Experimental Thermal and Fluid Science 53 (2014) 236–243

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Engine combustion network: Influence of the gas properties on the spray penetration and spreading angle

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ARTICLE INFO

Article history:
Received 1 February 2013
Received in revised form 17 December 2013
Accepted 18 December 2013
Available online 30 December 2013

Keywords:
Diesel injection
Spray
Spray characteristics
Engine combustion network

ABSTRACT

In this work, three Engine Combustion Network (ECN) single-hole nozzles with the same nominal characteristics have been tested under a wide range of conditions measuring spray penetration and spreading angle. n-Dodecane has been injected in non-evaporative conditions at different injection pressures ranging from 50 to 150 MPa and several levels of ambient densities from 7.6 to 22.8 kg/m^3. Nitrogen and Sulphur Hexafluoride (SF_6) atmospheres have been explored and, in the first case, a temperature sweep from 300 to 550 K at constant gas density has been executed. Mie scattering has been used as the optical technique by employing a fast camera, whereas image processing has been performed through a home-built Matlab code.

Differences in spray penetration related to spray orifice diameter, spreading angle and start of injection transient have been found for the three injectors. Significant differences have been obtained when changing the ambient gas, whereas ambient temperature hardly affects the spray characteristics up to 400 K. However, a reduction in penetration has been observed beyond this point, mainly due to the sensitivity limitation of the technique as fuel evaporation becomes important. The different behavior observed when injecting in different gases could be explained due to the incomplete momentum transfer between spray droplets and entrained gas, together with the fact that there is an important change in speed of sound for the different gases, which affects the initial stage of the injection.

1. Introduction

For several reasons, both experimental studies and diesel spray modeling are extraordinarily defiant problems that require non-conventional approaches. The spray in the vicinity of the nozzle tip is highly dense. In addition, the ambient gas-fuel interaction occurs at microscopic scales and high velocities, with droplets of less than 30 μm travelling faster than 100 m/s. Therefore, the application of conventional optical techniques is an arduous task, as it is the case of PIV or phase Doppler measurements. This makes the macroscopic characterization of the spray under cold conditions remain an extensively applied technique in order to comprehend the behavior of the spray, since a relatively basic setup leads to reliable results.

Macroscopic characterization of diesel isothermal sprays has proved itself to be a valuable tool for spray penetration measurements [1–3]. On the other hand, it is extremely challenging to obtain quantitative measurements of spreading angle since different studies related the obtained results to the optical setup or the processing technique utilized [4–6]. Then, spreading angle measurements cannot be considered quantitative, although qualitative comparisons are enabled by avoiding changes in the optical setup from measurement to measurement, thus providing extremely useful information related to the spray-air mixing process.

In order to promote international collaboration among experimental and computational researchers within the engine combustion field, the ECN (Engine Combustion Network [7]) was created, addressing the research to reference test conditions and identifying priorities for future research. To this end, Bosch donated five single orifice injectors to the ECN with identical nominal characteristics. Several measurements with these injectors have been carried out in order to compare the results obtained in different facilities [8,9] and to assess the techniques utilized [10–12]. The majority of these works consisted on allocating one of the injectors to each test facility and assuming an identical behavior due to the manufacturer specification. However, different measurements of the internal nozzle geometry such as X-ray tomography or microscopic orifice imaging [7] pointed out some differences among the a priori identical injectors. In addition, most tests based their efforts on studying only the ECN reference condition called "Spray A" (150 MPa injection pressure, 22.8 kg/m^3 ambient density, 900 K ambient temperature and 15% O_2 concentration), which is the forum's first priority.

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0894-1777/$ - see front matter
http://dx.doi.org/10.1016/j.expthermflusci.2013.12.014

Nomenclature

c	speed of sound
C_d	orifice discharge coefficient
D_i	nozzle orifice inlet diameter
D_0	nozzle orifice outlet diameter
k-factor	nozzle orifice conicity factor, defined as $k\text{-factor} = 100 \cdot \frac{D_i - D_0}{L}$
L	nozzle orifice length
P_{amb}	ambient pressure
P_{rail}	rail pressure
S	spray penetration
T_{amb}	ambient temperature
T	time from the start of injection
v_i	instantaneous spray velocity

Greek symbols

ΔP	$P_{rail} - P_{amb}$
ρ_{amb}	ambient density
θ	spray spreading angle

Subscripts

av	average

The present work focuses on the comprehension of the behavior of the different injectors beyond "spray A" conditions. Thus, several tests have been carried out in isothermal conditions with three ECN injectors by using Mie scattering technique in a large range of injection pressures and ambient densities. A high-density gas (SF_6 – sulfur hexafluoride) was used to simulate relevant diesel in-cylinder density conditions in order to compare the injectors. Additional tests have been performed using Nitrogen and executing a temperature sweep from 300 to 550 K with the aim of checking the effect of spray composition and temperature on the measurements.

The results obtained have been analyzed following two approaches: statistical, extracting an empirical correlation from the experimental results, and theoretical, comparing the experimental results to the prediction of the 1-D spray model presented by Pastor et al. [13].

2. Experimental tools

2.1. Injection system

The injection system implemented for the study consists of commercially available components, namely a high pressure volumetric pump driven by an electric motor and a common-rail with pressure regulator controlled by a PID system. Three common-rail solenoid actuated Bosch injectors with the same nominal characteristics are used in this study. The injectors embody a single axial hole with a nominal outlet diameter of 90 μm. Conicity (nominal k-factor = 1.5) and hydro-grinding were incorporated so that cavitation is avoided in the orifice and a discharge coefficient Cd = 0.86 is achieved. These injectors are three of the single-hole injectors employed by the ECN group during their research. Their actual internal geometry was previously characterized in depth. The results of this characterization are available on the ECN website [7] and summarized in Table 1.

2.2. Test chambers and optical setup

Two different test chambers with optical access have been used to perform the Mie scattering technique. The first one (hereinafter referred to as *test rig* 1 or *TR*1) was conceived for relatively low pressures (up to 0.8 MPa) bearing in mind the high density of the SF_6. On the other hand, the second test rig (*test rig* 2 or *TR*2 from now on) made it possible to analyze the effect of gas temperature on spray penetration. The spray was illuminated by two Xenon-arc light sources and a fast camera (Photron SA5) imaged the light that the fuel droplets scattered. The test rigs and the optical components employed in the experiments are described in detail below.

Table 1
ECN nozzle internal geometry characteristics, obtained via X-ray tomography by *Caterpillar Inc.* [3].

Injector	D_i (μm)	D_0 (μm)	L (μm)	k-factor (–)
Nominal	105	90	–	1.5
Uncertainty	2	1	5	0.1
210675[a]	116	89.4	1030	2.7
210677[a]	116	83.7	1026	3.2
210678[a]	117	88.6	1044	2.8

[a] Hereinafter, the injectors will be referred to as 675, 677 and 678, respectively.

– *Test rig* 1 (Fig. 1): designed to visualize the spray at ambient temperature in high density conditions. A typical issue for this kind of facilities is the high pressure required to achieve high density, thus leading to a reduced chamber size and limited optical accessibility. In this case, high density is obtained in the chamber by using SF_6 gas since its molecular weight is six times higher than that of the N_2, making it possible to reach high density while keeping the pressure to a limit. As a result, densities up to 50 kg/m^3 can be achieved even though mechanical limitations set the maximum pressure allowed in the chamber to 0.8 MPa. The gas is recirculated in a closed loop and fuel droplets are scavenged from the test chamber through the use of a root compressor. Spray penetration and spreading angle comparisons were also carried out in *TR*1 for SF_6 and N_2 at a relatively low ambient density (7.6 kg/m^3), the maximum that can be achieved in the latter case. A thorough description of this facility is given in [5]. Fig. 1 shows the test rig layout: each of the two light sources illuminates one side of the spray and the camera collects the scattered light in a perpendicular way.

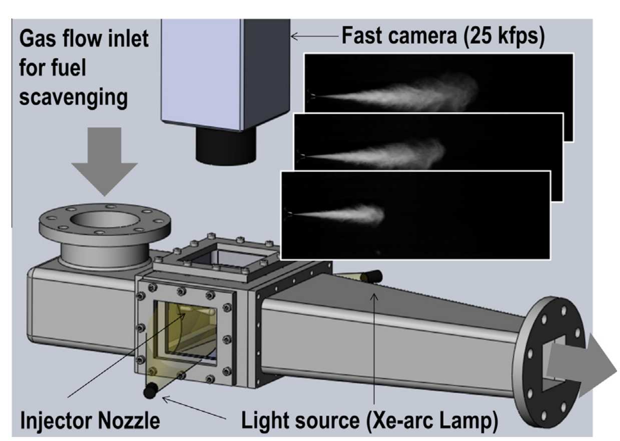

Fig. 1. Sketch of *TR*1 together with the optical arrangement.