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Investigations of the fuel injection and atomization with the use of laser illumination

Abstract: The paper presents some aspects of the application of selected methods of optical research whose aim is to obtain information on the course of the atomization and evaporation processes in the combustion chamber. The paper shows images of a gasoline fuel spray when injected to a high-pressure chamber. These images have been recorded using conventional sources of light and laser illumination. Research with the use of a YAG pulsed laser of high illumination pulse energy enabled an assessment of the fuel distribution in the transverse cross-section of the fuel spray. The paper describes such a possibility of modification of the experiment using laser illumination as to obtain information on the spatial distribution of both the liquid and gaseous phase of the injected fuel.

Key words: *fuel spray injection, laser illumination, exciplex*

Badanie wtrysku i rozpylenia paliwa z wykorzystaniem oświetlenia laserowego

Streszczenie: W artykule omówiono niektóre aspekty stosowania wybranych metod badań optycznych, których celem jest uzyskanie informacji o przebiegu procesu rozpylenia i odparowania paliwa w komorze spalania silnika spalinowego. Przedstawione zostały obrazy strugi benzyny wtryskiwanej do komory ciśnieniowej zarejestrowane przy wykorzystaniu konwencjonalnych źródeł światła i oświetlenia laserem. Badania z wykorzystaniem lasera impulsowego typu YAG o dużej energii impulsu oświetlającego umożliwiły ocenę rozkładu paliwa w poprzecznym przekroju strugi paliwa. Opisano możliwość takiej modyfikacji eksperymentu prowadzonego z oświetleniem laserowym, aby uzyskać informację zarówno o przestrzennym rozkładzie fazy ciekłej, jak i fazy gazowej wtryskiwanego paliwa.

Słowa kluczowe: *wtrysk paliwa, oświetlenie laserowe, exciplex*

1. Introduction

The efforts to improve the operating parameters of engines and the subsequent design modifications lead to a situation when we need to explain the course of many in-cylinder processes that are not yet sufficiently explored. An example could be the process of direct gasoline injection.

Contemporary high-pressure direct fuel injection solutions enable a better control over the fuel distribution inside the combustion chamber of an engine. A prerequisite for this to happen is to obtain precise information on the formation of the injected fuel spray during the injection and the distribution of the fuel concentration inside the fuel spray and on its edges. In this respect optical research on fuel injection and fuel atomization plays a particular role.

The control of the parameters of the injected fuel spray is of paramount importance to the engine operation, particularly to its fuel consumption, exhaust emissions and resistance to knock combustion. Direct injection, through a synergy with supercharging, facilitates the obtainment of high values of mean effective pressure. This is how the downsizing principle is put to practice [1].

The application of direct injection is technically justified only when the fuel spray parameters are sufficiently controllable under all engine operating conditions. This task has only been partially realized, which is proven in modern engines, in which, beside direct injection to the combustion chamber, injection to the intake manifold is realized as well. In such solutions, for some engine operating conditions the fuel is injected into the manifold not directly into the cylinder [2]. The improvement of fuel injection systems is thus a difficult task and it is advised to seek new research techniques that will enable the visualization of the in-cylinder processes. This search is facilitated by the application of new technologies in image recording and laser illumination [6]. Numerous investigations of the in-cylinder processes conducted with the use of laser illumination for at least 30 years now [10, 11] are currently verified, modified and perfected. The advancement of such research became possible due to a relatively wide accessibility to lasers of parameters that were not achievable in the past.

2. Laser in engine research

2.1. Laser as a source of light

In modern engine investigations solid-state YAG lasers are used frequently. The multitude of scientific and industrial applications of this type of laser facilitates a continuous improvement of its design at dramatically limited production costs. Today lasers are manufactured in thousands of units maintaining parameters that were unachievable decades ago [9]. For this reason we can see a reduction of use of the excimer lasers widely used in the past. Figure 1 presents the view of the uncovered laser head and a description of the most important components. This is a typical contemporary YAG pulsed laser of the power sufficient for the majority of applications in in-cylinder research.

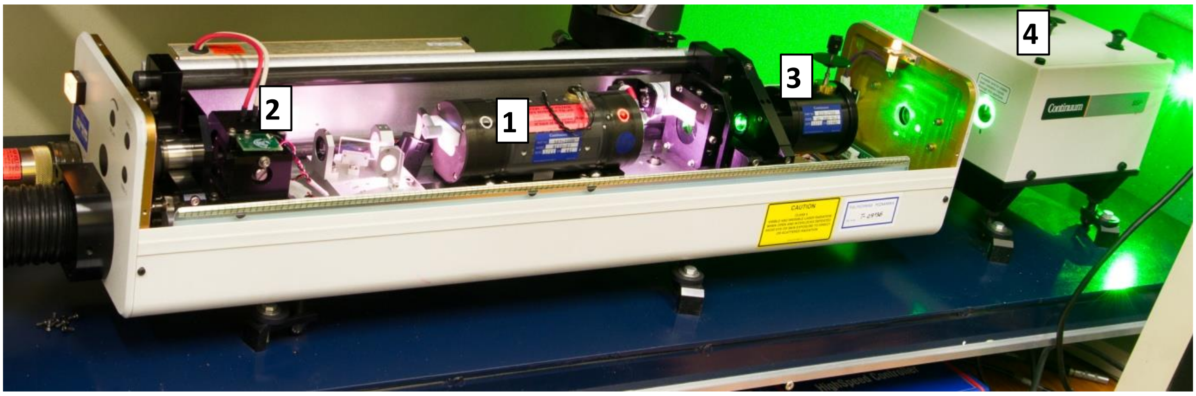

Fig. 1. The view of the YAG laser head used in the engine research; 1: laser head with the rod and pumping lamp, 2: Q-switch, 3: second harmonic generator, 4: harmonic separator

The light of a laser has unique features that can be used in engine research if the experiment is properly conceived.

2.2. Monochromaticity

The majority of lasers emit a laser beam of a very narrow spectrum of the wavelength. The monochromaticity of the laser light is an advantage that facilitates the elimination of the laser light from the footage if narrow band filters are applied. In this way, light processes are recorded as induced by the laser not its light that may have an excessive intensity in terms of the recording matrix sensitivity. The application of narrow band filters of a given wavelength allows tracking the process of formation and displacement of particles, interesting in light of the analyzed process.

2.3. The wavelength

The wavelength of the laser light can be widely modified. The necessity of changing the wavelength, resulting from the specificity of certain experiments, sets special requirements for the design of lasers and is usually done at the cost of limiting of the power of the laser beam. The YAG laser emits a beam of light of the wavelength equal to 1064 nm. If wave frequency dividers are applied, built with the use of non-linear optical crystal properties, we can convert the wavelength into 532 nm, 355 nm or 266 nm. The conversion is followed by a partial loss of the energy of the laser beam. For the laser presented in figure 1 we can obtain the following pulse energy in individual spectrum ranges: 1064 nm: 650 mJ, 532 nm: 300 mJ, 355 nm: 160 mJ, 266 nm: 80 mJ. The module for the generation of the harmonics has been presented in Fig. 2.

Almost any variable change of the wavelength can be obtained using a dye laser. The power of the dye laser is usually very limited. A precise adjustment of the wavelength is critical for the Laser Induced Fluorescence experiments. In other cases, usually green light of the wavelength of 532 nm is used.

Fig. 2. Optical system with a birefringent crystal functioning as a wave frequency divider, generator of the third harmonic of the wavelength of 355 nm

2.4. Polarization

The light of the laser is entirely polarized. The reflected light usually loses its polarization and owing to a polarization filter we can separate a selected part of the light.

2.5. Divergence of the laser beam

A laser beam is characterized by a very low divergence. Under engine laboratory conditions the beam can be sent to any distance, which facilitates the positioning of the testing equipment. The optical chain can be formed using mirrors or fiber optics. The laser beam of a circular cross-section can be transposed into a light sheet using a cylindrical lens. A light sheet enables illumination of selected cylinder areas and allows generating tomographic images. Figure 3 presents an optical system for the creation of light sheet optics.

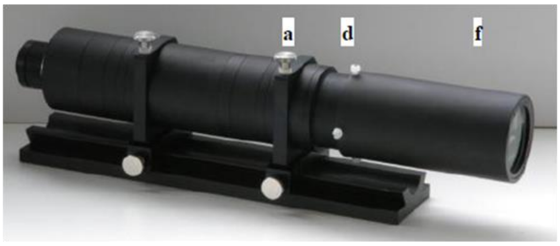

Fig. 3. Optical system for the creation of light sheet; a: system of lenses focusing the beam, cylindrical lens, f: collimator [3]

2.6. Pulse duration

In engine research YAG pulsed lasers play a particular role. They release all the energy accumulated in the laser rod emitting a beam of light in a time limited to several nanoseconds. The flash of the camera lasts at least 10000 times longer. In the light of a pulsed laser we can freeze any stage of the processes taking place inside the cylinder. In theory, for an engine operating with a speed of 6000 rpm we can take more than 5000 consecutive images with the exposure time of 5 ns before the crankshaft turns by 1 °CA. We need to note, however, that the nanosecond laser can emit very short light flashes, yet the consecutive pulses are separated with a relatively long time needed for the pumping of the laser rod. Usually, the frequency of the pulses is several Hz but it can be increased at the cost of a reduction of the pulse energy. We can synchronize two lasers, thus freely reducing the time intervals between the light pulses and the accuracy of the synchronization is very high (usually 1 ns).

2.7. Energy concentration in time and space

A laser beam usually has a diameter of 6-9 mm corresponding to the diameter of the laser rod. We can thus obtain a high spatial concentration of energy. In the case of a pulsed laser of the design as shown in Fig. 1 we can obtain the light pulse energy of approximately 1 J in the time of 5 ns. The power of the stream of light emit-ted by the laser is in this case 0.2 GW and is much greater than the power obtainable for other sources of light.

3. Recording of a liquid fuel spray in a conventional and laser illumination

Injection and fuel atomization are non-illuminating processes. If we want to record footage we need to pro-vide an external source of light. A light bulb is usually used for that purpose. A light bulb gives a divergent stream of continuous light, non-polarized, incoherent in time and space, of limited range intensity and a wide spectrum of wavelength. The listed features of the stream of light make it hard to efficiently focus on the selected plain of the chamber to which fuel is injected. We can only obtain a uniform illumination of the whole chamber. A photograph of a fuel spray under the conditions of illumination of the whole chamber is a two-dimensional image of a three dimensional space. Each point of the obtained image is a sum of the light intensity recorded along a virtual line leading from the camera lens to the chamber to which the fuel is injected. The recorded image is attributed spatial characteristics but on its basis the analysis of the fuel spray parameters in individual points of the space is impossible.

The unique features of laser light make the laser beam of a circular cross-section transformable through an optical system into light sheet of the thickness of less than 1 mm. Using such a beam we can record images of the fuel spray in any cross-section. We can scan the cross-sections of the fuel spray at different depths against the virtual line towards the camera lens. This is how tomographic images are obtained.

In the chair of combustion engines at Poznan University of Technology investigations were carried out consisting in injecting gasoline to a chamber with a backpressure. Maintaining constant injection parameters two series of measurements were realized: using illumination of halogen lamps and that of a laser. The aim of the investigations was to compare the usefulness of both illumination methods to determine the dynamics of the area covered by the liquid fuel in the course of the gasoline injection. Injection parameters representative of modern injection systems were selected: fuel pressure of 10 MPa and the injection duration of 600 μs. The backpressure of the nitrogen-filled chamber was 1 MPa and the temperature was 20 °C. The volume of the chamber was 1.2 dm3. For the recording of the images the authors used a high-speed camera (LaVision High Speed Camera HSS 5). The above-mentioned part of the equipment and many other auxiliary devices are a standard equipment of the optical research laboratory as described in detail in earlier authors’ publications [5, 7, 8].

Figure 4 presents images recorded with the halogen and the laser illumination. In the first case two lamps with bulbs of 250 W were used and in the second case the image illumination was realized by Laser Continuum Surelite SL II-10 [9].

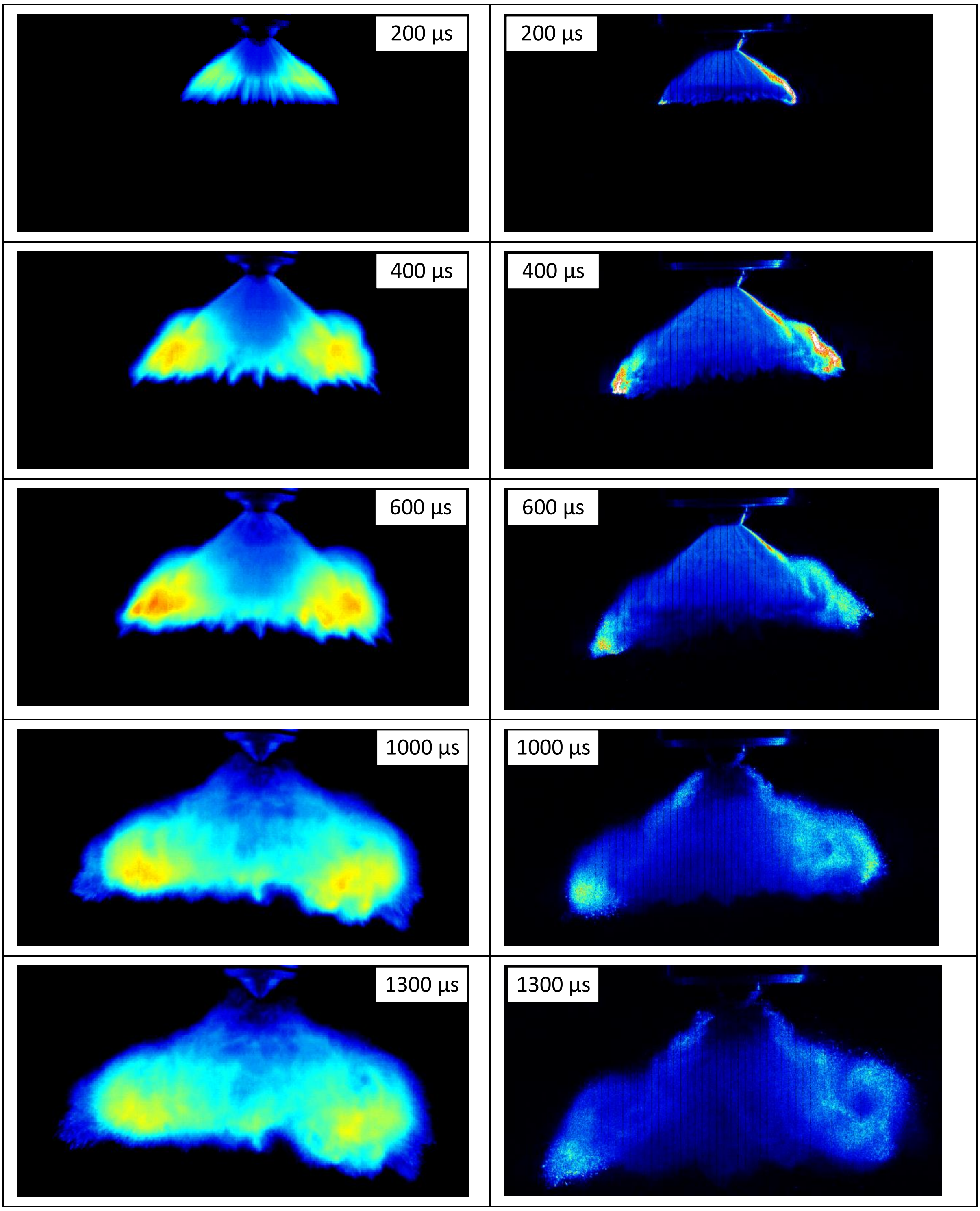

Fig. 4. Fuel spray images recorded in the halogen lamp (left) and laser (right) illumination; the subsequent rows show the fuel spray in time 200, 400, 600, 1000 and 1300 µs from the onset of the injection

The laser generated a beam of light of the wavelength of 532 nm and duration of the pulse of approximately 5 ns. The light sheet of the height of 45 mm and thickness in the focus of less than 1 mm was obtained through an optical system shown in Fig. 3. The laser shown in figure 1 used in the experiment under these conditions allows an obtainment of the pulse energy greater than 300 mJ. For the recording of a properly illuminated image the energy of approximately 1 mJ is sufficient. The pulse energy was then limited through the adjustment of the Q-switch delay parameter and the voltage of the flash pumping the laser.

Greater energy is an important but not the only advantage of laser illumination in comparison with the traditional one. Laser illumination is also better from traditional illumination because the laser pulse is shorter, illuminating only the selected plain. Owing to the said features the images recorded in laser light show many more details that are invisible if illuminated traditionally. Figure 5 presents an image that is a continuation of the sequence from Fig. 4. The image was taken 1400 μs from the onset of the injection in a laser light. The enlargement of the image allows observing individual, fast moving fuel droplets that form the fuel spray. In the case of traditional illumination such detailed images could not be recorded.

The advantage of the use of laser illumination in generating images of the narrow central plain of the combustion chamber is that they carry information on the spatial structure of the movement of the fuel droplets at the edges of the fuel spray. This information is eliminated if the image is recorded using halogen illumination. The differences are conspicuous particularly in the last of the presented phases of the fuel atomization, recorded 1300 μs from the onset of the injection.

In the experiments presented in the paper the authors used a laser of very high pulse energy but its pulse frequency was limited to 10 Hz. The individual images forming the sequence shown in Fig. 3 had to be recorded in the subsequent processes of the injection. In the presented case no visible negative consequences of this type of action are seen, which results from the repeatability of the course of the recorded process of injection. The pulse frequency is a design parameter of a laser, critical for the thermal stability of the optical cavity. In modern technology we may observe increased application of lasers of the pulse frequency of several tenths of kHz and energy sufficient to perform an experiment as the one described in this paper.

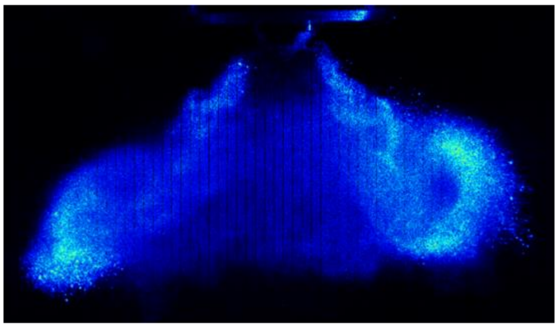

Fig. 5. Individual fuel droplets visible on an enlarged image of the fuel spray recorded under laser illumination, 1400 μs from the onset of the injection

In the comparison of the two presented illumination techniques it is noteworthy that for the visualization of the fuel liquid phase a very low power of the laser is required. The laser light of the wavelength falling in the middle of the visible range is dispersed by the fuel droplets and recorded by the camera. Due to a high intensity of light of unmodified wavelength there are not any particular requirements as to the camera sensitivity. In the case of investigations of the process of fuel injection, laser illumination may turn out easier to put in practice than it is in the case of halogen illumination.

4. Investigations on the distribution of the fuel vapor

4.1. Elementary LIF experiment

In some cases of research issues images of the spatial distribution of the fuel liquid phase inside the engine cylinder must be supplemented with information on the distribution of the fuel vapor. In these cases we can fully benefit from the laser light illumination. The laser beam in these cases is directed inside the cylinder to induce the fuel molecules or the marker added to the fuel and force fluorescence. There are several varieties of the experiment based on the above principle generally referred to as the LIF method.

4.2. Fluorescence of fuel molecules

In the simplest experiment the photons emitted by the laser are subject to inelastic collision with the molecules of hydrocarbons that form the fuel vapor. In some of the collisions part of the energy of the photons is absorbed by the molecules of hydrocarbons making the molecules turn into an excited state. In the process of return to the basic energetic state the molecules emit radiation of the energy lower than the energy of the exciting photons of greater wavelength. The fluorescence lasts approximately 1-10 ns and denotes a possibility of recording light of the wavelength shifted towards red (against the laser light). The whole area occupied by the fuel in both the liquid and gaseous phases is recorded. At the same time using the second optical chain with appropriate filters we can record another image of the same space for the same wavelength that is characteristic for the laser light. Such images contain information on the area occupied by the fuel in the liquid phase. By overlaying the images we can determine the areas of occurrence of the liquid and gaseous phases of the fuel.

4.3. LIF Exciplex

An alternative way to determine the areas occupied by the liquid and gaseous phases of the fuel is the LIF exciplex method. Exciplex is a mixture of two appropriately selected hydrocarbons added to the fuel in order to enable a quantitative assessment of the fuel concentration in the observed areas of the combustion chamber. The physical and chemical processes in exciplex make both the fuel liquid and its vapor fluorescent while the wavelengths in both cases are different. The liquid and gaseous phase may be distinguished by the application of double optics and optical filters placed before the camera lens. The schematic idea of the LIF exciplex has been presented in Fig. 6.

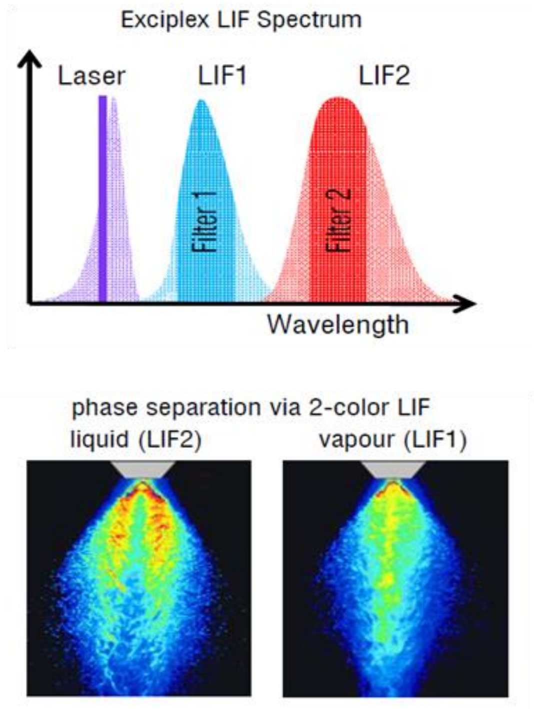

Fig. 6. Schematic presentation of the idea of the LIF exciplex experiment; LIF 1: fuel in the liquid phase, LIF 2: fuel vapor [4]

In the research devoted to the processes of diesel fuel atomization and evaporation exciplex is added to the fuel (it is a mixture of naphthalene and N,N,N',N"-tetramethyl-p-phenylene diamine – TMPD). The excitation of the atoms and fluorescence is obtained through the illumination by the laser light of the wavelength of 266 nm or 355 nm ('Laser' in Fig. 6). The fluorescence, occurring in the fuel vapor, is recorded as a light of the greatest intensity for the wavelength equal to approximately 390 nm (LIF1 in Fig. 6). In the area occupied by the fuel liquid phase the fluorescence of the greatest light intensity is recorded for the wavelength of 480 nm (LIF 2 in Fig. 6) [10].

Conclusions

The application of laser illumination significantly extends the possibilities in the research of the processes of fuel injection and its atomization. Currently, in the research related to in-cylinder processes YAG solid-state lasers are most frequently used. Along with the ever-growing scope of application of such lasers their price and parameters are becoming increasingly attractive.

The key benefit of the replacement of the halogen light illuminating the fuel spray with laser illumination is a greater energy of radiation in a shorter time. Besides, the properties of the laser light enable creating a sheet light that allows a selective illumination of precisely defined areas of the fuel spray.

The above-mentioned advantages of laser radiation were used in a comparative experiment whose results have been presented in this paper. The images of the fuel spray recorded in the laser illumination allow obtaining more information than it is in the case of analogical images obtained with the use of halogen illumination.

Another unique feature of laser light is its monochromaticity enabling interaction with the fuel molecules or with a special additive dissolved in the fuel. The excitation of the molecules and the transfers among the energy levels result in fluorescence that can be recorded with a camera. A properly conducted experiment allows a visualization of areas of the occurrence of the fuel liquid phase and the fuel vapor.

Nomenclature/*Skróty i oznaczenia*

LIF Laser Induced Fluorescence/Fluorescencja wymuszona światłem lasera

YAG Yttrium Aluminium Garnet/Granat itrowo-aluminiowy

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