Journal of Energy and Environmental Sustainability, 1 (2016) 56-66

An official publication of the International Society for Energy, Environment and Sustainability (ISEES)

Journal of Energy and
Environmental Sustainability

Journal homepage:www.jees.in

Evolution, Trends and Applications of Endoscopy in Internal Combustion Engines

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ARTICLE INFO

Received : 17 July 2015
Revised : 13 September 2015
Accepted : 22 September 2015

Keywords:
Endoscopy;
Combustion visualization;
Fuel spray;
Temperature distribution;
Soot distribution.

ABSTRACT

Due to increasing number of alternative fuels and strict emission norms globally, extensive experimental investigations are being conducted for understanding and improving fuel sprays and combustion of internal combustion (IC) engines. Main objective of this study is to assess the effect of advanced fuel injection equipment (FIE) and in-cylinder processes to improve efficiency and reduce pollutant emissions, in addition to improved understanding of combustion and pollutant formation mechanisms. In order to gain understanding of actual combustion processes and spray characteristics in production grade engines, researchers have developed various optical diagnostic techniques. Endoscopic optical visualization technique is a very effective and relatively cheaper but very challenging technique with great potential amongst them. This paper presents a summary of evolution of endoscopic optical visualization technique for analyzing spray and combustion characteristics in IC engines, current trends in engine endoscopy and some application case studies. This endoscopic technique has great scope in research and development activities for automotive industry.

1. Introduction

Internal combustion (IC) engines are the most common power plants used in automotive systems such as cars, trucks, boats, ships, trains, as well as stationary power generating machines, earth moving equipment, construction machines and agricultural equipment. It is impossible to imagine modern transportation system without IC engines, as on today. Fuel economy and stringent emission norms are the major challenges being faced by automotive sector worldwide. In recent years, the urge for developing high engine power output with superior fuel economy and lower emissions from IC engines has increased tremendously. To satisfy these requirements and complying with contemporary stringent emission legislations, more effective and environmentally-friendly combustion systems have to be designed and manufactured. Therefore automotive industry is making research and development efforts to meet these challenges. Diesel engines are becoming increasingly popular because they offer greater thermal efficiency and are rugged in nature compared to their gasoline counterparts however a major concern with diesel-powered vehicles is relatively higher level of pollution, that they emit. Diesel engines are a source of two major pollutants; oxides of nitrogen (NOx) and particulate matter (PM) [Pierpont et al., 1995]. NOx contribute towards acid rain and ground-level ozone formation, whereas PM leads to major health hazards by penetrating deep into human lungs. To reduce such harmful emissions, some engine designer favor exhaust gas after-treatment, while others prefer more sophisticated fuel-injection system modifications and control of pollutants in the formation stage itself.

Improvements using these techniques were adequate to meet emission legislations upto Euro-IV however they are grossly inadequate to meet prevailing global emission legislations of Euro-V and above. Emission norms upto Euro-IV could be complied by combustion optimization and/ or by employing less expensive exhaust gas after-treatment methods. For achieving emission norms beyond Euro-IV, automotive industry has to consider expensive and more complex after-treatment technologies such as diesel oxidation catalysts (DOC), diesel particulate filters (DPF), selective catalytic reduction (SCR), lean NOx traps (LNT), etc. along with very efficient in-cylinder combustion control. However, the most effective way still remains is reducing the bulk emissions at source, and for this, they need to develop fuel-injection systems capable of meeting these requirements over entire range of engine operating conditions.

Combustion in diesel engines is strongly dependent on fuel-air mixing process and optimized in-cylinder flows [Bevan and Ghandi, 2005]. Bevan and Ghandhi, 2005 suggested that improved fuel-air mixing rate is a significant factor resulting in shorter combustion duration and higher combustion efficiency, which improves overall engine efficiency. To examine this, researchers focused on homogenous fuel-air mixing in CI engines, which reduced NOx to negligible levels [Maurya and Agarwal, 2011; Singh et al., 2014] in HCCI combustion mode, however this concept has its own merits and demerits. Fuel-air mixing can be optimized by an engine control unit (ECU) controlled fuel injection system, which can control start of injection (SoI) timings, fuel injection pressure, injection duration, and number of injections. Fuel-air mixing also depends on fuel spray structure and atomization levels [Park et al., 2009], and is affected

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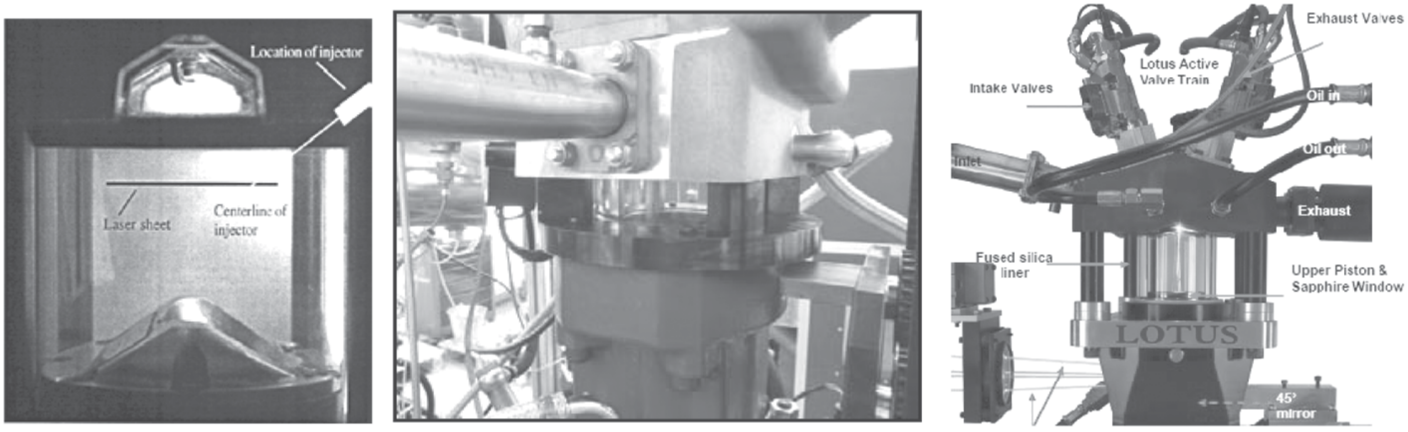
by the fuel injection strategy. Fuel-air mixing strategies also affect the degree of completion of combustion, which is quite important for diesel engines because it controls PM formation inside the engine combustion chamber. Generally, turbulence adds value to in-cylinder flow structures however heat transfer is also influenced by the in-cylinder flows [Heywood, 1988]. Certain level of turbulence is required inside the engine combustion chamber for mixing the atomized fuel with compressed air to obtain efficient combustion. Therefore it is essential to understand the flow structures inside the cylinder in order to improve combustion and enhance IC engine performance. Engine design and combustion chamber geometry also affects the combustion. Different designs of combustion chambers for direct and in-direct injection of fuel are proposed by manufactures, which reduce emissions and improve engine performance.

For optimizing these characteristics, it is very important to closely observe the parameters, which directly affect the in-cylinder flow characteristics. In-cylinder visualization of fuel-air mixing and combustion becomes very important scientific study. In-cylinder combustion images can be captured by using a high-speed camera and associated visualization equipment in a customized engine. From these images, various combustion parameters and spray characteristics can be analyzed with the help of image processing software. However, optical access to the engine combustion chamber is the biggest challenge for applying optical diagnostic techniques to the IC engines. Optical access to the traditionally opaque cylinder is essential in order to enable researchers to apply optical diagnostic techniques to the IC engines. There are different ways for gaining optical access through the engine cylinder and it differs according to the requirements of measurement and available financial resources. Two main types of optical access arrangements can be done, namely; full optical access in an Optical research engine; and limited optical access using engine endoscopy in a production grade engine.

1.1 Optical research engine

An optical research engine allows full optical access to the combustion chamber. This special engine is used for studying the fuel-air mixing, in-cylinder flows, combustion, and flame propagation through the optical liner, which is made of high quality quartz and a transparent piston. Early efforts on gaining optical access were by using a transparent acrylic resin, which was assembled on the extended part of the cylinder. A quartz window was installed at the top of the extended piston, which enclosed a mirror inclined at 45^o to observe the in-cylinder flows. Bowditch [1961] modified a production grade engine for optical access through the piston crown and developed it as a new tool for combustion research in 1961. After that, several researchers and automotive companies improved this type of engine and implemented this technique with transparent window in strategic locations such as cylinder, cylinder head and piston for investigations in the firing conditions. Fully transparent cylinder was also implemented in some engines for non-firing studies. Normally, transparent windows are made by fused silica or high temperature quartz, which is able to withstand high temperature and high pressure prevailing during engine combustion. This type of engine can be fired for very short periods only because visibility of the optical window decreases due to soot deposition. Therefore, regular cleaning is required after each firing experiment. Optical engines can't be tested at higher loads and speeds [Pundir, 2010]. Allen et al. [2000] used new design of optical research engine, developed by Lotus Engineering for fuel spray and combustion investigations were done employing laser diagnostics. They tested the engine upto 5000 rpm and 60 bar peak in-cylinder pressure. Han et al. [2008] used optically accessible direct injection diesel engine for soot and temperature analysis using laser diagnostics. The main advantage of this engine was that entire combustion event could be captured for one full combustion cycle using suitable high-speed charge coupled device (CCD) camera. Hence this type of engine was very helpful in analyzing various combustion characteristics, which were not understood well using conventional techniques. Huang et al. [2004] used a transparent cylinder, which was made of Plexiglas and a section of aluminum cylinder. A chrome metal liner was inserted between the Plexiglas cylinder and the crankcase. An elongated hollow cylindrical aluminum frame was used instead of the original piston. The top end of the cylindrical frame was screwed to the piston head. Richter et al. [1999] used standard Bowditch layout, in which a quartz cylinder of 80 mm height was mounted to access the combustion chamber (Fig. 1 (a)).

Singh et al. [2015] used an optical research engine (AVL 5402) for PIV experiments in motored conditions. The engine had full optical access through the quartz optical liner and a transparent piston (Fig. 1 (b)), installed at Engine Research Laboratory, IIT Kanpur, India. Lotus single cylinder optical research engine (SCORE) was designed for optical diagnostics. The cylinder liner was made from fused silica and a sapphire window was inserted in the piston crown in order to provide full optical access to the combustion chamber (Fig. 1(c)). Optical diagnostics using full optical access is very useful for real time data analysis however optical engines have following limitations [Allen et al., 2000]:



(a) (b) (c)

Fig. 1 (a): Optical access with 80 mm quartz liner [Richter et al., 1999]; (b): Single cylinder optical research engine; (c): Single cylinder optical research engine (SCORE) [Binjuwair, 2013]

- Optical research engines suffer from several restrictions such as balancing difficulty of a single cylinder, which is due to the added mass of the elongated piston. Therefore it limits engine's maximum speed.
- This type of engine can only be operated from low-to-medium loads and speeds because structural strength of the optical window is a limiting factor due to its large size.
- Quartz window is very expensive and a specific window is required for a particular engine according to its geometrical configuration. Hence, this technique can't be used in a production grade engine.
- It can only be used for research in a highly customized research engine test cell environment, which is prohibitively expensive.
- The optical engine can be operated for short durations only due to low heat transfer rates through the optical components and lack of cooling of the optical liner.
- The optical walls must be cleaned and combustion products must be removed very frequently. This is quite tedious task generally.

As a result of these limitations, several optical diagnostics techniques use optical access using an endoscope, which is relatively easier and endoscopic technique can be applied to any production grade engine with some modifications to the engine hardware.

1.2 Engine endoscopy

Endoscopy is an important and useful optical diagnostics technique for spray and combustion diagnostics in an engine environment. It has the additional benefit that it can be implemented in any production grade engine and can be used in high loads and speeds. It needs a very small area for optical access into the engine cylinder and can be implemented with minor modifications/ structural changes in the cylinder head compared to the previous technique involving full optical access through the quartz liner and transparent piston top. The main advantage of this technique is that it can be implemented in a wide range of applications in both, SI and CI engines. Combustion in SI and CI engines can be visualized by modifying the cylinder head and piston appropriately, while mixture formation in the port fuel injected SI engine can be visualized by appropriate modifications in the intake manifold. This technique is used as a tool to diagnose engine combustion therefore it does not require special design of any engine component. This technique can be employed in any type of engine, ranging from conventional DI single cylinder generator engines to highly optimized variable speed automotive engines. It is useful in diagnosing the problems in the interior parts of the engine in a vehicle, where other visualization techniques can't be implemented.

Engine endoscopy always provides faster diagnostics and reduces material consumption and time required in disassembling the engine. Hardware required for this technique consists of a high-speed CCD/ IR camera, a high temperature industrial endoscope, an optical window and an optics protection arrangement. Most components such as optics protection sleeves and hole in the cylinder head can be easily custom-designed according to the application requirements. Therefore, it is not as expensive a technique for optical diagnostics as an optical engine.

In this study, important application areas of engine endoscopy have been discussed. Engine endoscopy is an economical technique for IC engine application and provides valuable information related to engine combustion and emissions. These aspects have been discussed in following sub-sections.

2. Evolution of endoscopes

Endoscopy is a very popular and effective optical visualization technique for several medical as well as industrial applications. This technique is normally used by doctors during complex medical surgeries, for capturing view of interior organs in a human body, while making very small incisions. It was used for the first time by Philippbonzzini (1806) in Mainz using light conductor for examining the cavity in a human body. After many improvements in this technique, Georg wolf (1873–1938) introduced rigid endoscopes in 1906. Flexible endoscopes were introduced in 1911. During the World War-II, several modern technologies emerged in medical science landscape. In 1945, Karl-Storz, who is famously known as "father of endoscopy" introduced a new endoscope, which was used with an external light source for investigations interiors of a human body. Afterwards, this concept was widely used in the industrial applications also for investigating various problems of the interior parts/ components of different machines, which had limited space for optical access.

Of late, this technique is being considered for myriad of applications in SI and CI engines e.g. combustion diagnostics, spray evolution diagnostics and fuel-air mixture formation studies etc. with minor modifications in existing production grade engines. Special endoscopes are designed for optical investigations in automotive applications; such as to capture the images of in-cylinder combustion, fuel sprays and fuel-air mixing along with assessing the effects of modifications in cylinder head, intake manifold etc.

3. Principle of endoscope

Endoscope is a large, thin tube, consisting of achromatic lens or rod lens combination, which is used for transferring images from the viewing end to the ocular (eye piece). Image is transferred through the image lenses and field lenses, which are set in the guide tube alternatively. These pairs of lenses form an image reversal system, which repeats the reversal of image and finally transfers the image straight through the endoscope (Fig. 2 (a)) [Dierksheide et al., 2001].

In Fig. 2 (a), object image is firstly projected at plane B1 and then it is transferred through the image reversal lenses (L1/L2) from there and projected on to the plane B2. Image on the plane B2 is a mirror image of plane B1. In the same way, image is again transferred on to plane B3, where the image is similar to the image at plane B1. C-mount adapter is attached to the ocular, which consists of a focusing arrangement.

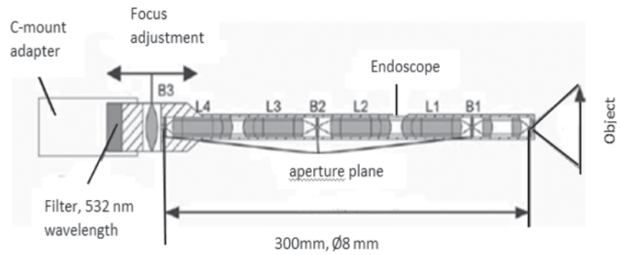


Fig. 2 (a): Image transformations through an endoscope [Dierksheide et al., 2001]

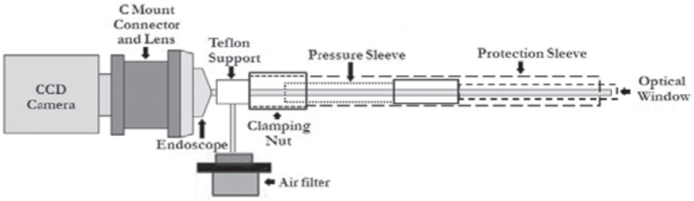


Fig. 2 (b): Schematic of the endoscopic access system [Agarwal et al., 2015]

Fig. 2 (c): Typical engine endoscope

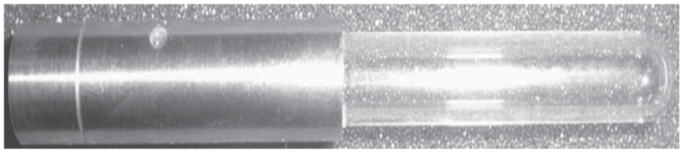


Fig. 2 (d): Optical window for 70^0 engine endoscope

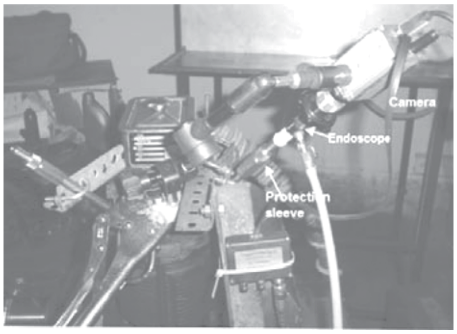


Fig. 2 (e): Common arrangement of engine endoscope with camera

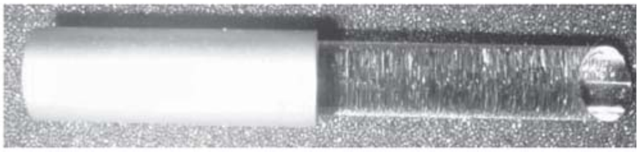


Fig. 2 (f): 70^o degree Illumination Tip

Fig. 2: Principle and Components of the Engine Endoscopy

4. Engine endoscopy

Engine endoscopes gain access in to the engine combustion chamber through the cylinder head and modifications are required to be done in the cylinder head and the intake manifold for this, according to the specific application. For combustion and spray diagnostics in an IC engine, a hole is made in the cylinder head such that its endoscopic view can capture the illuminated area of interest and it covers maximum possible view of the combustion and fuel spray. Schematic of the engine combustion chamber endoscopic access is shown in Fig. 2 (b) and its components are described briefly in following subsections.

4.1 Engine endoscopes

Normally, two types of endoscopes are used for engine applications according to the cooling requirements, based on temperature and pressure conditions, namely combustion chamber endoscopes and general cavity endoscopes. Each engine endoscope is designed for different viewing angles (0^0, 30^0 and 70^0) of the front lens in order to capture the view of the combustion chamber because an endoscope has limited field of view.

4.1.1 Combustion chamber endoscope

Combustion chamber endoscopes are used for high temperature, high pressure applications such as visualization of in-cylinder combustion processes and fuel sprays. It provides direct access to the engine combustion chamber with the help of a quartz optical window, used for its thermal protection from hot, high pressure combustion chamber environment. This type of endoscope is coupled with an integral cooling arrangement to protect its optics from the high temperature and high pressure gases in the engine cylinder during combustion. Combustion images are captured in the absence of light because sufficient light is emitted by incandescence of soot formed in the combustion chamber. However for fuel spray visualization, illumination from an external light source is essential. Dry, pressurized, dust-free air is circulated through the endoscope assembly at ~5-6 bar pressure to remove the heat convected to it from the high temperature combustion chamber environment, in order to avoid damage to the optics.

4.1.2 General cavity endoscope

General cavity endoscopes are used in low temperature, low pressure conditions, where external cooling is not required e.g. visualization of mixture formation in the intake manifold of a SI engine. An optical fiber is coupled with the lens system of the endoscope for transmission of light, which is used for illuminating the target area for capturing the images in the region of interest.

4.2 Protection sleeve and pressure sleeve

Protection sleeve is used for protecting the endoscope from engine vibrations. Protection sleeve is inserted into the cylinder head through a hole and held in place using external fine threads. The stainless steel sleeve with external threads is inserted into the hole having internal matching threads. The sleeve thus fits well in the cylinder head. Inside the protection sleeve, a pressure sleeve is inserted for protecting the endoscope from the high cylinder pressure environment. In cooled endoscopes, compressed air is circulated through the pressure sleeve in order to remove the heat from the endoscope. The hot air comes out from the holes, drilled in the upper part of the pressure sleeve and vented to the surroundings through the holes made in the clamping nut.

4.3 Optical window

Optical windows are very important and expensive component in the endoscopic system. They are cylindrical quartz tubes, fitted inside the steel tubes (Fig. 2 (d)).

An optical window is inserted into the protection sleeve. Quartz section of optical window directly faces the engine combustion chamber heat and pressure. Optical window provides optical access to the endoscope and protects it from exposure to high pressure and temperature (~ 60 bar, 2500 K) gas in the combustion chamber, which is undergoing combustion. The length and shape of quartz window may be different for every endoscope, depending on its viewing angle and the type of endoscope.

4.4 Camera

Normally CCD/ IR camera is used for engine endoscopy, depending on the objective of research. The camera is connected to the endoscope ocular with an optical connector. For real time in-cylinder combustion and spray imaging, it is synchronized with the crankshaft encoder and cam phase sensor signals, with the help of a micro-controller based circuit. A common arrangement of the engine endoscope with the camera is shown in Fig. 2 (e). For high speed optical investigations such as particle imaging velocimetry (PIV), images are captured using a high-resolution double-frame CCD camera with 1024x1280 pixels for each frame, and 12-bit dynamics [Dierksheide et al., 2001].

4.5 Lighting unit and illumination tip

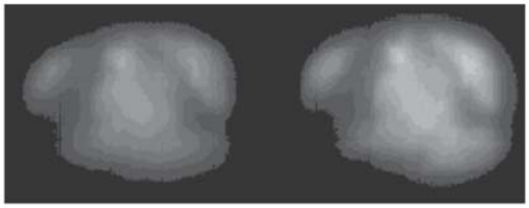
This unit is used during low intensity engine applications such as spray imaging, mixture formation investigations etc. It includes an illumination tip and a light guide. Illumination tip (Fig. 2 (f)) is inserted into the protection sleeve, which is fitted into another hole in the cylinder head. Illumination tips are designed according to the endoscopy angle.

5. Research trends and applications of endoscopy in IC engines

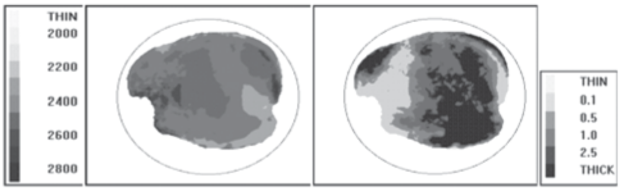
Endoscopy has been used to investigate different combustion and spray parameters in IC engines since long time. It has been combined with laser diagnostic techniques to understand complex engine geometries and used for combustion characterization and mixture formation in DI and IDI engines. Endoscopy was successfully used for optimizing fuel utilization and reducing soot emissions from modified combustion chambers. Off-late, endoscopy has been used in several other advanced applications in automotive industry, which were otherwise difficult for conventional techniques, such as determining piston temperature, study of pilot diesel spray combustion, understanding the effect of intake change condition on the combustion chamber temperature distribution and in-situ soot formation etc. Diverse applications of this technique are briefly discussed in the following sub-sections.

5.1 Combustion analysis in CI and SI engines

Combustion analysis is very important for optimizing the performance of Internal Combustion engines. Many researchers used endoscopic technique for diagnosing the effect of different spray parameters such as fuel injection angle, injection timing etc. on the engine combustion. Hampson and Reitz [1998] investigated the effect of double injections over single injection on in-cylinder combustion temperatures and in-cylinder soot distribution using endoscopic visualization. They captured combustion images in a modern, heavy-duty diesel engine equipped with common rail electronically-controlled fuel injection system, which injected fuel at very high pressure compared to normal injection systems. Combustion temperature distribution and soot distribution were analyzed using two-colour pyrometry technique on the endoscopic combustion images. They also developed multi-dimensional simulation model for verifying the data and there was good agreement between experimental and simulation results. They explained the reasons for lower soot with split injection and advanced injection using endoscopic images in conjunction with modeling results. Main aim of their research was to understand the benefits of spilt injection. The combustion images and contours of temperature, and soot KL factor are shown in Fig. 3 (a)-(c).



(a)



(b)

Fig. 3 (a): Combustion image captured by an endoscope; [Hampson and Reitz, 1998]

Fig. 3 (b): Temperature distribution and soot distribution obtained by an engine endoscope [Hampson and Reitz, 1998]

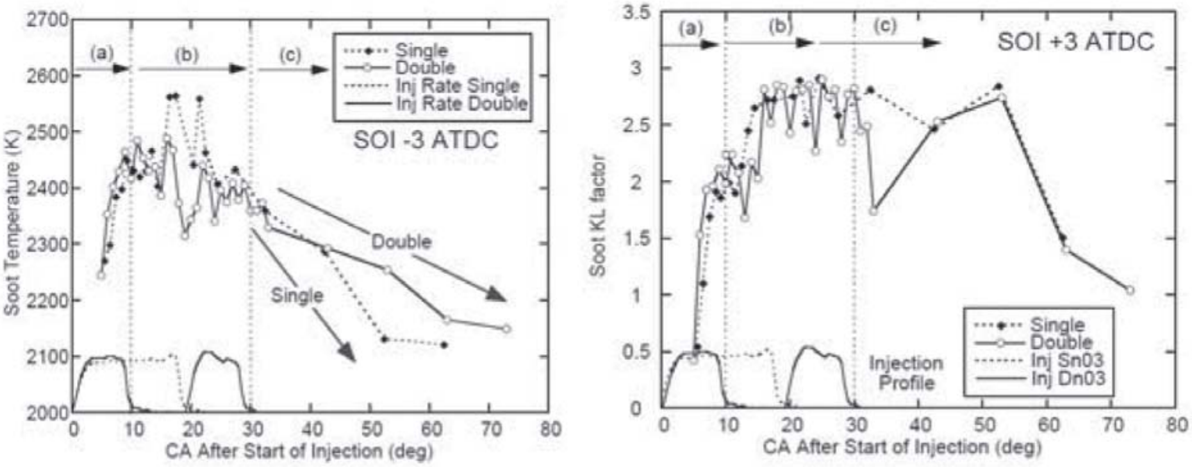
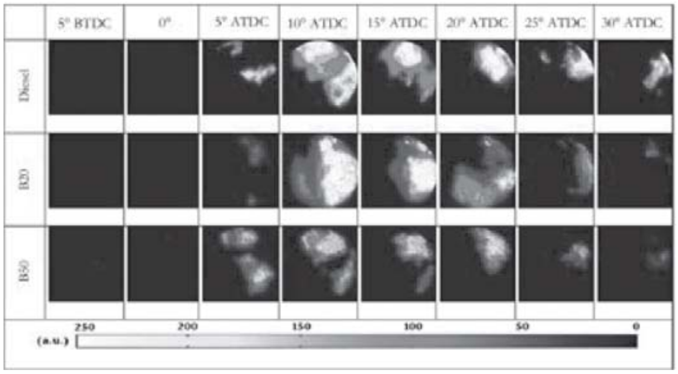
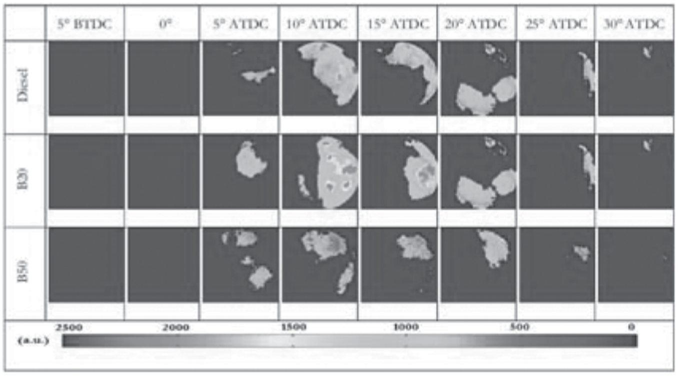


Fig. 3 (c): Soot temperature vs. crank angle after SoI [Hampson and Reitz, 1998]



(d)



(e)

Fig. 3 (d): Contours of R intensity for different test fuels using engine endoscopy [Agarwal et al., 2015]

Fig. 3 (e): Spatial and time resolved in-cylinder flame temperature distribution for different fuels using engine endoscopy [Agarwal et al., 2015]

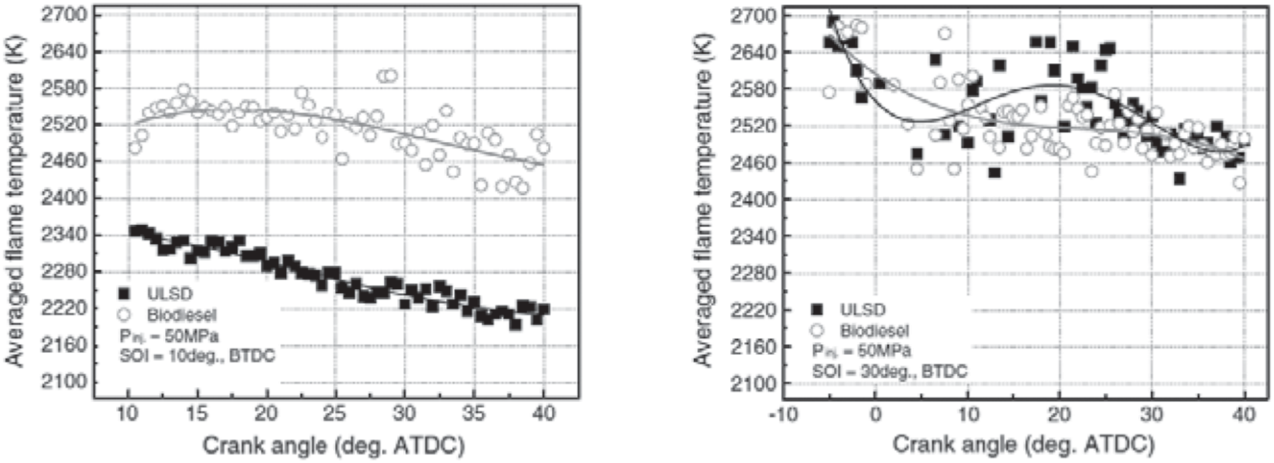


Fig. 3 (f): Average flame temperature of biodiesel and ULSD at two injection timings [Jeon et al., 2013]

Behavior of maximum temperature and KL factor are plotted w.r.t. crank angle for both single and multiple injections (Fig. 3 (c)). The temperature and soot distribution plots (Fig. 3 (b)), which were determined from the endoscopic images clearly showed that soot temperatures reduced with increasing crank angle and were followed by increased in-cylinder temperature during phase (b) due to combustion of fuel injected during second injection pulse. While in case of single injection; rise in temperature was due to termination of injection. It can also be observed that soot factor was higher in single injection due to continuous injection of fuel, while during double injection, it dropped due to end of first injection. It substantially dropped at 30° after SoI due to end of second injection. Hence, reduction in soot concentration was clearly observed in double injection case. Eismark et al. [2009] performed the experiments on a heavy-duty diesel engine to investigate soot oxidation by statistical analysis of the engine data. They also used in-cylinder high speed photography using endoscope along with CFD simulations to examine large scale in-cylinder fluid motion.

Agarwal et al. [2015] investigated soot distribution in a diesel, and biodiesel (B20 and B50) fuelled diesel engine. They investigated the behavior of soot distribution during combustion at different engine loads. They reported that spatial distribution of soot in the combustion chamber increased after the start of combustion (SoC). However after attaining maxima, it started to decrease, which represented oxidation of soot particles in late combustion phase. Fig. 3 (d) shows the variation in R intensity for different test fuels at different crank angle positions. R intensity is defined as the intensity of red color in the diffusion flame, which denotes the soot induced digital coloration of the flames. They also discussed a very important finding that endoscopic combustion visualization of highly oxygenated fuels is not as effective as mineral diesel because intensity and color of the combustion images are slightly inferior due to lower emission of radiations from the unburned soot particles. In the same study, Agarwal et al. [2015] also investigated variations in flame temperature distribution. Fig. 3 (e) shows the variation of flame temperature distribution for different test fuels during combustion. Results showed that higher biodiesel blends showed relatively lower flame radiation temperature however it was primarily due to lower soot radiations. However higher oxygen content of biodiesel led to higher NOx formation during combustion.

Jeon et al. [2013] also carried our engine endoscopy with ultra-low sulfur diesel (ULSD) and biodiesel and measured flame temperature distribution. Fig. 3 (f) shows that during ULSD combustion, the flame develops rapidly and the flame temperature is distributed uniformly. However, biodiesel flame distribution develops both slowly and locally. Due to slow evaporation rate and the lower atomization of biodiesel, the fuel-air mixture is not as homogeneous as that of ULSD, even though the ignition delay of biodiesel is longer. They also examined the effect of SoI on flame temperature distribution. Fig. 3 (f) shows the difference between the average flame temperatures. It is evident that biodiesel flame temperature is distributed around 2500 K, while ULSD flame temperature is scattered between 2220 K and 2340 K. However this is true, when the SoI was at 10° BTDC. If the SoI was advanced to 30° BTDC, the difference between the flame temperature of biodiesel and ULSD vanishes (Fig. 3 (f)).

In-cylinder combustion phenomenon was also investigated by Spicher et al. [2000] in a direct injection spark ignition (DISI) engine using endoscopy. They analyzed combustion characteristics such as flame propagation speed [Koch et al., 2002], flame radiations and compared them for homogeneous and stratified modes of combustion. Optical spark plug and endoscope were inserted in place of an exhaust valve in a 4-valve engine cylinder head. Combustion flame fronts were captured at every 0.20° CA and plotted contours. These contours show the increasing flame-front till the maximum propagation and decreasing flame-front upto the end of combustion (EoC). It was found that maximum flame propagation for stratified charge was lower than homogenous charge due to unburnt mixtures. It was also found that flame-front propagation was uniform from maximum flame-front to the observation center in the homogenous charge mode due to homogenous fuel-air mixing, while behavior of flame-front was rather irregular in case of stratified charge mode. Sauter et al. [2006] modified the DISI engine and observed the flame area using endoscopic access system. Effect of ignition angle on the flame area was analyzed using image analysis and the flame area was found to be lesser for later ignition angle due to lower cylinder pressure and temperature.

5.2 Determining ignition sites in diesel engines

Ryan et al. [1994] used endoscopy in a 4-valve diesel engine to analyze the effect of fuel injection pressure and intake air density on ignition and combustion location at different engine speeds, loads, injection pressures and intake air pressures. They captured the movie of combustion using high speed camera and found that increased fuel injection pressure or intake air density reduced the ignition delay, leading to start of ignition near the nozzle. Locations of ignition and combustion are independently affected by fuel injection pressure and intake air pressure. They also found that spray tip velocity and wall impingement increased if fuel injection pressure was higher than 150 MPa. These observations were helpful in improving fuel-air mixing in order to optimize emissions.

Ignition sites for pilot injection were investigated by Ricart and Reitz [1996] and Ricart et al. [1997] using engine endoscopy in a heavy-duty single cylinder engine. They conducted experiments for different fuel quantities (during pilot injection), which were 10, 15 and 20% of the total fuel injected at 75% engine load, and 1600 RPM at different SoI timings. They captured combustion images for pilot injection and characterized the combustion by ignition sites, which were located below the point, where spray hits the piston bowl surface. They observed that majority of combustion started at multiple ignition sites, at the bottom of the piston bowl and spread along the bowl edges. SoI mainly retarded due to ignition sites existing above the spray impingement point.

5.3 Combustion characteristics of alternative fuels

Several studies were conducted for comparing combustion characteristics of different alternative fuels vis-à-vis mineral diesel using engine endoscopy. The main aim of these studies was to develop efficient substitute of mineral diesel by improving combustion characteristics of these alternative fuels. Endoscopes proved to be very helpful in such studies because different real-time characteristics could be analyzed by changing different engine variables and the fuel injection system. Miersat et al. [2004] conducted similar studies on Sun-diesel, which is an alternative biodiesel derived from wood chips. Endoscope was installed in a Mercedez A-class turbocharged DI engine equipped with common rail direct injection (CRDI) system. They analyzed soot concentration factor from the combustion images for both test fuels at different SoI timings. They found that peak of soot concentration factor becomes higher for advanced SoI timings. However, for late combustion cycles, soot concentration factor was higher for retarded SoI. This was due to reduction in turbulence and in-cylinder pressure, which reduced the soot oxidation rate in late combustion cycle. For Sun-diesel, rate of soot production was higher compared to diesel, primarily due to shorter ignition delay and relatively higher viscosity. Agarwal et al. [2015] compared the combustion characteristics of mineral diesel and biodiesel blends (B20 and B50) using endoscopic imaging. They reported that area of luminous flame zone was higher in B20 compared to mineral diesel. On the other hand, the area of luminous flame zone decreased on further increasing biodiesel content in the test fuel upto B50 at the same engine load. Dominating nature of two different properties of biodiesel, lower calorific value and higher oxygen content were responsible for such a trend.

5.4 Fuel-air mixing optimization

Endoscopy was used for investigating the mixture formation process in SI engines. Air-fuel mixing is a very critical process for SI engines, which strongly affects engine performance and emission characteristics. Mixture formation images were captured by Schänzlin et al. [2001] in a DISI engine using fiber endoscope, which was coupled with a 300 W xenon light source (Fig. 4 (a)).

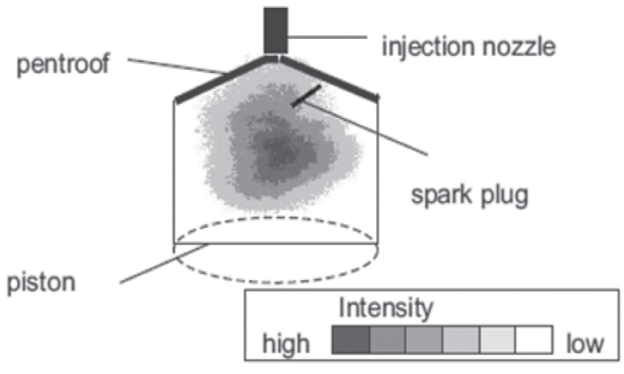


Fig. 4 (a): Endoscopic view of the observed mixture formation region [Schänzlin et al., 2001]

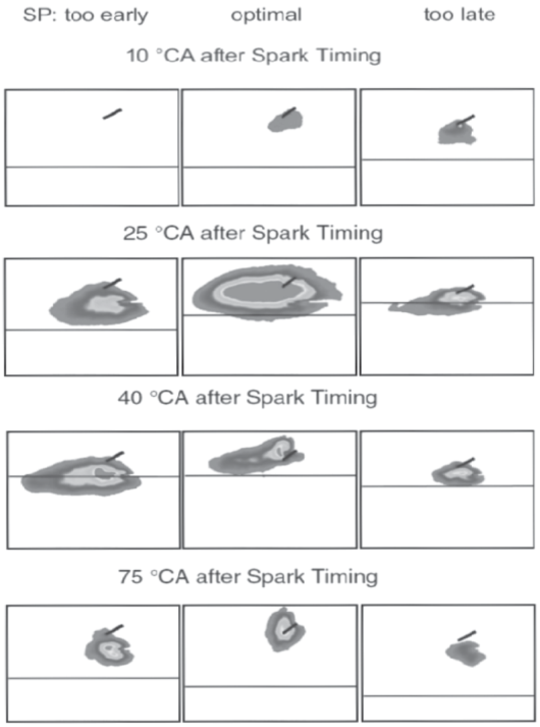


Fig. 4 (b): Endoscopic combustion images with different spark timings in stratified charge mode [Schänzlin et al., 2002]

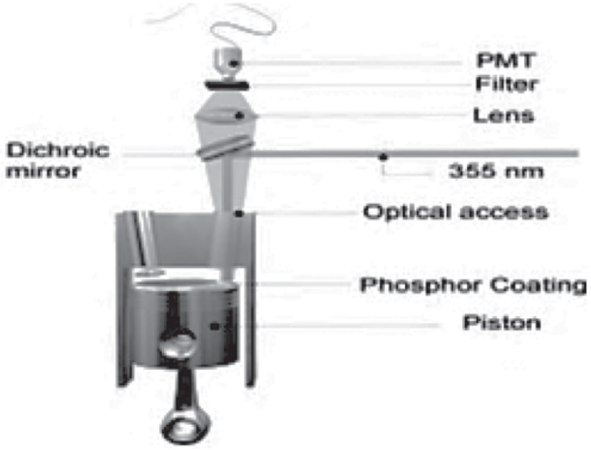


Fig. 4 (c): Experimental setup for piston temperature measurement [Husberg et al., 2005]

They visualized three different phases of mixture formation process in three different modes: homogenous mode; stratified mode; and stratified low temperature mode. They compared the effect of fuel injection pressure, swirl level and engine load for all test modes. They reported that swirl level has highest effect and injection parameters have lowest effect on combustion. They also reported that stratification is very important for initiating optimum combustion reactions. Schänzlin et al. [2001] discovered compact burning zone in high-swirl case and widespread combustion in low-swirl case. They further investigated the effect of spark timings on combustion. If spark timing was too advanced, flame surface was very small and the fuel spread was due to improper mixing with air. In case of too retarded spark timing, fuel and air mixed homogenously and produced lowest soot, which is shown by lowest soot intensity in Fig. 4 (b).

During optimum spark timing, when the fuel consumption was lowest, advanced SoC was observed. It was also observed that fuel spreads in wider area, burning fuel-air mixture became leaner and the flames propagated very slowly. In Toyota Motor Company, Sakata et al. [1990] developed a Toyota Reflex Burn (TRB) system to optimize the fuel-air mixture formation in a DI diesel engine. At that time, gaseous and particulate emissions were a huge environmental concern for small DI diesel engines. They modified the combustion chamber shape, which generated complex air motion with high turbulence. Endoscope with a high-speed camera was used to visualize the mixture formation, and spray and flame behavior to achieve optimum impingement intensity. TRB system generated complex air motion from the impingement with a reflex edge in the combustion chamber cavity, which generated highly turbulent air motion. They found that deflection of fuel spray away from the reflex edge reduced wall-wetting, which reduced the particulate emissions. Werlberger and Cartellieri [1987] also used endoscopic high-speed combustion imaging in a high speed direct injection (HSDI) diesel engine to investigate the effect of pilot injection on fuel-air mixing and combustion. They also observed the effect of wall temperature on the combustion development.

5.5 Optimizing combustion chamber geometry

Endoscopy has proved to be a very successful technique for investigating the effect of combustion chamber geometry on combustion parameters. Flame propagation during combustion was observed by Zhang et al. [1995] for three different combustion chamber geometries. Average flame velocity vector and flame distribution was calculated using statistical cross-correlation method for different combustion chamber geometries (Dish type, Re-entrant type, Production type). They analyzed combustion images by endoscopy and reported that ignition delay was almost similar for all combustion chamber geometries however average flame velocity was highest for production type combustion chamber geometry due to highly swirling air motion. Smoke emission was also lowest for production type combustion chamber geometry due to better utilization of inducted air.

5.6 Determination of ignition delay and combustion timings

Ignition delay and combustion duration are very important factors for combustion in diesel engines because they influence soot and NO_x formation. Endoscopic technique is very helpful in analyzing SoC because combustion can be easily seen in the combustion images. Several studies were carried out to determine the ignition delay and combustion duration for different fuels [Bittle et al., 2010; Hotti and Hebbal, 2011; Huang et al., 2004]. Researchers calculated ignition delay and combustion duration from the heat release curves and mass burn fraction curves as well. Mtui et al. [1996] used engine endoscopy for investigating ignition delay and combustion duration in case of pilot injected liquid diesel with high pressure direct injection of natural gas and compared it with 100% diesel fuelling at the same speed and load conditions. They also investigated the effect of gas injection on pilot liquid flames. For calculating the ignition delay and combustion duration, they used endoscopic combustion imaging and mass burn fraction (MBF) calculations and got almost similar results by both methods. They captured the endoscopic images using CCD camera for (i) 100% diesel, (ii) 30% pilot diesel and 70% natural gas injection and (iii) only pilot diesel injection. From the combustion images, combustion duration and ignition delay were calculated and it was found that there was no effect on combustion duration and ignition delay on natural gas injection with diesel compared to 100% diesel.

For validating the endoscopic results, Sauter et al. [2006] analyzed the start of flame detection, maximum flame detection and end of flame detection from endoscopic images and correlated them with 5%, 50% and 95% mass burn fraction (MBF) timings respectively for different engine operating conditions. They found linear results with high regression coefficient (~1) for 5% and 50% MBF but there were huge fluctuations in correlating the end of combustion flame with 95% MBF, because a small irregularity in beginning could have a significant impact on the end of combustion process [Reckers et al., 2002]. Jeon et al. [2013] performed endoscopic experiments to compare the combustion characteristics of ULSD and biodiesel. They concluded that ULSD had a similar ignition delay as biodiesel, higher peak combustion pressure and higher BMEP compared to biodiesel due to its similar cetane number and relatively higher heating value for the same fuel quantity injected. In another study, Jeon et al. [2014] used endoscopes for visualization of combustion in a DME fuelled diesel engine. The experiments were performed at different conditions and results showed similar ignition delay at different engine speeds. DME combustion was relatively faster and resulted in higher peak combustion pressure than ULSD.

Agarwal et al. [2015] also performed engine endoscopy in a production grade engine and validated the results obtained from engine endoscopy with combustion results from the thermodynamic analysis. In their experiments, they investigated the combustion of diesel, and biodiesel blends (B20 and B50) and found significantly different combustion pattern for each test fuel. They also compared the results obtained by thermodynamic combustion analysis and endoscopic images for SoC and combustion duration for each of these test fuels.

5.7 Spray analysis

Endoscopy is very useful in spray characterization inside an engine because this technique provides direct optical access to the combustion chamber and can focus on the nozzle tip. Several studies [Dent, 1971; Lefebvre, 1989; Park et al., 2009; Agarwal and Chaudhury, 2010; Lee et al., 2005] were carried out for spray investigations using other visualization techniques however they were limited to constant volume spray chambers and not in real firing engines. Using endoscopes along with lighting arrangement has proved to be a very successful tool for capturing the spray images during combustion events [Poster et al., 2000]. General cavity endoscopes are used for such low light applications. Light is passed through an optical fiber, which is coupled to the endoscope. Alam et al. [2005] captured the spray images in a diesel engine for different blends of dyglyme with diesel (20% w/w dyglyme blended with BP15 ("O-20"), 40% w/w dyglyme blended with BP15 ("O-40") and 95% w/w dyglyme blended with BP15 ("O-95")). They compared the SoI timings and spray penetration length for these fuels and reported that O-20 had earliest SoI and O-95 had shortest spray penetration length.

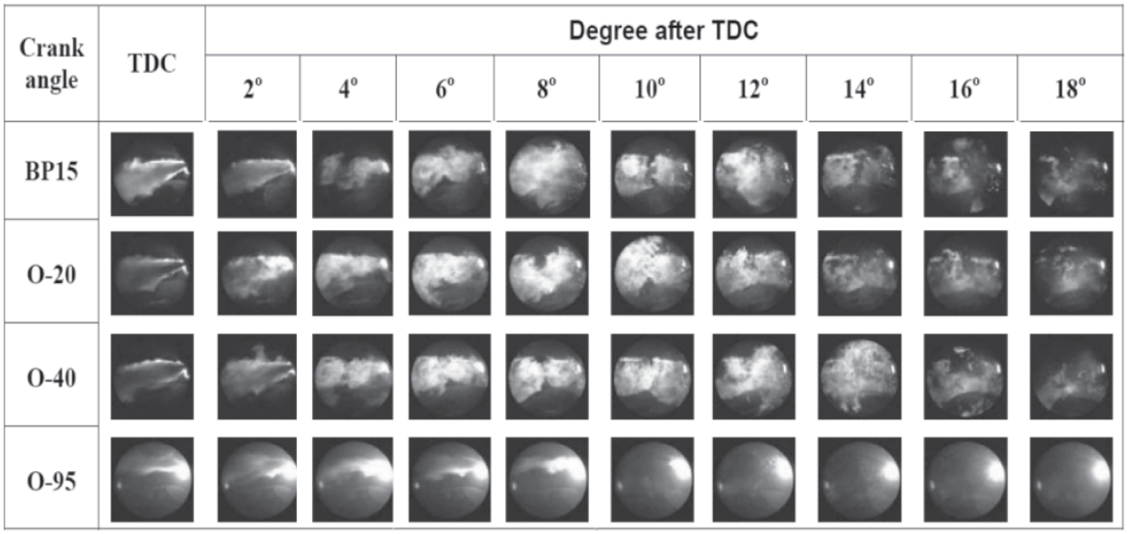


Fig. 5 (a): Spray and combustion visualization of a direct injection diesel engine operated with diglyme-diesel blends [Alam et al., 2005]

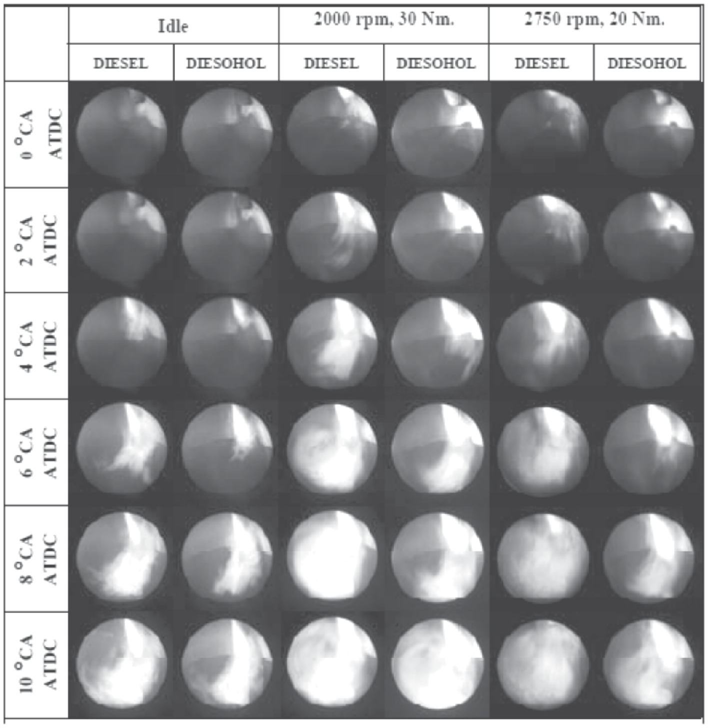


Fig. 5 (b): Images of spray formation in pre-chamber for reference diesel and diesohol at selected operating points [Wattanavichien and Azetsu, 2004]

Jeon et al. [2014] also investigated the spray and combustion behavior of DME fueled single cylinder engine. They investigated effect of various engine operating conditions such as different injection timings; engine speeds and engine loads on DME fuel spray atomization, combustion and emission characteristics. They used endoscopic visualization system consisting of a CCD camera, an endoscope, an illumination device, and AVL ThermoVision software. The endoscope equipped with CCD camera was installed on the cylinder head, to visualize the upper combustion chamber.

Wattanavichien and Azetsu [2004] also used an endoscopic visualization system with lighting arrangement to compare the fuel spays of diesohol and mineral diesel in an IDI engine. They captured the spray images from low to medium loads with all other injection parameters fixed. They observed relatively superior atomization, longer spray penetration length and wider spray angle for diesohol due to its lower viscosity compared to mineral diesel. Schänzlin et al. [2001] implemented endoscopic technique in a spray-guided DISI gasoline engine. They performed in-cylinder optical investigations to provide information on the liquid phase distribution of fuel in the combustion chamber at different times after the start of fuel injection. They also performed numerical analysis for liquid phase fuel distribution and found a good qualitative agreement between the simulation results and endoscopic results. This technique was also extended to multi-cylinder engines fuelled with alternative fuels such as alcohols, and biofuels to investigate fuel-air mixing, flow pattern inside the combustion chamber and complex combustion characteristics [Disch et al., 2013; Allocca et al., 2013].

5.8 Piston temperature distribution and other in-cylinder applications

Apart from investigations of combustion and fuel-air mixture formation in IC engines, endoscopy is also widely used for various other challenging applications. Husberg et al. [2005] measured piston temperature in a single cylinder engine using endoscopy. They used a thin coating of thermographic phosphor on the surface of the piston and installed an optical window for endoscopy by removing one of the exhaust valves (Fig. 4 (c)).

As seen in Fig. 4 (c), Nd-YAG laser was directed into the combustion chamber with the help of an optical prism and a dichroic mirror for exciting the thermographic phosphor. Excited photonic emissions with wavelength in visible light range were transmitted through the same mirror and then detected by a photomultiplier tube, which was mounted along with the endoscope. Photomultiplier tube sensed the exponential decay of excited phosphor emissions through the endoscope and produced a voltage signal corresponding to the lifetime of the phosphor emissions. Piston temperature was previously calibrated with the lifetime of the phosphor material, which was chosen according to the range of temperatures expected on the piston surface.

Nikolic and Iida [2007] used endoscopic imaging in a single cylinder rapid compression machine (RCM), which was used for simulating diesel combustion. They investigated the effect of CO_2 concentration, used for diluting intake air in the EGR to control NO_x formation. Soot distribution and ignition properties were analyzed with the help of endoscopic combustion images. They captured and compared the combustion images at 0, 4.3, 9.5, 14.3 % CO_2 concentrations in the intake air. The flame temperature and maximum soot concentration decreased upon increasing CO_2 concentration in the intake air, which in-turn also prolonged the ignition delay.

Korczewski [2011] investigated the component failure mechanism in a marine engine using endoscopy. They concluded that endoscopic imaging helps in evaluating technical state of directly accessible construction elements of an engine. Many material defects on the surface of components such as piston, liner and bearing, which limit working of an IC engine, can be detected by endoscopy. On the basis of the character and dimensions of the identified damages, it is possible to evaluate and make technical corrections of such faulty components. Therefore endoscopy has emerged as one of the newest methods in technical diagnostics.

5.9 Engine flow analysis: Endoscopic PIV

Nishiyama et al. [2012] used an air-cooled endoscope in a PIV experiments to investigate exhaust gas flow in a SI engine. They performed experiments in a 2.5 l, four-cylinder spark-ignited engine with a four valve per cylinder, pent-roof combustion chamber. Endoscopic setup comprised of a quartz lens and a stainless steel cage for adequate heat resistance. For direct observation of the interiors of the exhaust manifold, the endoscope chosen had outer diameter 15 mm and length 175 mm. A sapphire window with cooling-air passage was used for observation (Fig. 6 (a)).

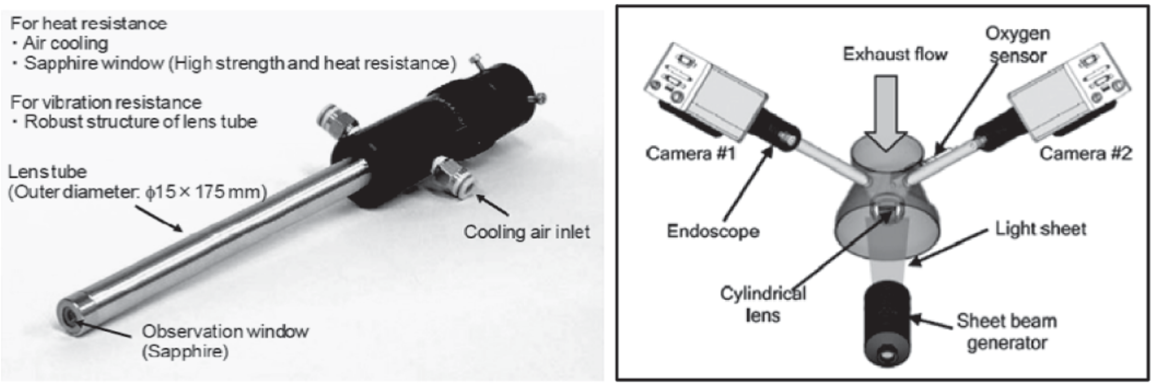


Fig. 6 (a): Schematic view of endoscopic PIV [Nishiyama et al., 2012]

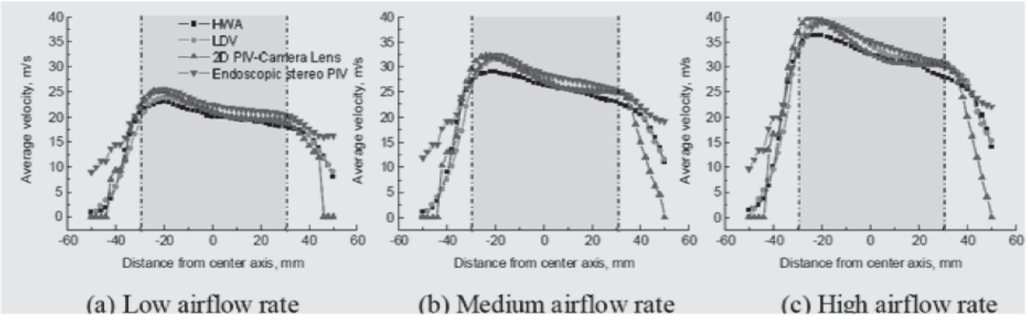


Fig. 6 (b): Comparison of HWA, LDV and stereo PIV results in the steady-flow test rig [Nishiyama et al., 2012]

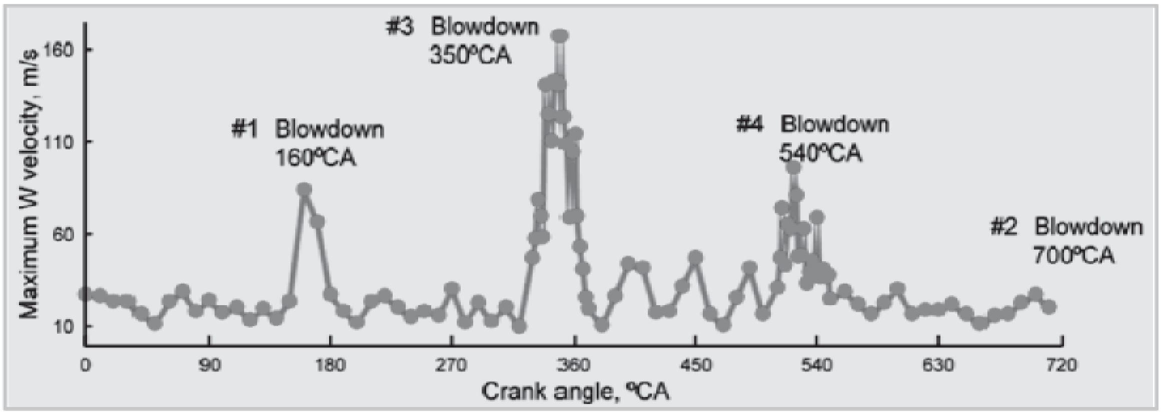
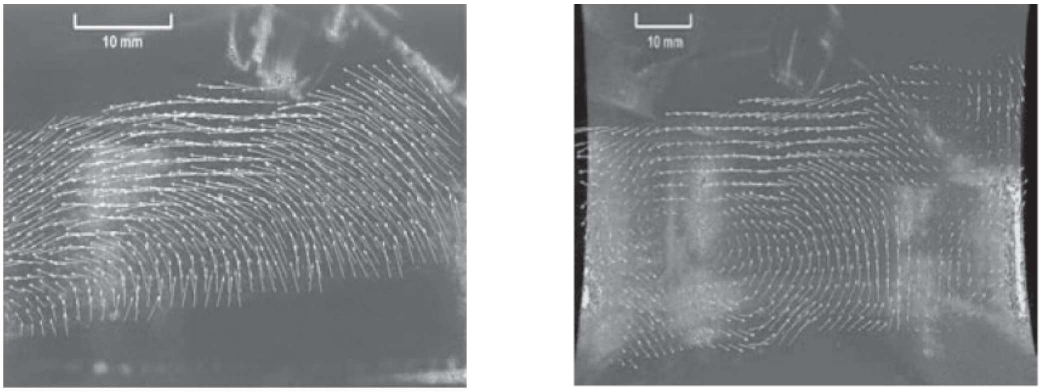


Fig. 6 (c): Maximum downstream velocity with crank angle [Nishiyama et al., 2012]



Tumble flow via large window; **Tumble flow via endoscopic**

Fig 6 (d): Comparison of flow-field through full optical access and endoscopic access [Dierksheide et al., 2001]

They performed an experimental evaluation of the endoscope's performance and compared the results with established flow measurement techniques such as hot wire anemometry (HWA), laser Doppler velocimetry (LDV), and 2D-PIV. A comparison of results (Fig. 6 (b)) showed that various measurements were in good agreement with each other for all mean velocities.

Main objective of the study was to measure 3D velocity field in the exhaust of an engine using endoscopic PIV. The blow-down behavior of each cylinder was identified under firing condition (Fig. 6 (c)). The results showed that a strong downstream flow greater than 60 m/s was produced after the exhaust valve opening of each cylinder. However, the velocity distribution pattern and maximum velocities were different, depending on the cylinder.

PIV is a technique, which is non-intrusive in nature and has been in practice for many years now and is being widely used for flow visualization of fluids. PIV can be either macroscopic or microscopic. Macroscopic PIV is generally used with full optical access however microscopic PIV is applied with endoscopic access. Singh et al. [2015] used full optical access in an optical research engine using tomographic PIV and investigated the effect of engine speed on air-flow pattern in the engine cylinder under motored conditions. However this is quite expensive and challenging technique. Therefore several research groups have performed endoscopic optical diagnostics in IC engines however they were unable to determine air-flow characteristics in the engine cylinder due to limited access. Dierksheide et al. [2001] presented and compared endoscopic PIV measurements through an 8 mm optical access in an IC engine using endoscopy and compared the results with the measurements using standard optical access using a large window in the same area of interest. They demonstrated that the use of endoscopic devices, both for illumination of the light-sheet plane and for the recording of the PIV images, has proved to be successful for the investigation of in-cylinder flow structures developed in IC engine. It was also noticeable that the amount of information about the in-cylinder flow structures increased, when endoscopic device was used (Fig. 6 (e)). Nauwerck et al. [2000] used endoscopy to investigate the in-cylinder flow structures during the gas exchange process inside a small two-stroke engine. They successfully implemented this system for PIV under a variety of engine operating conditions and speeds upto 6000 rpm, which is certainly not possible in an optical engine.

6. Conclusions

Engine endoscopy is an important optical technique for analysis of engine combustion and spray formation process. It can be used in wide variety of engine investigations ranging from fuel-air mixing in SI engines to combustion visualization in CI engines. Endoscopy can be also used to optimize the engine design parameters e.g. shape of combustion chamber, piston bowl etc. in addition to analyzing the effect of designs of different component on engine performance, combustion and emissions. Engine endoscopy is widely used for determining spatial flame temperature distribution and spatial soot distribution. Spray visualization in the engine combustion chamber is another important application of endoscopy. Several researchers also employed endoscopy to the exhaust manifold in order to investigate the exhaust flow behavior. Endoscopy offers enormous advantages in engine experiments due to limited space for optical access. Another major advantage offered by this technique is that the measurements can be done in production grade engine at high speeds and loads, rather than special configuration complex optical engines with limited operating range, which are extremely complex and expensive.

References

1. Agarwal AK, Agarwal A, Singh AP, 2015, Time resolved in-situ biodiesel combustion visualization using engine endoscopy, Measurement, 69, 236–249.
2. Agarwal AK, Chaudhary VH, 2010, Spray characteristics of biodiesel/ blends in a high pressure constant volume spray chamber, Exp. Therm. Fluid Sci., 42, 212-218.
3. Alam M, Song KH, Boehman A, 2005, Spray and combustion visualization of a direct injection diesel engine operated with diglyme fuel blends, Int. J. Engine Res., 7, 503-521.
4. Allen J, Law D, Pitcher G, Williams P, 2000, A New optical access research engine for advanced fuel spray and combustion analysis using laser based diagnostics, Monograph of 33rd International Symposium on Automotive Technology and Automation (ISATA), Dublin, Ireland.
5. Allocca L, Catapano F, Montanaro A, Sementa P, 2013, Study of E10 and E85 effect on air fuel mixing and combustion process in optical multi-cylinder GDI engine and in a spray imaging chamber, SAE Technical Paper 2013-01-0249.
6. Bevan KE, and Ghandhi JB, 2005, PIV measurements of in-cylinder flow in a four-stroke utility engine and correlation with steady flow results, SAE Small Engine Technology Conference & Exposition, 2004-32-0005.
7. Binjuwair SA, 2013, Characterization of flow structures inside an engine cylinder under steady state condition, Doctoral Thesis, Department of Aeronautical and Automotive Engineering, Loughborough University.
8. Bittle JA, Knight BM, Jacobs TJ, 2010, Interesting behavior of biodiesel ignition delay and combustion duration, Energ. Fuel., 24, 4166–4177.
9. Bowditch FW, 1961, A new tool for combustion research: A quartz piston engine, SAE Technical Paper 610002.
10. Dent JC, 1971, Basis for the comparison of various experimental methods for studying spray penetration, SAE Technical Paper 710571.
11. Dierksheide U, Meyer P, Hovestadt T, Hentschel W, 2001, Endoscopic 2D-PIV flow field measurements in IC, 4th International Symposium on Particle Image Velocimetry Göttingen, Germany.
12. Disch C, Kubach H, Spicher U, Pfeil J, 2013, Investigations of spray induced vortex structures during multiple injections of a DISI engine in stratified operation using high-speed-PIV, SAE Technical Paper 2013-01-0563.
13. Dowell LJ, Gillies GT, 1991, Errors caused by baseline offset and noise in the estimation of exponential lifetimes, Rev. Sci. Instrum., 62(1), 242-243.
14. Eismark J, Balthasar M, Karlsson A, Benham T, 2009, Role of late soot oxidation for low emission combustion in a diffusion-controlled, high-EGR, heavy duty diesel engine, SAE Technical Paper 2009-01-2813.
15. Hampson GJ., Reitz RD, 1998, Two-colour imaging of in-cylinder soot concentration and temperature in a heavy-duty DI diesel engine with comparison to multidimensional modelling for single and split injections, SAE Technical Paper 980524.
16. Han YT, Ki-bum K, Lee G, 2008, The investigation of soot and temperature distributions in a visualized direct injection diesel engine using laser diagnostics, Meas. Sci. Technol. 19, 115402-115412.
17. Heywood JB, 1988, Internal Combustion Engine Fundamentals, McGraw-Hill.
18. Hotti SR, Hebbal O, 2011, Performance and combustion characteristics of single cylinder diesel engine running on karanja oil/diesel fuel blends, Engineering, 3(4), 371-375.
19. Huang Z, Lu H, Jiang D, Zeng K, Liu B, Zhang J, Wang X, 2004, Combustion behaviors of a compression-ignition engine fuelled with diesel/methanol blends under various fuel delivery advance angles, Bioresour. Technol., 95(3), 331–341.
20. Husberg T, Gjirja S, Denbratt I, 2005, Piston temperature measurement by use of thermo-graphic phosphors and thermocouples in a heavy-duty diesel engine run under partly premixed conditions, SAE Technical Paper 2005-01-1646.
21. Jeon J, Jong Lee T, Lim YS, Kwon SI, Park YH, Cha J, Lee K, Park S, 2013, Flame temperature distributions of biodiesel fuel in a single-cylinder diesel engine, Fuel Process. Technol., 110, 227–234.
22. Jeon J, Kwon SI, Park YH, Oh Y, Park S, 2014, Visualizations of combustion and fuel/air mixture formation processes in a single cylinder engine fueled with DME, Appl. Energ., 113, 294–301.
23. Koch T, Schänzlin K, Boulouchos K, 2002, Characterization and phenomenological modeling of mixture formation and combustion in a direct injection spark ignition engine, SAE Technical Paper 2002-01-1138.
24. Korczewski Z, 2011, Endoscopic image processing and analysis of pistons service failures of marine diesel engines, Journal of Polish CIMAC, 6(2), 127-136.
25. Lee CS, Park SW, Kwon SI, 2005, An experimental study on the atomization and combustion characteristics of biodiesel-blended fuels, Energ. Fuel., 19, 2201–2208.
26. Lefebvre AH, 1991, Measurement and modeling of diesel sprays, Atomization Spray., 1(4), 467-478.
27. Maurya RK, Agarwal AK, 2011, Experimental study of combustion and emission characteristics of ethanol fuelled port injected homogeneous charge compression ignition (HCCI) combustion engine, Appl. Energ., 88, 1169-1180.
28. Miers SA, Ng H, Ciatti SA, 2005, Emissions, performance, and in-cylinder combustion analysis in a light-duty diesel engine operating on a fischer-tropsch, biomass-to-liquid fuel, SAE Powertrain & Fluid Systems Conference & Exhibition 2005-01-3670.
29. Mtui PL, Hill PG, 1996, Ignition delay and combustion duration with natural gas fueling of diesel engines, SAE Technical Paper 961933.
30. Nauwerck A, Gindele J, Spicher U, Rosskamp H, 2000, Investigation of the transient in-cylinder flow inside a two stroke engine with particle image- velocimetry, SAE Technical Paper 2000-01-0902.
31. Nikolic D, Iida N, 2007, Effects of intake CO_2 concentrations on fuel spray flame Temperatures and soot formations, P. I. Mech. Eng. D-J Aut., 221(12), 1567-1573.
32. Nishiyama A, Jeong H, Ikeda Y, Sawada R, 2012, Application of endoscopic stereo PIV to 3D exhaust gas flow measurements in a practical SI engine, 16th Int. Symp on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal.
33. Omrane A, Ossler F, Alden M, 2002, Two dimensional surface temperature measurements of burning materials, P. Combust. Inst., 29(2), 2653–2659.
34. Park SH, Hyung JK, Suh HK, Lee CS, 2009, Experimental and numerical analysis of spray-atomization characteristics of biodiesel fuel in various fuel and ambient temperatures conditions, Int. J. Heat. Fluid. Fl., 30 (5), 960-970.
35. Park SH, Hyung JK, Suh HK., Lee CS, 2009, A study on the fuel injection and atomization characteristics of soybean oil methyl ester (SME), Int. J. Heat. Fluid. Fl., 30(1), 108–116.
36. Pastor JV, Garcia JM, Molin S, 2000, Analysis methodology of diesel spray and flame by means of in-cylinder endoscopic imaging, Advanced Sensors and Instrumentation Systems for Combustion Processes IEEE Seminar, Birmingham, 13, 1-4.
37. Pierpont DA, Montgomery DT, Reitz RD, 1995. Reducing particle and NOx using multiple injection and EGR in a D.I. diesel, SAE Technical Paper 950217.
38. Pundir BP, 2010, I. C. Engines: Combustion and Emissions, Narosa Publishing House, New Delhi, India.
39. Reckers W, Schwab H, Weiten C, Befrui B, Kneer R, 2002, Investigation of flame propagation and cyclic combustion variations in a DISI engine using synchronous high-speed visualization and cylinder pressure analysis, 5th International Symposium on Internal Combustion Diagnostics, AVL Deutscwand, 27-32.
40. Ricart LM, Reitz RD, 1996, Visualization and modelling of pilot injection and combustion in diesel engines, SAE Technical Paper 960833.
41. Ricart LM, Xin J, Bower GR, Reitz RD, 1997, In-cylinder measurement and modelling of liquid fuel spray penetration in a heavy-duty diesel engine, SAE Technical Paper 971591.
42. Richter M, Axelsson B, Aldén M, Josefsson G, Carlsson L-O, Dahlberg M, Nisbet J, Simonsen H, 1999, Investigation of the fuel distribution and the in-cylinder flow field in a stratified charge engine using laser techniques and comparison with CFD modeling, SAE International Fuels & Lubricants Meeting & Exposition, 1999-01-3540.
43. Ryan TW, Shahed SM, 1994, Injection pressure and intake air density effects on ignition and combustion in a 4-valve diesel engine, SAE Technical Paper 941919.
44. Sakata I, Ishisaka K, Yanagihara H, Sami H, 1990, Development of TOYOTA reflex burn (TRB) system in DI diesel, SAE Technical Paper 900658.
45. Sauter W, Nauwerck A, Han K-M, Pfeil J, Velji A, Spicher U, 2006, High-speed visualization of combustion in modern gasoline engines, Second International Conference on Optical and Laser Diagnostics (ICOLAD 2005), J. Phys.: Conf. Ser., 45, 120-132.
46. Schänzlin K, Koch T, Boulouchos K, 2002, Characterization of the Combustion in a Direct Injection Spark Ignition Engine, SAE Technical Paper 2002-01-0834.
47. Schänzlin K, Koch T, Tzannis A, Boulouchos K, 2001, Characterization of mixture formation in a direct injected spark ignition engine, SAE Technical Paper 2001-01-1909.
48. Singh AP, Gupta A, Agarwal AK, 2015, Tomographic particle image velocimetry for flow analysis in a single cylinder optical engine, SAE Int. J. Mater. Manf. 8(2):472-481.
49. Singh G, Singh AP, Agarwal AK, 2014, Experimental investigations of combustion, performance and emission characterization of biodiesel fuelled HCCI engine using external mixture formation technique, Sust. Energ. Technol. and Asses., 6, 116-128.
50. Spicher U, Kölmel A, Kubach H, Töpfer G, 2000, Combustion in spark ignition engines with direct injection, SAE Technical Paper 2000-01-0649.
51. Wattanavichien K, Azetsu A, 2004, Studies of visualized diesohol combustion phenomena in IDI engine, C-2, CNG and Alternative Fuels, Oxygenated Fuels, 423-430, 6th International Symposium on Diagnostics and Modeling of Combustion in Internal Combustion Engines (COMODIA), Thailand.
52. Werlberger P, Cartellieri W, 1987, Fuel injection and combustion phenomena in a high speed di diesel engine observed by means of endoscopic high speed photography, SAE Technical Paper 870097.
53. Zhang L, Ueda T, Takatsuki T, Yokota K, 1995, A study of the effects of chamber geometries on flame behavior in a di diesel engine, SAE Technical Paper 952515.