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Diesel ignition delay and lift-off length through different methodologies using a multi-hole injector

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HIGHLIGHTS

- Lift-off length and ignition delay are measured through different methodologies.
- Oxygen concentration, temperature and injection pressure sweeps are performed.
- A multi hole injector is compared with an equivalent single hole injector.
- Multi hole injector has shorter ignition delay and lift-off length than single hole.
- Empirical correlations were calculated for an analytical description of the results.

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ABSTRACT

In this paper, lift-off length has been measured via both broadband luminosity and OH chemiluminescence. In addition, ignition delay has also been measured via broadband chemiluminescence and Schlieren imaging. A 3 orifice injector from the Engine Combustion Network (ECN) set, referred to as Spray B, and a single component fuel (n-dodecane) was used. Experiments were carried out in a constant flow and pressure facility, that allowed to reproduce engine-like thermodynamic conditions, and enabled the study to be performed over a wide range of test conditions with a very high repetition rate. Data obtained was also compared with results from a single orifice injector also from the Engine Combustion Network, with analog orifice characteristics (90 μm outlet diameter and convergent shape) and technology as the injector used. Results showed that there is good correlation between the ignition delay measured through both methodologies, that oxygen concentration and injection pressure plays a minor role in the ignition delay, being ambient temperature and density the parameters with the highest influence. Lift-off length measurements showed significant differences between methodologies. Minor deviation was observed between injectors with different nozzle geometry (seat inclination angle), due to temperature variations along the chamber, highlighting the importance of temperature distribution along combustion vessels. Empirical correlations for lift-off and ignition delay were calculated, underlining the effect of the conditions on the parameters studied. Coefficients of the correlations were compared with results for the single orifice injector, this showed that variations of test conditions have the same impact on ignition delay and lift-off length regardless the nozzle orifice configuration.

1. Introduction

Pollutant emissions have been a major concern for diesel engines for over a decade. Driven by climate change and environmental effects, stricter emission regulations push the engine designers to look for solutions to build cleaner engines. Many studies have shown that optimized mixing of the injected fuel with the ambient gases was key to reducing pollutant emissions [1–3]. Although Computational Fluid Dynamic (CFD) simulation results are of great help when designing thermal engines [4–6], experimental data are crucial not only to validate these models, but also to define the boundary conditions of the problem. One particularly interesting aspect is the difference in flow and combustion for sprays interacting with one another or in isolation [7]. A few studies have been carried out to compare different spray spacing [8,9] or the differences between multi- and single-hole nozzles [10]. The former studies have been performed in an optical engine, while the latter

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Nomenclature

Δp_{inj}	fuel pressure drop in nozzle orifice	CFD	Computational Fluid Dynamics
Δy	total intensity increment	CPF	constant-pressure flow (facility)
ρ_{amb}	ambient density	CWL	center wavelength
ρ_{fuel}	fuel density	D_o	orifice diameter
p_{inj}	injection pressure	ET	energizing time
T	ambient temperature	ID	ignition delay
y	total intensity	LOL	lift-off length
k-factor	nozzle orifice conicity factor	O_2%	ambient oxygen concentration
A, a, b, c, d	empirical correlations parameters	SoC	start of combustion
ASOE	after start of energizing	SSI	second stage ignition
ASOI	after start of injection		

was done in an optically accessible vessel. The level of detail achieved by the investigation from Jung et al. [10] goes well beyond what the Chartier's and Lequien's group has been able to extract. For instance, the quiescent and nearly constant conditions in the spray chamber allowed the authors to understand the detailed effects of low-lift needle motion on spray opening and evaporation. The authors suggested that these observations should impact global mixing and combustion processes under reacting conditions.

Optically accessible vessels with high-pressure and temperature capabilities are necessary tools to study the development and combustion processes of fuel sprays into ambient conditions relevant to thermal engines. The Engine Combustion Network (ECN) is an international collaboration group whose objective is to establish a library of reliable experimental data appropriate for model validation, and to leverage the scientific understanding of spray combustion at engine relevant conditions [11]. For this purpose, the experimentalists use state-of-the-art optically accessible chambers in which nominally identical injectors are mounted to generate sprays under tightly controlled conditions [12,13]. As part of the scope of research, the ECN uses single and multi-hole injectors with nominally identical specifications [14]. The study by Jung et al. [10] mentioned earlier compared the multiple and single orifice injectors from the ECN in an optically accessible vessel under inert, evaporative conditions. Yet, a follow-up study remains to be performed where the same conditions are analyzed under reacting conditions, in order to confirm the expectations based on the non-reacting tests.

In this work, a three hole injector (Spray B) from the ECN was used. This injector has a particularity as the three holes are not equally spaced, so that one of the orifice would be more isolated from the others to offer better optical access. A similar injector, featuring an axially-drilled orifice (Spray A), and also from the ECN, has been used as comparison to the three-hole version. The geometry and characteristics of both these injectors are well known and available on the ECN website [11]. Because of the relative simplicity of Spray A (single-hole), highly detailed experiments have been performed on this injector and spray system, but the geometry of Spray B comes closer to the multi-hole injectors found in production engines, thus driving significant interest from experimental and numerical researchers. The sprays have been injected in a high-pressure and high-temperature constant-pressure flow facility (CPF). This facility allows performing experimental studies simulating the conditions found in the combustion chamber of current compression ignition engines in terms of temperature, pressure or oxygen concentration. The tests performed in this study focused primarily on measuring the ignition delay and the flame lift-off length under a range of conditions. The parametric variation carried out in this study concerned chamber pressure (gas density), gas temperature, ambient oxygen concentration and fuel injection pressure. Several optical diagnostics have been used to measure ignition delay and lift-off length: Ignition delay detected by high-speed broadband flame chemiluminescence, as well as with high-speed schlieren imaging. Quasi-steady lift-off length was measured via OH-chemiluminescence with an intensified camera, while time-resolved flame stabilization was measured with a high-speed camera acquiring broadband flame luminosity.

This paper has been divided into four sections. Following this introduction, the experimental facilities are detailed, along with descriptions of the optical setups and experimental methods used in this work. The results are presented next, with the comparisons to the single-orifice from the ECN. The results are discussed in this same section, and correlations are proposed to predict ignition delay and lift-off length with the three hole nozzle, compared to the correlation coefficients from the single orifice experimental results. Finally, the last section presents the conclusions of this study.

2. Experimental setup and procedures

The following section briefly presents the experimental chamber and injection equipment used to carry out the experiments, followed by the test matrix, where test conditions are summarized, concluding with the optical setup and image processing methodology employed.

2.1. Spray chamber and injection system

According to the convention used by Baert et al. [15], an optically accessible constant-pressure flow (CPF) test chamber was used. This chamber is not only able to reproduce the thermodynamic conditions of a Diesel engine, but also, compared to other high-pressure high-temperature vessels [15–17], has the unique feature of presenting nearly quiescent and steady thermodynamic conditions within the chamber, allowing to test wide range of conditions and multiple repetitions without the penalty of long testing periods [12,13].

The facility can be divided into four parts: compressors, heaters, test vessel and control system. High pressure gas, stored in reservoirs, enters the chambers through a 30 kW electric heating system, rising the temperature to the desired level. Then the hot gases exit the vessel and are cooled to be recirculated to the compressors or thrown to the atmosphere. When recirculating the gases, its possible to control the oxygen concentration in the test section. The control system is a closed loop PID that adjusts both the pressure in the chamber, and the power output of the heaters. To reduce temperature differences within the test chamber, the vessel has a double wall configuration: the external wall acts purely as a structural element, while the inner wall is thinner