Fuel 183 (2016) 20–33

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

The effect of nozzle geometry over internal flow and spray formation for three different fuels

Raul Payri [a,*], Juan P. Viera [a], Venkatesh Gopalakrishnan [b], Patrick G. Szymkowicz [b]

[a] CMT-Motores Térmicos, Universitat Politècnica de Valencia, Camino de Vera s/n, 46022 Valencia, Spain
[b] Diesel Engine Systems Group, Propulsion Systems Research Lab, GM R&D Center, MC: 480-106-252, 30500 Mound Rd., Warren, MI 48090-905, USA

HIGHLIGHTS

- Two single hole nozzle (cylindrical and convergent) are used.
- A complete hydraulic characterization is done along with spray visualization.
- A fast pulsed light source is synchronized to a fast camera working at 160 kHz.
- The effect of nozzle geometry is analyzed for three different fuels.
- A large set of experimental data was obtained, which could be used for model validation.

ARTICLE INFO

Article history:
Received 15 March 2016
Received in revised form 3 June 2016
Accepted 7 June 2016

Keywords:
Nozzle flow characteristics
Macroscopic spray development
Surrogate fuels
Isothermal spray vizualization

ABSTRACT

The influence of internal nozzle flow characteristics over macroscopic spray development is studied experimentally for two different nozzle geometries and three fuels. The measurements include a complete hydraulic characterization consisting of instantaneous injection rate and spray momentum flux measurements, followed by a high-speed visualization of isothermal liquid spray in combination with cylindrical and conical nozzle configurations. Two of the fuels are pure components—n-heptane and n-dodecane—while the third fuel consists of a three-component surrogate to better represent the physical and chemical properties of diesel fuel. The cylindrical nozzle with 8.6% larger diameter, in spite of higher mass flow rate and momentum flux, shows slower spray tip penetration when compared to the conical nozzle. The spreading angle is found to be inversely proportional to the spray tip penetration. The spreading angle is largely influenced by the nozzle geometry and the ambient density. Rail pressure was found to have weak influence on the near-field spreading angle and no influence on the standard deviation of the spreading angle. n-Heptane spray shows slowest penetration rates while n-dodecane and the surrogate fuel mixture show very similar spray behavior for variations in injection pressure and back pressure. However, the surrogate fuel mixture shows higher penetration than n-dodecane when using the conical nozzle and lower penetration than n-dodecane when using cylindrical nozzle.

1. Introduction

Discovered over a century ago, internal combustion engines have shaped and defined the world known today. Engine performance, fuel economy, and pollutant control have improved dramatically over the last three decades. Nevertheless, there is still interest in further development that warrants a critical and detailed evaluation of the combustion process largely influenced by fuel–air mixing [1,2]. To this end, computational fluid dynamic (CFD) models offer unmatched advantages over experimental approaches due to the large amount of temporal and spatial information they are able to provide. The predictive capability of validated CFD models can cut final product costs dramatically. However, current state of the art models are not completely predictive and hence, high-fidelity experimental data is still necessary to validate these models and provide accurate initial and boundary conditions to the simulations.

Majority of current spray models employ initial and boundary conditions at the nozzle exit as an indirect coupling to the flow inside the nozzle [3–6]. Such methods often dampen or lead to loss of smaller scale nozzle flow characteristics. Hence, the computed spray development using the indirect coupling is mainly dictated by momentum, aerodynamics, and mixing. In support of such

* Corresponding author.
E-mail address: rpayri@mot.upv.es (R. Payri).

http://dx.doi.org/10.1016/j.fuel.2016.06.041
0016-2361/

methods, Badock et al. [7] and later Ganippa et al. [8] presented results claiming that nozzle flow characteristics have negligible influence over the spray formation and that momentum is the only controlling variable for mixing. Contrasting these studies, several authors show that the flow inside the nozzle influences the near-nozzle region of the spray in terms of liquid-phase break-up, liquid length, and spray angle [9–16]. Many other studies also evidence the effects of nozzle flow characteristics over the macroscopic spray [3,4,6,11,17–20]. This contrast, along with the remaining uncertainty on the effect of nozzle geometry on entrainment, combustion, and pollutant formation, leave room for fundamental questions on the subject.

Fundamental questions demand detailed information on physical phenomena that are difficult to observe experimentally. This information can be obtained from a properly validated computational spray model that directly couples the nozzle to the spray volume. A few authors have published computational models that employ a full grid comprising the nozzle internal geometry and the spray [21–26]. It is important to point out that the work presented by Desantes et al. [21,26] and Xue et al. [24,25] have benefited significantly by the considerable size and quality of the Engine Combustion Network (ECN) open database and efforts (http://www.sandia.gov/ecn/, [27]), which allowed access to very high resolution tomographies of the internal nozzle geometry, along with extensive experimental data from different institutions around the world. However, the effects of nozzle geometries on spray formation, and to some extent, fuel properties, were still out of the scope of these studies and so these publications do not answer the questions raised about the effects of nozzle flow and fuel characteristics over the macroscopic spray.

In order to achieve fully predictive CFD models, it is essential to eliminate the uncertainty in physical and chemical properties. The development of surrogate fuels is one way to achieve this while providing detailed chemical kinetic mechanisms [28–30] further reduced to computable sizes [29,31] that can be employed in a fully reactive spray model. Surrogate fuels are often carefully tailored to mimic the behavior of real diesel fuel over the particular diagnostic being performed [29,32,33].

For some years, the surrogate of choice for diesel fuel has been a single-component species n-heptane. There have been more than a hundred studies of diesel combustion that have used n-heptane as a convenient surrogate. There have been two important reasons for this choice. First, n-heptane has a Cetane number of 56 that is reasonably close to the Cetane number of common diesel fuel, so its ignition is similar to that of diesel fuel which is convenient for ignition or heat release studies [4,28,31,34,35]. In addition, a detailed kinetic reaction mechanism for n-heptane was published by Curran et al. [28] in 1998 with all of the detail required to carry out thorough combustion studies. Recently, it has become apparent that n-heptane is not sufficient as a diesel surrogate, for instance, Idicheria and Pickett [36] showed that the n-heptane flame produces considerably less soot than a #2 diesel flame at similar conditions, and the soot distribution within the flame was also found to be quite different. Therefore, richer surrogates containing aromatics and other species that are important components in diesel fuels must also be represented in the surrogate selected for this study.

Although combustion performance is out of the scope of this publication, different fuels will present different behaviors regarding nozzle flow characteristics. Som et al. [37] presented a study of the effects of fuel properties on cavitation characteristics and nozzle-outlet turbulence kinetic energy. However, the study does not show the influences that different cavitation regimes found for each fuel may have on spray formation. Chen et al. [38] presented a study analyzing the effects of diesel and four alternate fuels on droplet diameters, spray penetration and cone angle. However, the effects of cavitation and nozzle flow characteristics are not contrasted with fuels in the paper. On this context, although the link between nozzle flow characteristics and macroscopic spray formation has been partially studied—especially linking the effects of nozzle geometry and cavitation to the spray formation—little to no information is found in the literature regarding the effects of fuel properties on nozzle flow and the corresponding macroscopic spray development, especially combining these with cavitating regimes [39].

This study is a contribution to the current understanding of the effects of nozzle flow characteristics over the macroscopic spray development. All experiments were performed for two different nozzle geometries and three fuels. The experimental campaign consisted in a complete hydraulic characterization—instantaneous injection rate and spray momentum flux measurements—followed by a high-speed visualization of the isothermal liquid spray. With these experiments, two main goals are pursued: first, to evaluate the influence of nozzle flow characteristics over the macroscopic spray with supporting experimental data and second, an effort is made in obtaining and reporting high-quality experimental data in order to gather a large database useful for CFD model validations with different fuels. Therefore, state of the art experimental techniques are applied at each particular diagnostic performed in order to guarantee the quality of data reported.

2. Materials and methods

2.1. Hardware

2.1.1. The fuel injection system

A common-rail injection system consisting of a high pressure pump and a conventional rail with an electronic pressure regulator is used. This system can generate relatively high rail pressures of up to 220 MPa and maintain it at the set value while injecting fuel. The injector body temperature was maintained close to 343 K using a special injector holder designed to have coolant flowing at a controlled temperature in direct contact with the injector body [40], as depicted in Fig. 1. This temperature is used to estimate viscosity and density of fuel inside the nozzle. The injector's return line was pressurized to 0.6 MPa as required by the injectors to work properly. The entire fuel injection system is electronically controlled and all the settings are introduced digitally.

2.1.2. Nozzles

All experiments were performed for two different nozzles, mounted on two independent injector bodies. Table 1 summarizes the injectors utilized and their nominal nozzle geometries. The injectors are piezo-electric actuated injectors. The two nozzles are micro-sac type single-hole nozzles, with different conicity but equal hydro grinding (13.5% each) and nominal flow rate (124 cm^3/min/10 MPa each). Note that Table 1 includes reference symbol and color columns which indicates the symbols and/or colors that will be used to distinguish nozzles in Section 3.

2.1.3. Fuels

All experiments were also performed for three different fuels. The first fuel selected is n-heptane. As stated in Section 1, n-heptane has long been utilized as a diesel surrogate to mimic diesel fuels in ignition and/or heat release studies [4,28,31,34]. The second fuel selected is n-dodecane, which features similar carbon content and boiling characteristics to those of diesel fuels, so it is expected to better mimic the mixing behavior of diesel fuels. This is one of the reasons n-dodecane was also selected as the primary fuel of study for the main ECN campaign [27], and it has been extensively characterized in the complete spectrum of experimental diagnostics and numerical simulations performed by the group.