

Autoignition and combustion of *n*-hexane spray in subcritical and supercritical environments

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Abstract In this study, processes of a liquid fuel spray ignition and heat release during its combustion were under investigation. The purpose of this study was to elucidate whether the ignition properties and heat release process of a liquid fuel injected into the environments of parameters exceeding its critical values differ from those obtained for subcritical regimes. Therefore, the fuel was injected into the environments of parameters below, around and above its critical values. The ignition and combustion processes were observed by monitoring the pressure in the combustion chamber and by using a high-speed camera through transparent piston. The ignition process was characterized by ignition delay, while the combustion process by heat release and rate of heat release. The ignition delay was determined by pressure rise according to tangential method. Ignition delay determined that way included both physical delay and chemical delay. Obtained results revealed stochastic nature of the spray ignition of *n*-hexane. No major difference in ignition delay in terms of exceeding critical parameters was noticed. The only parameter directly influencing the ignition delay was the injectant initial temperature.

Keywords Autoignition · Ignition delay · Spray combustion · Rapid compression Machine · Injection

Introduction

Spray combustion appears in a broad variety of power systems, such as furnaces, industrial burners, gas turbines and reciprocating engines. The engine performance, emissions and energy conversion efficiency are directly dependent on the quality of spray combustion. For many decades, spray combustion concerned only CI (compression ignition) engines. However, since direct injection was applied to SI (spark ignition) engines, it concerns both types of engines. In CI engines, the start of combustion is controlled by the injection of the fuel. Therefore, a reliable and predictable autoignition is required. In SI engines, in turn, where the start of combustion is controlled by a spark, autoignition should be avoided. Therefore, the spray autoignition and combustion characteristics of the fuel are of crucial importance.

The stricter environmental legislations force engineers and scientists to switch from conventional fuels to alternative ones. Alternative fuels may be especially developed and produced to replace conventional ones like various types of biodiesel [1, 2] or derived from a broad variety of by-products. Imposed levels of recovery and recycling of secondary raw materials from waste enforce measures aimed at economic use [3]. This also applies to the oil industry. The existing legislations for VOCs (volatile organic compounds) force oil companies to reduce the emissions of APG (associated petroleum gas), which is the by-product arising during the oil production. This is usually done by thermal oxidation in flares, where generated heat is transferred to the atmosphere without any benefit. Further solutions in environmental policies will force oil companies to introduce productive utilization of associated gas, what still in some environments poses a challenge [4]. The existing solutions for beneficial utilization of associated gas require either

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removing the condensate to required level [5] or compressing the gas to high pressure [6]. Under high pressure some hydrocarbons contained in associated gas like propane and butane condensate. Thus, only part of the gas can be utilized productively. The remaining condensate is usually utilized in conventional way, by flaring, even though it could be used as an engine fuel. There are different possible scenarios of utilizing natural gas condensate for power generation, among which a system based on simultaneous direct injection of the condensate and diesel fuel (injected for ignition) seems to be a promising one. This solution, however, requires the knowledge on spray ignition behavior of light hydrocarbons under heavy-duty CI engine conditions.

Spray autoignition properties of conventional diesel fuel are commonly known [7] and have been described in detail by many researchers [8–11]. However, the spray autoignition properties of light hydrocarbons in environments of pressures and temperatures typical for heavy-duty CI engines were not investigated widely so far. Spray combustion involves many phenomena, such as diffusion, evaporation, convective mixing, jet and droplet breakup and heat transfer, which influence the ignition process. Therefore, the autoignition cannot be regarded separately from these phenomena, and it is expected to be strongly dependent on them.

The parameters in the combustion chamber of highly charged CI engines at the SOI (start of injection) may exceed the critical parameters of the injected liquid. The chamber pressure can reach 10 MPa, while the temperature may reach the level of 800 K. These values are far beyond the critical parameters of typical hydrocarbons which are presented in Table 1. In such conditions, the phenomena involved in the fuel–air mixing process may be completely different than in subcritical conditions.

Chehroudi et al. [13] noticed that no droplets could be detected when the backpressure approached and exceeded the critical pressure of the injectant. They noticed visual impression of gaseous jet and the inhibition of transition into the full atomization regime. They associated it with the fact that surface tension approaches zero when fluid pressure approaches and exceeds critical value. Segal and Polikhov

[14], in turn, concluded their study with the statement that transitional and supercritical mixing can be observed when only one of the parameters, the temperature or the pressure, is higher than the critical value of the injected liquid.

Besides the surface tension, the other important parameter is the latent heat. When a fluid parameter reaches and exceeds critical values, the latent heat approaches zero. Dahms et al. [15] visualized the structure of n-dodecane jets at conditions of relevance to diesel engines. They noticed that for higher temperature, the transition from liquid to gaseous state appeared to be much smoother than at low-temperature conditions. Experiments made by Rachedi et al. [16] for swirling injector related to gas turbine showed that behavior of supercritical hydrocarbon jet and supercritical CO₂ jet was similar in most investigated aspects.

The recent studies done by Dahms and Oefelein [17, 18] confirmed findings of previous researchers that in high temperature and pressure environments, the nature of mixing may change. They, however, stated that simply reaching and exceeding supercritical conditions of the injectant may not be sufficient to experience transitional and supercritical mixing. In their theoretical study [17], they concluded that enthalpy contained in hot unburnt ambient gases is not sufficient to heat up the gas–liquid interface to its critical temperature and that the transition between two-phase and single-phase interface dynamics is not necessarily induced by diminished surface tension forces alone [17]. They applied Knudsen number criterion in order to determine whether the mixing process is sub- or supercritical. Their study was, however, focused on multicomponent systems where usually surface tension cannot be neglected. They admitted that in single-component liquids, the situation is much more simple and that surface tension may be neglected when critical pressure of the liquid phase or a critical pressure of a mixture is exceeded. In this study, the criterion of exceeding critical parameters of the injected liquid was selected due to its simplicity and the fact that in the conducted experiment, high-purity single-component fuel was used.

The other important issue is the fact that mixing characteristics may be also dependent on the distance from the nozzle outlet. Dahms and Oefelein [18] concluded that the association of the continuum regime, where statistical fluctuations are negligible and $Kn < 0.1$, is only valid in the dilute gas regime but not in the dense-fluid regime associated with high-pressure liquid injection processes.

In terms of autoignition of the injected liquid, it is important to look closer into the characteristics of the air–fuel mixtures which are expected to autoignite. The study done by Dahms and Oefelein [17] showed that mixtures of mixture fraction below 0.5 can be described as an ideal gas and the effects of real-fluid behavior do not play a role. It means that for mixtures which are capable of autoignition,

Table 1 Critical temperatures and pressures for selected hydrocarbons (obtained from [12]); the parameters of n-hexane were written in bold

Species	Critical temperature/K	Critical pressure/bar
propane	369.9 ± 0.2	42.5 ± 0.1
butane	425 ± 1	38.0 ± 0.1
<i>n</i> -hexane	507.6 ± 0.5	30.2 ± 0.4
<i>n</i> -heptane	540 ± 2	27.4 ± 0.3
iso-octane	543.9 ± 0.4	25.7 ± 0.2
<i>n</i> -dodecane	658.2 ± 0.9	18 ± 1
<i>n</i> -hexadecane	722 ± 4	14 ± 2

the real-fluid effects do not occur. Nevertheless, it needs to be taken into account that before the autoignition occurs, the combustible mixture needs to be formed. The process of mixture formation may be affected by real-fluid behavior. The process of mixture formation, in turn, highly influences the physical delay of spray autoignition. Thus, one can expect that the autoignition characteristics of the fuel injected into supercritical environments will be different to those in subcritical environments. Therefore, the aim of this study was to investigate whether the spray autoignition phenomena of *n*-hexane significantly change after exceeding *n*-hexane supercritical parameters. Moreover, for selected measurement points the process of ignition and combustion was analyzed in terms of rate of heat release in order to show whether the rate of heat analysis corresponds to ignition delay and whether it depends on the parameters in the chamber at SOI.

In most studies, autoignition phenomenon was represented by the ignition delay parameter [19]. A common feature of these studies is to report ignition data in terms of ignition delay time t_{ig} as an Arrhenius function of initial air temperature T (measured at the instant of injection) and species concentrations in the form [19]:

$$t_{ig} = A \exp(E/(RT))[\text{Fuel}]^a[\text{Oxygen}]^b$$

where A is an empirically determined constant, E is defined as a global activation energy, R is the universal gas constant, $[\]$ represents a species concentration (mol cm^{-3}), and a and b are also empirical constants [19].

Most researchers have considered the ignition delay as comprising a physical delay and a chemical delay. The physical delay essentially refers to the mixture preparation time prior to any significant chemical activity. This would include atomization time, evaporation time and fuel vapor–air mixing time. The chemical delay refers to a period of significant chemical activity, involving generation of a radical pool and heat release reactions, leading to onset of a flame [19]. In supercritical environments, as stated above, mixing process differs from that in subcritical ones. Thus, when the pressure and temperature in the chamber at SOI (start of injection) exceed critical parameters of injected fluid, ignition delay is expected to decrease due to the lack of latent heat.

The effect of the pressure on the ignition delay was in most studies neglected or included indirectly by measuring its influence on E parameter. Ikura et al. [20] showed that the pressure influences the autoignition delay. Aggarwal [19], referring to their study, noted that when the pressure is increased, it decreases not only the ignition delay but also the activation energy. The study made by Ikura et al. [20], however, was conducted for backpressure ranging from 0.1 to 1.1 MPa, which is far below the critical pressure of the hydrocarbons they used.

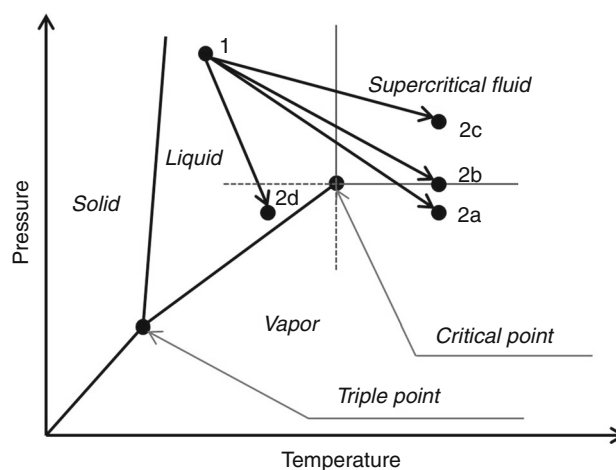


Fig. 1 Schematic diagram of the thermodynamic transition of fluid injected into the environment of different parameters; *point 1* represents the thermodynamic state of the fuel in the injector before the injection, while the *points 2a–2d* represent the parameters which are reached by the injectant after it is injected). Depending on the parameters in the chamber (2a–2d), the fluid during the single injection process experiences the transition 1–2a, 1–2b, 1–2c or 1–2d

Although it was shown that ignition delay is influenced by backpressure, which probably can be linked with higher energy entrainment into the fuel jet, there arises a question whether there is a change in the energy exchange between the liquid jet and the surrounding air when the conditions become supercritical. This question seems to be important, especially taking into account that physical delay is influenced by atomization, evaporation and fuel vapor–air mixing, which are different in supercritical environments than in subcritical ones.

Therefore, the aim of this study was to investigate the influence of environmental parameters on ignition delay by injecting the fuel into the environment of parameters below, around it and beyond the critical parameters of the injectant. The schematic diagram of cases of interest is presented in Fig. 1.

Thermodynamic states presented in Fig. 1 marked as 2a, 2b and 2c represent the major states of interest. The state 2d was the additional one, investigated in order to characterize the ignition behavior when not only pressure but also temperature is below the injectant's critical parameters.

Experimental setup

The study of the autoignition process of *n*-hexane occurring after the injection was conducted in a rapid compression machine (RCM) at Poznan University of Technology. The view of the RCM on the test bed is presented in Fig. 2.

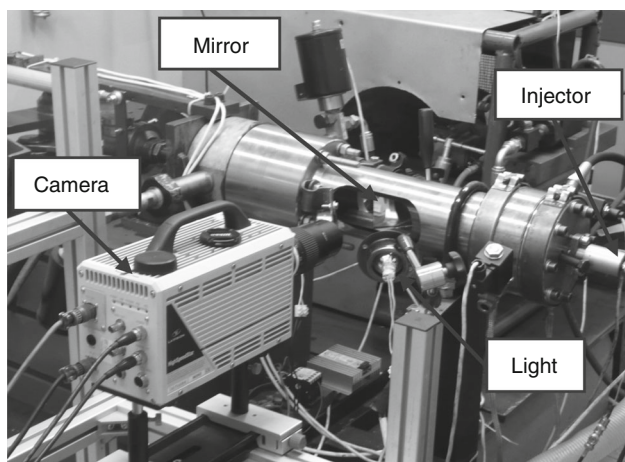


Fig. 2 View of the experimental apparatus (figure by authors)

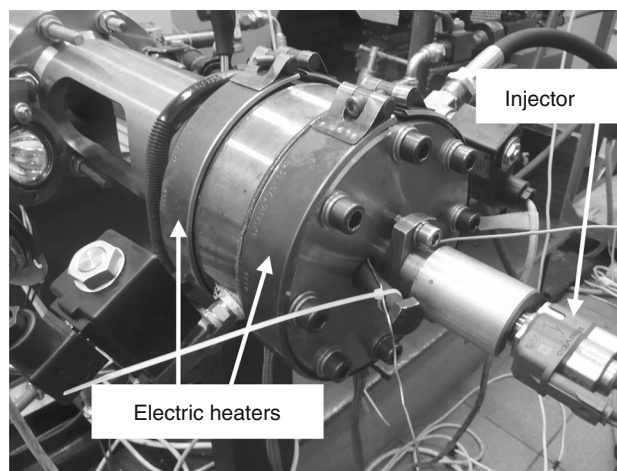


Fig. 4 Electric heaters and injector position at the RCM head (figure by authors)

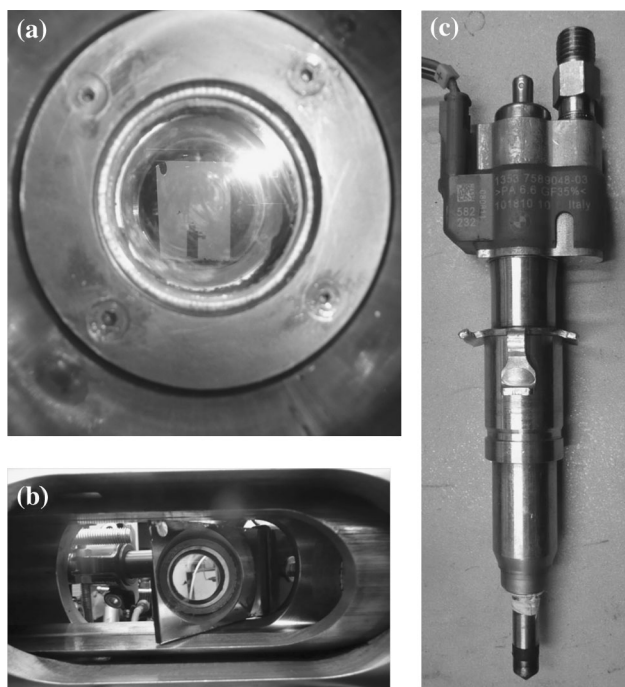


Fig. 3 Elements of the experimental apparatus: **a** transparent piston, **b** mirror inside the piston, **c** injector (figure by authors)

The RCM was equipped with optical window in the piston crown (Fig. 3a) and a mirror (Fig. 3b) allowing to observe the processes taking place inside the cylinder.

The RCM was able to withstand the pressure of over 10 MPa. In order to simulate real engine conditions, the RCM was equipped with electric heaters capable of increasing the temperature of the RCM up to 200 °C (cylinder and head temperature). The heaters are presented in Fig. 4. The main features of the RCM are presented in Table 2. More detailed description is presented in [21, 22].

Table 2 Rapid compression machine main features

Parameter	Value	Unit
Stroke	81	mm
Bore	80	mm
Geometrical compression ratio	9	–
Compression pressure	0.85–2	MPa
Mean piston speed	~ 1 (depends on the air pressure under the piston)	m s ⁻¹

In presented experiments, a gasoline outward-opening injector was used. The injector is presented in Fig. 3c. The injector was mounted centrally at the top of the head (Fig. 4). The maximum needle lift was of 36 μm [23], and the static flow rate was of 35 g s⁻¹ [24]. The hydrocarbon was supplied to the injector by a high-pressure gasoline direct injection automotive pump.

The process of injection and autoignition was observed in two ways: by indicating the combustion chamber and by visual observation of the combustion chamber through the window in the piston crown. For recording the pressure evolution in the chamber, AVL Indicom 621 equipped with AVL GM11D piezoelectric pressure transducer was used. The sensitivity of the pressure sensor was of 2.25 pC bar⁻¹, while the amplification was of 19,98 bar V⁻¹. The pressure-recording frequency was of 5 kHz. Visual observation was done within visible wavelengths by the LaVision HSS5 CMOS high-speed camera (Fig. 2). The visible range of wavelengths was under investigation. The combustion chamber was illuminated by the externally located two halogen lights (500 W each) through the window in the piston crown. The reflected light was recorded by the camera. The recorded images resolution was of 384 × 304 pixels, and it was sufficient to detect the small ignition

spots. The image-recording frequency was of 20 kHz—the highest available for selected resolution.

In this study, *n*-hexane was chosen as the injectant due to its relatively low critical point parameters and the fact that it remains in liquid form under ambient conditions. The critical point parameters of *n*-hexane and selected hydrocarbons are presented in Table 1.

In order to minimize possible impurities' influence on crucial parameters of the injected fluid, especially on the surface tension and critical point parameters, analytically pure *n*-hexane (assay min. 99 %, water max. 0.02 %, residue after evaporation max. 0.001 %) was used in conducted experiments.

Experimental conditions

N-hexane was injected into the environments of different parameters in order to analyze and compare ignition and spray combustion characteristics in terms of exceeding *n*-hexane critical parameters. One needs to be aware that the fact of reaching and exceeding critical parameters of the injectant does not need to necessarily result in so-called supercritical mixing. However, the critical parameters were selected as a convenient indicator of chamber conditions in relating them with fuel-specific parameters; especially, it was also used by many researchers in the past. The schematic diagram presenting thermodynamic transitions of interest is shown in Fig. 1. The precise parameters in RCM at SOI obtained in the research are presented in Fig. 5. In order to clarify how far the parameters in the RCM at SOI were from the critical parameters of *n*-hexane, two lines corresponding to critical pressure and temperature of *n*-hexane were plotted on this graph.

The temperature at SOI was estimated from the initial chamber parameters in the RCM before the compression. It was done by relatively simple method which is based on the assumption of uniform pressure, density and temperature in the cylinder and on the assumption that polytropic exponent remains constant during the compression stroke. The polytropic exponent was calculated based on the acquired pressure data. Detailed description of this method can be found in [21]. Rothamer and Murphy [10] pointed out that the assumption of uniform temperature and density is improper and stated that two-zone method based on real gas equation gives the most reasonable temperature estimate. Nevertheless, the precise calculation of the temperatures at SOI was not the aim of the study. Temperature values at SOI were needed just to estimate to which thermodynamic state (presented in Fig. 1) the parameters in the chamber at SOI correspond. Therefore, the method based on the assumption of constant polytropic exponent was chosen.

The composition of the gas in the chamber remained the same in all investigated cases, and for this purpose, normal

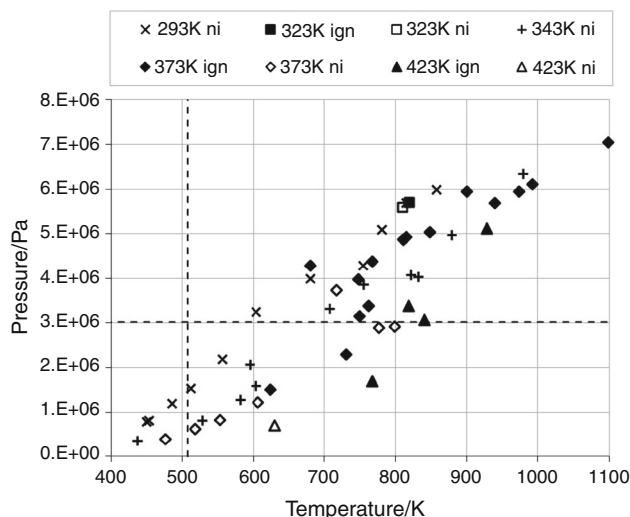


Fig. 5 Parameters in RCM at SOI: the results were collected in a group made for the same initial temperature of the injectant; points with ignition are denoted as “ign,” while the points without ignition are denoted as “ni”

air was used. In all cases, *n*-hexane was introduced into the injector under the same pressure and temperature. The parameters of the injectant before and after the injection are presented in Table 3.

Ignition delay determination

In diesel engines, the ignition delay is generally defined as the time duration between the start of fuel injection (SOI) and the start of combustion (SOC) [25]. This definition concerns all cases of spray autoignition no matter if it is in an engine, RCM or constant volume vessel.

Ignition delay can be measured by a phototransistor, by monitoring the pressure rise, temperature rise or by several other means [19]. In this study, the process of autoignition was observed in two ways: by indicating the combustion chamber and by visual observation of the combustion chamber by means of high-speed camera. However, for quantitative study the pressure-based ignition delay measurement was used. There are many commonly used methods of ignition delay determination based on the pressure rise. Kobori et al. [8] in similar experiments conducted in RCM used the pressure recovery point method (PRP). In case of a constant volume vessel, this method is based on the time measurement between the SOI and the moment when pressure recovers to its initial level at injection, after an initial drop due to evaporation (latent heat) and possible endothermic reactions [26]. In case of RCM, the pressure recovery is assumed to occur when the pressure in the chamber after initial drop reaches the level of the base pressure in the chamber (obtained for compression without injection). Hu et al. [26] compared this method with tangential method (other common method for ignition delay

Table 3 Measured ignition delay for relevant temperature and pressure in the RCM at SOI for three different initial temperatures of the injected fuel

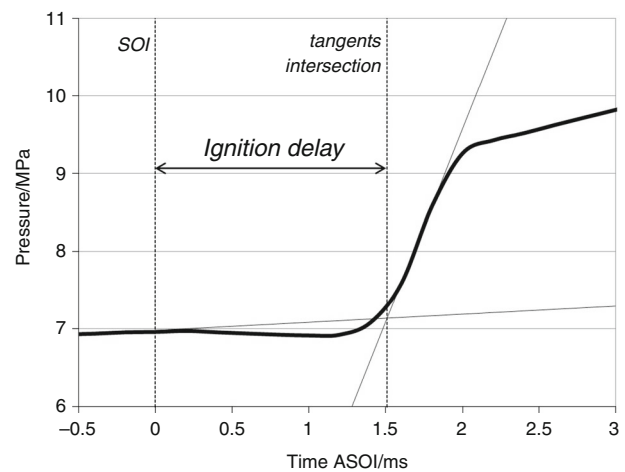
Case no.	Injector		RCM		Ignition delay/ms
	Pressure/Pa	Temperature/K	Pressure at SOI/Pa	Temperature at SOI/K	
1	2.E+07	323	5.70E+06	819	9.5
2	2.E+07	373	5.95E+06	900	7.3
3	2.E+07	373	5.70E+06	939	4.1
4	2.E+07	373	5.95E+06	973	5.5
5	2.E+07	373	5.05E+06	847	3.6
6	2.E+07	373	3.15E+06	749	3.3
7	2.E+07	373	7.06E+06	1098	1.5
8	2.E+07	373	6.12E+06	991	4.8
9	2.E+07	373	4.94E+06	814	3.7
10	2.E+07	373	4.39E+06	767	3.8
11	2.E+07	373	4.29E+06	679	5.5
12	2.E+07	373	4.88E+06	810	2.7
13	2.E+07	373	3.99E+06	747	5.8
14	2.E+07	373	3.38E+06	762	5.5
15	2.E+07	373	2.30E+06	730	3.2
16	2.E+07	373	1.51E+06	623	3.3
17	2.E+07	423	5.13E+06	928	1.1
18	2.E+07	423	3.39E+06	817	1.5
19	2.E+07	423	3.07E+06	840	1.8
20	2.E+07	423	1.70E+06	766	2.1

determination) and chose the tangential method. Rothamer and Murphy [10] made a more extensive comparison of different methods for ignition delay determination based on the pressure rise. They compared six different methods and pointed out that the method based on extrapolation of maximum slope of heat release induced pressure rise to baseline (tangential method) is the most universal one. Its universality appears especially in terms of comparing results from different facilities and results from different device types (engine, constant volume combustion chamber, shock tube, RCM, flow facility, etc.) [10]. Therefore, this method was selected to be used in this study. The way of determination of ignition delay with the use of this method is shown in Fig. 6.

According to this method, the ignition delay is determined as a time from start of injection to two tangents intersection. One represents the pressure rise in the chamber without injection and combustion, while the other one is tangent to the pressure curve at the maximum slope of rapid growth caused by combustion.

Results

In twenty of fifty-five investigated cases, autoignition occurred. The parameters in RCM at SOI in investigated cases are presented in Fig. 5. One can easily see that cases

**Fig. 6** Determination of the ignition delay

with and without ignition are mixed and there is no limit between them. There was no single case where the ignition appeared, while the temperature at SOI was lower than critical temperature of *n*-hexane. This, however, shall be linked with autoignition temperature of *n*-hexane rather than with its critical temperature. As for the critical pressure of *n*-hexane, there were cases with ignition where pressure in RCM at SOI was lower than critical pressure of

n-hexane. However, the number of these cases was very low—only three cases.

For all the cases where ignition occurred, the ignition delay was determined. The ignition delay was determined by pressure rise according to tangential method. The way of determination of ignition delay was the same for all cases. The determination of ignition delay using this method for case no. 7 is presented in Fig. 6.

The measured ignition delay as well as the parameters of the injectant before and after the injection is presented in Table 3.

The measured ignition delays were also plotted on a graph presented in Fig. 7. The size of the circles plotted in the graph quantitatively represents the ignition delay at corresponding temperature and pressure in RCM at SOI.

The obtained results showed that the major factor influencing the ignition delay was the initial temperature of the injectant. As for the parameters in RCM at SOI, their influence on spray ignition delay did not follow any rule. The results revealed the stochastic nature of the spray ignition. Although the differences in ignition delays within the group of tests made for the same initial injectant temperature did not vary much, they did not reveal any explainable dependency on the temperature and pressure in RCM at SOI.

The average ignition delay was of 9.5, 4.24 and 1.63 ms for the cases, where the initial fuel temperature was of 323, 373 and 423 K, respectively. It needs reminding that for the initial *n*-hexane temperature of 323 K, there was only one case where ignition occurred. Although that for the fuel initial temperature of 373 K, the reasonable number of cases with ignition were recorded, there was no possibility to fit any empirical law describing the *n*-hexane spray ignition behavior.

As discussed above, Segal and Polikhov [14] stated that the different nature of mixing process is dependent on the fact whether at least one of the parameters of the environment (pressure or temperature) to which a liquid is injected exceeds or not the critical parameters of the injectant. Due to that statement, a difference in ignition delay for different thermodynamic transitions presented in Fig. 1 was expected. However, this study did not confirm these expectations. As for the critical pressure of *n*-hexane, the three cases with ignition where pressure in RCM at SOI was lower than critical pressure of *n*-hexane did not differ much from the rest of the results. However, the number of these cases is too low to make any serious conclusions regarding this parameter.

The lack of any explainable ignition delay dependency on temperature and pressure in RCM at SOI within the group of tests made for the same initial temperature of the injectant was the major concern. This led to the question about the validity of the obtained ignition delay results. In order to check the obtained data validity, the ignition delay values determined by tangential method were compared with the visual data obtained by high-speed camera.

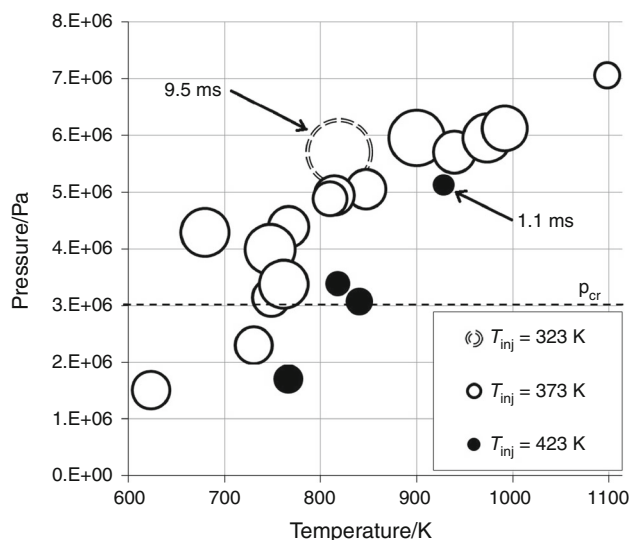


Fig. 7 Measured ignition delay for relevant temperature and pressure in the RCM at SOI for three different injected fuel initial temperatures (T_{inj}); size of the circles quantitatively represents the ignition delay

The obtained values of ignition delay appeared to be consistent with the visual observation. However, on the recorded images small ignition spots were usually observed 0.05 ms earlier than the start of ignition determined by the tangential method, what corresponds to the pressure recovery time. The images recorded by high-speed camera were processed using similar procedures as described by Pielecha [27]. The processed images for one of the cases (case 17) are presented in Fig. 8. The figure shows the recorded images at and around 1.1 ms after SOI in case where ignition delay determined by tangential method was of 1.1 ms.

Visual observation of the combustion process confirmed that the ignition delay values obtained by tangential method were determined properly. The differences in ignition delay must have come either from physical delay or from chemical delay. Finesso and Spessa [9] evaluated the physical delay as the time required to achieve complete vaporization. They determined this time as a time needed to achieve by the injected fuel the location at which it is completely evaporated, which is actually equal to the time needed to achieve a stable liquid length by the spray. The time needed to achieve stable liquid length by the spray was estimated from images recorded by high-speed camera. The assumption that these times are equal to physical delay did not explain the observed differences in ignition delays and led to conclusion that the differences in overall ignition delay resulted from chemical delays. This, however, does not correspond to the theory for chemical delay determination proposed by Curran et al. [28]. The model proposed by Curran was used for *n*-hexane by Zhukov [29] and provided reasonable results.

Taking these two approaches leading to opposite conclusions into account, it is more probable that the observed

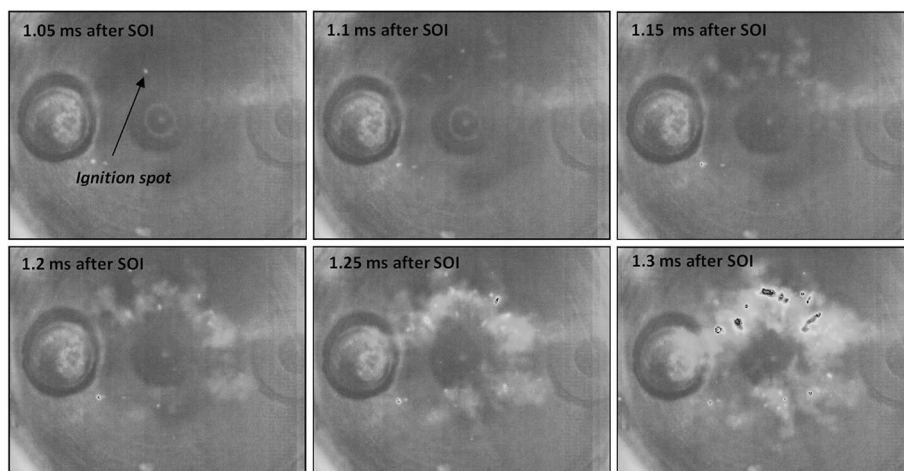


Fig. 8 Ignition in case 16 recorded by high-speed camera—the ignition delay for this case determined by tangential method was of 1.1 ms

differences in ignition delay come from physical delay, which is influenced by number of factors which may be not completely repeatable in RCM. Chung and Mizutani [30] studied the turbulence influence on droplets ignition and noted that the ignition limiting temperature was considerably lowered by the turbulent mixing and that the ignition delay was shortened. The turbulent mixing also changed the ignition process from a chemical kinetics-controlled mode into a droplet evaporation-controlled one. Their study clearly indicates that the turbulent mixing has an important role in the spray ignition process. Therefore, it is assumed that the *n*-hexane spray ignition stochastic behavior results from the mixing process.

In order to provide additional knowledge on the intensity of ignition and combustion process for selected measurement points, the process of ignition and combustion was analyzed in terms of rate of heat release. The heat release calculations were done for cases corresponding to thermodynamic transitions 1–2a, 1–2b and 1–2c presented in Fig. 1. In these three cases with ignition, the pressure in RCM at SOI was above, around and below critical pressure of *n*-hexane. Additionally to these three cases, one case without ignition was analyzed in terms of negative heat release caused by the evaporation of the injected fuel. The case without ignition was obtained for pressure in RCM at SOI lower than the critical pressure of *n*-hexane. In all of the four cases analyzed in terms of heat release, the temperature in RCM at SOI was higher than critical temperature of *n*-hexane, and the initial temperature of the injectant was of 423 K. The calculated released heat as well as rate of heat release is presented in Figs. 9, 10, 11, 12. The heat release calculations were done using AVL Concerto v4.3 software.

In the analyzed cases, the calculated rate of heat release did not correspond to ignition delay. The highest peak of heat release was obtained for case 19, while the

shortest ignition delay was observed for case 17 where the temperature and pressure in the RCM at SOI were the highest.

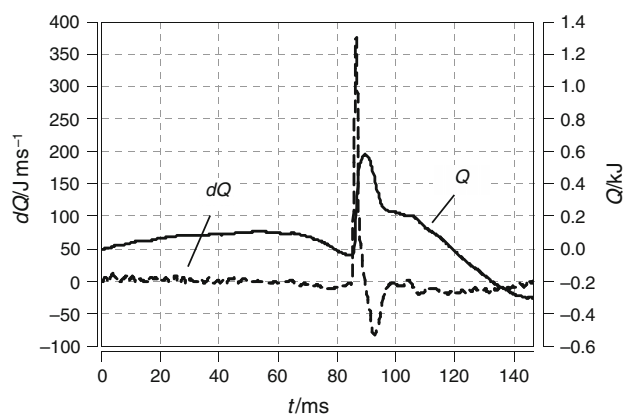


Fig. 9 Calculated heat release and rate of heat release for case 17 ($p_r = 1.7$; $T_r = 1.83$)

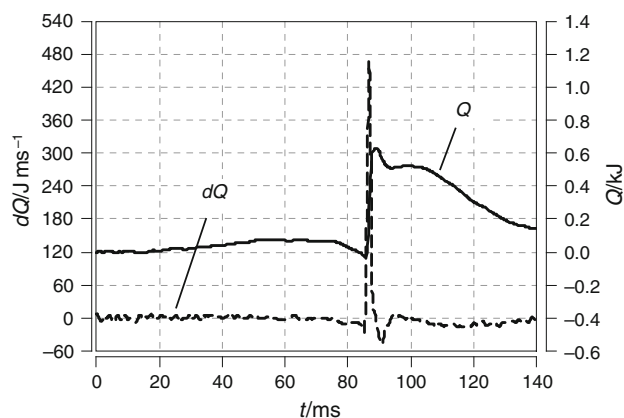


Fig. 10 Calculated heat release and rate of heat release for case 19 ($p_r = 1.02$; $T_r = 1.65$)

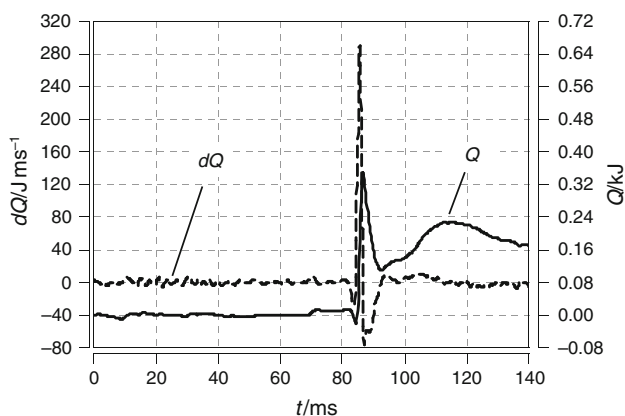


Fig. 11 Calculated heat release and rate of heat release for case 20

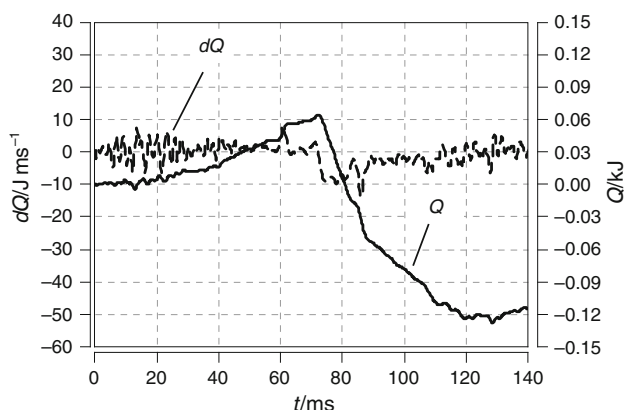


Fig. 12 Calculated heat release and rate of heat release for case without ignition ($p_r = 0.24$; $T_r = 1.24$)

Conclusions

The study showed that the results of ignition delay determination done by tangential method were consistent with the visual observation done by means of high-speed camera. This allowed to draw a series of conclusions without the concern over the accuracy of the ignition delay determination method.

This study did not confirm the expectation that different environmental conditions related to critical parameters of the injectant (sub- and supercritical conditions) would strongly influence the ignition delay. It needs to be noted, however, that the number of the cases with ignition and pressure in RCM at SOI lower than critical pressure of *n*-hexane was too low to make serious conclusions about that. Moreover, the recent theoretical studies [17, 18] clearly point out that reaching and exceeding supercritical conditions of the injectant may not be sufficient to experience

transitional and supercritical mixing, so this could be the reason for that.

It was noticed that the major factor influencing the ignition delay was the initial temperature of the injectant. The average ignition delay was of 9.5, 4.24 and 1.63 ms for the cases, where the initial fuel temperature was of 323, 373 and 423 K, respectively.

The obtained results confirmed the stochastic nature of the spray ignition of *n*-hexane in RCM. In twenty of fifty-five investigated cases, autoignition occurred and there is no limit between the cases with and without ignition. The determined ignition delay values also confirmed the stochastic nature of *n*-hexane spray ignition. Although that for the fuel initial temperature of 373 K, the reasonable number of cases with ignition was recorded, the obtained results did not reveal any dependency on the environmental parameters, and it was not possible to fit any empirical law describing the spray ignition behavior of *n*-hexane. Moreover, there was no significant change in ignition delay when backpressure became higher than critical pressure of *n*-hexane. One can see differences in ignition delay between single cases, but these differences could not be linked with critical parameters of the injected liquid.

Taking into account that physical delay is influenced by number of factors, which may be not completely repeatable in RCM, one can conclude that it is more probable that the observed stochastic differences in ignition delay come from physical delay rather than chemical delay. This can be linked with either the mixing process which is not completely repeatable in RCM or temperature inhomogeneities arising during the compression. The obtained ignition delays did not correspond to calculated rate of heat release values. The highest peak of rate of heat release was obtained for case 19, while the shortest ignition delay was observed for case 17 where the temperature and pressure in the RCM at SOI were the highest.

In general, the presented study revealed the stochastic nature of the spray ignition of *n*-hexane in RCM, which to some degree confirms that the application of light hydrocarbons in heavy-duty CI engines requires additional fuel injection for reliable ignition.

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