HIGH PRESSURE DIESEL-LIKE INJECTIONS FOR GDI ENGINE: EXPERIMENTAL AND NUMERICAL APPROACH

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ABSTRACT

Multihole injectors, working like diesel valve coverage orifice (VCO) or mini-sac nozzle, seem to be the future trend for GDI (Gasoline Direct Injection) applications. The GDI approach through this injector type is very similar to diesel one.

A diesel-like electronically controlled Common Rail injection apparatus has been used for pressure up to 100 *MPa*. An axially disposed single hole 0.18 *mm* in diameter and 1.0 *mm* in length injected a gasoline-like fluid in an optically accessible vessel filled with inert gas (N_2) and controlled in pressure up to 1.2 *MPa*. The jets emerging from the injector hole have been lightened by a pulsed laser sheet at different instant from the start of injection. The images were collected by a CCD camera, synchronized with the light, and processed by professional software to extract the significant parameters of the evolving spray (penetration, cone angle, velocity).

Some results of a work in progress aiming to select and validate proper models for the various stages of spray development are also discussed. Four different models have been compared, to evaluate the one that better represents the characteristics of the generated spray. The final goal of the research activity is to set up the KIVA 3V code for its extensive use in the design and development of GDI engines.

1. INTRODUCTION

In the last years many different combustion strategies have been proposed for Spark Ignition Direct Injection (SIDI) engines. Depending on the combustion control adopted, different type of injectors (swirled, shaped, air-assisted, …) have been used by manufactures with features related to the air/fuel mixture formation. Multihole injectors, working like diesel valve coverage orifice (VCO) or mini-sac nozzle, seem to be the future trend for GDI (Gasoline Direct Injection) applications. They can have a variable number of holes, different size and shape enabling a hollow-cone like fuel conical pattern, offset of the centroid fuel pattern with respect to injector axis and spray pattern angles ranging between 30° and 90°.

The GDI approach through this injector type is very similar to the diesel one with technological difficulties related to the smallness and closeness of the holes. An effective contribution to the experimental activity, characterized by a multitude of nozzle arrangement to be tested and new fields of injection pressures, could come by numerical simulations. They allow to run different configurations varying all the possible injection parameters referring to geometrical and physical setting. Obviously the codes need to be calibrated in their operative conditions, choosing the suitable constants and verifying the correspondence of the results with the experimental data. The most simple and successful arrangement to calibrate the code is the use of a single hole injector in typical experimental conditions of a GDI apparatus.

In this work an experimental and numerical analysis of GDI sprays has been performed. Using a Common Rail injection system, a gasoline like fluid (EXXSOL D40) has been injected into a quiescent gaseous environment. The sprays have been lightened by means of a pulsed sheet (100 μm thickness and 12 *ns* duration) generated by a Nd-YAG laser operating on its second harmonic and the images have been collected, at right angle, using a CCD camera synchronized with the injection command and the laser pulse. Numerical simulations have been run using an improved version of the KIVA-3 code with a new breakup model, obtaining a good agreement with experimental data.

2. EXPERIMENTAL DEVICE

The experimental apparatus depicted in Fig. 1 is made up of a Common Rail injection system, a spray chamber, an imaging system and a data acquisition system.

The fluid has been sprayed in an optically accessible vessel, controlled in pressure and temperature, equipped with three large quartz windows (80 *mm* diameter), filled by inert gas (N_2) and operating at pressures up to 1.2 *MPa*.

The jets have been generated in single-shot mode by a Common Rail (CR) injection system via an Electronic Control Unit (ECU) for setting pressure, duration and timing of the injections. Single injection strategy 1.0 *ms* in duration and pressures of 40, 50, 80 and 100 *MPa* have been set for the injections delivering fuel quantities reported in Table 1. A non-volatile gasoline-like calibration fluid (EXXSOL D40) has been used (ρ=762 kg/m^3, ν=1.05 *cSt* at T=40 °C).

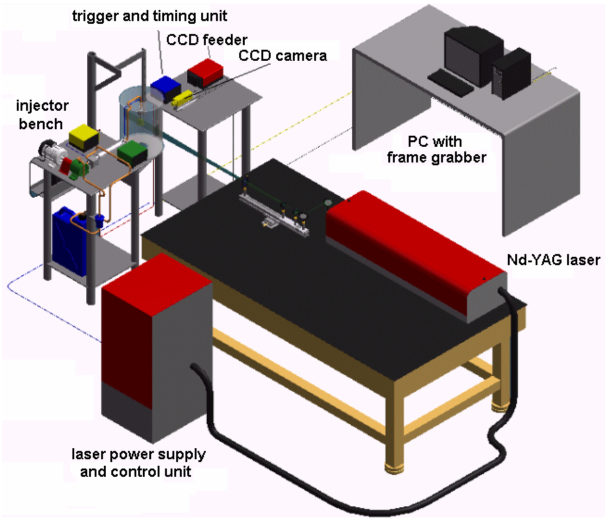

Fig. 1 - Experimental apparatus.

Table 1 reports the fuel injection rates measured for the stated injection pressures by an AVL meter working on the Bosch tube principle [1,2]. Because of the improper use of gasoline-like fluid in diesel injection system and test bench, the fuel rates have been compared with equivalent weights averaged on 1,000 shots. The differences have varied between 0.5 to 3.1 %.

Table 1 - AVL meter and weighted fluid injected quantities comparison.

Injection pressure	Weight	AVL Meter
400 *bar*	4.22 *mg/str*	4.24 *mg/str*
500 *bar*	4.89 *mg/str*	4.74 *mg/str*
800 *bar*	6.21 *mg/str*	6.33 *mg/str*
1000 *bar*	6.86 *mg/str*	6.68 *mg/str*

The nozzle is provided of an axially disposed VCO single-hole with 0.18 and 1.0 *mm* diameter and length, respectively. The emerging sprays have been lightened, at different times from the Start Of Injection (SOI), by a pulsed laser sheet, 100 μm thickness and 12 *ns* duration, generated by a Nd-YAG laser operating on its second harmonic. The images have been captured by a PULNIX TMC-6 CCD camera, synchronized with the laser pulse, providing images size of 768 x 568 pixels at 8 bits intensity resolution. An images processing software has provided the sprays analysis to extract their structures, morphologies, cone angles and penetrations.

Further characteristics of the experimental set-up and procedures are reported in ref. [3,4].

3. NUMERICAL DEVICE

Describing the interaction between an evolving liquid jet and a gaseous medium is a fascinating challenge for CFD simulations. On the other hand it has still to be greatly improved to be reliably used in engine design.

Using VCO injectors, the fuel enters the chamber, through each nozzle hole, as a single coherent bulk liquid column that, because of its internal turbulence, cavitation effects inside the nozzle and aerodynamic interaction with the gas, quickly breaks up in a large number of droplets and ligaments (*primary breakup*), that further break up into always smaller droplets as they evolve into the chamber (*secondary breakup*).

CFD simulations have been performed using an improved version of the Kiva 3 code. It solves the finite volume discretization for the three-dimensional equations of chemically reactive flows with sprays. The liquid column is simulated, following the Reitz approach, as a train of computational parcels (*blobs*) with characteristic size equal to the nozzle diameter, each of them representing a group of physically similar drops.

A lot of different atomization models has been proposed in the last twenty years, based on different physical mechanisms. In the present work, four different models (TCH, WH, TAB, KH-RT), whose main features are reported in Table 2, have been compared, to evaluate the one that better represents the characteristics of the generated spray.

The turbulence induced-cavitation induced hybrid model [5] and the WAVE hybrid model [6], indicated in the following as TCH and WH for the sake of simplicity, distinguish between jet primary breakup and droplet secondary breakup. In the TCH model, jet turbulence and cavitation effects inside the nozzle are supposed to be the competing factor in determining the birth of perturbation waves on the external jet layer that, interacting with the gaseous phase, exponentially grow until they detach as drops. On the other hand, the WH model supposes the jet aerodynamic interaction with the gas in the chamber as the main reason of the atomization process; as a consequence, the WAVE model [7] is used to simulate primary atomization. In each model, the primary drops formed can now undergo secondary breakup. Depending on their Weber number ($We = \frac{\rho_g D U^2}{\sigma_l}$), different breakup regimes can be observed and different breakup models have been used (Table 1). Both TCH and WH models have been previously tuned and used by the authors [8, 9] for Diesel spray analysis, achieving a good predictive capability.

The TAB model [10] is based on the analogy between an oscillating and distorting droplet and a spring mass system. It doesn't distinguish between primary and secondary breakup. Droplet breakup is due to the amplification of droplet deformation caused by the surface vibrational resonance.

In the KH-RT model [11, 12], Rayleigh-Taylor and Kelvin-Helmhotz instability effects are supposed to be the competing factors influencing the atomization process.

Table 2 - Summary of the four models employed.

Model name	Model features		
TCH	*Primary breakup*	Turbulence-cavitation induced atomization model	
	Secondary breakup	$12<We<16$ (vibrational)	TAB
		$16<We<100$ (bag)	DDB
		$100<We<1000$ (stripping)	WAVE
		$We > 1000$ (catastrophic)	WAVE-RT
WH	*Primary breakup*	WAVE	
	Secondary breakup	$12<We<16$ (vibrational)	TAB
		$16<We<100$ (bag)	DDB
		$100<We<1000$ (stripping)	WAVE
		$We > 1000$ (catastrophic)	WAVE-RT
TAB	TAB		
KH-RT	WAVE-RT		

Further details about the models employed can be found in [5-7, 10-13].

4. RESULTS AND DISCUSSION

4.1 – Experimental results

Pseudo-color conversion and binary transformation techniques [4] have been applied to spray images for extracting shapes and structures across the axial plane. The techniques have allowed determining the overall characteristic parameters as penetrations, cone angles and velocities.

In Fig. 2 the tip penetrations of the jets versus time from the SOI have been reported for 40, 50, 80 and 100 *MPa* injection pressures at atmospheric backpressure. The curves develop linearly in time showing stronger penetrations and stabilities at higher injection pressures. The gas in the vessel does not affect significantly the spray tips and their velocities range between 313 and 136 *m/s*, at 100 and 40 *MPa* injection pressure respectively.

In Figg. 3 and 4 the penetrations of the sprays at 0.6 and 1.2 MPa vessel nitrogen pressures are reported. The penetrations start assuming the typical linear trend followed from a square root behaviour at later time from the SOI. The penetrations are longer for higher injection pressures while the 40 *MPa* curves show some instability. In Fig. 3, penetration values of 50 *mm* (CCD field of view) are reached in 700 μs at 40 *MPa* injection pressures while at 100 *MPa* the flight time shortens to 400 μs. In Fig. 4, the higher backpressure in the vessel slows down significantly the droplet velocities and the spray tip penetration because of the stronger brake effect of the gas. In fact, at 600 μs from the SOI the tip penetraions reach values between 47.3 mm at 100 *MPa* and 36.2 *mm* at 40 *MPa*.

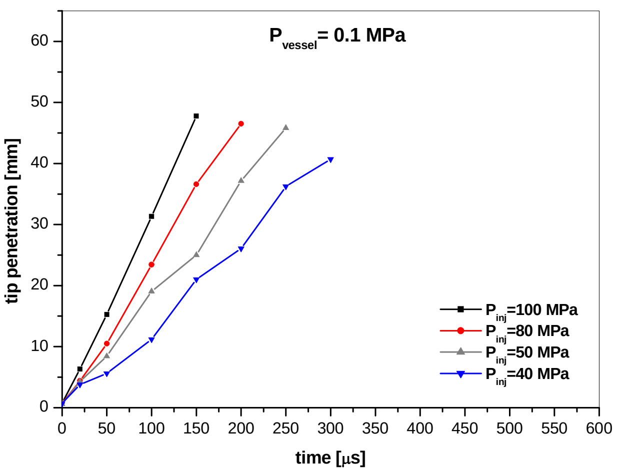

Fig. 2 - Tip penetrations at 0.1 *MPa* backpressure.

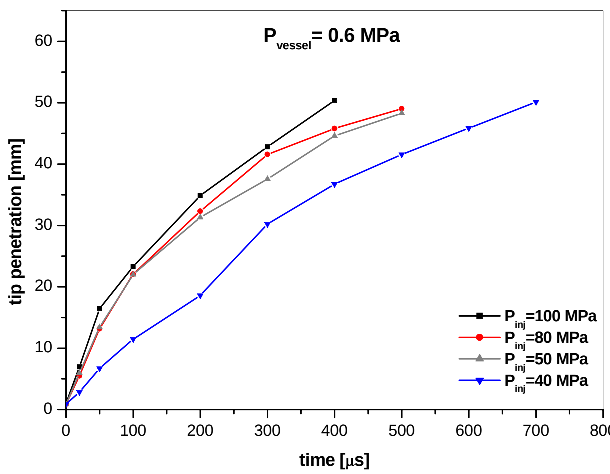

Fig. 3 - Tip penetrations at 0.6 *MPa* backpressure.

Fig. 5 shows the jets far cone angle behaviours versus the injection pressure for different backpressures. Higher nitrogen pressure in the vessel produces greater cone angle of the sprays. The interaction is typical of a diesel spray where the backpressure makes shorter the penetration increasing the cone angle. The asymptotic values vary from 13.1° at atmospheric backpressure to 13.8° at 0.6 *MPa* to 17.5° at 1.2 *MPa* of the gas in the chamber.

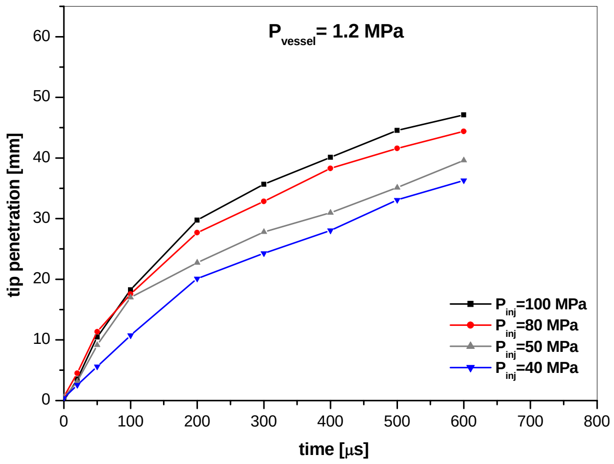

Fig. 4 - Tip penetrations at 1.2 *MPa* backpressure.

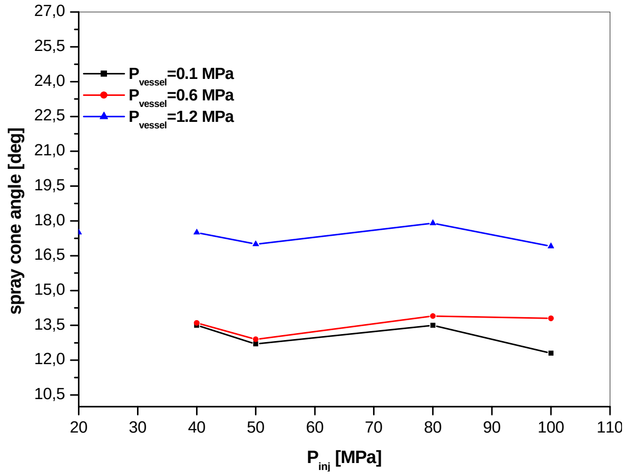

Fig. 5 - Spray cone angle vs. injection pressure.

In Fig. 6 a comparison of the jets morphologies and structures for 0.1, 0.6 and 1.2 *MPa* backpressures are reported for 50 *MPa* injection pressure and time from the SOI varying between 50 to 400 μs. It can be observed, in the temporal sequences, the effects of the backpressures on the developing sprays in terms of tip shortness and cone enlargement. The gas pressure exerts a great influence on the boundary layers of the jets. The fluid-dynamic interactions between gas and liquid produce disturbance waves with decreasing wavelength at increasing backpressures. The tip of the spray rounds, indicating a stronger brake effect with reduced droplet speed and high probabilities of coalescence effects [14].

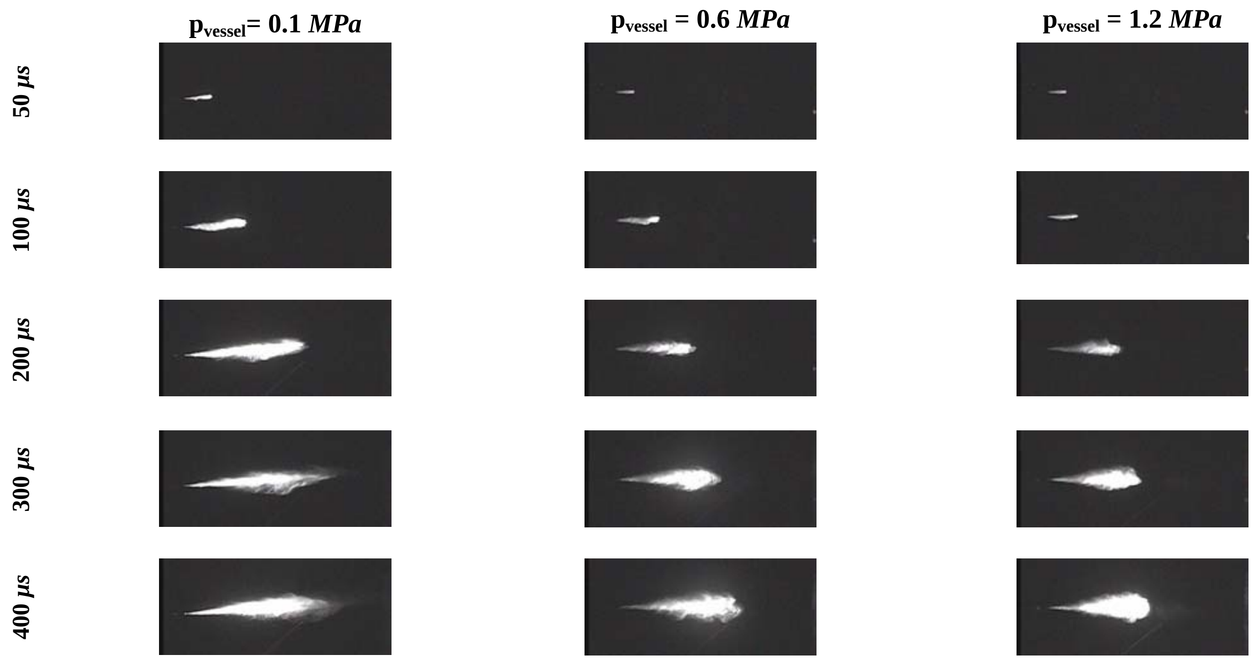

Fig. 6 - Spray temporal evolution at different backpressures and at 50 *MPa* injection pressure.

4.2 – Numerical results

The aim of the numerical work is the to select and validate proper models for the various stages of spray development and to setup a model, implemented into the KIVA 3V code, able to simulate spray structure and evolution, at different operating conditions. Models details are reported in the paragraph “numerical device”.

Figg. 7, 8 and 9 show some comparisons between experimental and numerical tip penetration curves, obtained with the used breakup models, being 50 *MPa* the injection pressure and 0.1, 0.6 and 1.2 *MPa*, respectively, the backpressures.

Models are based on the calculation of a characteristic breakup time, after which blob or drop breakup may occur. Analyzing Fig. 7, it could be said that all the models fit the experimental data in a reasonable way at ambient backpressure; on the other hand Figg. 8 and 9 highlight that only the TCH and WH ones show good capability predictions when the backpressure increase, while TAB and KH-RT ones strongly underestimate tip penetration and velocity. This is probably due to an underestimation both of the breakup time and of the after-atomization droplets size. A good agreement between experimental data and TCH and WH calculations is achieved for all the backpressures; nevertheless a slight difference in tip penetrations, late from SOI, is observed at 0.6 and 1.2 *MPa*.

Fig. 10 shows, for an ambient backpressure of 0.1 *MPa*, the experimental and numerical tip penetration curves, obtained with TCH and WH models, for 50 and 80 *MPa* injection pressures. Increasing injection pressure, tip penetration slightly increases, being its trend quite similar, and computations can predict these effects.

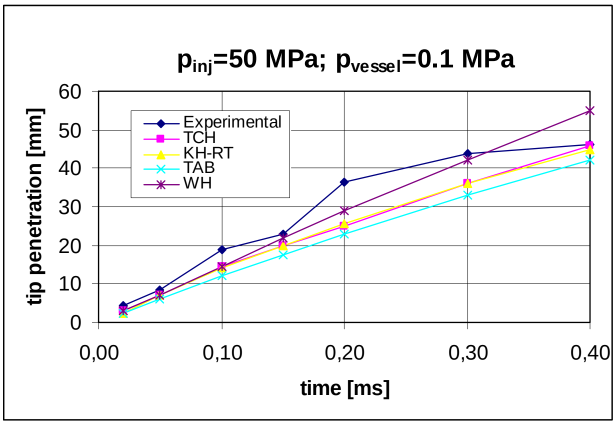

Fig. 7 - Tip penetration curves at 50 *MPa* injection pressure and at 0.1 *MPa* backpressure.

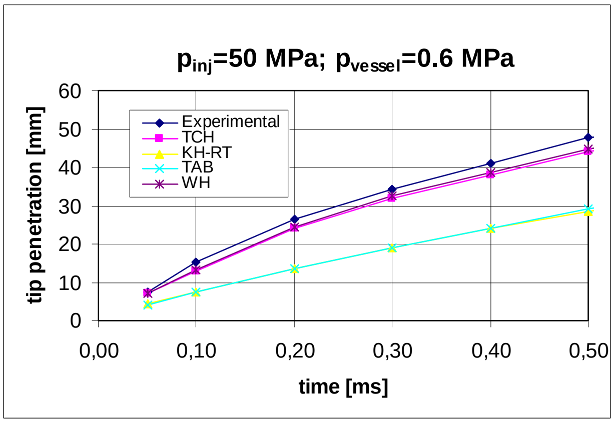

Fig. 8 - Tip penetration curves at 50 *MPa* injection pressure and at 0.6 *MPa* backpressure.

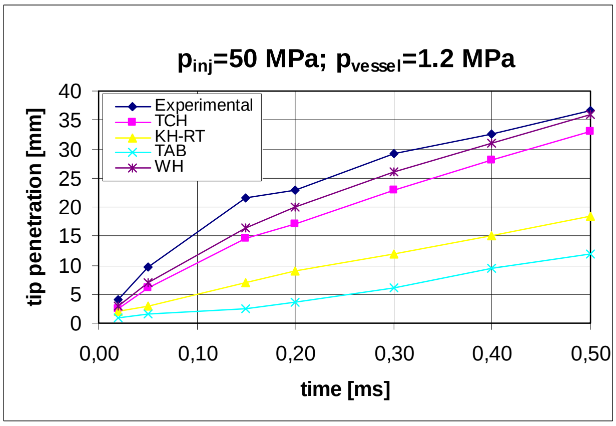

Fig. 9 - Tip penetration curves at 50 *MPa* injection pressure and at 1.2 *MPa* backpressure.

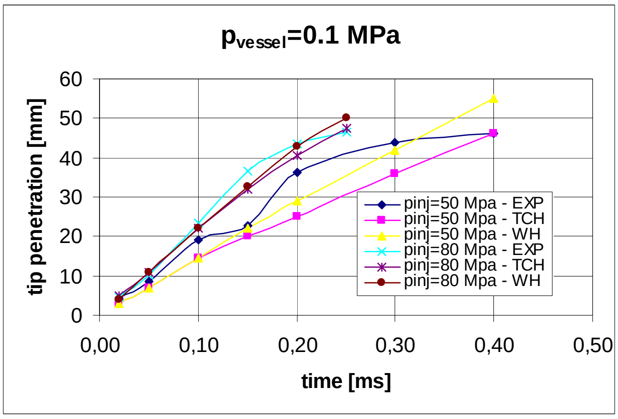

Fig. 10 - Tip penetration at 0.1 *MPa* backpressure; injection pressure effect.

A comparison between experimental and numerical spray images is reported, for TCH and WH models, in Fig. 11, being 50 MPa the injection pressure, 0.1 *MPa* the backpressure and 0.3 *ms* the time after the SOI. As previously said, both the models can well predict the tip penetration trend, but only TCH seems to be able to reproduce in a reasonable manner the spray morphology. In particular, it shows a wide range of droplets radius, meaning different breakup mechanisms, while the WH model shows just one droplet size and a higher value for breakup time, more than 0.3 *ms*.

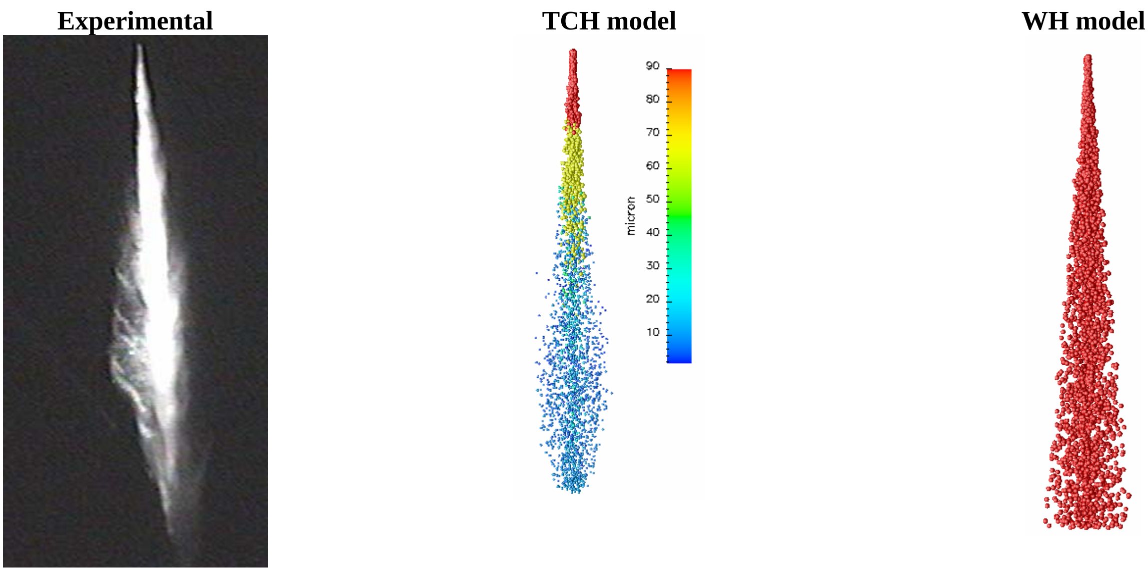

Fig. 11 - Experimental and numerical spray images (p_{inj}=50 *MPa*, p_{vessel}=0.1 *MPa*, t=0.3 *ms*).

TCH model seems to be attractive for new-generation GDI spray simulations. Some important physical phenomena are captured in its computations: the shape and structure of the spray, the spray variations due to the different values of the injection pressure, the fuel-gas fluid-dynamic interaction with the formation of finely atomized droplets, the reduction of droplets momentum, the penetration decrease; on the other hand, there is a slight underestimation of the breakup process location, particularly at higher backpressures.

5. CONCLUSIONS

An experimental and numerical study of GDI sprays from a Common Rail injection system has been performed.

A non-evaporative gasoline-like fuel has been injected into a high-pressure test chamber, at room temperature and quiescent gaseous environment, from a single hole VCO high pressure electronic controlled injector. Sprays have been lightened by a pulsed laser sheet from a Nd-YAG at 532 *nm* (100 *μm* thickness and 12 *ns* duration) and acquired by a CCD camera at different time from the SOI. Image processing techniques have enabled to get detailed informations about shape, temporal and spatial evolution of the spray, at different operating conditions.

Some preliminary results of a work aiming to select and validate breakup sub-models have also been reported. Four different models (TCH, WH, KH-RT, TAB) have been tested in order to find out the one that better simulates the spray features.

The analysis of results points out the following considerations:

1. the experimental set up and the used image processing technique have enabled to obtain detailed information about shape, structure and morphology of the spray, allowing also their quantitative description, in terms of spray cone angle, tip penetration and velocity;
2. backpressure effects on the sprays are analogous to Diesel sprays ones. Increasing the backpressure, spray penetration and velocity reduce, spray cone angle increases. The fluid-dynamic interactions between gas and liquid produce disturbance waves with decreasing wavelength at increasing backpressures;
3. increasing injection pressure, tip penetration slightly increases, being jet morphology and evolution quite similar;
4. the agreement between experiments and calculations, in terms of tip penetration, is quite good for all the tested models at atmospheric backpressure but, if this one increases, only the TCH and WH models keep satisfactory predictions;
5. only the TCH model seems to show a good agreement in terms of spray morphology. Some important phenomena are captured in its computations: the shape and structure of the spray, the spray variations due to the different values of the injection pressure, the fuel-gas fluid-dynamic interaction with the formation of finely atomized droplets, the reduction of droplets momentum, the penetration decrease; on the other hand, there is a slight underestimation of the breakup process location, particularly at higher backpressures. WH model needs further work to better evaluate and improve its morphology predictive skills

The numerical code, set up for single-hole injectors and single injection strategies, has now to be tested with multi-hole injectors and multiple injection strategies.

NOMENCLATURE

Latin letters

D	droplet diameter [m]
p	pressure [Pa]
T	temperature [K]
U	droplet-gas relative velocity [m/s]
We	droplet Weber number [dimensionless]

Greek letters

ρ	density [kg/m^3]
σ	surface tension [kg/s^2]
ν	kinematic viscosity [cSt]

Subscripts

g	gas
inj	injection
l	liquid
$vessel$	inside the vessel

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