ENDOSCOPIC OBSERVATIONS OF FLAME PROPAGATION IN DI DIESEL ENGINE

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Abstract. In the paper the results of combustion process investigations in experimental one-cylinder DI diesel engine have been presented. The observations of flame intensity and its propagation inside the cylinder of working engine have been made with use of quartz glass-window, endoscope and digital camera. Pictures received in a stroboscopic way have been stored in a computer for later interpretation. This technique allows observations of flame area inside combustion chamber for chosen crank angle. For more observations that are done at one crank angle one can obtain the fluctuations of the flame propagation between several cycles. One can create an average picture by using special techniques of picture post-processing, as well. By storing frames for different crank angles and then reconstructing observations on a computer one can achieve pictures of an average combustion process with the accuracy of 0,2 deg. CA. Interpretation of these pictures makes it possible to determine flame propagation. Its correlation with pressure history in combustion chamber has been examined.

The experimental work has been made for different engine speeds and loads with use of the Engine Video System 513D by AVL/Graz/Austria. Both observations and possible ways of interpretation with their limits have been presented and discussed.

1. Introduction

For improvement of thermal efficiency in I.C. engines precise information about all possible parameters of combustion process has great importance. The knowledge of parameters and combustion process course is very useful for high speed D.I. Diesel engines, especially. Expected further optimisation of combustion process would be possible only then, when the dependence of combustion parameters from fuel injection course will be known and described as cause-result intercourse.

One of important research questions is, what would the correlation be between combustion process course and its results on cylinder pressure history, which has fundamental importance for engine power, efficiency, thermal stresses, noise, emissions and many others. Flame propagation in combustion chamber could be used as one of the parameters characterising the combustion process.

There are some new research techniques like photography, holography, laser induced fluorescence or scattering, which could be useful in solving such tasks. Observations of in-cylinder process by means of highspeed-cameras are not only very costly, but also induce many problems by investigations themselves and by film post-processing. Even the very good equipment for optical investigations working with frequency 30 000 Hz rich its best accuracy of getting pictures every 1,2-2,4°CA. It is too rough for answering some research questions.

An interesting alternative offers video-technique. Its is not so fast in taking pictures as picture converter, but – thanks to combining with the stroboscopic way of getting a picture – makes it possible to film a combustion process at almost every crank angle. Truly, it is not possible to film one combustion process with a very high angle resolution, but one can obtain sequence of pictures from different combustion processes building together a quasi-continued process. The way of getting pictures in stroboscopic way has been illustrated in

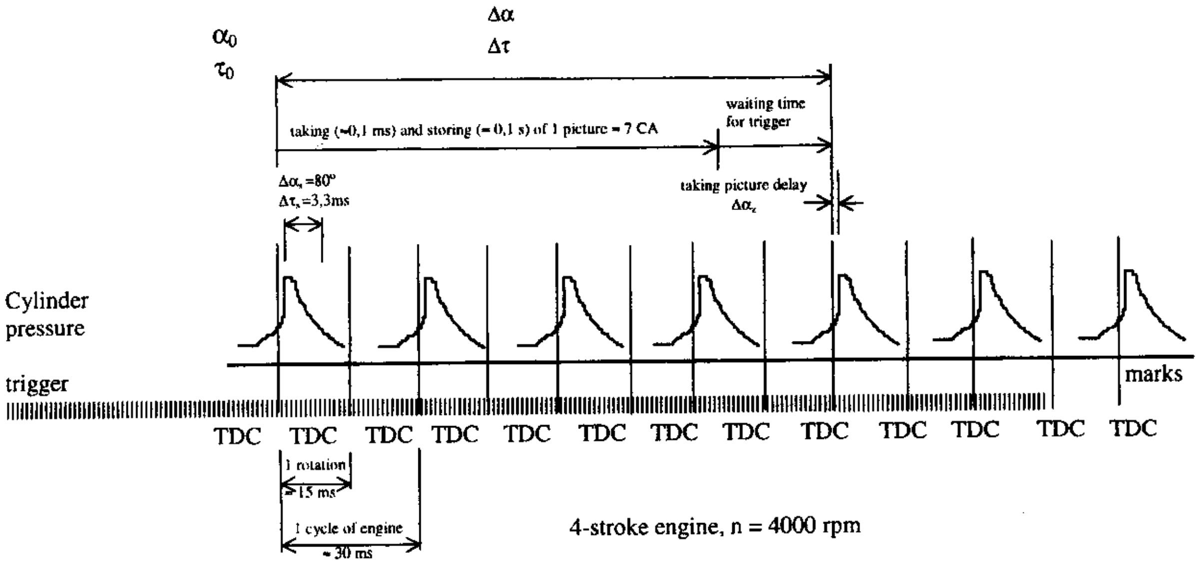

Fig. 1. Principle of stroboscopic observation method

By taking more pictures at one crank position, one obtains repetitions of several cycles and from them an average picture. When, after some repetitions at this crank angle position, the point of taking pictures will be shifted by some crank-angle value (e,q. 0,1; 0,5 or 1,0° CA), one can obtain the sequence of many average pictures. For good repeatability of combustion process course, this sequence of picture could be interpreted as the observation of one average combustion process. This, in some cases very dangerous simplification is strongly compensated by a much lower cost of the equipment, in comparison to high-speed cameras, and by the possibility of leading the observations almost on-line, during engine running.

The described video-technique has been applied in the investigations of combustion in D.I. diesel engine. The main task was to detect any correlation between flame propagation and cylinder pressure history. The other reason was to get practical knowledge of the method and to formulate questions for further investigations.

2. Experimental set up

2.1. Test Engine

The experimental engine SB 3.1. has been used in the experiments. It is the horizontal, one-cylinder, four-stroke diesel engine with two valves a in cylinder head, driven by classical means (OHV). The combustion chamber of toroidal shape is located in the piston. The fuel injector is mounted axial in the central point of combustion chamber. The engine is water-cooled by an external cooling system AVL 533, which allows continues temperature control (cooling, heating). Some engine working parameters have been collected in table 1.

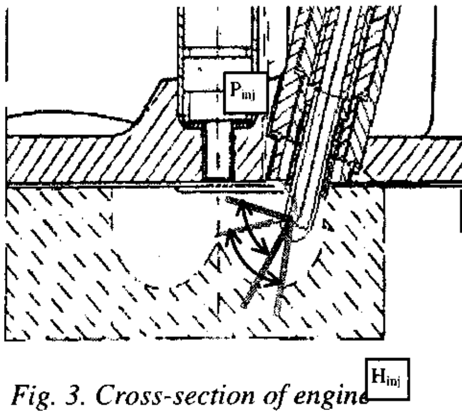

Fig. 3. Cross-section of engine cylinder head with built in 30° or 70° endoscope and quartz-glass

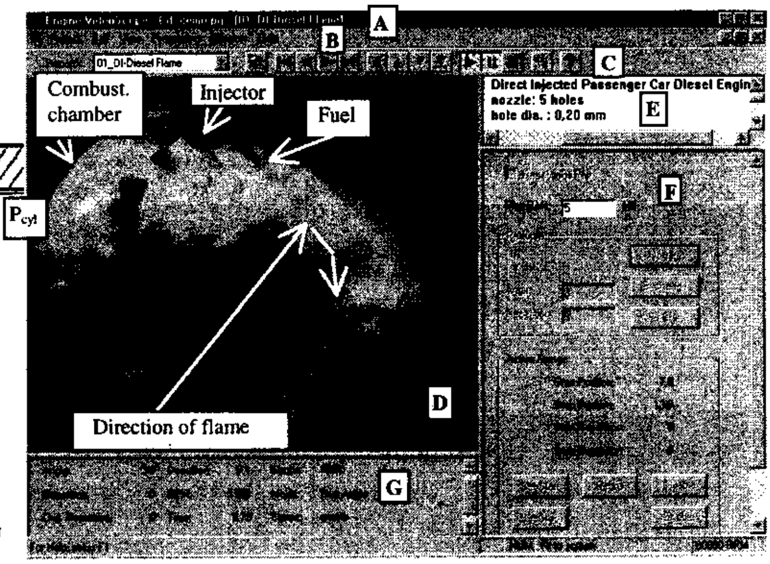

Fig. 4. Computer monitor during in-cylinder investigations

correspondingly. Fields E, F and G are the windows of control values of observation process. In the window D the observations of injection and combustion process have been carried out.

By analysing every pixel of the picture and modification of it according to the result one is going to achieve, it is possible to realise filtering or different transformations of the picture. Some of such standard functions like *Transformation, Median, Extract flame, Add Border* or *Mask* implemented in the *Engine Video Scope* program have been applied for this analysis.

3. Experimental approach

The investigations have been carried out within two engine speeds (1200 and 1600 rpm) in selected engine working points from no load up to full load. Some measurements have been carried on at 1000 and 2000 rpm, too. For the chosen engine speeds, loads of 0, 20, 40, 60, 80, 100 Nm have been examined. Because of a very big amount of collected data, especially from video observations[1], only results from one engine working point could be presented here. Load of 40 Nm by 1200 rpm has been chosen for this purpose, where 20 full cycles have been recorded. The results of measurement as a multicycle diagram are shown in fig. 5.

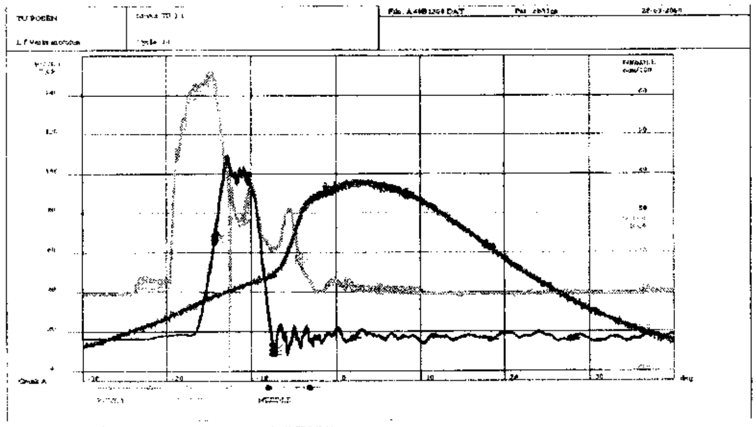

Fig. 5. Multicycle indicating diagram: Cylinder pressure, needle-lift and injection pressure vs. crank angle (n = 1200 rpm, 40 Nm of load)

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[1] Indicating of 20 cycles ($\Delta\alpha$=0,1°CA) at 1 engine working point needs about 1,16 MB of computer memory. One picture generated by the Engine Video System 513D needs about 1,1 MB; for 5 repetitions by every crank angle position and for leading observations within the range ca. –10...20°CA in every 1,0°CA steps, the HDD capacity will be occupied by ca. 203 MB (186 pictures).

By averaging the cylinder pressure history over all 20 cycles an representative cycle has been generated and applied for thermodynamic analysis calculations. With use of the above mentioned program ETA, temperature T_i, heating of cylinder charge Q_i, politropic exponent and cylinder pressure raise have been calculated. The nondi-mensional function of the cylinder charge heating $X_i = Q_i/Q_{i\text{-}max}$ has been generated as well. The results were used for the interpretation of the results of the flame propagation observations.

The indicated representative cycle was the basis for determination of its characteristic points. The results are collected in table 2.

In the same working point as for indicating, the endoscopic observations have been carried out. For reaching the same engine conditions as these during indicating, the working point was verified by values of engine load and speed, fuel and air consumption, cooling water and exhaust temperatures. The observations have been made within the range –10 up to 20°, in some cases up to 60°CA, for every 0,5°CA step. In every point of the range 5 repetitions of observation have been recorded for later generating of the average picture. Then, this average picture has been compared with the average indicating diagram of the cycle.

Table 2. Characteristic points of indicated cycle

Parameter	*Unit*	*Value*
Start of fuel delivery	°CA	-24,0
Start of injection	°CA	–16,3
End of injection	°CA	–7,9
Start of combustion (thermodynamic)	°CA	–11,8
Point of maximal pressure rise rate	°CA	–4,8
Point of maximal pressure	°CA	3,0
End of combustion (thermodynamic)	°CA	83,5

The pictures of flame propagation in the combustion chamber have been recorded in the RGB-model of colours as a 24-bit computer word. For soot flames in the middle range of combustion process very intensive radiation has been observed. In the pictures recorded for the range from the start of injection up to some degrees after the start of combustion, radiation was much lower because of small soot concentration.

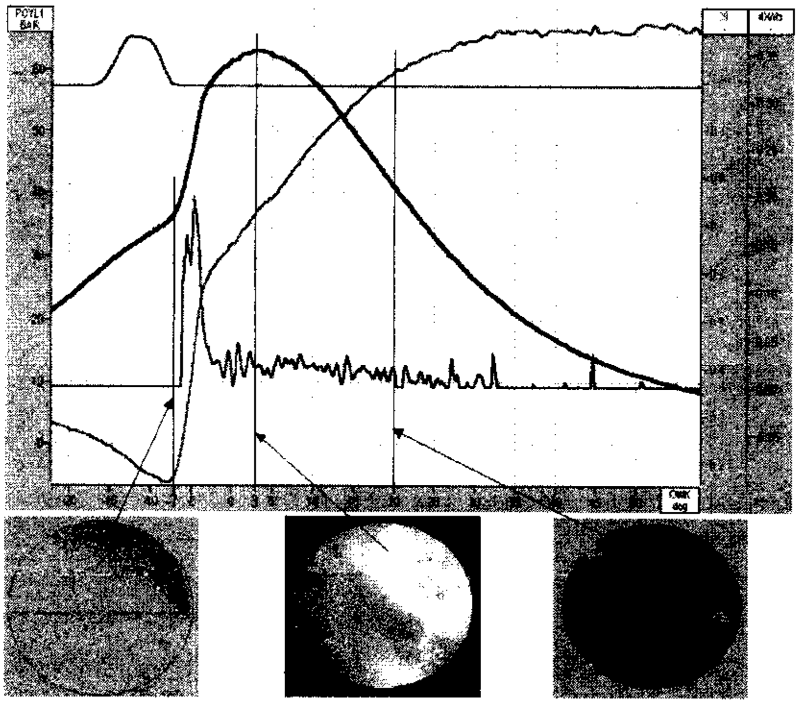

Fig. 6. In-cylinder observations in characteristic points of combustion process

The detection of early flames based on RGB-model of colours were difficult and inaccurate. For that purpose conversion in the HSI-model of colours has been applied. In this case a small radiation has been detec-ted shortly before –8,0°CA point. The observations of flame made for 3 characteristic points of the combustion process (i.e. start of combustion, P_{max}- and 20°CA-points) have been shown in fig. 6 compared with indi-cating diagram having curves of needle-lift, cylinder pressure, indicated heat release and heating rate. In the beginning of intensive heating of cylinder charge very small area is occu-pied by flame of low radiation, what could be detected only in HSI-picture. By maximum cylinder pressure the flame occupied almost the whole observed area, with the highest intensity of radiation. By 20°CA combustion process and radiation of flame strongly broke down and only some remains of the flame were observed faraway from the injector.

4. Interpretation of observation results

The comparison of flame propagation interpreted in HSI-pictures with the cylinder pressure history during early range of the combustion process has been presented in fig. 7.

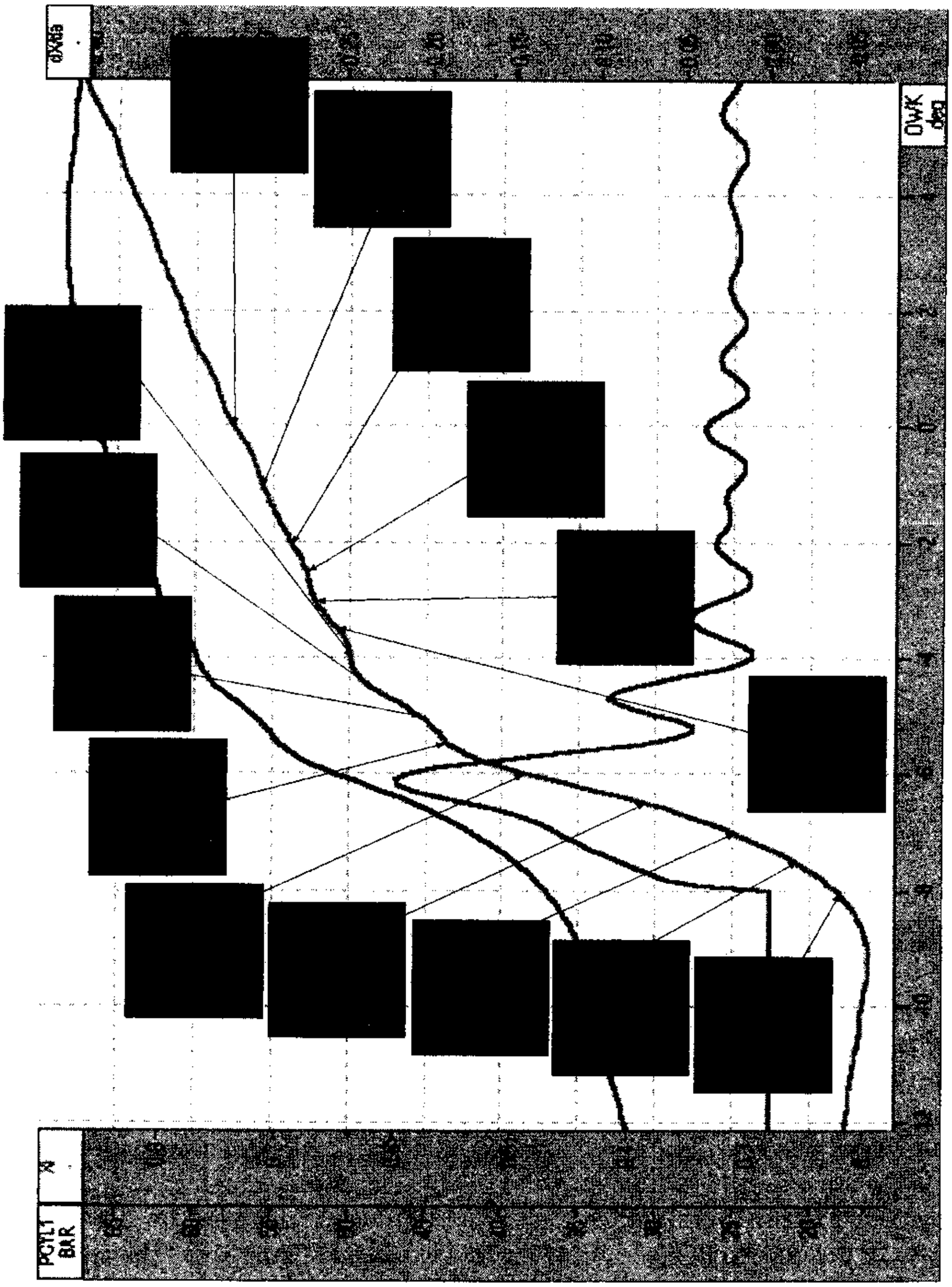

Fig. 7. Indicated cylinder pressure, indicated heat release and its rate vs. crank angle compared with flame observations on HSI pictures (M_o = 40 Nm, n = 1200 rpm)

that its value is dependent on picture post-processing method, especially on the power and the kind of filter, which has been applied. For poor filtering (e.q. mask and extract) the "saturation" of the resulting value has been achieved for a wide range of combustion, fig. 10. This kind of filtering should be used for detection of early flames and the end of combustion. Using a "strong" filter (e.q. mask r150) the region of strongest radiation could be detected (here 1-3°CA). There is the region of highest combustion temperatures, most important for forming of NO_x pollution. If the applied filters would be properly calibrated, the qualification of energetic level of radiation in every point of the process could be possible. Such an approach would be similar to the two-colour method, which is being already used for the determination of the local temperature in the combustion chamber.

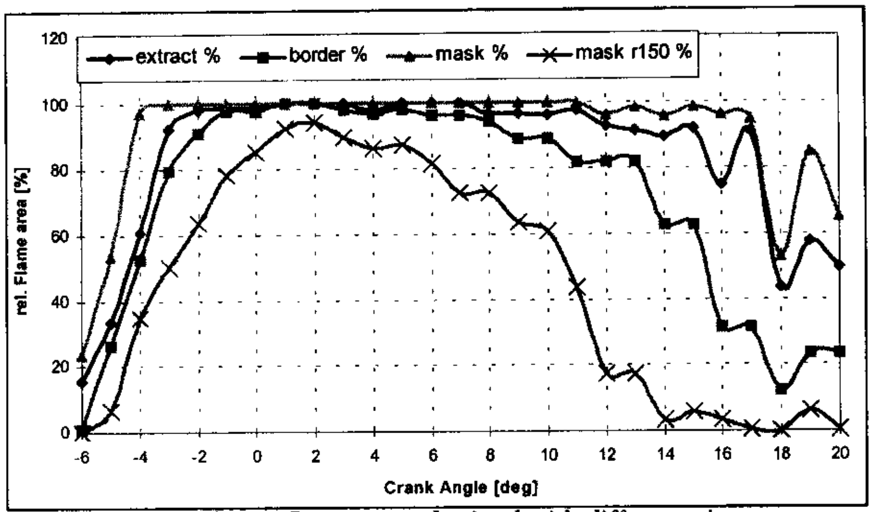

Fig. 10. Relative flame area obtained with different picture post-processing methods vs. crank angle

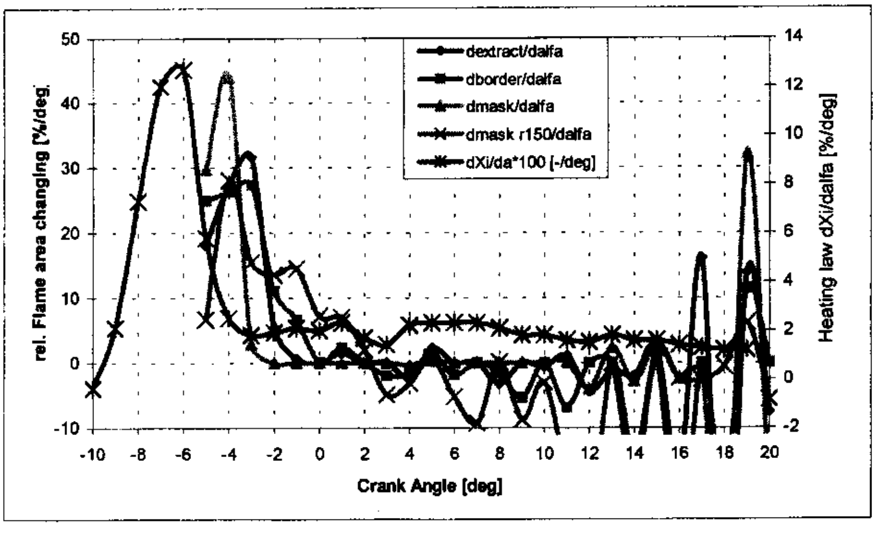

Fig. 11. Flame area rate calculated from curves in fig. 10 compared with heating law dXi/dalfa

The comparison of heat release rate with the changes in relative flame area achieved with different filters has been shown in fig. 11. It could be noticed, that the shapes of all the curves are very similar to one another. At the beginning of combustion the changes in relative flame area are very fast, as that of heat release rate. It was observed, that flame radiation recorded by the endoscope was delayed versus heat release rate for about 2°CA. In the late phase of combustion there are big fluctuations in calculated flame area changes. The reason for this is the interpreting of the average cycle achieved in a stroboscopic way. Non-repeatability of com-bustion processes following after one another causes big values of its rate, especially in the last part of combustion, where the area occupied by flame is getting very small. These fluctu-ations could be filtered out without any significant influence on the examined correlation.

The correlation between relative flame area changes (≈flame propagation rate) and heat release rate has been proved and confirmed. The high values of correlation coefficient R^2

a prędkością narastania ciśnienia w cylindrze dP/dα. Zauważono także wysoką korelację pomiędzy prędkością wykorzystania ciepła $dX_i/d\alpha$ a względną prędkością rozprzestrzeniania się płomienia; wartości liczbowe współczynników uzyskanych funkcji zależą od rodzaju (siły) filtra cyfrowego użytego do przetwarzania zarejestrowanego obrazu. Właściwy dobór filtra cyfrowego pozwala na wyznaczenie kąta OWK, przy którym występuje największa temperatura wynikająca z intensywności świecenia płomienia silnikowego.

Wykorzystanie obserwacji procesu spalania do dokładniejszej jego diagnostyki wymaga opracowania metody cyfrowego przetwarzania obrazu oraz odpowiedniej kalibracji.