Penetration and scale law for a GDI swirled spray and its surrounding air pattern

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A hollow cone spray produced by a GDI swirled injector was studied at different ambient air pressure, to investigate its shape by means of high speed photography, and its surrounding air pattern by laser Doppler velocimetry.
The images show the spray initial hollow cone structure that collapses inwardly to form a narrower full cone spray, at a distance which is function of the air pressure. The air surrounding the spray tip is pushed ahead by the spray, then recirculates to be entrained by the spray body, forming a toroidal head vortex. The penetration of the spray and of the toroidal vortex scale with the air pressure with very similar laws, so that a unique scale law can be used to describe and predict the spray and vortex location and structure in a wide range of ambient pressure.

1. Introduction

Gasoline Direct Injection is considered by car manufacturers a technology that could help them to enhance fuel consumption and pollution emissions of spark ignition internal combustion engines [1]. Different injector concepts, spray shapes and injection strategies are possible, with injection conditions spanning in a much wider range than those found in port fuel injection engines: the spray is injected into air that could be at sub-atmospheric pressure and ambient temperature in the induction stroke, or at more than 10 bar and hot temperature in the compression stroke. This strong difference in the ambient condition dramatically affects [2] the fuel spray shape and its mixing properties with the surrounding air, which are crucial to the following combustion.
The aim of the present work is to study the effect of the air density on a swirled spray and on the air flow pattern generated by the injection, and to investigate if a common behavior of the studied phenomena can be found at different ambient conditions.

2. Experimental set-up and conditions

The injector used to produce the hollow cone spray was designed for automotive GDI applications; the fuel used was iso-octane, supplied at 71 absolute bar. The spray nominal angle is 60°, and the injected mass is 47 milligrams for a pulse length of 3 milliseconds. The shape of the spray and the pattern of the surrounding air vortex were studied by fast digital photography and laser Doppler Velocimetry. All measurements were performed into a closed bomb equipped with optical accesses.
When the hollow cone spray is formed, the effect of the air flow induced by the spray itself is a collapse of the wide hollow cone structure, which changes to a narrower full cone [2]. The higher is the air density, the shorter are the time and length required to see this structure

change. Strong effects are seen also on the spray penetration, which depends on the air density and on the spray front section,
The effect of a very lower ambient pressure is to widen the dimensions of the spray and to delay the structure change so much that, to observe the same phenomenon, it is necessary to investigate a much wider area for a longer time; this fact required the use of two different set-up configurations.
The air pressure in the test bomb was kept constant, ranging from 0.2 to 4 bar absolute pressure, so the investigated pressure range spans up to a ratio of 20 times.
For experiments above atmospheric pressure, the bomb was equipped with 100 millimeters diameter windows, and a CCD camera (PCO FlashCam), 752x572 pixels resolution, 1 μs exposure time, was used.
For sub-atmospheric pressure condition the bomb was used in a different position with a 220 millimeters diameter window, to investigate a more extended spray region. A CCD camera, 1280x1024 pixel resolution (Dantec) was used, with the exposure time determined in this case by the 4 μs flash lamp. The test case at atmospheric conditions was studied in both configurations, to verify the influence of the different set-up on the results, and to correct for the slight difference in the light distribution.

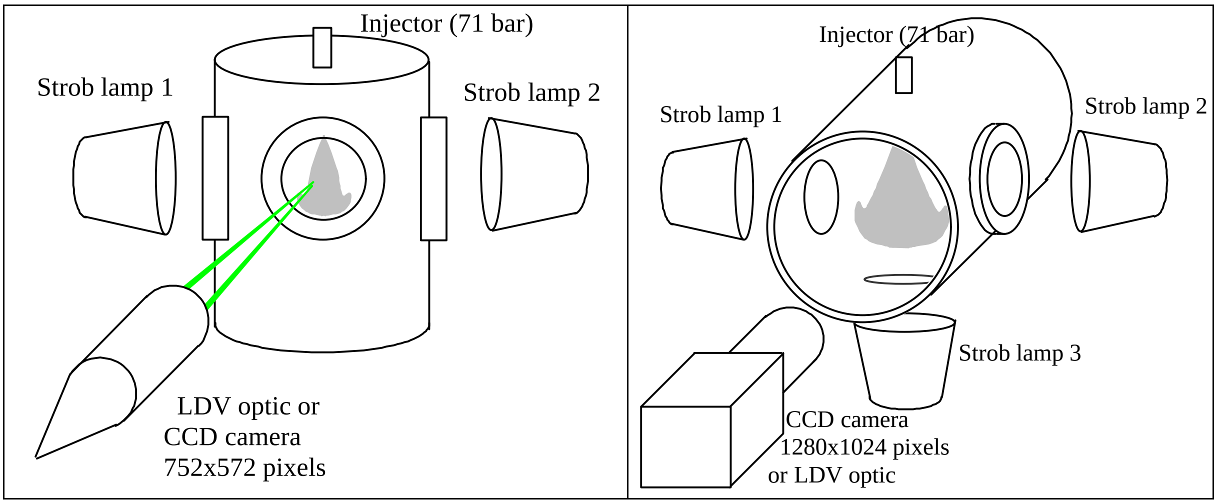


Fig. 1 the test bomb for experiments above (left) and below (right) atmospheric pressure.

Injections were triggered at the maximum frequency of 1 Hz, with a slight air flush to avoid fuel vapor accumulation. The injector was kept open until the spray tip reached the end of the field of view, resulting in longer injections at low air pressure. The injection trigger was always used as the temporal origin for all the samplings; the real opening and closing of the injector show small delays (0.4 – 0.5 ms respectively) from the electronic signal.
Spray pictures were acquired at different delays from the injector trigger, with ten images at each delay for better statistical averaging.
Time resolved LDV data were acquired over many successive injection, to collect up to 6000 data at each location, over a time window a few millisecond longer than the spray pulse, and the results were superimposed to describe the average flow field evolution. The instrument used is a PDA Processor by Dantec, set in back scatter configuration for only velocity measurements. The LDV grid was chosen to describe, at each air pressure, the evolution of the air field pattern on one side of the spray. Fuel droplets left by previous injections were used as tracers at high air pressure; at sub-atmospheric conditions, when iso-octane evaporated quickly, Diesel fuel droplets produced by an air atomizer were added in the bomb.

Table 1. Experimental cases and conditions

Test Case	Air Pressure	Injection pulse	Pressure Set-up	Image size (mm)	LDV grid (Ver x Hor)	LDV step (Ver x Hor)
A	0.2 bar	6 ms	Low Pr.	75.2x57.2 mm	110 x 70 mm	10 x 10 mm
B	0.4	5	Low Pr.	75.2x57.2	110 x 60	10 x 10
C	0.7	4.5	Low Pr.	75.2x57.2	100 x 60	10 x 5
D	1	4	Low Pr.	75.2x57.2		
D2	1	3 (47mg)	High Pr.	128x102.4	90 x 50	10 x 5
E	2	3	High Pr.	128x102.4	60 x 30	5 x 5
F	4	3	High Pr.	128x102.4	60 x 25	5 x 2.5

3. Data processing and elaboration

LDV data were first elaborated to calculate the air velocity in each point of the measurement grid, averaged per time slots of 0.2 ms; then the vectors were reconstructed and added to the spray image to get a visual overview of the phenomenon, partially reported in the figure 2.
Small asymmetric pre-jet and post-injections, often present in this kind of injectors, are visible, but they do not interfere with the spray evolution. The spray shows similar behaviors at all air pressures, with an initial hollow-cone structure and the formation of a toroidal vortex around the spray head, that advances and is followed by the air entrainment, characterized by inwardly directed air flow. At the same time the spray shape, under the effect of the entrainment flux, changes from hollow cone to full cone, with a gradual narrowing of the cone angle. This structure evolution happens very quickly at high air pressure, and much later and at further distance from the injector at very low air pressure.
Both the entrainment flux and the toroidal vortex had already been observed in other kind of impulsive injections, both for gaseous [3] and liquid injected fluids [4], and the vortex head penetration was analyzed and correlated to that of the spray or jet tip. The position of the toroidal vortex center can be calculated from LDV data by finding the position, at each time step, where the horizontal air velocity turns from outward pushed to inward entrained, so the vortex penetration can curve is found.
In the present case the vortex shape is often disturbed by the presence of the spray tip and of the entrained gas, whose combined action stretches the vortex to assume an elliptical and irregular shape, so the method proposed by [5] was used with some adaptations. The method, theoretically based on the computation of the vorticity of a combined vortex, finally results in the use of an average radial air velocity profile along the axial direction. The radial velocity, averaged over three or more points external to the spray cone surface, is used to find the vortex center position, as the point where the profile crosses the zero value at any given time. The point positions used for the computation were not fixed but they follow the spray profile, that changes position with the distance from the injector and with the air pressure, as seen in the images reported in figure 2.
Digital images were directly elaborated to calculate the spray length at each delay, allowing to draw spray tip penetration curves. The algorithm used, already described in other works [6] allows to detect the spray front, which is considered more representative of the whole spray, rather than the furthest detected drop, which is more representative of the pre-swirl injection and is often more unstable. The algorithm also showed to be very insensitive to light intensity variation, and allowed to correct for the different light distribution of the two pieces of set-up, through the experiment at atmospheric conditions performed with both set-up configurations.

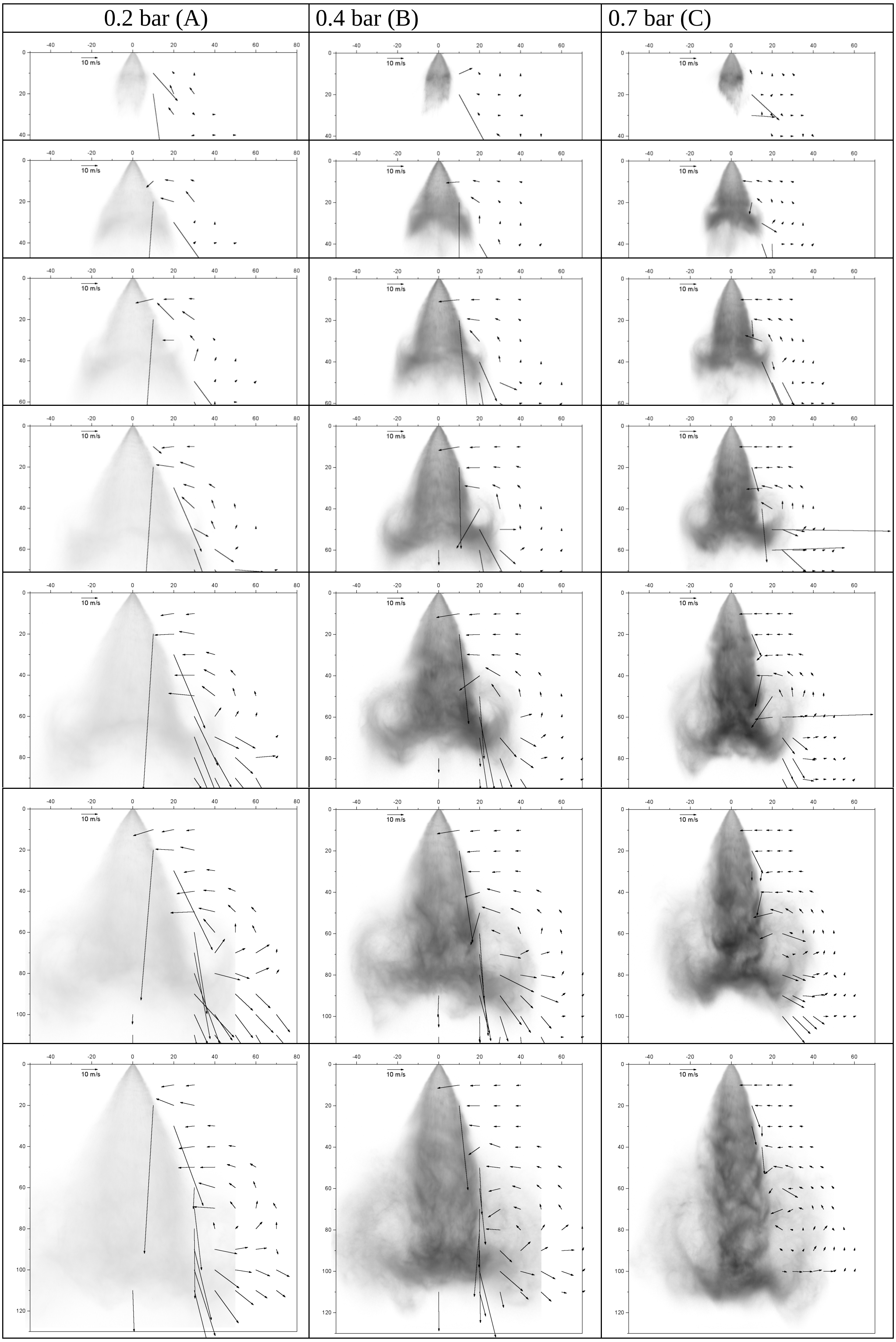


Fig. 2a: spray images and air pattern (0.2, 0.4, 0.7 bar)

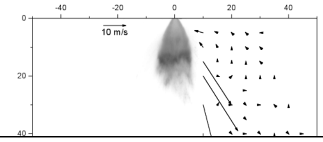
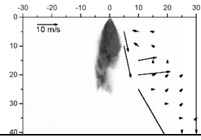
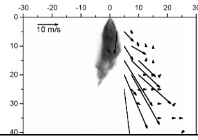
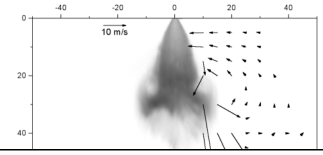
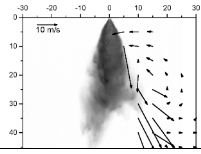
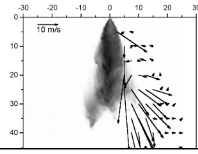
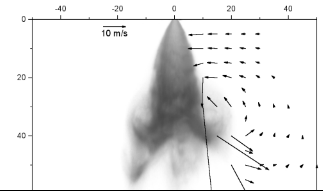
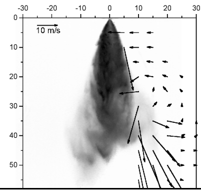
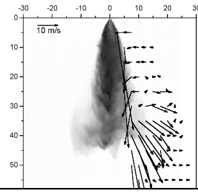
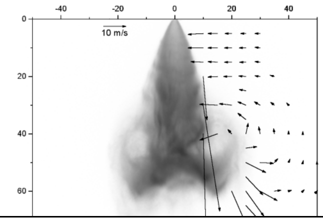
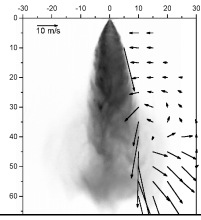
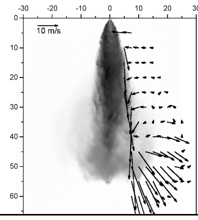
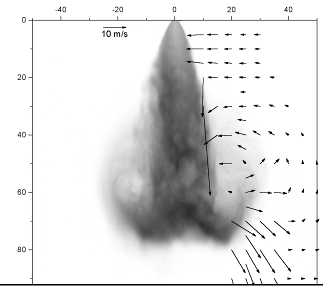
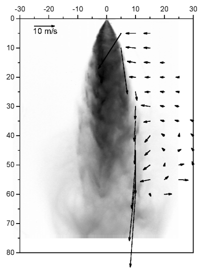
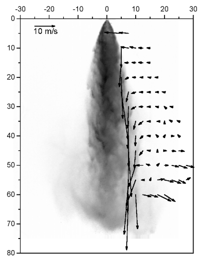
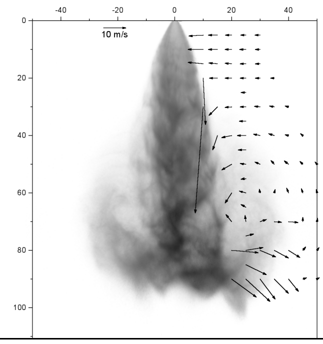
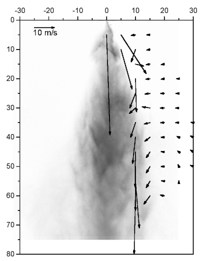
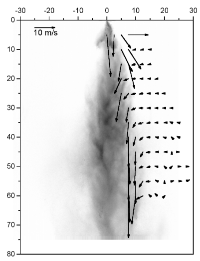
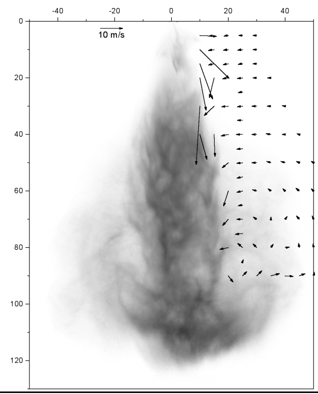
1 bar (D)	2 bar (E)	4 bar (F)	
			0.8 ms
			1.2 ms
			1.6 ms
			2.2 ms
			3.0 ms
			3.8 ms
			4.8 ms

Fig 2b: spray images and air pattern (1, 2, 4 bar)

4. Penetration curves and scale law

The penetration of both the spray tip and of the toroidal vortex center are reported in figure 3. The spray tip always shows similar behaviors: the initial tip velocity is near the same in all the examined conditions (52 m/s), then it immediately decreases to reach gradually a value close to 19 m/s, at that point the spray structure is already changing with the collapse of the hollow cone structure, the spray angle becomes narrower and the tip velocity becomes almost constant, showing a linear penetration curve. The vortex center penetration curves are all almost linear, with a different origin, but quite similar velocity near 12.5 m/s.

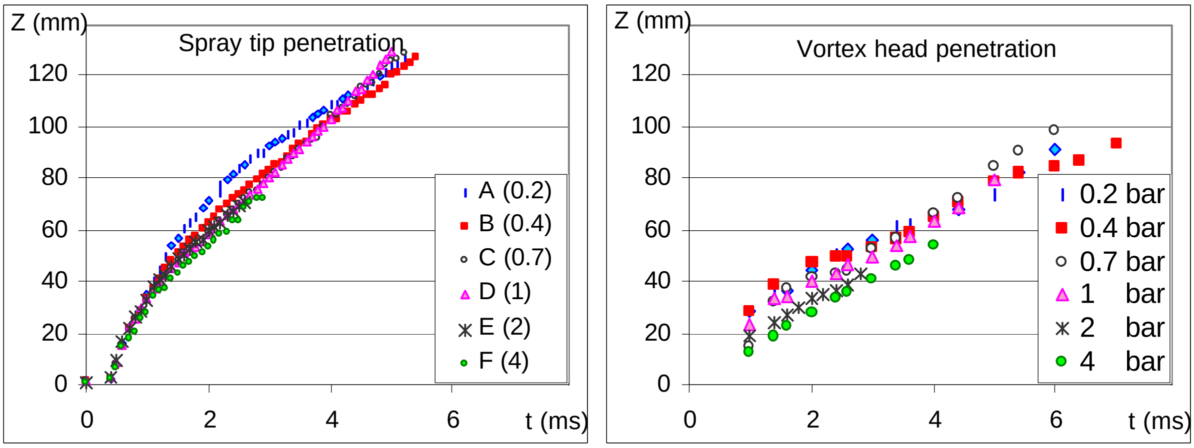


Fig. 3 Penetration of the spray tip and of the vortex center

The common behaviors of the spray at different air pressure suggests the presence of a scale law, able to describe the tip penetration by a unique curve in appropriate new coordinates. As suggested by the well known equations for Diesel sprays [4, 7] and gas jets [3], both from theoretical investigations and experimental results, a new transformed coordinate system can be chosen in the form:

$t_{tr} = (t\text{-}t_0) * (p/p_0)^{\alpha}$ $\qquad Z_{tr} = Z_{tip} * (p/p_0)^{\beta}$ [eq.1] , where:

t = time elapsed from the injection trigger
t_0 = opening delay of the injector, 0.4 ms
Z_{tip} = tip penetration
P = air pressure
α, β = coefficients to be optimized

With the present experimental data, the optimal result was obtained with the values α=0.38 and β= 0.34, when all the tip penetration curves are well overlapping in the new t_{tr} and Z_{tr} coordinates. The full adimensionalization of the results could be obtained by the use of other factors in eq.1, generally a characteristic length of the injector, and a characteristic time of the spray [4, 7], that in the case of only one tested injector and one fuel pressure would result in constant factors and therefor are here omitted. Also the use of the reference pressure at ambient conditions in eq. 1, that is equivalent to a gas density ratio as used by other authors, leads to transformed coordinates that are the same of the reference case at ambient pressure. The penetration curves in transformed coordinates are reported in fig.4, both for the spray tip and for the vortex center, together with the functions chosen to fit the experimental data.
As first approximation, for the vortex center a linear function was used for all the data; for the spray tip penetration, the data up to 60 length unites were interpolated by an exponential function, then followed by a unique linear function for the data beyond that point.

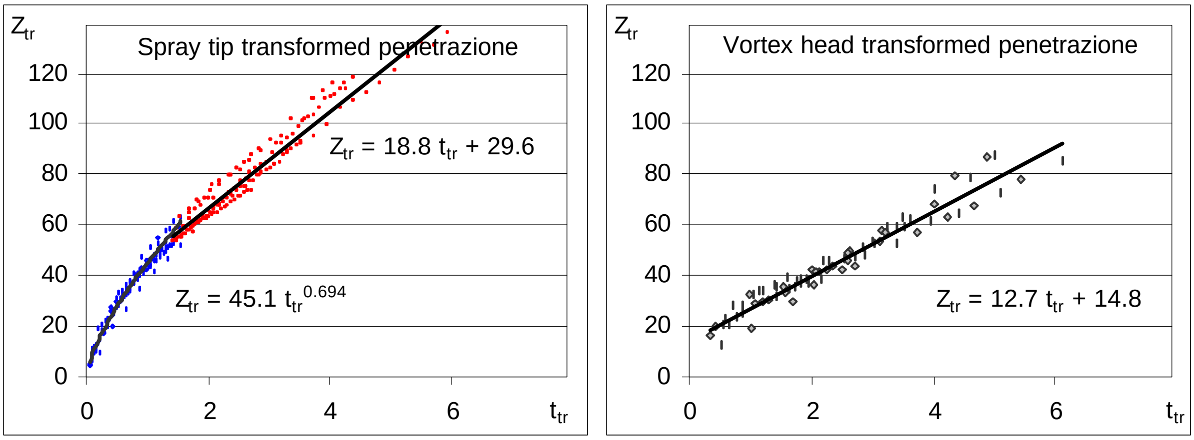


Fig. 4 Penetration of the spray tip and of the vortex center

The intersection of the two functions indicates in the transformed coordinates the point where this penetration velocity, after decreasing, reaches a constant value, and the spray shape changes from a hollow cone to a full cone. By reversing eq. 1 this point is expressed as a function of the real coordinates, and the tip penetration can be described, with the approximation of the linear part of the penetration curve heaving the same speed for all the tested pressures, by the equations:

$$\begin{cases} Z_{tip} = 45.06\,(t-t_0)^{0.6936}\,P^{-0.0764} & (t-t_0) < 1.3\,p^{-0.38} \\ Z_{tip} = 18.83\,(t-t_0)\,P^{0.04} + 29.55\,P^{-0.34} & (t-t_0) > 1.3\,p^{-0.38} \end{cases}$$

If the intersection point in transformed coordinates (t_{tr}=1.3 Z_{tr}= 54) is reversed to real coordinates, it become the function $Z = (t-t_0)^{0.895}$ that delimitates the two region of the real space with different behavior of the spray; the function is reported in the figure 5 together with the penetration data.

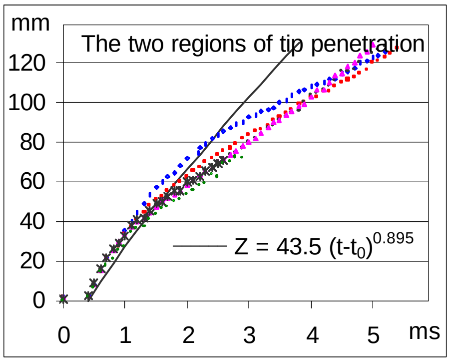


Fig. 5 The function delimitating the regions of the tip penetration.

5. Discussion and notes

The scale law found in this work is optimised for this injector only, but to keep a more general validity was not refined up to reach a perfect matching of the experimental data; with another injector of the same kind it is expect to keep its general aspect with different constants in its expression. A more precise tuning of the interpolations could be tailored over a specific injector to capture more details. In the present case the tip velocity in the linear part could be better fitted by a straight line with a more correct slope, function of the ambient pressure, that can approximate the penetration data in the short range of the experimental set-up typical of engine applications, or the data could interpolated by a different function able to predict also the expected spray tendency at much further distance [8].

The fact that the injection pressure was kept constant at 71 bar due to the fuel pressurised system, instead of taking constant the injection pressure difference, is expected to result in an initial injection velocity difference that, evaluated with Bernoulli equation, is around 2.7%, and in fact it is so small that could not be observed in the initial spray development.

It must be pointed out that all exposed procedure depends also on some arbitrary parameters, the most important being certainly the definition of the spray length, that is also dependent on the quality of the available images.

6. Conclusions and future work

A GDI swirled injector was used to study the behaviour of a hollow cone spray generated in air at different pressures. The spray shape and the induced air vortex pattern were studied by fast shutter digital images and Laser Doppler Anemometry. After data processing, spray tip and vortex head centre penetration curves were obtained. The curves were used to deduce an experimental scale law, that delimits the tip penetration in two regions, the first one with decreasing velocity, followed by an almost constant velocity in the studied region, limited by the set-up to dimensions that are comparable to those of actual car engine production. The presented results are now being used to investigate the internal part of the spray at low ambient pressure, when measurements are easier, and to report the results to high air density, where some kinds of optical measurements investigations are nearly impossible because of the excessive fuel density.

7. Acknowledgments

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