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Full Length Article

The effect of nozzle geometry over the evaporative 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

- The study follows up a previous study on isothermal sprays produced with the same nozzles and fuels.
- Simultaneous liquid and vapor phase visualizations are carried out with different techniques.
- The effect of nozzle geometry is analyzed for three different fuels along a wide test matrix.
- 144 test conditions are evaluated in the high temperature/high pressure test rig.

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ABSTRACT

The influence of internal nozzle flow characteristics over the evaporative spray development is studied experimentally for two different nozzle geometries and three different fuels. This is a continuation of previous work by the authors where non-evaporative isothermal spray development was studied experimentally for the same nozzle geometries and fuels. Current study reports macroscopic spray characteristics by imaging the liquid and vapor phases of the spray simultaneously using independent cameras and optical techniques. The liquid phase is captured by a fast-pulsed diffused back illumination setup, while the vapor phase is captured by a single-pass Schlieren setup with diaphragm. The nozzle geometries consist of a conical nozzle and a cylindrical nozzle with 8.6% larger outlet diameter when compared to the conical nozzle. Among the three fuels, two are pure components—n-heptane and n-dodecane—while the third consists of a three-component surrogate to better represent the physical and chemical properties of diesel fuel. For a fixed ambient density, the liquid penetration is controlled by ambient temperature while the vapor penetration is controlled by injection pressure. The cylindrical nozzle, in spite of higher mass flow rate and momentum flux, shows slower vapor spray tip penetration when compared to the conical nozzle. Also, the cylindrical nozzle consistently produced shorter liquid lengths. The vapor spray spreading angle is found to be inversely proportional to the spray tip penetration, largely influenced by the nozzle geometry and the ambient density. n-Heptane spray shows the shortest liquid lengths, followed by n-dodecane and finally the Surrogate. No significant difference in vapor penetration rates was found between fuels, confirming that the vapor spray is controlled by momentum, which is independent of fuel. This was not the case for the non-evaporative isothermal sprays previously studied by the authors. Liquid lengths show the expected responses to parametric variations of ambient temperature and density. Two empirical predictive models are presented and utilized to analyze the influence of fuel properties on the liquid length. The primary factor controlling the liquid length between fuels is found to be their volatility. Finally, the cylindrical nozzle exhibits larger line-of-sight contour fluctuations in both the liquid and vapor phases, which in turn contributes to the shorter liquid lengths and slower vapor penetration.

1. Introduction

The performance and emissions of direct injection internal combustion engines are significantly controlled by the air-fuel mixture preparation. Fuel injection system technology and capability play

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

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Nomenclature

ρ	ambient density
ρ_f	fuel density
σ	standard deviation
τ	optical thickness
θ	vapor spray spreading angle
A	density ratio
B	specific energy ratio
C_a	area coefficient
$C_{p,liq}$	liquid phase constant pressure specific heat capacity
d_o	orifice nominal diameter
d_{eff}	orifice effective diameter
h_{vap}	specific enthalpy of vaporization
I	pixel intensity
k	proportioning constant
m	mass fraction
P_r	rail pressure
T_a	ambient temperature
T_b	boiling temperature
T_f	fuel temperature at the orifice
T_{90}	temperature at 90% evaporation
x_{liq}	predicted liquid length
$k0$	cylindrical nozzle
$k15$	conical nozzle
CFD	computational fluid dynamics
ECN	Engine Combustion Network
FOV	field of view
LED	light-emitting diode
PAH	polycyclic aromatic hydrocarbon
RMSE	root-mean-square error
SOI	start of injection

key roles in the mixture formation processes [1]. Fuel sprays, being primarily characterized by physically complex phenomena and intrinsically stochastic behavior, are remarkably challenging to comprehend by engine and combustion researchers. Over the last three decades, experimental researchers have studied fuel sprays thoroughly in search for a better understanding of these phenomena and also for supporting data that permits validation of detailed numerical models [2].

Among all challenges presented by the physics of fuel sprays injected in-cylinder, the effect of nozzle geometry on the formation, mixing and combustion of the diesel spray is still of interest to the research community and the automotive industry. Even though it has been studied before, the true extent of the effect of nozzle geometry over a wide span of operating conditions (including fuels) and response variables is not yet fully understood. For instance, Badock et al. [3] and later Ganippa et al. [4] 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 [5–11]. Many other studies also evidence the effects of nozzle flow characteristics over the macroscopic spray [6,12–18]. This contrast, along with the remaining uncertainty on the effect of nozzle geometry on entrainment, combustion, and pollutant formation, leaves room for fundamental questions on the subject.

These fundamental questions could be addressed from the information provided by computational fluid dynamic (CFD) models, which output a large amount of temporal and spatial data that the experimental approach is unable to acquire [2]. The predictive capability of validated CFD models can cut final product costs dramatically. Nevertheless, current state-of-the-art models still require high-fidelity experimental data for validation and accurate bounding of the problem. Majority of current spray models employ initial and boundary conditions at the nozzle exit as an indirect coupling to the flow inside the nozzle [14,16,17,19]. Such methods often dampen or lose smaller scale nozzle flow characteristics, and also present numerical issues such as different time-step lengths for each model to be coupled. Hence, the computed spray development using the indirect coupling is mainly dictated by momentum, aerodynamics, and mixing. Recently, a few authors have published computational models that employ a full grid comprising the nozzle internal geometry and the spray [20–25]. It is important to point out that the work presented by Desantes et al. [20,25] and Xue et al. [23,24] have benefited significantly by the considerable size and good quality of the Engine Combustion Network (ECN) open database and efforts (http://www.sandia.gov/ecn/ [26]), 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. These type of models could provide significantly more detail to the mechanisms and physics that control the relationship between nozzle flow, cavitation, and spray development, but they still need large amounts of experimental data for validation and bounding of the problem.

Fully predictive CFD models demand minimal uncertainties in physical and chemical fuel properties. The development of surrogate fuels is one way to achieve this while providing detailed chemical kinetic mechanisms [27–29] further reduced to computable sizes [28,30] 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 diagnostic being performed [28,31,32]. 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 [16,27,30,33,34]. In addition, a detailed kinetic reaction mechanism for n-heptane was published by Curran et al. [27] 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 [35] 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. [36] presented a study of the effects of fuel properties on cavitation characteristics and