Experimental Thermal and Fluid Science 86 (2017) 235–247

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Spray flow structure from twin-hole diesel injector nozzles

D. Nguyen [a,*], D. Duke [b], A. Kastengren [c], K. Matusik [b], A. Swantek [b], C.F. Powell [b], D. Honnery [a]

[a] *Laboratory for Turbulence Research in Aerospace and Combustion, Department of Mechanical and Aerospace Engineering, Monash University, VIC 3800, Australia*
[b] *Energy System Division, Argonne National Laboratory, Lemont, IL 60439, USA*
[c] *X-Ray Science Division, Argonne National Laboratory, Lemont, IL 60439, USA*

ARTICLE INFO

Article history:
Received 6 October 2016
Received in revised form 13 February 2017
Accepted 15 April 2017
Available online 18 April 2017

Keywords:
Twin-hole nozzle
Diesel
Spray
Penetration
Spray merge
X-ray radiography

ABSTRACT

Two techniques were used to study non-evaporating diesel sprays from common rail injectors which were equipped with twin-hole and single-hole nozzles for comparison. To characterise the sprays, high speed optical imaging and X-ray radiography were used. The former was performed at the Laboratory for Turbulence Research in Aerospace and Combustion (LTRAC) at Monash University, while the latter was performed at the 7-BM beamline of the Advanced Photon Source (APS) at Argonne National Laboratory. The optical imaging made use of high temporal, high spatial resolution spray recordings on a digital camera from which peripheral parameters in the initial injection phase were investigated based on edge detection. The X-ray radiography was used to explore quantitative mass distributions, which were measured on a point-wise basis at roughly similar sampling rate. Three twin-hole nozzles of different subtended angles and a single-hole nozzle were investigated at injection pressure of 1000 bar in environments of 20 bar back pressure. Evidence of strong cavitation was found for all nozzles examined with their C_D ranging from 0.62 to 0.69. Penetration of the twin-hole nozzles was found to lag the single-hole nozzle, before the sprays merged. Switching in hole dominance was observed from one twin-hole nozzle, and this was accompanied by greater instability in mass flow during the transient opening phase of the injectors.

1. Introduction

High pressure fuel injection has been a major area of research for some time, with many studies reporting on the effects of injector exit conditions on far-field macroscopic spray properties such as penetration, tip velocity and spread. Because of the experimental advantages to their use, particularly in optimizing the spatial resolution of the measurement domain, single-hole nozzles (SHNs) have been a significant focus of many of these past studies [1–7]. There is however a growing recognition of the need to study nozzles which are more representative of the multi-hole nozzles used in engines (e.g. [8–15]) if advances are to be made in our understanding of spray structure and dynamics, and to improve engine performance.

Multi-hole nozzles are used in engines because they distribute the atomized fuel more evenly in the combustion chamber, facilitating better fuel-air mixing. Nozzle holes are generally uniformly spaced around the nozzle tip to ensure uniform mixing of the fuel and air. A group-hole nozzle (GHN) is a variation of this design, in which rather than being uniformly spaced, the nozzle holes are spaced closely together to form a group, with the groups, if more than one, being spaced around the tip. Because of their potential benefits to fuel consumption and emissions [16], GHNs, particularly in the form of a twin-hole nozzle (THN), have recently been a focus of interest [9,10,16–20]. An important feature of GHNs is they enhance spray to spray interaction whether through direct merging of closely spaced sprays [9], or indirectly through modification to air entrainment into individual but unmerged sprays as they compete for the surrounding air.

As well as having a more complex structure to the sprays produced, relative to a SHN, THNs are expected to have different internal fluid properties and more complex internal flow. For example, relative to a SHN with the same orifice diameter, the increased mass discharge which accompanies the increased number of holes in a GHN is likely to lead to reduced nozzle sac pressure [17]. Aside from altering nozzle exit velocities [13], this could also alter the nozzle needle lift profile particularly affecting the initial opening and closing transients [13,21]. Hole number and hole position have also been shown to strongly influence spray stability and near field spray breakup [13,18,20,21]. This influence is thought to arise from modification to the internal flow structure which accompanies change to these parameters. Vortical structures have been shown to be present in multi-hole nozzle internal flow [22], and the transport of these through the nozzle hole is thought to give rise

---

* Corresponding author.
E-mail address: dungt.nguyen@monash.edu (D. Nguyen).

http://dx.doi.org/10.1016/j.expthermflusci.2017.04.020
0894-1777/

Nomenclature

A_l, A_n	liquid flow area at nozzle exit and nozzle exit area (mm^2)
C_ρ, C_v	area and velocity coefficients
C_D	discharge coefficient
d_i, d_o	hole passage inlet and outlet diameters (μm)
I, I_o	transmitted and incident X-ray beam intensities
k	cavitation number
K	K-factor
$\dot{m}$	mass flow rate (g/s)
M	projected mass ($\mu g/mm^2$)
p_i, p_c	injection and chamber pressures (bar)
p_v	vapour pressure (kPa)
TIM	transverse integrated mass (μg/mm)
U_p, $\overline{U}_n$	pressure driven and mean velocities of fuel at nozzle exit (m/s)
$\dot{V}$	volume flow rate (ml/s)
α	void fraction
β	twin-hole nozzle half angle (°)
θ	twin-hole nozzle hole angle (°)
ρ_l, ρ_v	fuel liquid and vapour densities (kg/m^3)
$\overline{\rho}_n$	mean density at the nozzle exit (kg/m^3)
μ	absorption coefficient

to the vortex like morphology seen in the phase contrast images of sprays from multi-hole nozzle as they exit the nozzle [21]. For merged sprays in particular, an additional aspect is the possible dominance either in spread or penetration within the merged spray by an individual spray, leading to asymmetry in merged spray structure. Factors which could influence spray dominance are hole geometry [23,24], injector needle movement [25], needle eccentricity [26], and cavitation [22,27]. Cavitation either in the nozzle sac (string cavitation), or on entry to nozzle hole (geometric induced cavitation) could be expected to alter mass discharge and its distribution across the nozzle exit thus altering spray characteristics [22,24,28–32]. Knowledge of the vapour distribution across the nozzle exit could yield detail on the type of cavitation present. The propensity of a flow to cavitate, but not the form the cavitation takes, is generally assessed by its cavitation number, which can be determined directly from the vapour phase properties of the liquid and its operating pressure [28]. To obtain the phase state, distribution techniques such as phase contrast imaging and X-ray radiography can be used [7,33]. Phase contrast imaging provides internal and external visualization of vapour and liquid distributions, whereas X-ray radiography provides quantification of the mass distribution from which phase state can be determined, although this approach is limited to the nozzle's external flow.

With these observations in mind, the focus of this paper is to investigate the near field properties of non-evaporating diesel sprays issuing from THNs of varying geometry, defined here by different nozzle hole angle. We focus on the near field because this enables closer examination of the role of nozzle exit conditions on spray structure. Comparison data are presented for a SHN with the same nominal diameter so that the effects of differences between these two nozzle types can be explored in detail. Sprays are characterized by their penetration and merging properties during the opening transient, and mass distributions during both transient and steady state operations. Spray merging and penetration were measured using a high speed visible light technique. Spray mass distribution, and from this density, was measured using X-ray radiography, while nozzle geometry was determined by X-ray tomography. We find evidence of cavitation in all nozzles examined with vapour appearing to extend across the exit flow profile of the nozzles. Near field THN penetration was found to lag the SHN, even before the sprays merged for the THNs. Switching in hole dominance during the transient phase was observed for one THN, and this was accompanied by greater instability in nozzle exit mass flow.

2. Experimental methodology

2.1. Experimental facilities

The fuel spray experiments were done in two different facilities using two complementary techniques [15]. Input parameters were set to be the same, i.e. pressure and nozzles. The high speed optical imaging experiments were undertaken in the Laboratory for Turbulence Research in Aerospace and Combustion (LTRAC). A Bosch common rail injector was located at the top of a fully instrumented constant volume vessel measuring 150 mm in diameter and 132 mm in height; more detailed description can be found in [1,34]. The injector was equipped with three different twin-hole nozzles, which directed two sprays inclined by three different hole angles of $\theta = 0°$, 5° and 10°, Fig. 1. For comparison, a single-hole nozzle was used which has a similar hole diameter of 200 μm. High pressure diesel fuel was supplied to this injector through a common rail from a feedback controlled pump able to maintain the pressure to within ±5 bar of the set value. This pump received diesel from a boost pump connected to the diesel tank. Standard automotive diesel was circulated in the fuel system and its temperature was maintained between 30 and 32 °C during experiments. The injection pressure used was 1000 bar and injection activation fixed at 0.3 ms. The vessel was pressurised to 20 Bar using compressed air at 22 °C.

Recording of the spray was done by use of a high speed HPV1 Shimadzu digital camera with a CCD array of $312 \times 260\ px^2$. A limitation with this camera is a maximum of 100 frames for each recording at any frame rate. Two high power TTL Met-Mecablitz flash units were used to provide spray volume illumination. The trigger signals for injector, flash units and the camera were produced and co-ordinated by use of a signal generator and a custom made control box. The start of recording could be tuned very close to the point of start of injection. For these measurements, the frame rate used was 500 kfps resulting in 2 μs time interval between frames (200 μs total recording time). The integration time used was 1/8 of this interval, i.e. 0.25 μs, to minimize blurring effects. Fitted to this camera was a micro Nikkon lens of 200 mm focal length with f-stop set at 5.6. The system was focused on a viewing area (W × H) of $21 \times 17.5\ mm^2$.

Optical measurement techniques using visible light sources are limited in exploring near field internal information due to multiple scattering effects in the dense spray region close to the nozzle tip. X-ray radiography is used to overcome this limitation. X-rays can penetrate dense flow fields with relatively little scattering. Use of a high-flux monochromatic beam can provide a local quantitative measurement of the fuel mass distribution by measuring line of sight transmission (c.f. [6,7,11,12,35–38]). This technique is based on the Lambert-Beer law which relates the X-ray transmission to the fuel mass present in the beam path via

$$\frac{I}{I_0} = e^{-\mu M} \tag{1}$$

in which I and I_o are the transmitted and incident X-ray beam intensities, μ is the absorption coefficient determined by calibration of the fuel, and M is the projected mass (units mass per area)