Detection of mixture stratification in controlled auto-ignition engine using spontaneous optical emission signal

J Hunicz

Lublin University of Technology, Faculty of Mechanical Engineering, Nadbystrzycka 36, 20-618 Lublin Poland

j.hunicz@pollub.pl

Abstract. In this study an optical-fiber sensor was utilized to observe spontaneous emissions of controlled auto-ignition (CAI) engine under stratified mixture combustion. Mixture stratification, achieved with the use of late direct fuel injection, is an effective approach to improve combustion controllability of the engine operated in the CAI mode. However, observed effects of injection timing on combustion show high combustion sensitivity even for early fuel injection. This study pertains identification of the reasons for such a high sensitivity to injection timing. To identify possible mixture stratification and resulting gradual combustion, optical-fiber sensor was used to observe spontaneous combustion emissions. Optical measurements enabled identification of stratified combustion, which was manifested by double optical signal peaks. The observed peaks of different amplitudes resulted from stepwise combustion in local zones with different mixture composition and flame temperature. The performed measurements enabled better understanding non-linear combustion timing behavior with variable degree of mixture stratification.

1. Introduction

In recent years combustion engines gained a reputation as sources of uncontrolled emissions of exhaust toxic compounds. However, there are some clean combustion techniques, which if applied in piston combustion engines are capable of fulfilling current emissions standards as well as fuel efficiency demands. Low temperature combustion is one of the promising technologies which can offer extremely low nitrogen oxides (NO_X) emissions in parallel with smokeless exhaust [1-3]. Low temperature combustion was successfully demonstrated in controlled auto-ignition (CAI) engines, alternatively and more generally known as homogeneous charge compression ignition (HCCI). Nevertheless, in the current study CAI term is used consistently, as stratified combustion is in contradiction to fundamental assumptions of HCCI combustion.

Internal exhaust gas re-circulation via negative valve overlap (NVO) is a production feasible approach to CAI engine fuelled with gasoline or other high-octane fuels. This technique provides introduction of additional heat into combustible mixture enabling auto-ignition at compression ratios typical of spark ignition engines. Additionally, exhaust gas re-circulation (EGR) is realized, which slows down reaction rate and increases fuel dilution which further reduce NO_X production [4,5]. Besides CAI combustion is basically relying on combustion of homogeneous charge, introduction of some degree of stratification can be an efficient combustion controllability enabler [6]. The effects of mixture stratification in CAI engines are summarized below.

Dec et al. [7] utilized port and direct dual fuel injection system to control fuel stratification. Stratification showed superior combustion rate controllability potential. In general, increase of fuel stratification enabled reduction of pressure rise rates (PRRs). However, it was found that intake pressure is another important factor that affect applicability of mixture stratification. Effective reduction of PRRs was observed only for boosted engine operation. Turkcan et al. [8] further explored the potential fuel stratification using direct injection system solely and split fuel injection technique. The delay of the second injection increased fuel stratification, and thus reduced the PRR. However, high degree of fuel stratification resulted in increased emissions of unburned hydrocarbons, CO and soot. The thesis on the effect of mixture stratification on combustion has been further proven on the basis of simulation studies [9,10]. Yang et al. [11] injected directly methanol into premixed air-gasoline mixture to achieve both fuel, and wider thermal stratification resulting from higher heat of vaporization of alcohol fuel. It has been found that stratified methanol mixture has higher retarding effect on the auto-ignition timing than gasoline. Recently using of two fuels of different reactivity to control combustion in nearly HCCI engines has been demonstrated as promising technique, providing acceptable combustion harshness and extremely low emissions [12,13].

It should be noted that the observed effects of mixture stratification in CAI/HCCI engines differ due to complex phenomena associated with auto-ignition and combustion of compositionally and thermally stratified mixtures. Previous author's studies [14,15], analyzing the effects of split fuel injection, have shown that the effects of stratification are not linear. Moving of the second fuel injection towards main event combustion in order to increase stratification indeed delayed auto-ignition and prolonged combustion. However, this effect was observable only for injection during the early stage of compression process. Further delay of the second injection advanced auto-ignition. This non-linear trend was ascribed to contracting influences of thermal and compositional stratification.

To deeper investigate the effects of late fuel injection the in-cylinder phenomena are still to be explained and evaluated for further progress in the research. A kind of insight into the combustion chamber is essential to enable distinguishing between the effects of compositional and thermal stratification. However, majority of studies utilized computational fluid dynamics simulations as research methods complementary to thermodynamic analysis of in-cylinder pressure. This approach provides additional spatially resolved mixture and temperature distributions that cannot be obtained via pressure analysis. It should be underlined that all the cited above papers aimed at decoupling of the thermal and compositional effects of late fuel injection [9–13] were based on the simulation research.

Utilization of natural combustion luminosity from a combustion chamber has been proven as a valuable research method, which can provide useful information, complementary to the pressure measurements. Although there is a vast number of optical studies of spark ignition and diesel engines, in this review only ones related to HCCI combustion and the most inspiring to the author will be mentioned. Martin et al. [16] utilized optical engine to study the natural luminosity in HCCI combustion in a diesel-fuelled engine. They have found that the natural luminosity risen along with increase of smoke and NO_X emissions, revealing the parasitic effect of fuel stratification. Ozaki et al. [17] utilized optically accessible engine to investigate fuel and EGR stratification. The studies have proven that the thermal stratification accompanying the compositional one has a crucial effect on combustion rates. Fatouraie and Wooldridge [18] investigated spark assisted HCCI combustion using different fuels. Although spark assist improved combustion stability and advanced combustion, an optically observed flame propagation period was hardly visible, because it was immediately followed by volumetric combustion of the remaining mixture in an HCCI style. Lundgren et al. [19] studied transitions from pure HCCI to premixed combustion and underlined the effect of thermal stratification and local temperatures on combustion. The authors pointed out cooling effect of late injection and its delaying auto-ignition impact.

However, it should be noted that designs of optically accessible engines introduce modifications to combustion systems which affect combustion itself to a high extent. Considering this, less intrusive methods, utilizing optical fiber access should be mentioned. Geiser et al. [20] demonstrated an optical fiber sensor and a method for detection of flame propagation at early stage of combustion. For this purpose a spark plug with optical fiber sensors was utilized. Hunicz and Piernikarski [21] used optical fiber sensor and monochromators to perform spectral analysis of the air-gasoline flame in spark ignition engine. This experimental approach led the authors to investigate and analyse cycle-resolved flame emission spectra and their sensitivity to excess air ratio.

In this study the natural luminosity signal from combustion chamber was recorded and analysed in order to detect mixture stratification in an HCCI engine. Simple, non-intrusive measurement technique, utilizing optical fiber sensor was applied. This measurement approach was aimed at identification of possible gradual combustion of compositionally stratified mixture. The author hypothesized that the observed in previous studies [14,15] non-linear behaviour of combustion at variable injection timings are related to competing effects of thermal and compositional stratification. The results proved that compositional stratification can be identified with the use of optical fiber probe. The appearance of compositional stratification was qualitatively linked to observed advance of auto-ignition.

2. Experimental facility and approach

2.1. Research engine and measurement instrumentation

The research was conducted using a single-cylinder engine installed on a dynamometer test stand. A valvetrain of the engine provided NVO valving strategy, thus enabling engine operation in the CAI mode. All engine geometrical data are shown in table 1. The design of combustion chamber is shown in figure 1. Fuel was delivered directly to the combustion chamber using a solenoid, swirl-type injector. More information on applied combustion system and the design of the variable valvetrain can be found in earlier author's works e.g. [22,23].

The engine control system was based on in-house PC software connected with a real-time timing module which governed injection timings and durations, as well as spark generation. The engine test bench was equipped with all necessary measurement and control instruments. Fuel consumption was measured using a fuel balance and intake airflow was measured with a thermal mass flow meter. The engine was also equipped with a set of pressure and temperature transducers in order to control the thermodynamic conditions of all media; intake, exhaust, cooling liquid etc.

Table 1. Research engine specifications.

Parameter name	Value
Displacement	498.5 cm^3
Bore	84 mm
Stroke	90 mm
Compression ratio	11.7
No of valves	2
Intake valve open/close	85/215 °CA
Intake valve lift	3.6 mm
Exhaust valve open/close	521/640 °CA
Exhaust valve lift	2.9 mm

In-cylinder pressure was measured with the use of a miniature pressure transducer installed directly in the engine head. The engine head was also fitted with optical-fiber probe, providing flame natural luminosity signal. The location of the optical probe enabled observation of the combustion chamber area close to the fuel injector, as shown in figure 1. The optical sensor was connected with wide-band visible-range photodetector with the use of a flexible bunch of optical fiber. Diameter of the whole optical path was approximately 4 mm, which provided high enough signal to the photodetector. It should be noted that low temperature combustion provides optical emission signals one or two order of magnitude weaker than flame propagation in spark ignition engines. Pressure and luminosity signal were recorded with a constant angular resolution of 0.1 °CA (crank angle degrees) for 100 consecutive engine cycles and ensemble averaged. It was supposed that step-by-step combustion process could be captured using said optical combustion sensor.

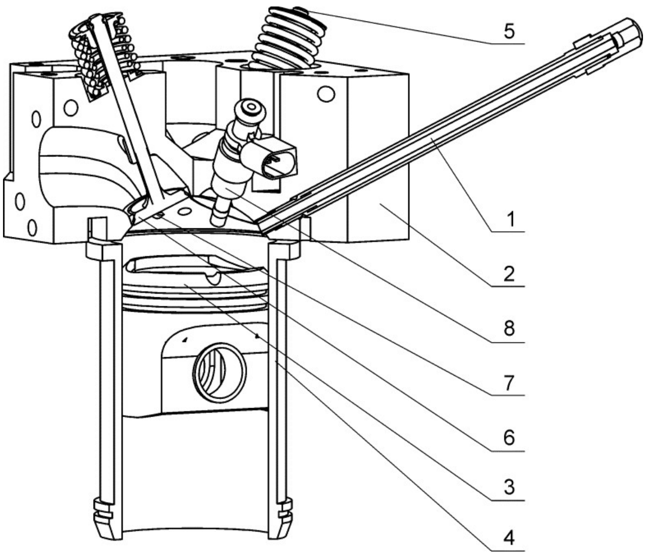

Figure 1. Cross-section of the research engine combustion chamber; 1 – optical-fiber sensor, 2 – engine head, 3 – piston, 4 – cylinder liner, 5 – intake valve, 6 – exhaust valve, 7 – spark plug, 8 – fuel injector.

2.2. Data analysis
The analysis of combustion evolution was performed with the use of AVL BOOST software on the basis of the measured pressure traces. Net heat release rate (HRR) was computed using the first law of thermodynamics in the form shown in Equation (1):

$$\mathrm{HRR} = \frac{\gamma}{\gamma - 1} p\, dV + \frac{1}{\gamma - 1} V\, dp \tag{1}$$

where *p* was in-cylinder pressure, *V* was volume above a piston, and the ratio of specific heats γ was computed according to instantaneous temperature and mixture composition in the cylinder. The BOOST software accommodated also mass flow model, which enabled estimation of the mass of trapped residuals.

2.3. Experimental conditions and procedure
The research was conducted at constant crankshaft rotational speed of 1500 rev/min. The temperature of the cooling liquid at the engine outlet was maintained at level of 90°C +/- 1. The engine was operated as naturally aspirated and with fully open throttle. The average intake temperature was kept at the level of about 40°C. The engine was operated in NVO mode and reduced lifts of the valves (see table 1) which resulted high amount of retained exhaust. The engine was fueled with Euro Super commercial gasoline with research octane number of 95. Fuel was injected directly to the cylinder in two portions. The first fuel dose was injected 40°CA bTDC (before top dead center) during the NVO period to provide premixed mixture. The second fuel dose was injected during the main compression at two selected timings 120° bTDC and 60°CA bTDC. These start of injection (SOI) timings were

selected because they provided opposite reactions to the mixture stratification i.e. delay and advance of auto-ignition with respect to fully premixed in-cylinder charge. The latter was achieved by injection of all fuel early during NVO and was used as a baseline condition. Additionally, two different split fuel ratios were applied, with equal fuel division between two injections and approximately 80% of fuel injected during the main event compression.

Indicated mean effective pressure (IMEP), which express the engine ability to do work, was approximately 0.2 MPa. Excess air ratio (λ) was kept constant at level of 1.24 via corrections of injection time. The rate of internal EGR, expressed as a ratio of mass of trapped residuals to the entire in-cylinder mass during the main event, was approximately 0.55. It should be noted however that all aforementioned parameters besides λ, which was actively controlled, were varying between investigated conditions because of the thermal effects of variable injection strategies and combustion timing, and its completeness. These effects further have an impact on the balance between the mass of aspirated fresh air and the mass of trapped residuals.

3. Results and discussion

Figure 2 shows in-cylinder pressure curves for investigated cases. Names for the cases in figure 2 correspond to second injection SOI timing and the fraction of fuel injected with second injection. Without any detailed analysis the pressure curves show how meaningful is effect of injection strategies on combustion. If fully homogeneous charge, achieved by injection of all fuel early during the NVO period is a reference point, one can note that fuel injection 120 °CA bTDC delays combustion, whereas fuel injection 60 °CA bTDC have an opposite effect. In both cases, however increase of fuel injected for stratification delays combustion. It should be also noted that stratified combustion reduces peak pressures and pressure rise rates for all investigated conditions.

More detailed data on combustion evolution is provided by the HRR curves, calculated according to equation (1) and shown in figure 3. It can be noted that variable second injection quantities and SOIs affect auto-ignition timing to a high extent. At reference conditions (homogeneous charge) 5% mass fraction burnt, calculated on the basis of cumulative heat release, appeared 2.3 °CA bTDC. Injection of 50% of fuel at 300 °CA (60 °CA bTDC) advanced 5% MFB by 3.5 °CA. In contrast, injection of 80% of fuel at 120 °CA bTDC retarded auto-ignition by 2.5 °CA. It proves that fuel stratification provides superior combustion controllability. It should be noted that regardless stratification effect on auto-ignition timing it affects combustion rates to a high extent. At all stratified combustion conditions peak HRR was reduced approximately 50% in comparison to homogeneous charge combustion. General rule of the thumb is that, the more fuel injected late and the later the injection, the lower peak HRR value.

Existing complex matrix of phenomena manifesting during combustion of stratified mixture requires deep understanding before these injection strategies can be employed to control combustion in CAI engines. Despite comprehensible effect of stratification on combustion rates, the non-linear trend in auto-ignition timing is not clear.

To help better understanding the aforementioned peculiar effects of fuel stratification on combustion, natural luminosity from the cylinder in the visible range was recorded and analyzed. Figure 4 shows optical (OPT) intensity signal expressed as a photodetector output voltage. Optical emission signals reveal the reasons for advance of auto-ignition at very late second injection. Emission curves for SOI = 60 °CA bTDC clearly indicate two-stage combustion despite the fact that gasoline combustion manifests only single exothermic reaction phase [24]. This could imply that at high degree of stratification hot-spots are created in the combustion chamber, which are the primary sources of ignition. For earlier injection it is plausible that fuel is more premixed, and auto-ignition delay results from local temperature reduction due to heat consumption for fuel vaporization. This phenomenon was observed by Lim and Iida [25] using a rapid compression machine. Analysis of the combustion luminosity showed that combustion process is realized gradually, starting from regions of higher temperature. Such a stratified combustion ran slower than combustion of homogeneous mixture, however auto-ignition was earlier.

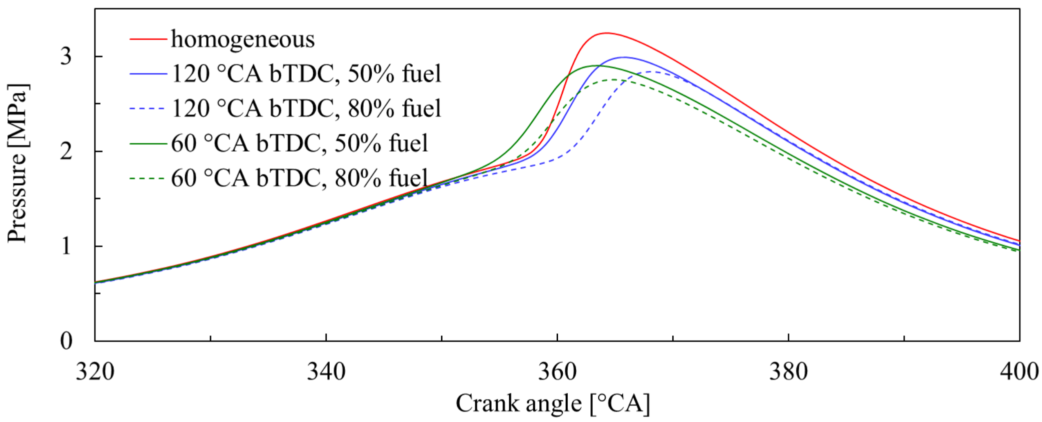

Figure 2. In-cylinder pressure for all investigated conditions.

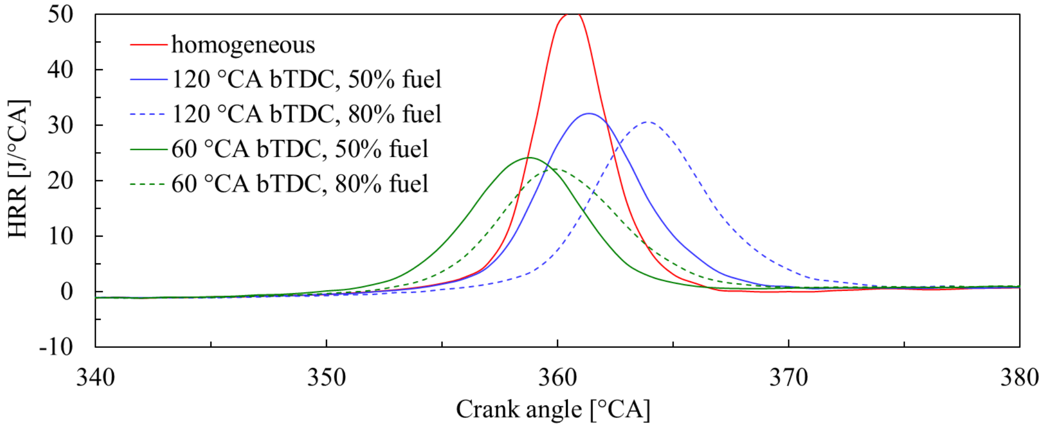

Figure 3. Heat release rate for all investigated conditions.

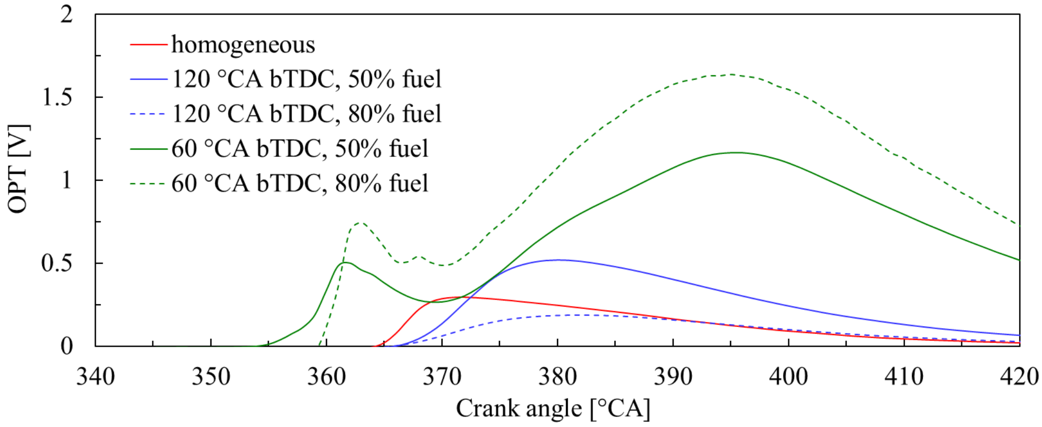

Figure 4. Natural luminosity signal from the combustion chamber.

It should be also noted that locations of the first peaks for SOI = 60 °CA bTDC correlate with HRR curves (figure 3). The other OPT curves seem to be correlated rather with in-cylinder temperature than heat release. In spark ignition engines it was verified that OPT signal is well correlated with HRR, because light emission is mainly composed of a chemiluminescence in the flame front [20]. In contrast, CAI combustion of premixed charge emits mainly thermal radiation.

4. Summary

A natural luminosity signal was used to analyze combustion in controlled auto-ignition engine. The results demonstrated that measurement of space-averaged natural luminosity with the use of optical fiber probe can be utilized to identify compositional stratification of the mixture. At late direct fuel injection, believed to create highly stratified mixture, luminosity signal showed two peaks. Such optical signal clearly indicated step-wise combustion in regions where mixture had different compositions and temperatures. It should be noted that heat release analysis did not indicate two stage combustion because amount of heat released in the first stage was low. The optical measurements provided explanation of the non-linear effects of fuel injection timing on combustion advance. Namely, earlier fuel injection during compression stroke delayed combustion, whereas later injection advanced it. Analysis of optical signals shown that compositional stratification, manifested by two signal peaks, appeared solely in the latter case. Auto-ignition advancing effect of compositional stratification resulted from creation in the combustion chamber regions that had higher temperature and favorable mixture strength. These regions ignited first. In contrast, at earlier injection during compression stroke in-cylinder charge was premixed before auto-ignition, however temperature was reduced due to heat consumption for fuel vaporization, which retarded auto-ignition.

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References

[1] Fuerhapter A, Piock W and Fraidl G 2003 *SAE Technical Paper* 2003-01-0754
[2] Hasan MM and Rahman MM 2016 *Renewable Sustainable Energy Rev.* **57** 282–91
[3] Sharma TK, Rao GAP and Murthy KM. 2016 *Arch. Comput. Methods Eng*. **23** 623–57
[4] Lavy J et al. 2000 *SAE Technical Paper* 2000-01-1837
[5] Zhao H, Li J, Ma T and Ladommatos N 2002 *SAE Technical Paper* 2002-01-0420
[6] Lee K, Cho S, Kim N and Min K 2015 *Energy* **91** 1038–48
[7] Dec JE, Yang Y and Dronniou N 2011 *SAE Int. J. Engines* **4** 1169–89
[8] Turkcan A, Ozsezen AN and Canakci M 2013 *Fuel* **111** 30–9
[9] Turkcan A, Altinkurt MD, Coskun G and Canakci M 2018 *Fuel* **219** 50–61
[10] Mikulski M and Wierzbicki S 2017 *Thermal Science* **21** 387–99
[11] YangD-b, Wang Z, Wang J-X and Shuai S-j 2011 *Appl. Energy* **88** 2949–54
[12] Zhang C, Zhang C, Xue L and Li Y 2017 *Energy* **125** 439–48
[13] Mikulski M and Bekdemir C 2017 *Appl. Energy* **191** 689–708
[14] Hunicz J and Kordos P 2011 *Exp Therm. Fluid Sci.* **35** 243–52
[15] Hunicz J, Tmar A and Krzaczek P 2017 *Energies* **10** 2172
[16] Martin GC, Mueller CJ, Milam DM, Radovanovic MS and Gehrke CR 2009 *SAE Int. J. Engines* **1** 1057–82
[17] Ozaki K, Lung D-W and Iida N 2013 *SAE Technical paper* 2013-32-9070
[18] Fatouraie M and Wooldridge MS 2014 *J. Eng. Gas Turbines Power* **136** 081507.
[19] Lundgren M, Rosell J, Richter M, Andersson Ö, Johansson B, Arne A and Alden M 2016 *SAE Technical Paper* 2016-01-0768
[20] Geiser F, Wytrykus Fand Spicher U 1998 *SAE Technical Paper* 980139
[21] Hunicz J and Piernikarski D 2001 *Proc. SPIE Int. Soc. Opt. Eng.* **4516** 307–14
[22] Hunicz J 2011 *SAE Technical Paper* 2011-24-0052
[23] Hunicz J and Medina A 2016 *Energy* **117** 388–97
[24] Zhang J, Li Z, Zhang K, Lv X and Huang Z 2015 *Thermal Science* **19** 1897–906
[25] Lim OT and Iida N 2012 *Exp. Therm. Fluid Sci.* **39** 123–33