

An Experimental Study of Gaseous Transverse Injection and Mixing Process in a Simulated Engine Intake Port

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ABSTRACT

The flow field resulting from injecting a gas jet into a crossflow confined in a narrow square duct has been studied under steady regime using schlieren imaging and laser Doppler velocimetry (LDV). This transparent duct is intended to simulate the intake port of an internal combustion engine fueled by gaseous mixture, and the jet is issued from a round nozzle. The schlieren images show that the relative small size of the duct would confine the development of the transverse jet, and the interaction among jet and sidewalls strongly influences the mixing process between jet and crossflow. The mean velocity and turbulence fields have been studied in detail through LDV measurements, at both center plane and several cross sections. The well-known flow feature formed by a counter rotating vortex pair (CVP) has been observed, which starts to appear at the jet exit section and persists far downstream contributing to enhancing mixing process.

In addition, jets of different gases have been investigated with various injection orientations, aiming to fully understand the behaviors of transverse jet and the mixing process in the simulated intake port under wide practical conditions. Particularly, jet injection against crossflow has been found favorable in this study. The results show that the injection direction can influence the flow field remarkably, while the effect of injected gas is negligible, when the appropriate scaling is applied. A detailed description of the flow field inside a model intake port of an engine fueled with gaseous fuel is provided by the presented study and can be the basis for future comparison with computations.

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INTRODUCTION

Transverse injection into crossflow has been studied over many years, due to its great relevance to many engineering applications, particularly in energy and propulsion systems, as a consequence of the near field enhancement of the entrainment of crossflow and superior molecular mixing, when compared with the free jet issuing into quiescent surroundings or co-flow jet [1]. Recent applications in automotive industry include port fuel injection (PFI) for internal combustion engines fueled with non-conventional gaseous fuels, such as methane, hydrogen, CH₄/H₂ mixtures or synthetic fuels. PFI of gaseous fuels has advantages in air-fuel mixing compared with in-cylinder direct injection, since it has been proved that in-cylinder direct injection may be affected by incomplete mixing due to the short available time in the speed range 1000-5000 rpm [2].

Earliest studies focused on jet main trajectory and structural features [3], the source and evolution of vortical structures [1, 4, 5, 6, 7, 8], crossflow entrainment and jet-crossflow turbulent mixing [1, 5, 9, 10], as well as the concentration field [11]. For steady jet, it is well known that

the jet's structure and trajectory depend on the jet-to-crossflow momentum flux ratio and crossflow boundary layer thickness, while jet temperature and Reynolds number have limited impact, at least in the near field and at high momentum ratios [3]. As a consequence, the jet trajectory of a turbulent jet issuing transversely into a uniform, steady crossflow can be described by a single function, when the space coordinates are normalized by the momentum flux ratio [1].

Numerous experimental studies have been carried out by using various techniques and revealed that several complex phenomena are associated even with the simple case of steady injection into a uniform crossflow [3, 4, 6, 12]. Different vortical structures have been observed by a number of investigations and four types of coherent structure have been discerned and analyzed. In particular, a counter rotating vortex pair (CVP) occurs as a result of the interaction between the jet and the crossflow, which originates in the near field and becomes the dominant flow feature after the jet has turned in the crossflow direction [5, 7, 11]. In addition, the presence of the CVP, which does not exist in the free jet,

favors entrainment and mixing of the crossflow by secondary effects [1, 13]. Other vortical structures include shear layer vortices, horseshoe vortices and wake vortices, which are described in detail in [1].

In the majority of the reported experimental studies, the CVP has been observed through hot-wire measurements [5, 14], which are nonetheless questionable in a three dimensional high turbulent flow, or by flow visualizations in a water channel, generally for high momentum flux ratios. More recent experiments investigated the near field characteristics of transverse jets at moderate velocity ratios in a water tunnel by particle image velocimetry (PIV) [13, 15], the scalar mixing and two-dimensional velocity field with combined planar laser induced fluorescence (PLIF) and PIV [16], as well as the CVP by stereoscopic PIV in a wind tunnel [17]. However, the mechanism of formation of the CVP remains poorly understood.

Most of the reported experiments have been performed in large wind tunnels, when the effect of wall confinement on the jet's trajectory is insignificant and only the boundary layer on the wall from which the jet issues affects the vortical structures in the wake of the jet. Jets in confined turbulent crossflow have received considerably less attention and only few experiments have been performed in a narrow duct [18, 19], and generally in water flows. Moreover, most investigations considered jets and crossflows having low turbulence and thin boundary layers, while most practical applications deal with turbulent inlet conditions. In the present experiment the crossflow is confined in a small square duct where the transverse jet interacts with all the surrounding walls, even at low momentum flux ratio, modifying its structure and this is expected to improve mixing.

Due to the reasons stated above, further studies on transverse jets are needed because of the complexity of the phenomenon and the wide range of conditions found in practical applications, despite the large amounts of reported investigations. The objective of the present study is to provide quantitative data on the mean flow and turbulence of gas jets issued into a confined cross-stream, simulating typical conditions of gaseous fuel injection in the intake manifold of internal combustion engines, since in most applications to date natural gas is injected in the intake manifold [20]. The analysis is motivated by the lack of experimental data in such flow conditions. Specifically, we report on gas injection into a steady crossflow confined into a transparent duct which provides the possibility for the application of optical diagnostic techniques, such as schlieren imaging and laser Doppler velocimetry (LDV). Schlieren imaging has been applied to observe the macro structure of the jet and its interaction with the walls, while mean and fluctuation velocity have been measured by LDV, at several cross-sections downstream of the injection port as well as at the center plane.

The experimental setup and techniques used are briefly described next. Then a detailed description of the flow field

induced by the injection of gas jets into crossflow under various conditions is provided through the combined analysis from the results of both schlieren imaging and LDV measurements. The effects of the jet-to-crossflow momentum flux ratio, injection angle, the confinement from duct sidewalls will be concerned as well as the injected gas composition. Finally, this paper summarizes the results and presents some concluding remarks.

EXPERIMENTAL SETUP

The experiments have been performed in a transparent straight duct made by Poly (methyl methacrylate), with a square cross-section $40 \text{ mm} \times 40 \text{ mm}$ and 500 mm in length, aimed at simulating the intake port of a normal naturally aspirated light duty natural gas engine, while allowing full optical access (Fig. 1(a)). The air stream, supplied by the laboratory's compressed air line, was introduced from one side of the duct through a cylindrical pipe (inner diameter = 19 mm) and exhausted to the ambient from the open opposite side. A perforated grid with void ratio (area of the holes to the total area) equal to 60.5% was inserted at the entrance of the duct, well upstream the jet injection cross-section to keep the turbulence of the crossflow approximately homogeneous and isotropic. In the reported experiments, the free stream velocity of the crossflow U_{cf} was maintained constant at 1.70 m/s . The volume flow rate of inlet air in the duct was regulated and monitored with a rotameter, under controlled temperature and pressure.

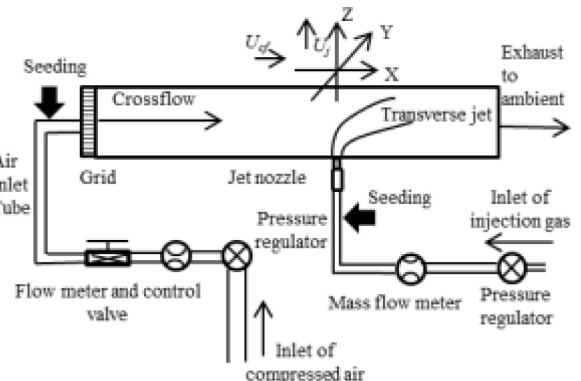


Figure 1(a). Schematic diagram of the duct with transverse gas injection, and the coordinate system

Figure 1. The test flow rig and the crossflow

It has to be stated that the thickness of the boundary layer of this crossflow (defined as position with 95% of U_{cf}) is 7.2 mm , according the results from LDV preliminary measurement on the crossflow, which is shown in Fig. 1(b). Thus the undisturbed area into the duct central region amounts to around 40% of the total cross-section. This observation underlines the importance of the boundary layer on the mixing process between the jet and the crossflow in such small geometry, not to mention its influence on the vorticity in the wake of the jet. The turbulence intensity is

almost constant ($\approx 10\%$) in the inner region of the flow, with a peak up to 27%, at around 2 mm from the wall, which is due to the flow being not fully developed yet and to the possible presence of corner vortices.

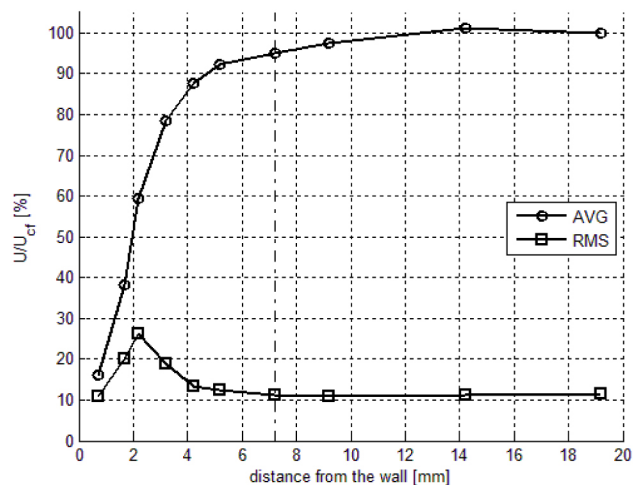


Figure 1(b). Mean (circles) and RMS (squares) velocity profiles of the crossflow measured by LDV, without any injection. The dashed line shows the limit of the boundary layer where $U/U_{cf} = 0.95$

Figure 1 (cont). The test flow rig and the crossflow

As indicated in Fig. 1(a), the incompressible gas jet entered the crossflow through a round pipe (inner diameter: $D = 6.4$ mm; length: $L = 10D$), whose outlet was mounted flush with one of the duct wall (called injection wall, hereafter), with a variable injection angle (shown in Fig. 2). When the jet is normally injected, the jet pipe axis resulted parallel to the Z direction of the coordinate system shown in Fig. 1(a) and Fig. 2(a) as well, which will be used throughout this paper, with the origin located at the center of the jet exit, and X axis being the direction of the crossflow. The jet axis was located 330 mm downstream of the inlet section and 170 mm upstream of the exit. The jet exit velocity U_j (time averaged volume flow rate divided by the exit area) ranged from 6 m/s to 14 m/s in the reported test conditions (see Table 1). All the jets studied here exhibits a fully developed turbulent top hat velocity profile at the outlet of nozzle, in absence of crossflow, as shown in Fig. 3. Highest turbulence intensity is measured at the edge of the jet, which is around 20%, while in the core of the jet it amounts to less than 10%. For all the experiments, the temperatures of both the jet and the crossflow were kept equal at ambient temperature (≈ 300 K).

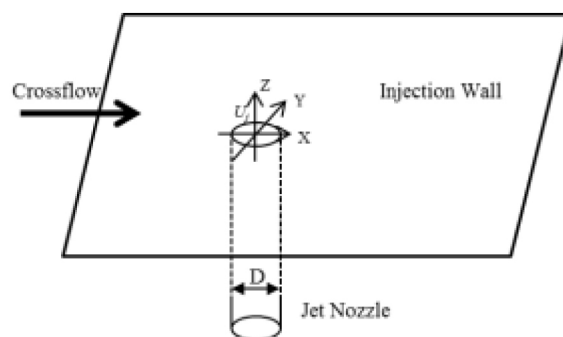


Figure 2(a). Schematic diagram of the jet nozzle mounted flush with the injection wall

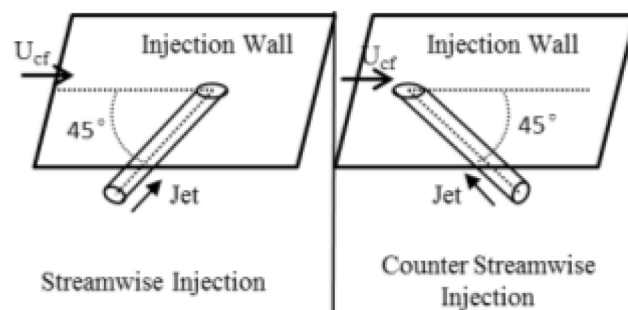


Figure 2(b). The injection with different injection orientation, corresponding with Table 1.

Figure 2. Schematic diagram of transverse injection

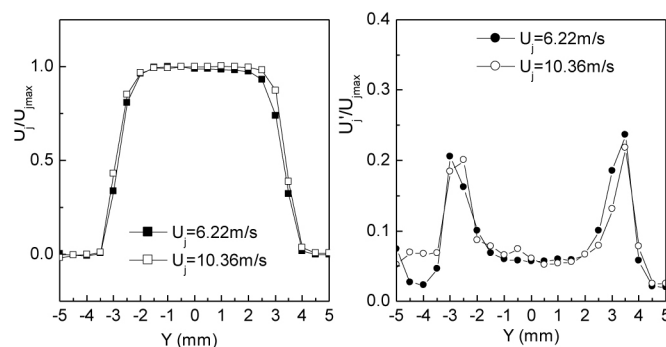


Figure 3. Mean (left) and RMS (rights) velocity profiles of the air jet measured by LDV, without crossflow. Both of them are scaled with the U_{jmax} (jet exit velocity in the center of injection nozzle outlet in each case)

The present investigation combines flow visualization with quantitative velocity measurements. Schlieren imaging were conducted firstly to study the topology of the jet, to acquire important insight into the flow field and to select the experimental conditions for subsequent LDV measurements. A Z-type schlieren imaging set-up was used to provide a light beam, normal to both jet and crossflow (Y direction in the coordinate system of Fig. 1(a)) [21, 22]. The schlieren images of the jets were illuminated by a stroboscopic xenon flash lamp and captured by a CCD camera (PCO SensiCam, 1280×1024 pixels) with a lens (Nikon, 60mm), using an

exposure time of 10 μ s, which is short enough to capture the instantaneous behavior of the flow field. The resolution of all schlieren images was set to be 10 pixels for 1 mm.

LDV was applied to provide space and time resolved measurements of the two-dimensional velocity field in several cross-wise (Y, Z) as well as stream-wise (X, Z) sections of the duct, by using two configurations of the optical set-up. A Dantec 2D Fiber-Flow optical system was used with a Spectra-Physics Stabilite 2017 argon-ion laser, and the Doppler signals were analyzed by two Dantec BSA processors. The LDV system was operated in the backscatter mode, and includes a Bragg cell to resolve directional ambiguity. For cross-wise sections measurements, the laser beams entered from the exit section of the duct and were slightly inclined to allow moving the probe volume in several cross planes (Y, Z) from a region close to the injection wall to the inner zone of the crossflow. Stream-wise measurements were obtained with the laser beams entering through the lateral wall of the duct, in order to measure the two velocity components in X and Z directions. In the first configuration a focal length of the transmitting optics of 600 mm has to be used to reach the target measurement cross section inside the duct, while in the second one the focal length was reduced to 300 mm with the addition of a beam expander, to reduce the probe volume dimensions. The grid spacing for all of the LDV measurements in this study is 1mm.

Separate pneumatic atomizers were used to simultaneously seed both the crossflow and the jet with oil droplets smaller than 2 μ m in diameter. The maximum measurable frequency of the flow fluctuations, limited by the inertia of the tracer oil droplets, is estimated to be around 2 kHz [23]. LDV sampling rate ranged from 10 to 1000 Hz, depending on the measurement location and operation conditions. The maximum statistical error at 95% confidence interval is estimate to be less than 5% with a number of statistically independent samples of at least 2000.

For both schlieren imaging and LDV tests, air was used for the crossflow, while the injected gas was mainly air for the LDV measurements and carbon dioxide (CO₂) for the schlieren visualizations, due to its large density difference with air, which improves the imaging sensitivity. It is well known that the characteristics of a jet in crossflow are primarily dependent on the jet to crossflow momentum flux ratio, R, and the crossflow Reynolds number, Re_{cf}, thus these two parameters are used to characterize the experimental conditions. The jet-to-crossflow momentum flux ratio R is defined as:

$$R = \sqrt{\rho_j U_j^2 / \rho_{cf} U_{cf}^2} \quad (1)$$

where the subscripts *j* and *cf* represent jet and crossflow respectively, ρ is the gas density, U_j is the time averaged volume flow rate divided by the area of the jet pipe outlet, and U_{cf} is the free-stream velocity of the crossflow, defined

directly through LDV measurements. When the density of both fluids is the same, R reduces to just the velocity ratio between the jet and crossflow. The details of the investigated conditions for LDV measurements are given in Table 1, where the following definitions of the Reynolds number are used:

$$Re_{cf} = U_{cf} l / \nu_{air} \quad (2)$$

where *l* is the cross stream characteristic dimension *l* = 40 mm;

$$Re_j = U_j D / \nu_j \quad (3)$$

where *D* is the jet exit diameter, *D* = 6.4 mm.

Table 1. Experimental conditions used for the LDV

Case	R	U _{cf} (m/s)	U _j (m/s)	Re _{cf}	Re _j	Injection Orientation*
Jet1N	3.7	1.7	6.22	4500	2630	Normal
Jet2N	6.1	1.7	10.36	4500	4400	Normal
Jet2S	6.1	1.7	10.36	4500	4400	Streamwise
Jet2CS	6.1	1.7	10.36	4500	4400	Counter-Streamwise
Jet2M	6.1	1.7	13.94	4500	3070	Normal

*refers to the orientation with respect to the crossflow, see Fig. 2(a) and Fig. 2(b)

The jet has been studied firstly with Normal injection, indicated by the capital letter 'N' in the case name, with two jet-to-crossflow momentum flux ratios. Then the jet nozzle was inclined at $\pm 45^\circ$, with respect to the crossflow, as indicated in Fig. 2(b). The two inclinations are referred to as Streamwise injection and Counter-Streamwise injection, indicated by the capital letter 'S' and 'CS' in the case name respectively. All the cases considered in this paper for LDV measurements refer to injection of air, as mentioned previously, except the last case, named 'Jet2M', which refers to the injection of a Mixture of helium and nitrogen (with a volume fraction ratio 1:1). This is aimed to simulate the density of methane ($\rho_m = 0.671 \text{ kg/m}^3$ at normal condition), and to study the influence of the gas composition. For this case, jet Reynolds number is lower caused by the higher viscosity of mixture ($\nu_m = 2.9 \times 10^{-5} \text{ m}^2/\text{s}$) [24]. Specifically, when CO₂ or the gas mixture was applied in the schlieren imaging experiment or LDV measurement respectively, the jet outlet velocity was adjusted to obtain the same jet-to-crossflow momentum flux ratio, according to Eq.1. Consequently, the jet Reynolds number changes as well.

It has to be noticed that for a naturally aspirated light duty engines with cylinder capacity of 0.5 liters, the intake air