# AN INVESTIGATION OF THE PRESENCE OF UNCONTROLLED COMBUSTION PHENOMENON IN SPARK IGNITION SINGLE CYLINDER OPTICAL ENGINE

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***Abstract***

*The objective of this paper is to investigate appearance of surface ignition - postignition experienced inside the engine cylinder and correlate it with the nature of the spark ignition combustion prior to the onset of surface ignition. The test engine used to carry out all experiments was a Jaguar optical single-cylinder engine, operating in spark-ignition mode, although with negative valve overlap. The optical configuration of the engine allows characterizing and analyzing combustion process based on the processing of captured images in correlation with in-cylinder pressure and other parameters recorded with regard to instantaneous engine operating conditions.*

*Results of the experiments covered in this publication focus on flame propagation and development as well as reveal occurrence of abnormal combustion processes. Experimental observations, especially the captured images show a relationship between the nature of normal combustion process initiated by spark discharge and the existence of abnormal combustion phenomena. All tests were performed under fixed engine conditions – constant speed and single component hydrocarbon fuel. Because the nature of fuel can shape the combustion process, a brief discussion and a proposed correlation of anti-knock, auto-ignition, and resistance to surface ignition qualities of a few single- and multi-component fuels is presented. Finally the publication leads to provide an indication of possible solutions concerning the problem of uncontrolled post-ignition events in optical engines.*

**Keywords:** *optical engine, combustion, surface ignition*

## 1. Introduction

Research Optical Engines have always played a crucial role in understanding phenomena involved in and governing internal combustion engines' performance. Since they allow continuous monitoring of in-cylinder events they became valuable research equipment to conduct investigations in the field of the flow diagnostics, the nature of combustion and even emission formation analysis. Despite the fact that Research Optical Engine provides precious insight into observation and measurement of processes inside the cylinder its unconventional and complex construction limits its operation to some extent. These restrictions may depend on the given engine's design and set-up of the experiment. Obtaining credible and comparable results require proper choice of set-up for the test to be conducted as well as estimation a period of time allowed for continuous operation of the engine. Whereas selection of individual components can be performed based on the engine specifications, the estimation of operation time is often a trial-and-error process. During all the experiments presented in this paper two different kinds of cylinder liner sleeves were used – a cooled metal cylinder liner and a non-cooled transparent glass liner. As the experimental results indicate, using a solid glass liner led to departures from the normal combustion sequence. However, not only did the non-cooled liner cause post-ignition flame initiation apparently related to surface ignition due to presumed elevated temperatures but uncontrolled combustion appeared from what appears at hot spots on the cylinder head walls in the proximity of the intake valves as well.

Abnormal combustion reveals itself in many ways. Of the various abnormal combustion processes which are important in practice, the two major phenomena are knock and surface ignition. These abnormal combustion phenomena are of concern because: (1) when severe, they can cause major engine damage; and (2) even if not severe, they are regarded as an objectionable source of noise by the engine or vehicle operator. [1]

Initial work has been done to define the behaviour of spark-ignition combustion initiated at 35 crank angle degrees (CAD) before TDC, particularly the directions of flame propagation and development. Further considerations lead to introduction and description of the nature of surface ignition which appeared in expansion stroke. First traces of deviations from normal combustion are visible at 25 CAD after TDC and these events last for at least consecutive 15-20 CAD. Since the recorded in-cylinder pressure curve has not shown any sharp pressure increases, all the ignition events caused by hot spots were classified as non-knocking and based on their occurrence as post-ignition. The captured images clarify the existence of abnormal combustion and suggest that these are possibly caused by elevated temperature of solid glass liner following the comparison between the results obtained with water-cooled and solid glass liners respectively. These investigations were carried out using the 2,2,4 trimethylpentane isooctane as a single fuel at a constant engine speed of 1000 rpm.

## 2. Experimental apparatus

<u>Research Single Cylinder Engine</u>

The Jaguar Optical Single Cylinder Research engine is four-stroke, water-cooled, naturally aspirated, spark-ignition. It has four valves, a pentroof and two overhead camshafts. Table 1 presents some data on the geometrical configuration and valve timing of this engine. It should be noted that the valve events include some negative valve overlap and late opening of the inlet valve.

*Table 1. Geometric characteristics of the Optical test engine*

| *Parameter* | *Value* |
|---|---|
| Bore | 89 mm |
| Stroke | 90.3 mm |
| Compression Ratio | 11 |
| Intake Valve Lift | 10 mm |
| Inlet Valve Open | 24° aTDC |
| Inlet Valve Close | 94° aBDC |
| Exhaust Valve Lift | 9 mm |
| Exhaust Valve Open | 64° bBDC |
| Exhaust Valve Close | 6° aTDC |

The research engine features both port injection and direct injection systems. The high pressure direct injection system has a capability to supply fuel twice per one engine cycle (double injection), as governed by the currently used engine control system, however all experiments covered in this paper utilized single injection. The control system for the engine was written in LabVIEW 7.1 programming environment and is based on three input signals coming from camshaft and crankshaft encoders. This system allows controlling PFI, DI timing and quantity, ignition timing, and triggering of the camera and laser diagnostics events. To control and process all inputs and outputs, a PC equipped with National Instruments Interface Card PCI- 6602 card is used. In between the PC and the test engine an interface box is employed which serves as an insulator-amplifier. Bosch™ high-pressure direct injector is controlled through its own electronic control unit which receives signals from the interface box.

Optical access and ICCD camera

One optical access port is sufficient for direct observation of combustion. For most optical techniques, two or more optical access ports are required when a light source is employed to illuminate or excite the in-cylinder species. The cylinder head wall, cylinder block liner, and piston top form the combustion chamber. There are therefore three ways to gain optical access to the combustion chamber through: the piston (cylinder head), side (cylinder liner) or bottom (piston) [2].

The Jaguar Single-Cylinder Optical Engine features all three access ports to the combustion chamber through the side – a glass liner, through the bottom - piston crown equipped with transparent window, and through a vertical triangular window installed directly in the cylinder head which enables either the additional observation of combustion chamber or illuminating the combustion chamber by laser beam when required. Figures 1 and 2 show cross sectional view of liners and piston used in this study and also indicate possible optical paths.

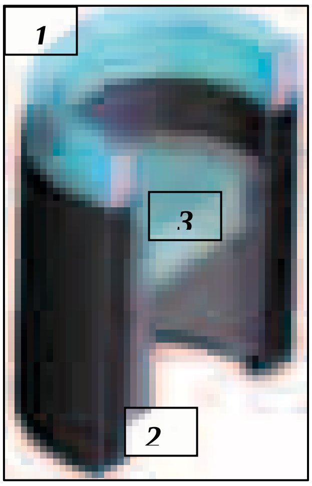



*Fig. 1. Cross sectional view of optical engine components*
*(1) Part- or full length solid glass liner*
*(2) Part or full length Cooled Cylinder liner*
*(3) Piston-crown window*

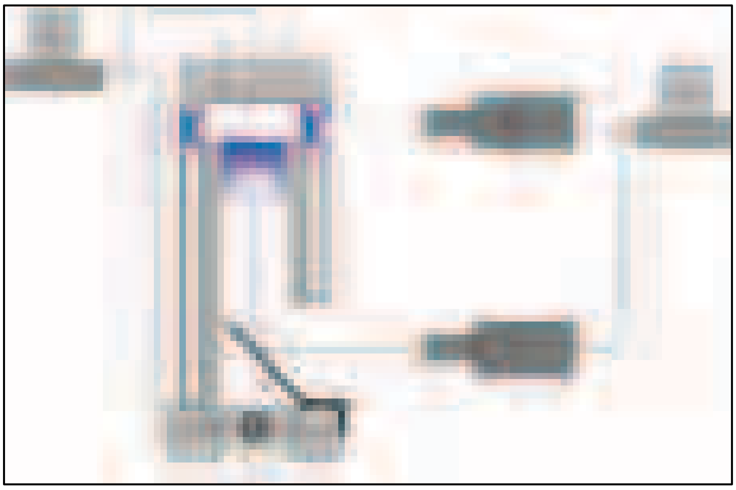


*Fig. 2. Experimental apparatus for combustion test – two optical paths used to carry out experiment*
*I – bottom access, II – side access*
*(1) – glass liner, (2) – piston-crown window,*
*(3) – vertical window in cylinder head,*
*(4) - 45° mirror, (5) – ICCD camera,*
*(6) – engine control system PC*
*(7) – data acquisition system PC*

One of the optical access paths is achieved directly through solid glass liner whether it forms a part of complete cylinder or is a complete liner itself. Second optical path is constructed through transparent glass window of 64 mm diameter in piston crown. The extended piston is hollowed and it allows installing appropriate 45° mirror on the engine crankcase. This solution permits to view the large portion of the combustion chamber. Some flow and combustion analysis work performed on a very similar configuration of the optical engine in the authors' lab was presented elsewhere [3, 4, 5].

All images were recorded by Andor iStar ICCD camera in the absence of external illumination. The camera was externally triggered by the engine control system.

The data acquisition system consists of an MS-Windows-based PC equipped with National Instrument Interface Card PCI-6023E and in-house code written in LabVIEW 7.1 software. In-cylinder pressure measurement was performed with Kistler 6052A type pressure transducer triggered by the signal coming from crank encoder every one degree. Other parameters such as inlet air temperature, exhaust gases temperature, manifold air intake pressure and lambda value were monitored and recorded. .

## 3. Operating conditions

All data and images presented in this paper were acquired under steady engine operation conditions. Engine rotational speed, injection timing, injection duration, injection pressure, ignition timing were set to constant values as summarized in Table 2.

*Tab. 2. Base engine operating conditions*

| *Parameter* | *Value* | *Parameter* | *Value* |
|---|---|---|---|
| Engine Speed | 1000 rpm | Injection Duration | 1.3 ms |
| Intake Air Temperature | 298 K (25°C) | Injection Pressure | 15 MPa |
| Intake Air Pressure | 67.8 kPa (absolute) | Start of SI Ignition | 35° bTDC |
| Start of Injection | 280° bTDC | $\lambda$ Value | 0.97 – 0.985 |

The test engine was fuelled by 2,2,4 trimethylpentane isooctane. The essential properties of the fuel relevant to the experiment and discussion of results are listed in Table 3.

## 4. Experimental results and discussion

Figure 3 and 4 show two sets of experimental frames taken by the ICCD camera of the combustion process, one viewed from underneath through the window in in the piston, and the other from the side through the glass liner and the vertical window. It should be emphasized that all pictures covered in this paper come from different cycles since the intensified camera frequency is 0.87 Hz. All images captured within this work are contained within 125 CAD of engine operation. Although it is well known that combustion duration in conventional spark-ignition engine lasts between 30 and 90 CAD, the objective of experiments advised to monitor it for slightly longer period of time.

In frame 1 of Figure 3 the image was taken one degree after spark discharge and the location of the spark plug in the combustion chamber is visible. It is apparent that the flame starts to propagate from the location of spark. Worthy of discussion is the fact of non-uniform nature of flame development evident in frames 4 to 8 of Figure 3. In fact the flame extends considerably quicker to the proximity of exhaust valves (red circles in the top part of the pictures) than in the direction of intake valves site. Between frames 6 and 8 the differences in the outermost distances from the centre of spark plug to the flame front were calculated and are 15.2 mm towards the area of exhaust valves and 4.6 mm towards the intake valves respectively. Those calculations confirm indication that flame develops unevenly. The non-uniform nature of combustion process led to leaving unburned charge remaining in one part of combustion chamber for a longer period of time whereas the part in the close proximity of exhaust valves is entirely enflamed which can also be observed in frame 3 of Figure 4 (where the exhaust valves are on the right hand side).

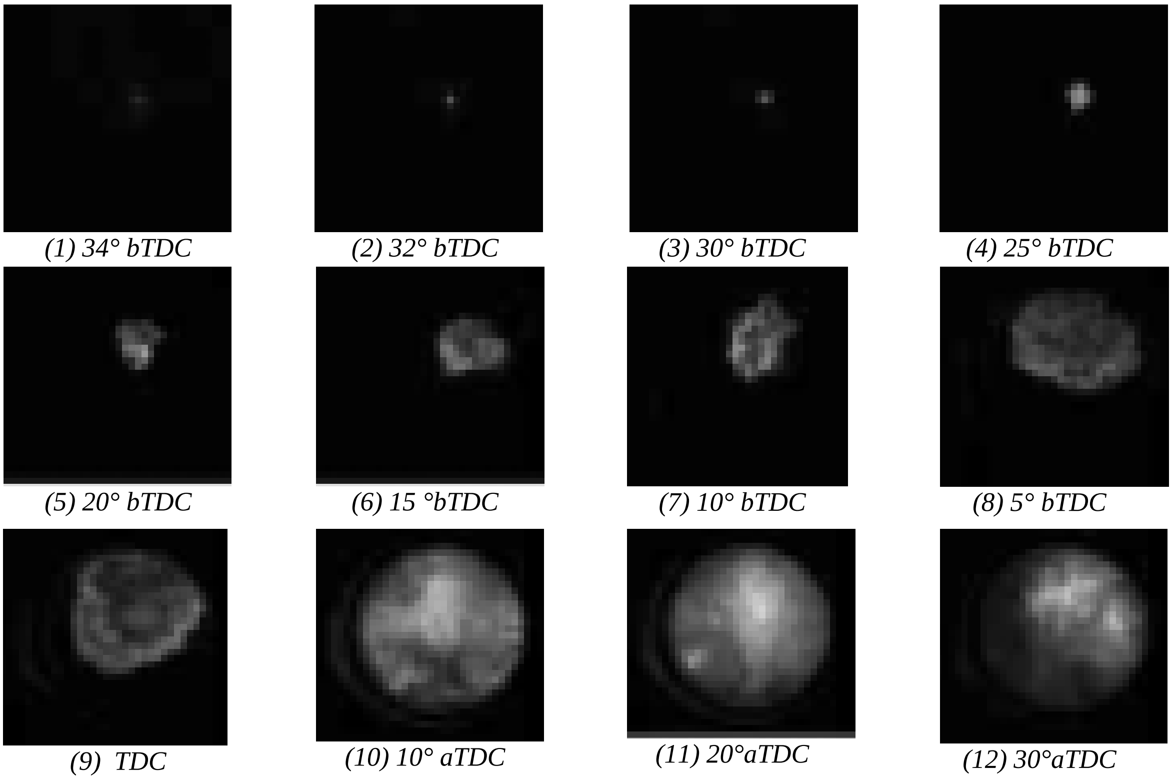



*Fig. 3. Spark-ignition combustion process – sequence of flame images (bottom view) 1000 RPM, 100% 2,2,4, trimethylpentane isooctane, A/F =14.59 – 14.82*

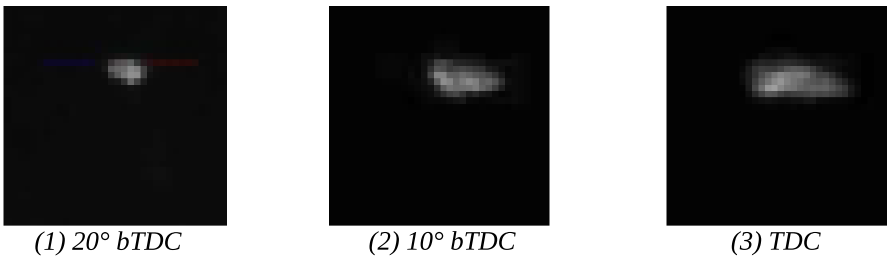
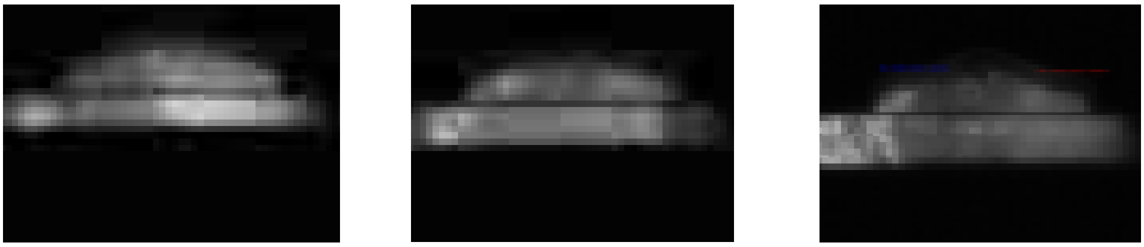



*Fig. 4. Spark-ignition combustion process – sequence of flame images (side view) 1000 RPM, 100% 2,2,4, trimethylpentane isooctane, A/F =14.59 – 14.82*

So far the nature of standard spark-ignited combustion process has been presented and discussed. Since the purpose of the tests was to understand and characterize the uncontrolled single flames appearing later in the engine cycle, the rest of this paper aims to present and discuss these. Figures 6 and 7 present the bottom and side view images, respectively, of the events taking place at late CAD in the expansion stroke. Even though part of the combustion chamber near the cylinder wall is not visible due to the limitation of window size, from Figure 6 the occurrences of single flames can be noticed and these are even more evident in the frames of Figure 7. These two sets of frames provide a source of insight into the location of the undesirable combustion. Although these flames can be positioned differently in combustion chamber, they nevertheless emerge from one side of the combustion chamber. The onset and appearance of all zones of single flames are situated near the wall. Since they seem to be "attached" and are adjacent to the glass liner wall it can therefore be reasoned that they may represent the post combustion involving surface-ignition events. Figures 6 and 7 show that the flames propagate from more than one source spontaneously and simultaneously. All of them occurred in the expansion stroke. In fact their presence could be correlated with the uncovering of the surface of solid glass liner which forms a part of the combustion chamber walls while the piston travels away from the top dead centre.

*(1) 25° aTDC* *(2) 30° aTDC* *(3) 60° aTDC*

*Fig. 6. Occurrence of single flames (surface ignition) – sequence of flame images (bottom view) 1000RPM, 100% 2,2,4 trimethylpentane isooctane, A/F =14.59 – 14.82*



*(1) 30° aTDC* *(2) 35° aTDC* *(3) 40° aTDC*

*Fig. 7. Occurrence of single flames (surface ignition) – sequence of flame images (side view) 1000 RPM, 100% 2,2,4, trimethylpentane isooctane, A/F =14.59 – 14.82*

It can be argued that possibly the hot surface of the un-cooled liner led to the occurrence of uncontrolled combustion phenomena. Surface ignition events commenced at the location of maximum interaction between the fuel mixture and the hot spots of liner surface and in the area where there is possibly some unburned mixture left available, which may be augmented by the unburned mixture emerging from the crevices. No knocking was observed on the pressure curves observed during the experiment (not presented here), thus these combustion events are non-knocking ones, which can be explained by the small portion of the charge that was ignited and burned. For the purpose of the present study this phenomenon was classified as non-knocking surface ignition (post-ignition).

The discussion above correlates the existence of what is seen as surface ignition events with the nature of spark-ignited combustion process and the application of an un-cooled transparent glass liner. Nevertheless, the effect of air-fuel mixture filling the crevices should be emphasized whereby some portion of the charge which was believed to be ignited by hot spots might be emerging from the crevice volumes.

The surface ignition process is essentially governed by the temperature gradients of surface elements. These are, however, not trivial to define. The process is dependent on many factors such as orientation of the hot surface, surface material, surface geometry, size, and the residence time of mixture near the hot surface and properties of fuel used. Figure 8 taken from [6] illustrates the possible occurrences of different ignition events in relation to different properties of hydrocarbon fuels such as the flash point, auto-ignition temperature and hot surface ignition temperature and to prevalent surface / mixture temperatures and fuel vapor pressures. The results presented in [6] showed that hot surface ignition has a statistical character that cannot be defined by a single ignition temperature. It was found [6] that the temperature of 50% probability of ignition is strongly correlated with the auto ignition temperature. The experiments [6] revealed existence of the ignition transitional zone, an intermediate temperature range between the zones of zero and 100% ignition probability where autoignition may or may not take place.

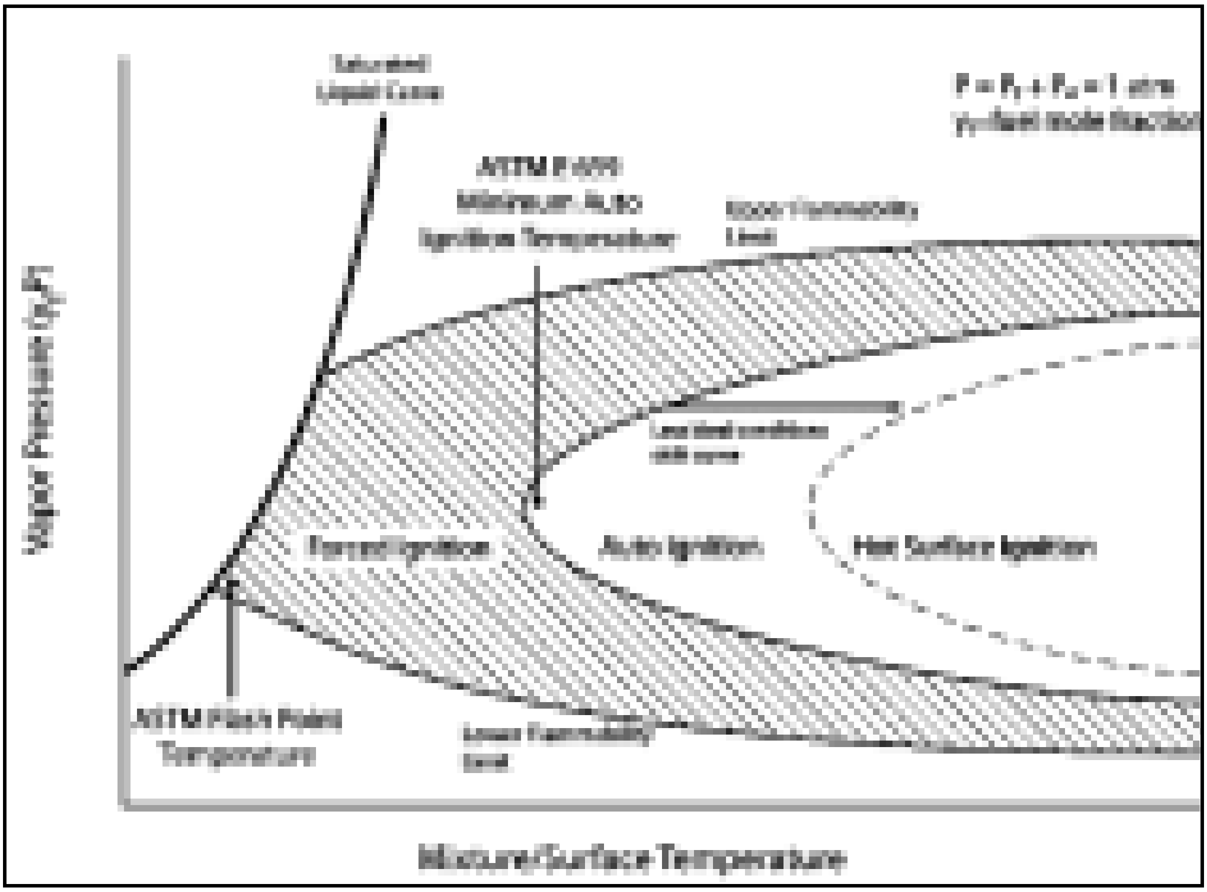



*Fig. 8. Flammability and ignition regimes as a function of temperature and fuel vapor partial pressure [6].*

Experimental relations between the surface temperatures corresponding to different probabilities of surface ignition for various fuels presented in [6] are shown in Table 3. It is proposed here that the relation between the standard research octane number RON of the fuel [7] and its temperature for 50% probability of surface ignition can be correlated and expressed by Eqn. 1. The 50% SI temperatures calculated from this relation are compared with experimental values from [6] in Table 3. The linear relation between RON and 50%SI (Eqn. 1) seems to be clearer than relations with the AIT presented in [6] and quoted in Table 3.

| | |
|---|---|
| Temp of 50% probability of SI [°C] = 1,4031(RON) + 652.45. | Eq. 1 |

A series of bench tests presented in literature [8] indicate the existence of strong dependencies between the surface ignition temperature for a given fuel and the material which made the surface. As indicated in [8], the hot surface ignition temperature for a given hydrocarbon fuel differs according to the surface material and so for three different sorts of materials it can show various hot surface ignition temperatures reaching the maximum difference of more than 100°C. However, in the case of experiments presented in the current work, the solid glass liner is made of fused silica and no specified hot surface ignition temperatures can be found for this material.

*Tab. 3. Comparison of auto-ignition, and surface ignition quality of fuels [6] and the correlation between fuel RON and the temperature for 50% probability of surface ignition proposed here (Eqn.1).*

| Fuel | Auto-Ignition Temp. AIT [°C] [6] | Minimum (LOW) Surface Ignition Temp SILT [°C] [6] | Temp. of 50% probability of Surface Ignition 50% SI [°C] [6] | Temp. of 100% probability of Surface Ignition HTNSI [°C] [6] | Fuel RON[7] | Temp. of 50% prob. of Surface Ignition 50% SI [°C] Eqn. 1 |
|---|---|---|---|---|---|---|
| **n-heptane** | 215 | 541 | 653 | 720 | 0 | 652.45 |
| **n-pentane** | 260 | 690 | 738 | 761 | 62 | 739.44 |
| **2,2,4 methylpentane iso-octane** | 415 | 751 | 794 | 809 | 100 | 792.45 |
| **2-methylbutane** | 420 | 743 | 791 | 805 | 99 | 791.36 |
| **93 gasoline** | 460[3] | 735 | 772 | 796 | AKI 93 | 782.93 |

## 5. Final remarks

The major objective of this paper was to investigate the presence of uncontrolled combustion events when non-cooled glass liner was used, as the experiments provided the opportunity to perform. The investigation conducted by the authors showed the existence of single flames late in the combustion sequence. As was observed all the events of what appeared as surface ignition were occurring in the expansion stroke and were correlated with the gradual exposure of hot surface of glass liner as a potential source of surface ignition. The tendency for single flames to occur was discovered to be in one common location which could be correlated with the nature of earlier spark-ignited flame development across the combustion chamber. Furthermore the temperatures governing the ignition processes – forced, auto and surface ignition were introduced from literature. The equation proposed in this work correlates the research octane number and surface ignition susceptibility of a given fuel showing the proportional relationship between RON values and temperatures for 50% surface ignition probability.

The characteristics of earlier spark-initiated combustion could contribute to the occurrence of surface ignitions because some charge could well be left unburned in the area of the combustion chamber part where subsequent single flames occurred. The nature of spark-ignited combustion may be explained by the possible existence of inhomogenity of air-fuel mixture inside an engine cylinder. Parallel studies of spray pattern utilizing the high resolution camera reveal irregular distribution of fuel droplets. The area "occupied" by air-fuel mixture at the end of injection process would match approximately the area of volume enflamed at TDC during the combustion process. The spray pattern studies are in progress and the details will be published elsewhere.

It was also observed that during experiments where a full-length water-cooled cylinder liner was used and where the engine operating parameters were held constant at the same values as tests covered in this paper the evidence of the existing surface-ignition have not been found. This seems to imply the possibility of surface ignition as classified above being caused by the overheating glass liner. The studies indicate that the time allowed for the engine to run in firing mode should be selected properly before uncontrolled abnormal combustion taking place and this is one of the important factors which need to be considered for research on optical engines. Further study will continue to investigate the exact reason of existence of certain portion of unburned charge and its correlation with the nature of combustion and the crevices volume.

## 6. Definitions and abbreviations

**TDC** – combustion top dead centre
**BDC** – bottom dead centre
**PFI** – port fuel injection
**DI** – direct fuel injection
**RON** – research octane number
**AKI** – antiknock index
**SILT** – the lowest surface ignition temperature
**50% SI** – temperature of 50 % surface ignition probability
**HTNSI** – the highest temperature causing 100% probability of surface ignition
**ICCD** – intensified charge coupled device
**AIT** - *Autoigntion temperature* – the lowest temperature at which a combustible material ignites in air without a spark or flames as determined by ASTM 659-78
**Flash point temperature** – the lowest temperature corrected to a pressure of 101.3 kPa (760 mm Hg) at which application of an ignition source causes the vapors of a specimen of the sample to ignite under specified conditions of test as determined by given ASTM standard

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