

Direct Injection of High Pressure Gas: Scaling Properties of Pulsed Turbulent Jets

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ABSTRACT

Existing gasoline DI injection equipment has been modified to generate single hole pulsed gas jets. Injection experiments have been performed at combinations of 3 different pressure ratios (2 of which supercritical) respectively 3 different hole geometries (i.e. length to diameter ratios). Injection was into a pressure chamber with optical access. Injection pressures and injector hole geometry were selected to be representative of current and near-future DI natural gas engines. Each injector hole design has been characterized by measuring its discharge coefficient for different Re-levels. Transient jets produced by these injectors have been visualized using planar laser sheet Mie scattering (PLMS). For this the injected gas was seeded with small oil droplets. The corresponding flow field was measured using particle image velocimetry (PIV) laser diagnostics. From the corresponding measurements, both the jet spreading angle and penetration have been determined according to different definitions and the inter-relation between these definitions has been examined. Results show that -beyond the initial transition period and almost up to the tip vortex region - (average) jet angle is almost constant. Furthermore, jet penetration is well predicted by correlations that implicitly assume momentum conservation at constant static pressure. Measurements suggest a different time-averaged velocity profile from that typically assumed in some of these correlations. Tip vortex position and size scale with transient jet penetration.

INTRODUCTION

In the coming decades the emissions of greenhouse gases by automotive transport will have to further decrease significantly. In part this reduction will be the result of the

introduction of renewable energy carriers such as biofuels and renewable electricity. But the biggest effect will come from the introduction of powertrains with better fuel efficiency. With SI engines the prime technologies of interest in the near-term are engine downsizing, lean charge combustion and direct fuel injection. Another near-term path for greenhouse emission reduction is the implementation of alternative fuels with lower carbon-content. Amongst these, natural gas is the the alternative fuel with the biggest potential contribution [1]. This explains the growing interest in recent years towards combining DI-injection technology with natural gas application, first with heavy-duty vehicles, but more recently also with light-duty applications.

Tests with direct injection of natural gas started more than 15 years ago on relatively larger (heavy-duty) engines in the US [2,3]. These tests immediately indicated the important fuel consumption increase resulting from the need to compress gaseous fuel to high pressure levels prior to injection. To avoid this penalty, Nissan, when testing direct injection of natural gas in a medium-duty engine, set injection pressure at 5 MPa [4]. Similar pressure levels were also selected for light-duty applications. Toyota tested direct injection of natural gas at 5 MPa pressure through a DI-gasoline atomizer nozzle and found promising results for both homogeneous and stratified combustion concepts [5]. And more recently, as part of the EU FP7 project NICE, an outwardly opening prototype injector with relatively large orifice - injecting at 2 MPa - was developed, also aimed at the light-duty market [6]. Injecting natural gas at lower pressures in order to limit fuel compression costs implies a longer injection duration as well as larger injection holes (and injectors) and this becomes even more problematic as engines are turbocharged and in-cylinder pressure levels increase. As demonstrated by

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Westport [7] this problem can however be circumvented by onboard storage of the natural gas as LNG. This liquefied gas can be pumped at smaller energy cost to a high pressure level (25-30 MPa) before vaporizing and injecting the fuel. Clearly, this approach could also be interesting for future light-duty applications. This short overview illustrates that in most DI natural gas studies the ratio of injection pressure to cylinder pressure would be supercritical. The resulting jets are referred to as under-expanded jets.

A crucial aspect of the development of a DI NG engine is that of setting up an appropriate fuel-air mixing process. This is increasingly done with the use of commercial CFD numerical codes [6,8,9]. Part of such development process then involves comparing the calculation results with indirect experimental data - such as in-cylinder pressure variation - obtained on a test engine. For a proper validation it is however preferable to have detailed data on the flow and mixing process set up by the fuel jet(s). Such data can be obtained by special (laser) diagnostics in a dedicated optically accessible test engine [13] or, alternatively, from experimental data on similar (supercritical) jets that can be found in the literature. A review of that literature learns that most studies on jets resulting from supercritical pressure ratios relate to steady-state jets. And most research on transient gas jets has been on jets resulting from subsonic pressure ratios. Only a few studies have provided detailed info on high pressure transient gas jets. In [9,10,11,12] transient under-expanded jet penetration was determined from jet envelope visualization with the well-known Schlieren technique. Tomita [11] in addition used Planar laser Mie scattering (PLMS) to determine the jet envelope growth process. Rubas et al. [13] and Bruneaux [14] applied Planar Laser Induced Fluorescence of a tracer substance (acetone respectively biacetyl) for this same purpose. Bruneaux used his experimental data to further obtain quantitative information on the (mean) fuel concentration variation inside the gas jet.

This paper presents results of a study that aims to extend this database on transient under-expanded gas jets, and more specifically aims to provide more data on the internal jet flow field.

INJECTOR DESIGN

Current DI fuelling equipment for large (heavy-duty and larger) natural gas engines uses multi-hole nozzles to set up an appropriate fuel-air mixing process. For light-duty applications different nozzle designs (single hole, pintle-type) have been used. Here it has been decided to use a single circular hole type nozzle. Furthermore it was decided to examine different nozzle hole geometries (i.e. l/d ratios). No rounding off of the nozzle hole entry was applied. Table 1 gives an overview of the different nozzle geometries tested.

Table 1.

Nozzle	d [mm]	l [mm]	l/d
A	0.52	2	3.85
B	1.3	2	1.54
C	1.3	10	7.69

Because no high pressure single hole nozzle injectors were commercially available, it was decided to design a modular type of DI gas injector starting from a commercial swirl-type gasoline injector. As shown in Figure 1, the original injector needle and its electromagnetic actuator unit were integrated in a support unit. To properly direct the needle motion, a guiding element is added. The tip of the injector needle rests on an insert to this support unit. This insert consists of a nozzle hole plate that is fixed in the support unit with a retaining nut. An O-ring prevents leakage from (high pressure) gas out of the injector unit. Three different nozzle plates have been made with geometries mentioned in Table 1. The original nominal maximum needle lift was increased such that - for a fully lifted needle - the smallest flow area was at the nozzle hole exit for all 3 geometries. A special driver unit was provided by TNO to realize the corresponding needle lift profile. As shown in Figure 1, a gas entry pipe feeds gas to the support unit, another pipe allows for gas exit flow (when the needle is not lifted). The complete unit was designed such that it withstands injection pressures up to 10 MPa.

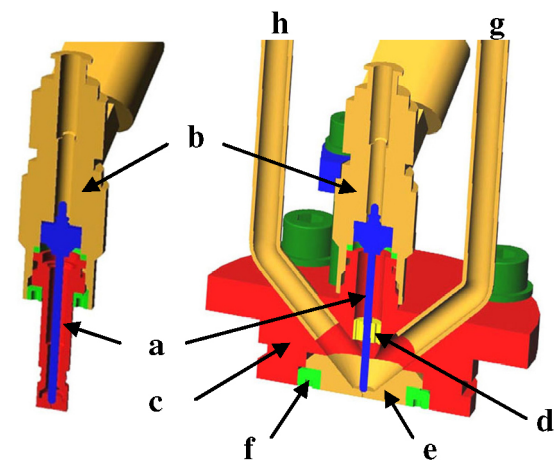


Figure 1. Left: original swirl injector unit. Right: gas injector design; (a) injector needle, (b) electromagnetic actuator, (c) support unit, (d) needle guide, (e) nozzle hole insert, (f) insert retaining nut, (g) gas entry pipe, (h) gas exit pipe.

EXPERIMENTAL APPARATUS AND METHOD

DIAGNOSTICS: PLMS AND PIV

As mentioned before it was the intention of this study to investigate not only the growth process of transient under-expanded gas jets but also the flow dynamics inside these jets. For this it was decided to apply two diagnostic techniques: PLMS and PIV. Both techniques rely on the detection of light scattered off small seeding particles that are carried with the flow. Scattering takes place when these particles move inside / pass through a laser sheet. This laser sheet is oriented such that the jet axis travels through this plane. With PLMS the outer jet envelope can be visualized. With PIV local velocities can be determined.

The PIV system that was used was a Dantec FlowMap system. A Continuum Surelite dual cavity laser with a pulse energy of 200 mJ (at 532 nm) and a pulse duration of 9 ns was used as light source. A PIV2100 signal processing unit supplied control signals to the laser cavities and performed the acquisition of dual-frame images from a Kodak ES 1.0 dual frame CCD PIV camera. The signal processing unit stored the dual frame images for subsequent processing. The image processing (i.e. interrogation, validation and post processing) was performed using an open-source PIV algorithm (UraPIV) which was tailored for this application. The necessary laser sheet was formed by a single negative cylindrical lens and a single spherical positive lens. The sheet thickness in the measurement plane was $< 1\text{ mm}$. The resolution of the PIV system depends on the field of view that is used, together with the interrogation size. When visualizing an area the size of the access window, the vector spacing was about 2mm;. This vector spacing results in a minimum visible vortex size of 4 mm, and flow structures below this scale cannot be visualized (but this resolution is of course increased when zooming in on a smaller area). The dynamic range of the velocity measurement is determined by the time spacing between the laser pulses and the interrogation size. With an interrogation size of 32 pixels and a minimum pulse-to-pulse delay of 2 μs , the maximum velocity is about 250 m/s. For even higher velocities, particle loss results in a loss of correlation. This is the case close to the nozzle exit. The maximum turbulence frequency that can be measured with this measurement system is about 10 kHz.

INTERMITTENT SEEDING

A Laskin nozzle has been used to generate olive oil seeding droplets. As shown in [Figure 2](#), this Laskin nozzle is built into a pressure chamber that will operate under a pressure corresponding to the gas injection pressure (i.e. up to 10 MPa). Gas will flow from a high pressure reservoir, through a pressure regulator to this seeding chamber. Manually

controlled valves are positioned upstream of the seeding chamber and downstream of the injector exit pipe.

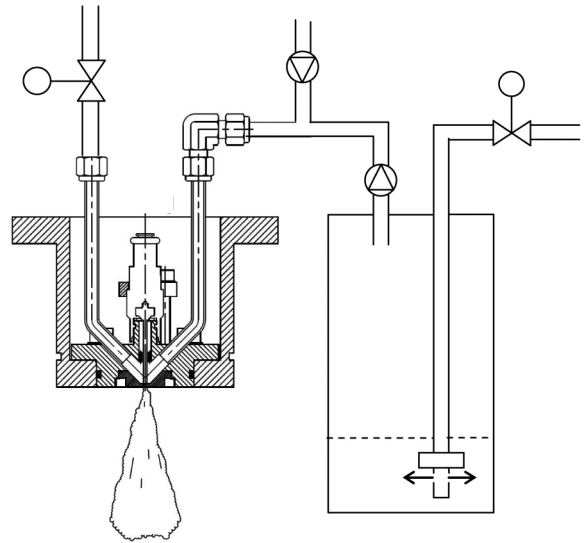


Figure 2. Injector fuelling and seeding system lay-out.
Laskin nozzle seeding unit is inside the pressure chamber on the right. Valves on inlet respectively exit line.

Just like the injection, seeding is intermittent. Prior to a measurement, both inlet and exit valve are open and droplet laden gas flows through the injector module; time is allowed for a steady-state flow/seeding situation to settle. Then, shortly before performing an injection experiment, the exit valve is closed. Injection follows, with start of injection and injection duration controlled electronically. After the test, the exit valve is opened and the injection module is purged with low pressure droplet free gas (fed in between seeding chamber and injector). Because the time between closure of the exit valve and injector needle lift is very short it is assumed that the seeding droplets do not have sufficient time to set or agglomerate. Of course this assumption is valid only if the seeding droplets are sufficiently small. Previous tests with the same Laskin nozzles indicated that droplet sizes could be expected in the range 1 to 3 μm . As the droplets have to accelerate and flow through the narrow nozzle hole, this could affect the droplet size distribution. Therefore an additional test was done to examine the seeding droplet size distribution downstream of the injector nozzle. In this test, the smallest diameter nozzle (A) was used and gas was fed at 0.5 MPa pressure into the seeding unit. Pressure downstream of the injector unit was atmospheric (hence sonic flow conditions in the nozzle). Droplet size distribution was measured using a Malvern Mastersizer S particle sizer that will detect particles in the range 0.05 - 900 μm . At these conditions, seeding droplet diameter was in the 0.7-3.2 μm range, with most droplets around 1 μm . As shown by Melling et al.[15], an oil particle with 1 respectively 2 μm diameter will follow a flow fluctuation up to a frequency of 10

respectively 2.5 kHz. This is in line with the frequency range limitations of the PIV set-up as described before. It is therefore expected that most of the vortices set up by/in the jet will be detected.

TEST CELL

The high pressure jet is injected into a cylindrically shaped test cell with a nominal 1.5 liter internal volume (similar to the design in [20]). Injection takes place on top; gas discharge takes place on the bottom. Four flat sapphire windows with 90 mm visible range allow optical access from 2 perpendicular directions. The construction of the chamber is such that it will withstand an internal pressure of up to 5 MPa. Pressure inside the chamber was measured with a GE Sensing PMP 1400 type sensor (0.15 % error in the range 0-6 MPa).

MEASUREMENT PROGRAMME

For safety reasons, in the tests, nitrogen has been injected instead of methane. With nitrogen the same Re-number and Ma-number values are obtained as with methane. With methane however, sonic speed is higher (and therefore more difficult to measure with PIV). The test cell was also charged with nitrogen gas. Test cell pressure and temperature were kept constant at 1 MPa respectively 300 K. The test cell volume is sufficiently large for a single injection to have a negligible effect on the chamber pressure and temperature. Injection experiments were performed for 3 different injection pressure levels: 1.5, 2.5 and 4 MPa. At the lowest injection pressure level, the pressure ratio across the nozzle is subsonic. At the higher pressure levels, a supercritical pressure ratio is set and under-expanded jets result. According to [16] the highest injection pressure results in a strongly under-expanded jet with a so-called Mach-disk, while the middle injection pressure level corresponds to a so-called moderately under-expanded jet (as evident from the introduction, all three types of jets may appear in future DI NG injection systems, but the under-expanded jet condition is certainly the reference). Duration of injector actuation was kept constant at 5.0 ms. Initial PLMS tests revealed that gas started to enter the test cell with some delay after start of needle actuation. For nozzle A a delay of 0.315 ms was measured. For nozzle C this delay was 0.52 ms. The moment of entering the test cell was taken as $t = 0$. Jet (PLMS or PIV) pictures were then taken with (nominal) 0.05 ms intervals until $t = 3$ ms. The resulting test matrices are shown in [Table 2](#) and [Table 3](#) for the different diagnostics. These tables also mention the numbers of pictures (for given t) as well as the information derived from them.

Table 2. PLMS test matrix. # refers to the number of measurements. Either jet spreading angle θ or penetration S is determined.

Nozzle	P	time	#	Target
	[MPa]	[ms]		
A	1.5	3	500	θ
A	2.5	3	500	θ
A	4.0	3	500	θ
B	2.5	3	500	θ
C	2.5	3	500	θ
A	1.5	0.5-3	50	S(t)
A	2.5	0.5-3	50	S(t)
A	4.0	0.5-3	50	S(t)
B	2.5	0.5-3	50	S(t)
C	2.5	0.5-3	50	S(t)

Table 3. PIV test matrix. # refers to the number of measurements. Axial velocity profile is determined.

Nozzle	P	time	#	Target
	[MPa]	[ms]		
A	1.5	3	100	U(x,y)
A	2.5	3	100	U(x,y)
A	4.0	3	100	U(x,y)
B	2.5	3	100	U(x,y)
C	2.5	3	100	U(x,y)
A	1.5	.5-2.5	50	U(x,y)
A	2.5	.5-2.5	50	U(x,y)
A	4.0	.5-2.5	50	U(x,y)
B	2.5	3	50	U(x,y)
C	2.5	.5-2.5	50	U(x,y)

RESULTS AND DISCUSSION

INJECTOR AND INJECTION PROCESS CHARACTERIZATION

For each of the nozzles and operating conditions separate tests were performed to determine the average flow rate through the nozzle during injection. For this N consecutive injections with 5 ms injection duration were done into the test cell. As the cell pressure increases as more gas is injected, the number of injections was limited such that after the experiment the pressure ratio across the nozzle would still be supercritical. This ensured that exit flow was not influenced by test cell pressure throughout the experiment. [Figure 3](#) shows that the injection pressure did show some variation, i.e. for the larger nozzles B and C, but this variation was limited. This pressure was measured at the original gasoline entry point at the top of the injector (see [Fig. 1](#)), and not close to