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Estimation of a suitable Schmidt number range in diesel sprays at high injection pressure

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ABSTRACT

The aim of this paper is to estimate a suitable range for the Schmidt number value in non-evaporative diesel sprays. For this purpose, mass distribution data obtained from X-ray absorption experiments existing in literature and a theoretical derivation for spray microscopic characteristics have been combined. Firstly, a procedure based on Gaussian concentration profiles has been proposed in order to interpret X-ray absorption results and relate them to physical parameters as local concentration or spray density. After this, information about FWHM (Full Width at Half Maximum) values has allowed to estimate spray angle in the tested conditions by the definition of Gaussian profiles for the mass radial distribution inside the spray. Following, a theoretical model dependent on momentum flux and Schmidt number has been used to simulate local mass concentration evolution along the spray axis and compare it with the values obtained from the experiments. The combination of the experimental and the theoretical data has allowed to estimate a suitable range for the Schmidt number value in such conditions as those existing in diesel sprays.

1. Introduction

High pressure sprays have been widely used in many different applications (combustion processes, internal combustion engines, etc.). Despite having been studied over decades, this kind of sprays involves many complex physical phenomena, such as atomization, coalescence, mass and momentum transfer and evaporation, and there are important questions related with these processes that still remain unclear [1–3]. One of the important aspects that have to be taken into account in the design process of pressure atomizers and injectors is the distribution of mass and velocity over the entire spray. This is especially relevant in applications such as diesel spray combustion, since the flame location and characteristics are a result of the air-fuel mixing process.

In this sense, both spray macroscopic characteristics, as spray tip penetration or cone angle [4–8], and microscopic features like droplet size, velocity or local concentration [9–13] have been measured with the help of different experimental techniques. Additionally, several theoretical models have been developed to understand and predict spray behavior [14–18]. As a result of most of these studies it can be seen that momentum flux at the nozzle exit can be considered as one of the most important parameters for the characterization of sprays [15,17,19–22]. For this reason, several experimental techniques have been developed for measuring momentum flux [23,24].

Some studies have revealed that Schmidt number has a significant influence on spray characteristics, especially in the near-nozzle field (axial positions lower than $50D_o$), where primary and secondary atomization take place [17]. Nevertheless, most of the experimental data available in the literature is restricted to positions far from the nozzle exit, where the spray concentration values are small enough to use optical techniques as PLIF (Planar Laser Induced Fluorescence) [25,26] or PDPA (Phase Doppler Particle Analyzer) [9–11,16,17]. In fact, typical ranges of study for these techniques are 20–50 millimeters, which implies axial positions higher than $200D_o$. For this reason, there are still few contributions that give accurate estimations for Schmidt number in diesel sprays. Only Prasad and Kar [27] gave a range of value of 0.7–0.8 using an injection pressure of 10–20 MPa and nozzle diameters between 0.4 and 0.57 mm. Nevertheless, injection parameters were quite far from current diesel injection conditions, both in terms of injection pressures and nozzle diameters.

In the last years, several researchers have made an effort to characterize diesel spray behavior in the near-nozzle field [28–30]. In this sense, Argonne National Laboratories have developed a technique for quantifying projected density distribution inside

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List of symbols

A	outlet orifice section [m^2]
$C(x,r)$	local spray mass concentration [−]
$C_{axis}(x)$	concentration at a determined axial position of the spray [−]
D	mass diffusivity [m^2/s]
D_{eq}	equivalent diameter [m]
D_i	orifice diameter at the inlet section [m]
D_o	orifice diameter at the outlet section [m]
f	generic radial function for spray velocity distribution [−]
i	counter in the Taylor series [−]
I	X-ray beam intensity after passing through the spray [photons/s]
I_0	X-ray beam incident intensity [photons/s]
j	counter in the calculation of Mean Squared Deviation from FWHM data [−]
k-factor	degree of conicity of the orifice, defined as $k-\text{factor} = (D_i[\mu\text{m}] - D_o[\mu\text{m}])/10\ [\mu\text{m}]$
M'	projected mass obtained from X-ray measurements [kg/m^2]
$\dot{M}$	momentum flux [N]
$\dot{M}_o$	momentum flux at the nozzle orifice outlet [N]
MSD_{θ_m}	mean squared deviation in the calculation of spray angle from FWHM measurements [kg/m^2]
$m_a(x,r)$	air mass [kg]
$m_f(x,r)$	fuel mass [kg]
$\dot{m}_f$	fuel mass flow rate [kg/s]
N	number of terms in the Taylor series [−]
n_x	number of measuring points in the axial direction [−]
P_{back}	backpressure [Pa]
P_{in}	injection pressure [Pa]
r	radial coordinate [m]
r_1	radial position of the X-ray beam at the central plane of the spray [m]
$R(x)$	radius of the spray obtained from velocity profile [m]
$R_m(x)$	radius of the spray obtained from concentration profile [m]
Sc	Schmidt number [−]
$U_{axis}(x)$	velocity at the spray's axis in the axial position x [m/s]
U_o	orifice outlet velocity [m/s]
$U(x,r)$	local spray velocity in the axial position x and the radial position r [m/s]
$V_a(x,r)$	local volume occupied by air [m^3]
$V_f(x,r)$	local volume occupied by fuel [m^3]
x	axial coordinate [m]
z	axial perpendicular coordinate used in the experimental X-ray measurements [m]

Greek symbols

α	coefficient of the Gaussian radial profile for the axial velocity [−]
$\delta M'(x)$	deviation in the prediction of M' from the spray width measurements at a determined axial position [kg/m^2]
μ_m	fuel extinction coefficient [m^2/kg]
$\rho(x,r)$	local spray density defined as $\rho(x,r) = (m_a(x,r)+m_f(x,r))/(V_a(x,r)+V_f(x,r))$ [kg/m^3]
$\rho_L(x,r)$	local fuel density defined as $\rho_L(x,r) = (m_f(x,r))/(V_a(x,r)+V_f(x,r))$ [kg/m^3]
ρ_a	ambient density [kg/m^3]
ρ_f	fuel density [kg/m^3]
ν	kinematic viscosity [m^2/s]
π	Pi number [−]
θ_m	spray cone angle obtained from mass distribution [°]
θ_u	spray cone angle obtained from velocity distribution [°]

the spray based on X-ray absorption. The advantage of using X-rays is that while other radiations in the electromagnetic spectra (as for example visible light) are rapidly attenuated by fuel particles, intensity loss for the X-rays is much lower, so that it can be used even in the densest zones of the spray [31–34].

In this paper, a combination of a theoretical spray model and X-ray measurements performed at Argonne National Laboratories is used to estimate Schmidt number of a diesel spray for two different nozzles. In the literature, X-ray absorption results express mass distribution inside the spray by an integrated parameter along the line-of-sight (projected mass density). Thus, the first step for this analysis consists in converting these results to local microscopic parameters such as local density or mass concentration. Afterwards, results about spray width based on Full Width Half Maximum parameter (FWHM) are used for quantifying spray cone angle. For this purpose, Gaussian radial mass concentration functions are used and fitted to the experimental values of FWHM. After this, axial evolution of X-ray absorption measurements is compared with the results obtained by a theoretical model which depends on Schmidt number. Thus, an estimated range for this parameter can be obtained.

Considering the procedure previously described, two important findings will be obtained. On the one hand, a methodology will be described in order to convert X-ray experimental data to local concentration values, which is a more usual parameter to describe spray behavior. On the other hand, the analysis of data available will lead to obtain a suitable range for Schmidt number under realistic diesel spray conditions, which is an important parameter to describe spray dynamics, especially for modeling purposes. Furthermore, the ability of this model to predict spray characteristics in the near-nozzle field will be analyzed, showing the potential of a simplified model to study the evolution of local velocity and concentration near the nozzle exit. As far as the structure of the paper is concerned, the article is divided in 5 sections. Firstly, in section 2, the model is presented, together with the radial profiles used for the variables studied along the paper (local velocity and local mass concentration). In section 3, a description of the X-ray absorption technique is made, as well as the experimental conditions and processing tools are summarized. Analysis of radial distribution results for the two nozzles is performed in section 4, leading to obtaining the spray cone angle value for the tested conditions. After this, a comparison of the axial evolution of X-ray measurements and the predictions obtained by the theoretical model is made for different Schmidt numbers. Finally, in section 5, the most important conclusions of the work are drawn.

2. Spray model

2.1. Background

Diesel sprays have been traditionally divided in two different regions depending on its internal characteristics (Fig. 1). In the first region (or intact core length) the fuel on the spray axis has not been