

Lift-Off Length and *KL* Extinction Measurements of Biodiesel and Fischer-Tropsch Fuels under Quasi-Steady Diesel Engine Conditions

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ABSTRACT

The relationship between ignition, lift-off length and soot formation was investigated for a collection of fuels in an optically-accessible modified 2-stroke engine under a set of typical quasi-steady state Diesel DI conditions. Five fuels including biodiesel blends and Fischer-Tropsch fuels have been selected for their potential to substitute conventional diesel with no major modifications on the engine hardware, and were previously characterized under ambient pressure following ASTM standards.

Fuels were injected into a large volume through a single-hole nozzle at three levels of injection pressure, by sweeping ambient temperatures at constant density, and ambient densities at constant temperature. The 8 ms single-shot injections were long enough to reach the stabilization of a free diffusion flame. The OH-chemiluminescence was imaged and lift-off length was measured *via* image post-processing. Simultaneously, flame opacity was measured along the flame axis using the laser extinction technique. The pressure trace analysis quantified the ignition delay.

In a first step, the averaged lift-off length measurements are presented and contrasted with both ignition delay and previous liquid length measurements performed in similar thermodynamic conditions but with an inert spray configuration. Statistical analysis permitted assessment of the influence of engine parameters such as air density, air temperature and injection pressure independently of fuel origin. The strong effect of air temperature and the more moderate ones of both air density and injection pressure presented by other authors were confirmed. Then, fuel stoichiometric mixture fraction and ignition delay have been

introduced in the analysis in order to investigate their implication in processes of lift-off stabilization.

In a second analysis, values of both lift-off length and *KL* were compared with a cycle-to-cycle approach. Results showed that, at fixed engine operating conditions, the scattering of lift-off length measurements is directly linked to that of *KL*. This result was confirmed when using average values and when comparing different parameters that were tested in the study. Different sensitivities were observed from one fuel to another.

INTRODUCTION

The decrease in availability of fossil fuels and the search for more sustainable means to harness energy in the transport area motivates research on alternative fuels. As the extraction cost of the crude oil keeps growing, the production of biofuels becomes more efficient, so that the perspectives foresee that 20% of the total energy dedicated for transport will be provided by alternative fuels by 2030 [1]. In order to extract the maximum benefits from these fuels in the optimization of engine design and calibration, a detailed understanding of their spray and combustion characteristics is fundamental.

The challenge of diesel combustion stands in converting a high amount of energy contained within the fuel into a pressure increase within a timescale of milliseconds. Thus, the combustion event in a diesel engine results in a very complex problem where a multitude of chemical and physical processes interact. However, all the fuel and engine parameters probably do not affect the combustion event with the same level of importance. The development of optical large volume facilities such as combustion vessels,

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compression machines and low-speed optical engines permits to study single free sprays, avoiding any spray/spray and spray/wall interactions. Additionally, their large volume reduces, or even annihilates the perturbation from the flame heat release and permits to study the spray under steady or quasi-steady conditions. Such facilities associated to multi-purpose optical diagnostics seriously helps in the understanding of the emission formation occurring in conventional metal diesel engines.

In a diesel engine, a liquid fuel is injected at very high pressure in a high density and high temperature environment. The liquid phase atomizes and penetrates up to a point where enough energy has been entrained to heat up and vaporize the fuel. The vapor-phase continues its progression downstream the chamber. If oxygen is available, the rich vapor region auto-ignites [2, 3], the flame tip spreads and the spray continues to develop downstream, up to a point where it stabilizes and results in a lifted turbulent mixing-controlled diffusion flame. The processes governing the position where the lift-off establishes for diesel sprays are still unclear [4]. In a first instance, the approach for Peters for atmospheric turbulent gas jets can be considered. This theory proposed that the flame stabilized where the flame velocity and spray velocity offset [5]. By forcing ignition with a laser upstream the natural lift-off position, Pickett showed that there is a strong interaction between the ignition location and the lift-off position [6]. Consequently, it is to expect that the ignition quality of the fuel affects its lift-off length as shown in [7, 8]. The sensitivity of each fuel to ambient injection pressure and ambient conditions is also expected to be different and needs to be quantified.

Under diesel conditions, the flame rather forms a large amount of soot which mostly oxidizes when it goes through the stoichiometric surface. Whenever the injection stops, the whole flame dynamics is highly affected and the last soot formed is likely extinguished rather than fully oxidized. It is believed that an important amount of the soot found in the exhaust comes from this critical end of combustion [9]. To avoid such an issue, it has been proposed to avoid the soot formation in diesel flames by increasing injection pressure, increasing the premixed burn, reducing ambient temperature and density, orifice diameter, etc. [10,11,12]. Several studies highlighted the importance of having a low equivalence ratio in the lift-off region to reach such non-sooting flames [6, 10,11,12,13,14,15,16]. However, this parameter may not be exclusive to explain the soot formation within the flame and needs further investigation [17].

The present work tries to assess the effect of both fuel type and operating conditions on the lift-off length and the soot formation within the flame. For that purpose, OH-chemiluminescence and laser extinction have been used simultaneously to measure respectively the lift-off length and flame opacity. Comparisons were made among different fuels under a large set of ambient and injection conditions and the effect of each parameter has been analyzed so that empirical correlations have been derived. The paper is structured as follows. After this introduction, the experimental facility and methodology is presented. Then, the results section analyzes subsequently lift-off length and soot formation within the flame. Finally, conclusions of the paper are presented.

EXPERIMENTAL APPARATUS

FUELS

Five fuels have been selected for their potential to be used in a diesel engine with no fundamental redesign of the engine, whilst having significant differences in both physical and chemical properties.

The first three fuels are widely known in the literature under the generic label “first generation biodiesels”. Indeed, they are partially or entirely issued from cereal feedstock. RME (Rapeseed Methyl Ester) is a fuel issued from the transesterification reaction between rape oil and methanol. B05 and B30 are blends of fossil diesel with respectively 5 and 30 mass percentage of this same RME.

Finally, the two last fuels are Fischer-Tropsch fuels issued from gas, coal or biomass liquefaction and will be referred as FT1 and FT2 in the following study. These fuels have been previously used by the authors in both single and multi-hole injector configurations, and under both reactive and non-reactive environments [18,19,20].

Various measurements of fuel properties have been performed off-engine. Thermodynamic properties, energetic content and equivalent formula have been measured following ASTM standards and are summarized in [Table 1](#). Results show that by increasing RME rate in biodiesel fuels, both density and viscosity increase as well, whereas Lower Heating Value (LHV) reduces because of the increasing oxygen content. Both Fischer-Tropsch fuels have a lower density compensated by a higher energetic content so that the energetic content per liter is similar between all these fuels. FT2 is singular by its very low viscosity and its small extra oxygen content.

Table 1. Fuel relevant properties.

Fuels Properties	Unit	Standard	B05	B30	RME	FT1	FT2
Density	[kg.m ⁻³]	ASTM D1298	833	849	878	784	773
Kinematic Viscosity	[mm ² .s ⁻¹]	ASTM D445	2.5	3.1	4.4	3.4	1.3
Lower Heating Value	[MJ.kg ⁻¹]	ASTM D240	42.11	41.77	38.24	44.76	44.24
Equivalent Chemical Formula	-	ASTM D5291	$C_{17.1}H_{36.0}O_{0.1}$	$C_{17.7}H_{35.7}O_{0.7}$	$C_{18.95}H_{35.2}O_2$	$C_{17}H_{35.5}$	$C_{12}H_{25}O_{0.2}$
A/F _{st} (20.9% XO ₂)	-	-	14.64	13.84	12.398	14.748	14.388

Chemical equivalent formulas have been measured using gas chromatography-FID and are also provided in [Table 1](#). They appear to be close to heptadecane (C₁₇H₃₆) and dodecane (C₁₂H₂₆) formulas for respectively FT1 and FT2 while RME's closest pure surrogate could be methyl-oleate (C₁₉H₃₆O₂). B05 and B30 have not been measured. Instead, their chemical formulas were estimated for the purpose of the study.

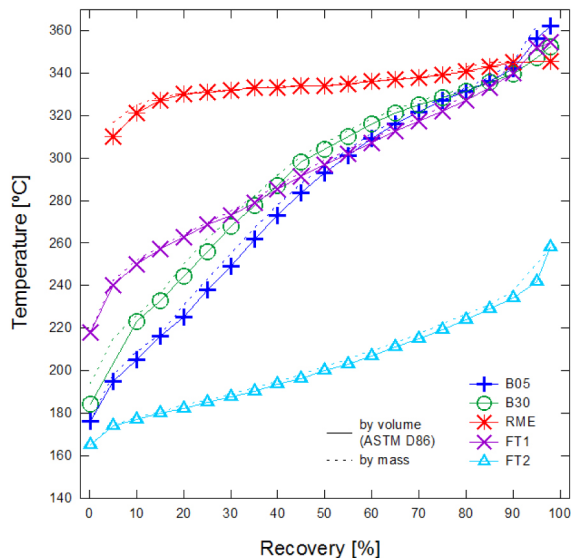


Figure 1. Distillation curves obtained via both ASTM D86 and mass recovery.

Distillation curves have been measured under the ASTM D86 standard. Besides, a weighing scale was measuring the collected mass simultaneously, in order to detect a possible shift between mass and volume recovery percentage. Results are presented in [Fig. 1](#). On one hand, RME and FT2 appear to have relatively flat distillation curves, which is the witness of their homogeneity and similitude to their corresponding surrogate. On the other hand, B05, B30 and FT1 have similar trends in evaporation under atmospheric pressure, starting from values close to FT2 and ending to values close to RME.

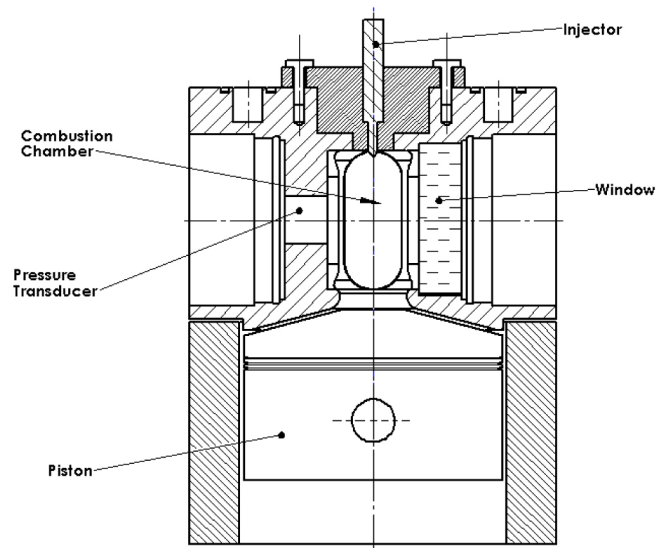


Figure 2. Cutaway view of the Hot Spray Test Rig.

Consequently, it can be expected that the lightest fraction of B05, B30 and FT1 are molecules heavier than FT2 (C₁₂H₂₅O_{0.2}) and that their heaviest fractions are close to RME in terms of molecular weight (C_{18.95}H_{35.2}O₂). For B05 and B30, their RME content is expected to correspond to this heavy fraction. No significant differences can be observed on the comparison between mass and volume percentage recovery. This supports that no important variations of density exist among the proper components of each fuel.

HOT SPRAY TEST RIG

Tests have operated in a rapid cycling machine described in [\[21\]](#) and illustrated in [Fig. 2](#). This facility is based on a modified loop-scavenged single cylinder 2-stroke direct injection diesel engine with three liter displacement and low rated rotational speed (500 rpm). This apparatus makes optical studies on free sprays under inert or reactive diesel-like thermodynamic conditions possible. Data relative to the engine geometry are collected in [Table 2](#).

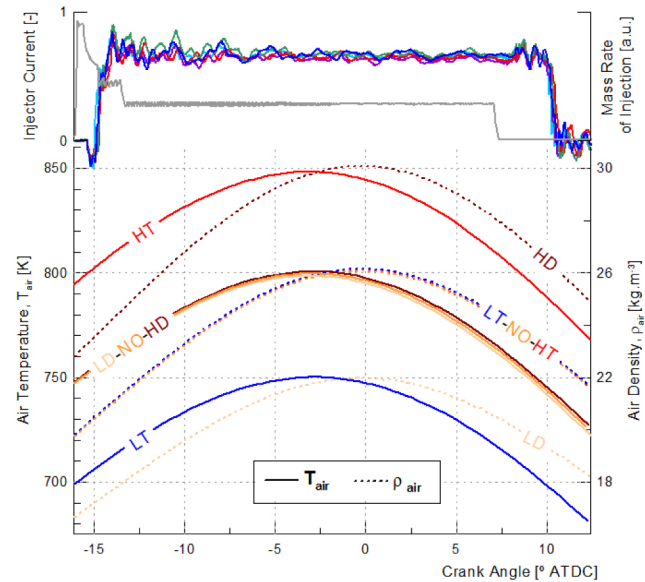
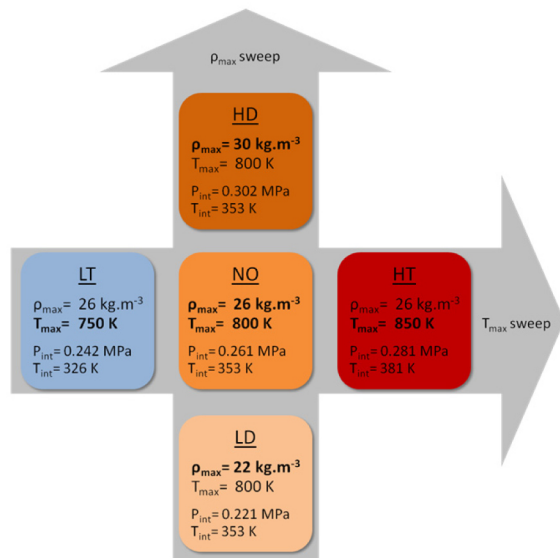


Figure 3. Schematic representation of the engine operating conditions and the resulting thermodynamic environment in the TDC vicinity. 8 ms energizing time is represented by the injector current.

Intake and exhaust being handled by transfers on the liner, optical access to the high-pressure chamber can be easily achieved through the cylinder head which encloses a cylindrical combustion chamber large enough to avoid spray impingement against engine walls. This chamber has an upper port where the fuel injector is mounted, and four lateral orthogonal accesses. One of them is used by a pressure transducer whereas the three other ones are equipped with oval-shaped quartz windows, 88 mm long, 37 mm wide, and 28 mm thick. For this study, the combustion configuration has been set by feeding the engine with natural dried and filtered air. To reach diesel conditions, the air was previously supercharged up to 3 bars and pre-heated up to 400 K.

Table 2. Hot spray test rig characteristics.

Hot spray test rig	
Type	Single-cylinder 2-stroke loop-scavenged engine
Displacement	3000 cm ³
Stroke	170 mm
Bore	150 mm
Distance between injector tip and piston head at TDC	87.8 mm
Compression ratio	14.8:1

OPERATING CONDITIONS

The rig has been operated under skip fire mode, i.e. one injection event occurs every 20 engine cycles. This strategy is used to let the system recover between combustion cycles and

therefore to minimize the cycle-to-cycle interactions. Although the engine is always motored because the fuel quantity injected is never high enough to keep this engine running, cycles without injection will be referred to in this paper as “motored cycles”, and cycles with injection will be referred to as “injection cycles”.

The current test matrix is the same as previously used by the authors under inert conditions [18]. It includes five engine operating conditions chosen to allow a sweep of three $T_{\max}$ at constant $\rho_{\max}$ (26 kg.m⁻³) and a sweep of three $\rho_{\max}$ at constant $T_{\max}$ (800 K) as represented in Fig. 3. The five operating conditions have been labeled NO, LT, HT, LD, (HE), standing respectively for NOMinal, Low Temperature, High Temperature, Low Density and High Density air setup. All five fuels have been injected under these five thermodynamic conditions, each time at three different injection pressures (50, 100 and 150 MPa). Intake conditions to carry out the test plan as well as the resulting temperature and densities in the TDC region are shown in Fig. 3.

In order to check the conservation of thermodynamic conditions during the combustion event, gas temperature of injection cycles has been calculated out of the averaged pressure traces assuming unvaried density between cycles with and without injection. This assumption supposes that the mass of fuel injected is insignificant respect to the trapped mass and that the blow-by leak is not affected by the temperature increase. Fig. 4 collects a set of selected cases to assess the effects of (a) injection pressure, (b) fuel, (c) air density ($\rho_{\max}$) and (d) air temperature ($T_{\max}$) on the air temperature steadiness. In (a), (b) and (c), where comparison with the maximum temperature of the motored cycle ($T_{\max}$

(NO) = 800 K) is possible, the temperature increase is about 70-80 K. Reasonably, the major differences are observed in (a), when the total mass and the mass rate of fuel injected are varied. The cycle-to-cycle dispersion of 100 cycles has been represented as well for the 100 MPa case using the interval $[T_{air}-\sigma; T_{air}+\sigma]$. In (b), differences among fuels are rather limited and consistent with the LHV's shown in [Table 1](#). This observation suggests that no major differences are to expect on the mass rate of injection from one fuel to another. A hierarchy of fuel ignition qualities already emerges with higher reactivity of Fischer-Tropsch fuels and lower reactivity of RME respect to B05 and B30. Such aspects will be approached more in detail when ignition delay will be considered. Plot (c) shows how decreasing air density, and so how decreasing the trapped mass in the cylinder, enhances the temperature increase. In (d), the temperature increase has been represented directly between the motored and injection cycles to make the comparison between LT, NO, and HT conditions possible. Since the trapped mass is theoretically the same, no major differences should be expected. The differences observed could be due to a slower combustion or different combustion efficiencies but these aspects will not be addressed in this study. To conclude, the temperature increase induced by combustion (~ 100 K) is significant respect to the temperature sweep proposed in the text matrix, and it should be considered in the analysis.

INJECTION SETUP AND MEASUREMENTS

As introduced in the previous section, a single-hole injector, equipped with a 82 μm conical nozzle, has been energized during 8 ms at 50, 100 and 150 MPa. The injector was triggered at -16°ATDC for an approximate duration of 24 CAD depending on the instantaneous angular speed of the engine i.e. depending on the operating conditions. More details about the nozzle and injection settings can be found in [Table 3](#).

The use of a single-hole injector presents several benefits compared to a multi-hole one. First, it impedes spray-to-spray interaction (aerodynamic + thermodynamic) and its position relative to the chamber allowed a much larger field for spray development and visualization (80 mm vs. 35 mm). Above all, the mass injected is strongly limited despite the relatively long injections performed. Consequently the heat release and the ambient temperature increases are relatively low, compared to a multi-hole injector nozzle

Measurements of the injection rate have been performed following the methodology described in [\[22\]](#). [Fig. 5](#) shows the result of the time-averaged mass flow rate extracted and averaged from the steady portion of 20 repetitions. Two levels of back-pressure have been set and are representative of the minimum and maximum in-cylinder pressures proceeding from the test matrix established. The five fuels

have a similar response to increased injection pressure. However, a slight decrease of the fuel mass flow rate appears for both Fischer-Tropsch fuels at the 100 and 150 MPa injection pressure conditions. The difference observed between the two back-pressures of the FT2 at 150 MPa could possibly be due to injector cavitation. [Fig. 3](#) shows a sample of the mass flow rate against CAD in arbitrary units. The curves for the 5 fuels overlap and the legend has been purposely hidden as the differences in injector opening and closing are rather small or inexistent, and definitely insignificant for a study using such long injections times.

OPTICAL DIAGNOSTICS AND MEASUREMENTS

The objective of this work is to study the relationship between ignition delay, flame lift-off length and soot formation processes for different fuels under a set of thermodynamic and injection conditions. Therefore, the pressure trace diagnostic, OH-Chemiluminescence visualization and the laser extinction technique have been performed simultaneously and associated in the analysis. For each combination of fuel (5), operating condition (5) and injection pressure (3), 100 injections were performed. OH-chemiluminescence and in-cylinder pressure were acquired at each injection while the laser extinction was repeated 10 times at 10 axial positions of the flame. The optical arrangement is presented in [Fig. 6](#). In the following section, details relative to these techniques are provided.

IGNITION DELAY

The acquisition of the in-cylinder pressure was performed at a frequency of 100 kHz. To measure the ignition delay, the average pressure of a motored cycle is subtracted to the average pressure in combustion, filtered *via* the Savitzky-Golay method [\[23\]](#), and differentiated. The averaged combustion cycle is calculated out of the 100 combustion cycles performed at each test condition, while the average of the motored cycle uses 200 cycles extracted from the second and third post-combustion one. The first cycle following the injection cycle was systematically removed because of the charge regeneration issues previously commented. Ignition delay is defined as the first instant exceeding a 10 MPa.s^{-1} threshold which aims at detecting the time of heat release recovering from the fuel vaporization heat consumption [\[24\]](#).

LIFT-OFF LENGTH

Line of sight images of the OH-chemiluminescence were collected to visualize the stoichiometric surface and measure the flame liftoff position relative to the injector. A gated 16-bit ICCD camera (Lavision Dynamight) equipped with a 100 mm-f/2-UV-lens and filtered at 310 nm was triggered 4 ms After the Electronic Start of Injection (AESI) as shown in [Fig. 4](#). Such delay was selected so the diffusion flame was

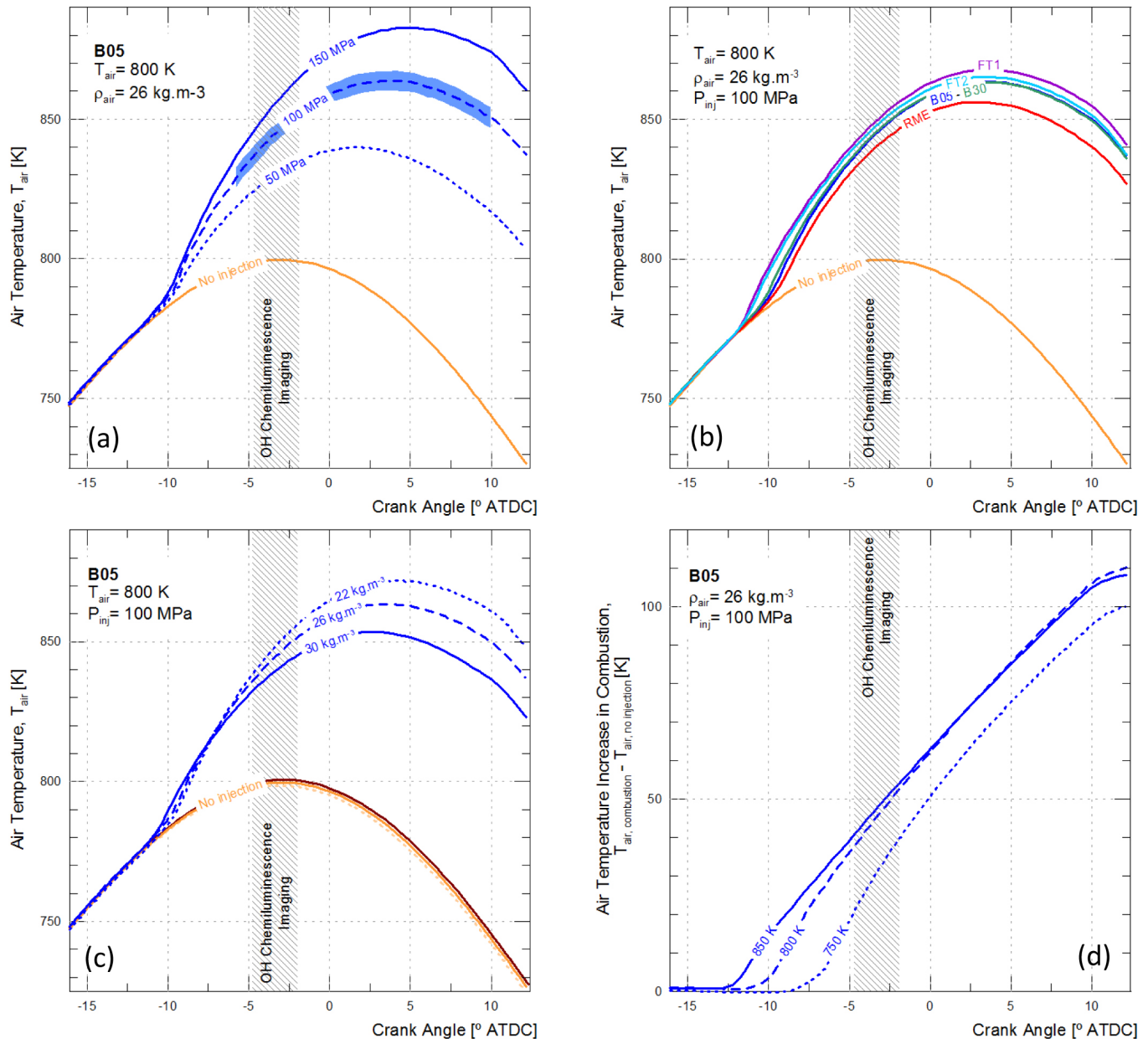


Figure 4. Variations of the in-cylinder temperature due to the combustion heat release. (a) Effect of injection pressure. (b) Effect of fuel type. (c) Effect of maximum ambient density. (d) Effect of maximum ambient temperature (750, 800 and 850 K are referring to the T_{max} for non-injected cycles used in the test matrix).

fully established when the camera was triggered. The intensifier gatewidth was set to 1 ms and the gain adjusted to maximize the use of the dynamic range while avoiding intensifier saturation. The 512×512 image resolution resulted in a 8.4 pixels/mm ratio. One frame per injection cycle was acquired.

The image processing was similar to [25]. Due to its “double-lip” shape, the flame is divided axially and each half-flame is processed independently. The closest pixel to the injector which exceeds the threshold value (12% of the camera dynamic range) is considered. The flame lift-off length is the

average of the distances between the injector and each point. Representative samples issued from the dataset of processed images are shown in Fig. 7.

FLAME OPACITY

The measurement of flame opacity was realized by passing a 2W, 1-mm diameter Argon-Ion (514.5 nm) laser through the flame at different axial position. The ratio between the incident beam intensity (I_0) and the transmitted one (I) informs on the soot concentration within the flame. The result of Eq. 1 is the dimensionless number KL , where K is the