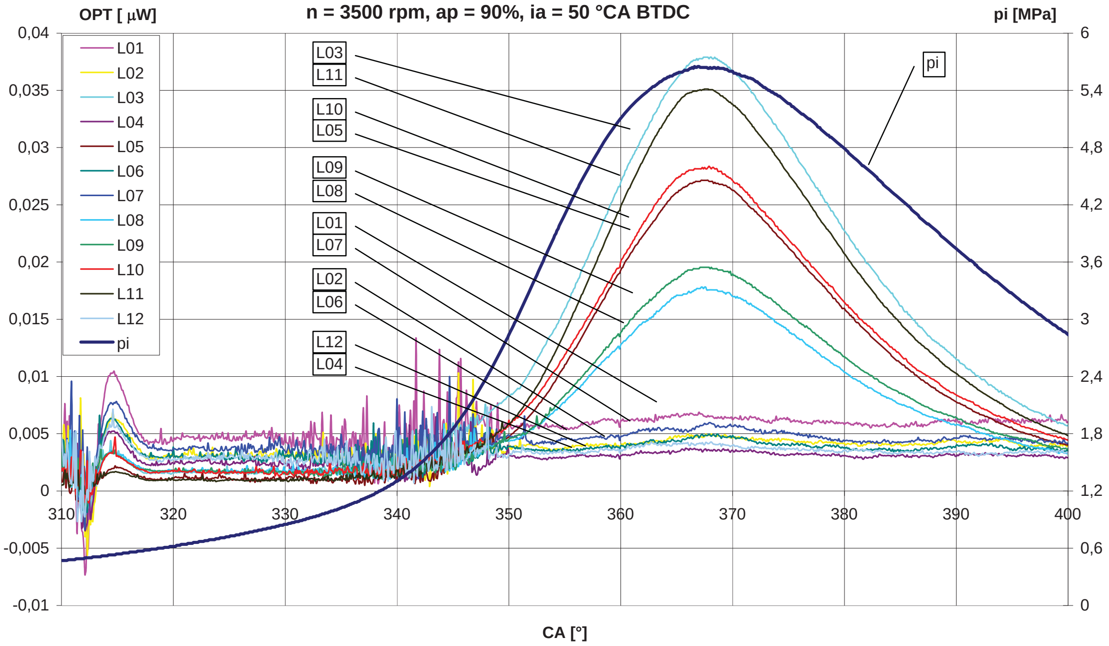

Fig. 5. Emission lines of all measured radicals and indicated pressure p_i for full load engine operating conditions

Figure 6 shows emission traces of some of the radicals recorded at engine operating conditions without knocking combustion. Again slight high frequency interference resulting from the spark discharge is visible. 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. 5, 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. 6), 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. 5). This probably can be associated with more stable course of combustion.

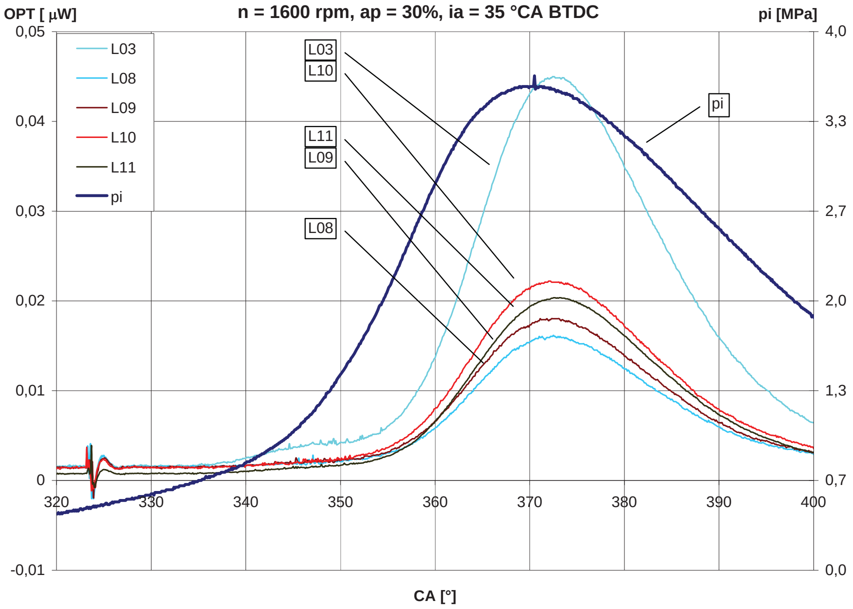

Fig. 6. Emission lines of radicals L03 – CH, L08 – CH, L09 – CN, L10 – HCHO, L11 – C_2 and indicated pressure p_i for engine operating conditions without knocking combustion

Knocking combustion shown on Fig. 7 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. 6. 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. 6), whereas in case of knock (Fig. 7) no shift was observed.

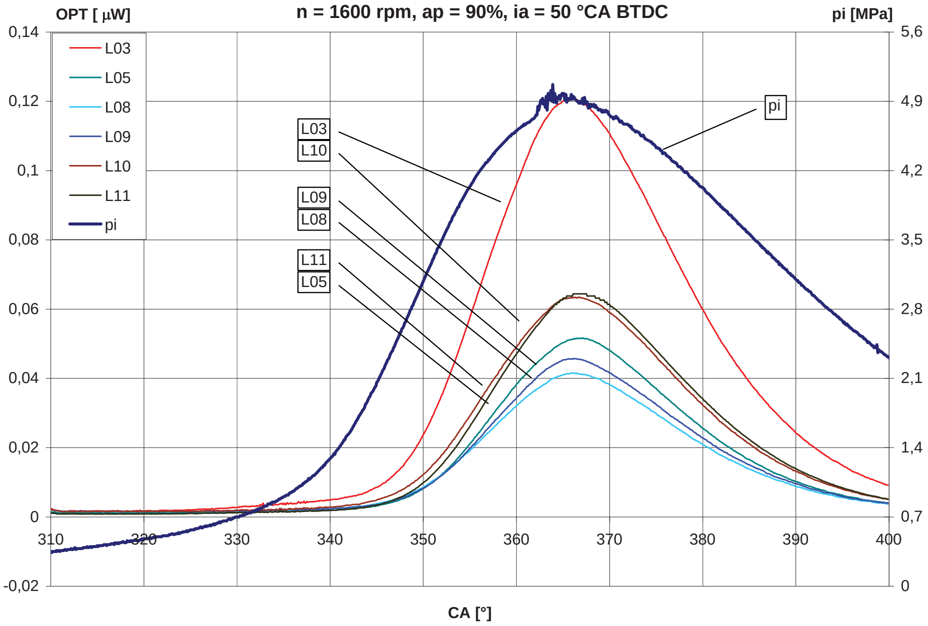

Fig. 7. Emission lines of radicals L03 – CH, L05 – C_2, L08 – CH, L09 – CN, L11 – C_2 and indicated pressure p_i for engine operating conditions with occurrence of knock

Figure 8 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.

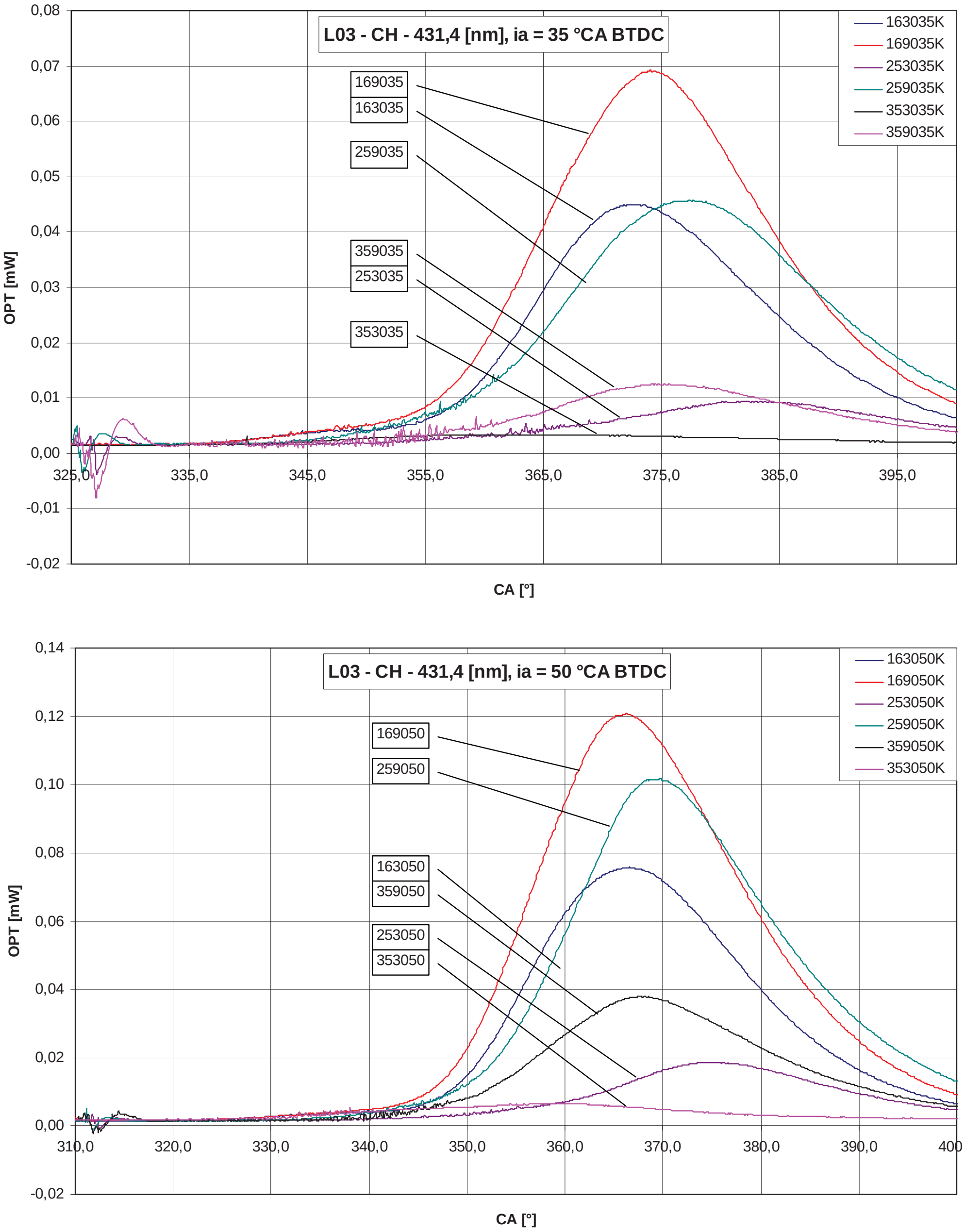

Fig. 8. Emission of CH radicals measured at 431,4 nm at different engine speeds (1600, 2500 and 3500 rpm), loads (ap = 30% and 90%) and ignition advances (i_a) of 30 °CA BTDC (upper) and 50 °CA BTDC (lower)

6. Conclusions

The main aim realized in this paper was to show whether emission spectra of different radicals can be used as a tool in detection of knock. Preliminary data analysis confirms usability of emission spectra in knock analysis – recorded signals varied in dependence of engine operating parameters. 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.

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