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Investigation on Diesel Spray Stability from a Heavy Duty Common Rail Injection System

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GENERAL CONSIDERATIONS

The technological challenge in i.c. engines field is to meet performances and consumption with the incoming more stringent emission regulations

The CR technology and the electronic control in heavy duty diesel engines has radically changed the fuel injection management.

The in-cylinder air motion is one of the main controlling factors that affect the injection parameters and the piston bowl design trade-off.

An accurate characterization of the spray process, as well as its interaction with the in-cylinder flow, becomes an important target to understand the development of the combustion.

OBJECTIVES

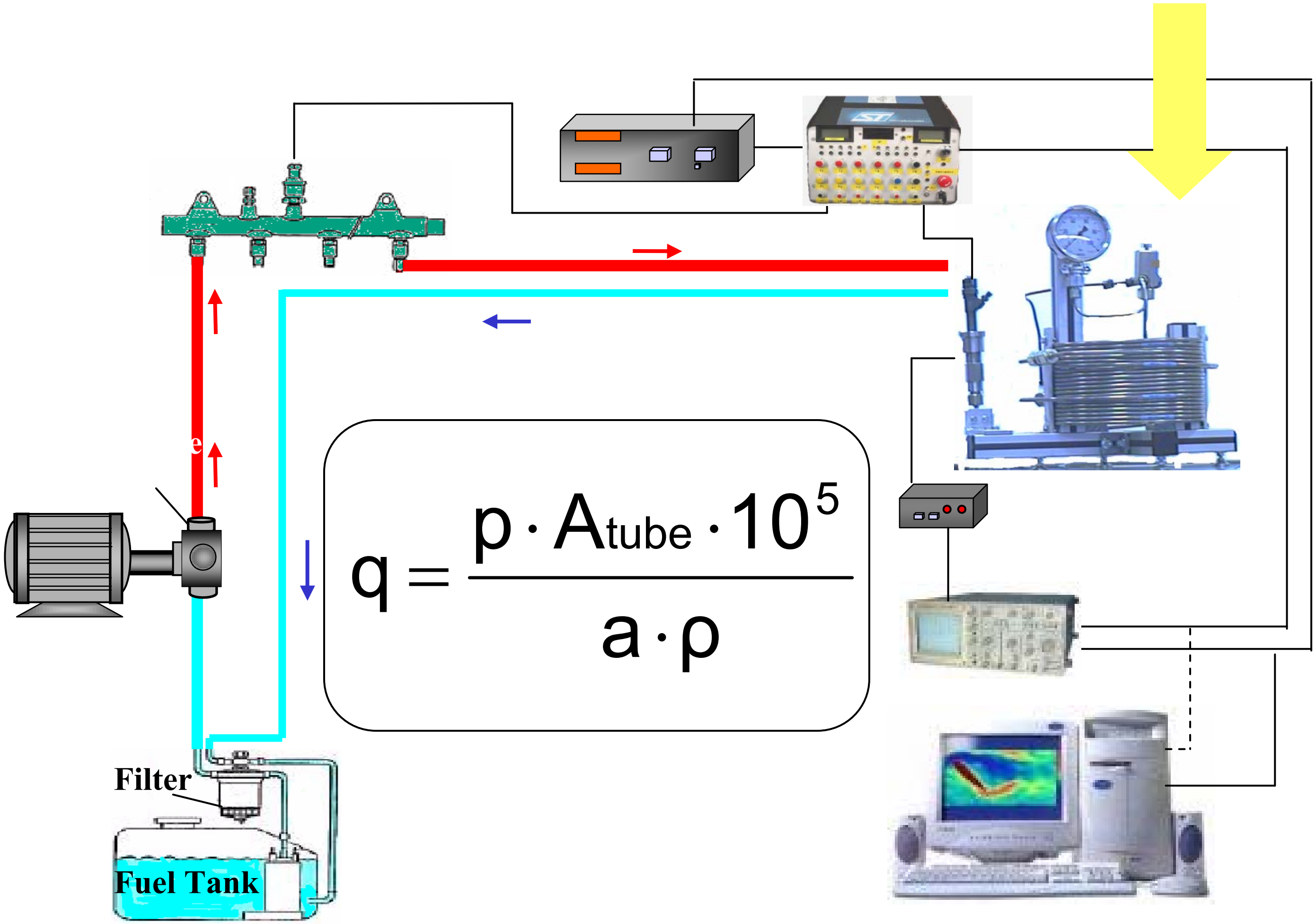
Aim of this work is an experimental and numerical investigation on a diesel spray generated by a CR injection system for heavy duty diesel engines

The investigated spray characteristics include:

- **instantaneous and total fuel flow rate**
- **fuel mass stability and cycle to cycle dispersion for pilot injections (by using commercial and prototype ECUs)**
- **PIV measurements to estimate the swirling air velocity vector distribution within the combustion chamber**
- **spray visualization both in non evaporative quiescent vessel and evaporative engine-like conditions**

Experimental data have been used as input to calibrate a computational model, by the 3-D Star_CD code, to evaluate the air flow field in the combustion chamber and the spray evolution

EXPERIMENTAL APPARATUS

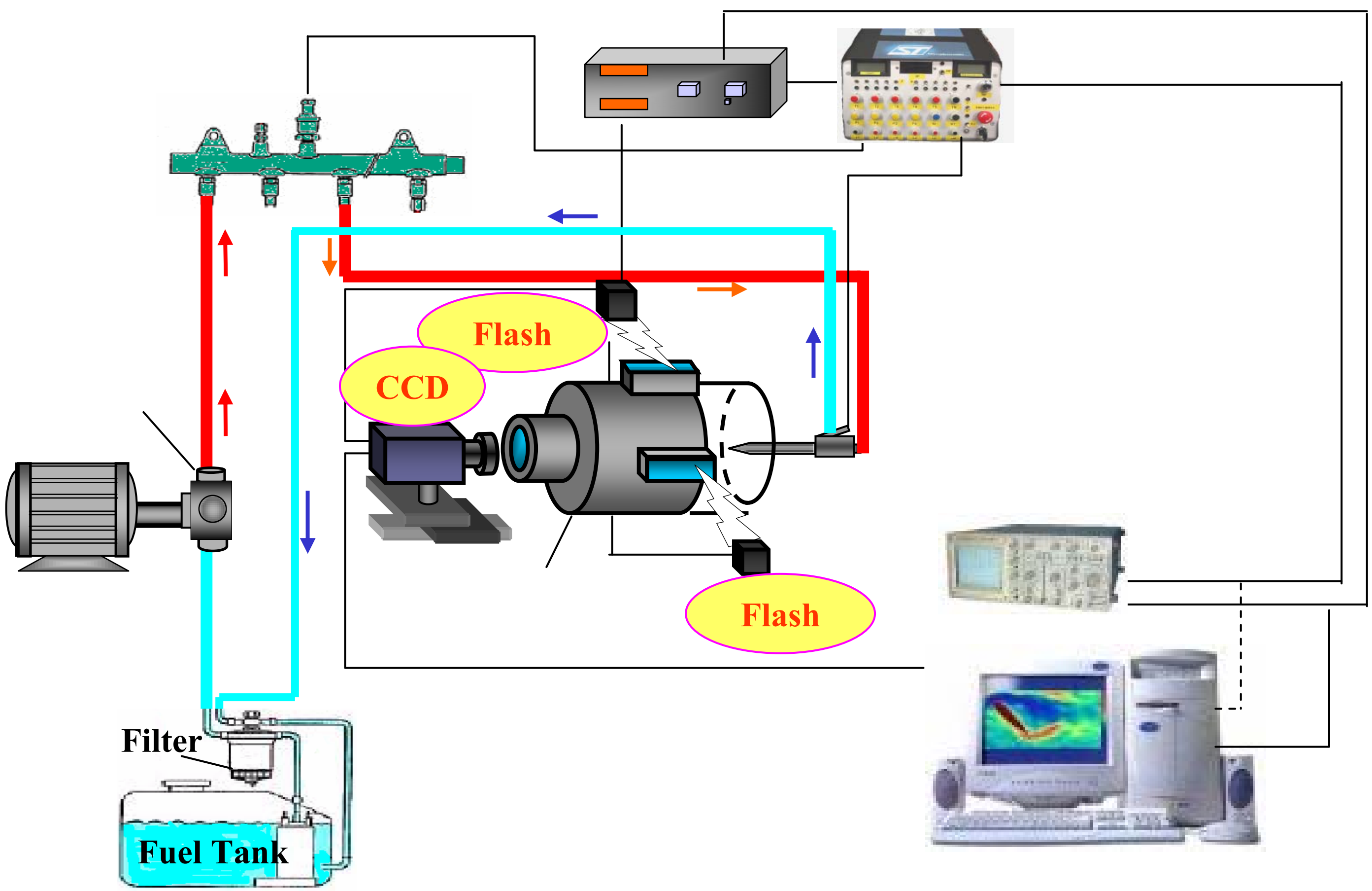


$$q = \frac{p \cdot A_{tube} \cdot 10^5}{a \cdot \rho}$$

The pressure variations collected by the transducer are proportional to the injected fuel

Experimental apparatus for instantaneous and total injected fuel measurements

EXPERIMENTAL APPARATUS



The sprays images are captured by CCD camera synchronized with the flashes at different time from the SOI

EVAPORATIVE TEST ENGINE SET-UP

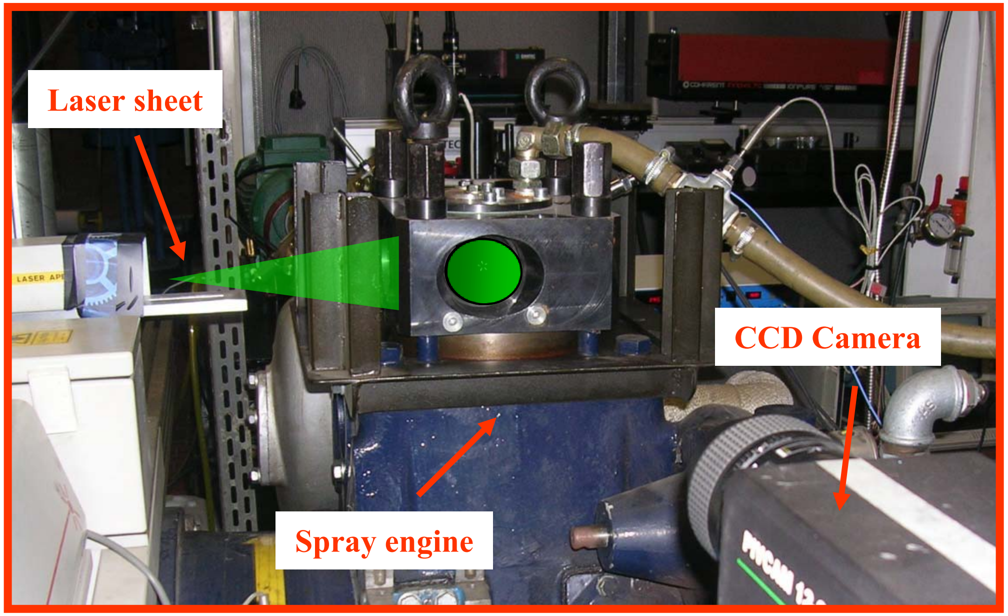
ENGINE SPECIFICATIONS

Single cylinder 2 stroke, loop scavenged

Bore	150 mm
Stroke	170 mm
Connecting rod	360 mm
Displacement	3000 cm^3
Combustion chamber	swirled
Air supply	roots blower engine
Compression ratio	10.1:1

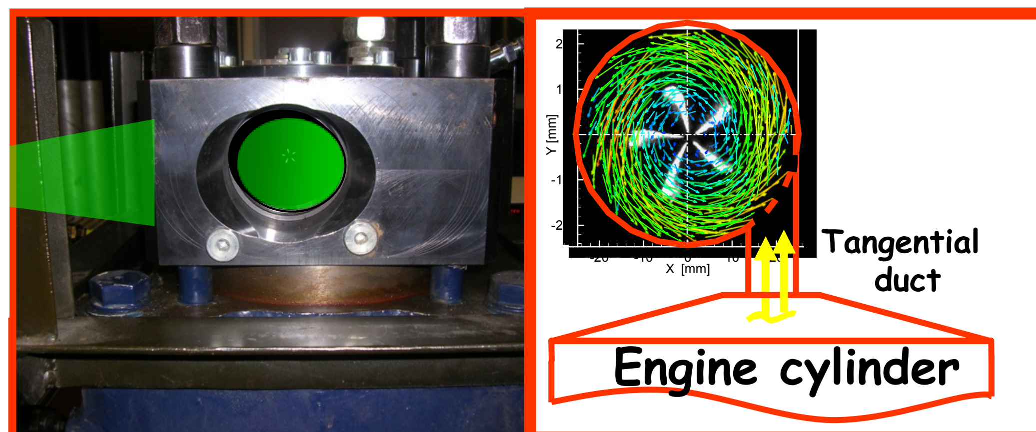
The fuel has been injected into a optically accessible single-cylinder 2-stroke direct injection Diesel engine to reproduce gas densities and temperatures typical of a real engine under swirled flow conditions.

PIV EXPERIMENTAL SETUP -1



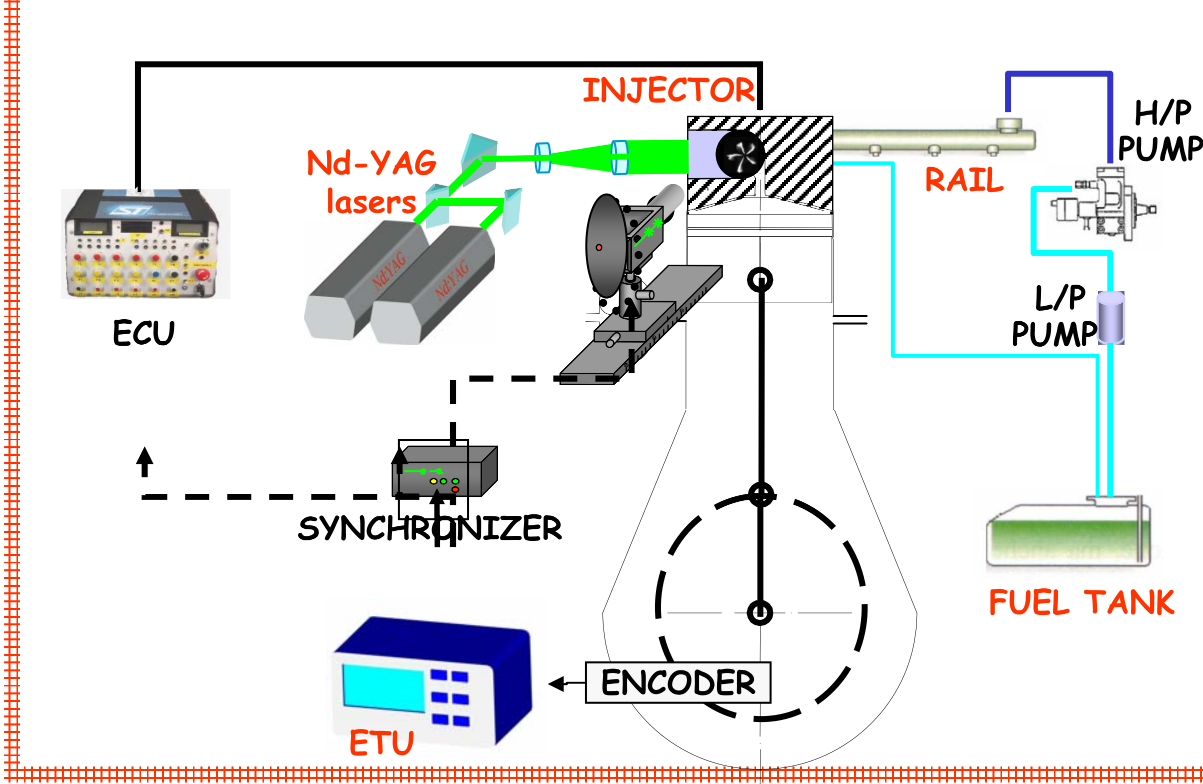
The experimental engine has been equipped with a cylindrical shape combustion chamber, able to stabilize swirl conditions during the compression stroke, to reproduce diesel engine-like fluid dynamic conditions with high swirl ratio.

The engine provides a circular optical access in front of the combustion chamber, used to collect PIV images, and a rectangular one at 90°, for the laser sheet input.



PIV EXPERIMENTAL SETUP -2

PIV images have been taken aligning the light sheet to a plane orthogonal to the injector axis

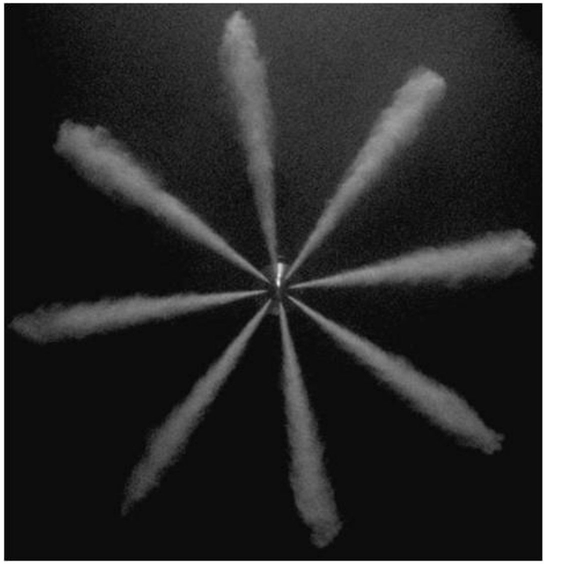


Test bench includes:

- **a common rail high pressure injection system**
- **an optically accessible single cylinder 2-stroke Diesel engine motored by an electrical motor,**
- **a PIV apparatus composed by two Nd:YAG lasers, a CCD camera and a synchronizer.**

An engine timing unit (ETU), driven by an optical encoder connected to the engine crankshaft, triggers the PIV synchronizer and the electronic control unit (ECU) of the injection system

TEST CONDITIONS -1



Injector type:

- 8 holes, Φ=0.21 mm
- 154° spray angle
- flow rate 1100cm^3/30sec@10MPa

Injection strategies:

- double injection (for non ev. condition)
- single injection (for ev. condition)
- total injected fuel: 200 mg/stroke
- pilot injected fuel: ≈ 10% of total

A commercial and a prototype ECU have been used for fuel delivery stability and performances evaluations

TEST CONDITIONS - 2

Non evaporative conditions

time [μs]	P_{inj} [MPa]	Total [mg/str]	Pilot [mg/str]	Main [mg/str]
355 - 900 – 1800	80	202.09	22.94	179.15
320 - 900 – 1550	100	204.76	26.72	178.04
240 - 900 – 1300	140	205.98	24.49	181.49

Evaporative conditions

AIR THERMO DYNAMIC CONDITIONS			
	ρ [kg/m³]	Air T[K]	Ω[rad/s]
25°c.a. ATDC (SOI)	17	620	300
INJECTION STRATEGY			
Inj. pressure [MPa]	80	100	140
Gas Density [Kg/m³]	17	17	17
Energizing time [μs]	355	320	240
Injected fuel [mg/str]	22.94	26.72	24.49

DISPERSION ANALYSIS AND FUEL INJECTION RATE MEASUREMENTS

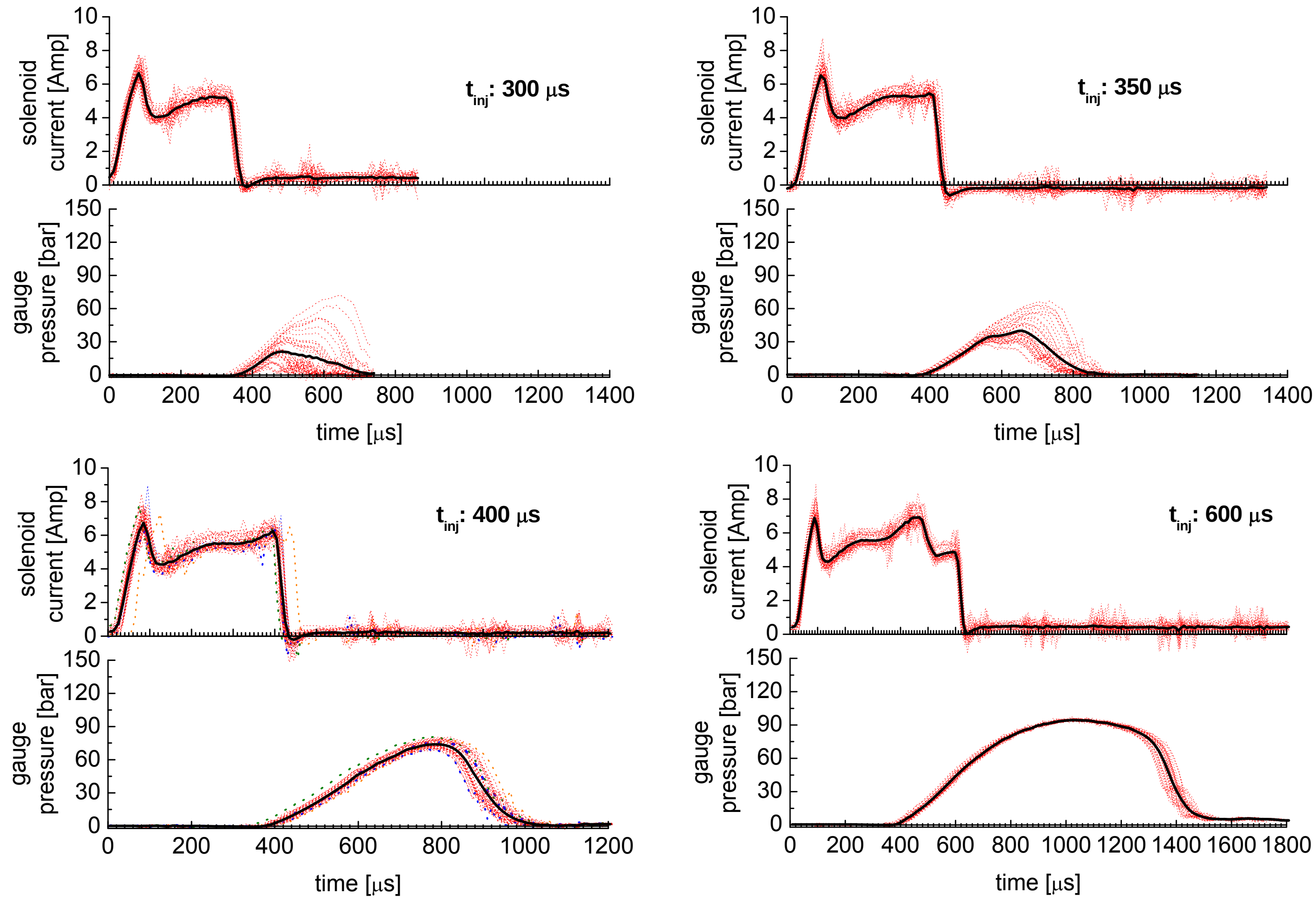
DISPERSION ANALYSIS

Fuel injection rate measurements have been made for different injection strategies to evaluate the injection system performances

A commercial and a prototype ECU have been used to check the operative limits of the system in terms of cycle-to-cycle fuel spreading for short current energizing time

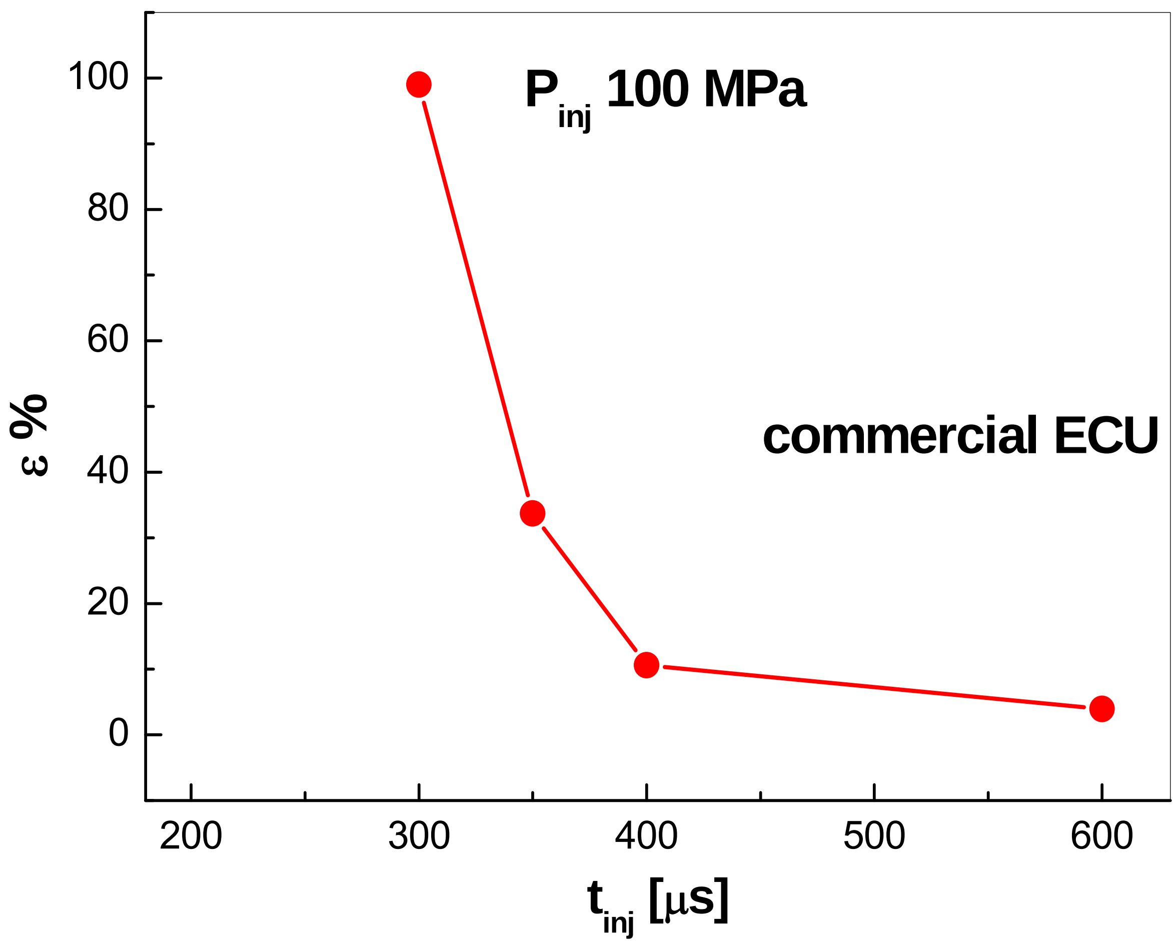
The dispersion analysis has been carried out acquiring forty injection cycles by AVL Indimodul 621 system

Cycle-to-cycle pressure dispersions in the AVL gauge meter for commercial ECU – P_{inj}= 100 MPa



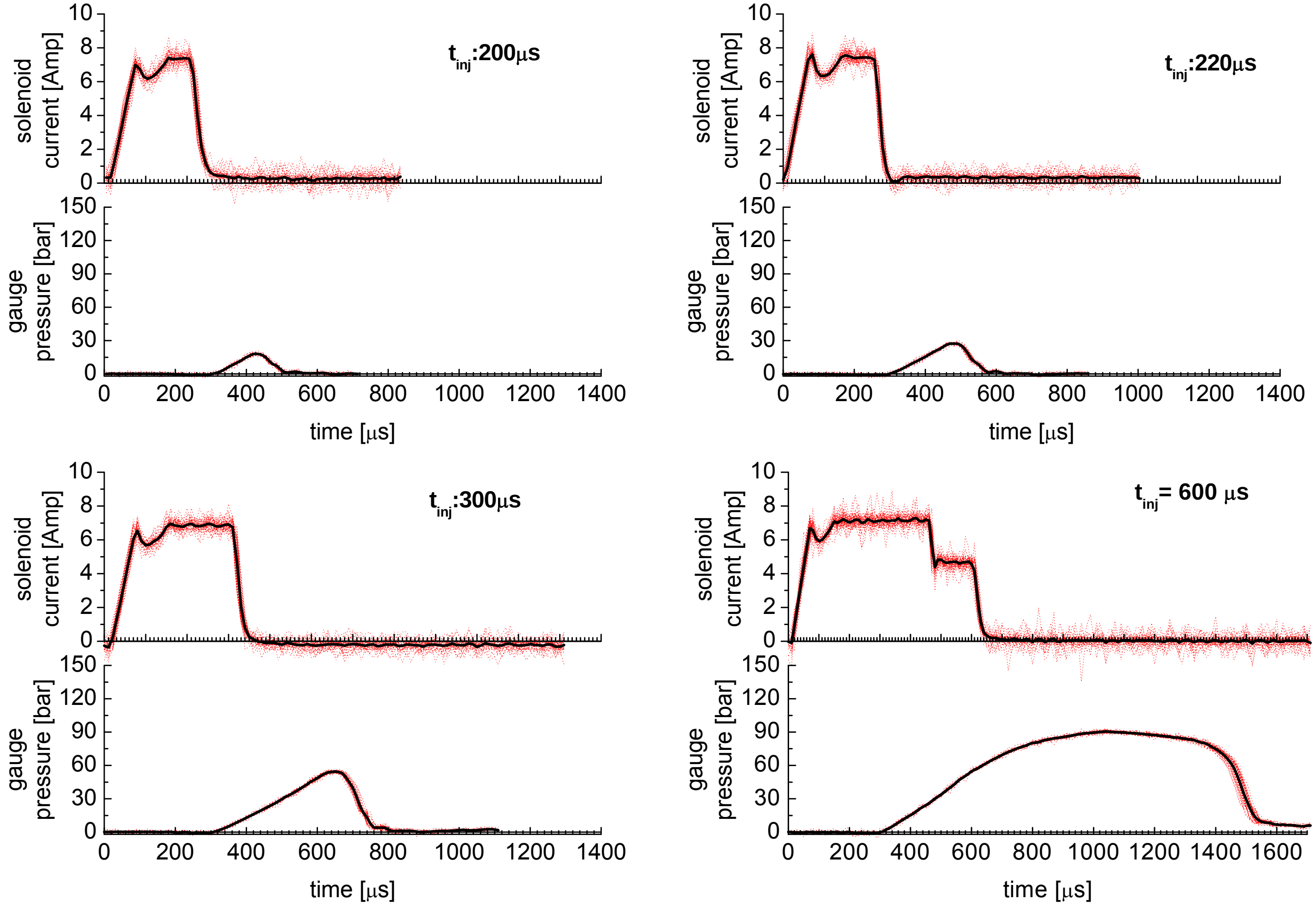
Significant cycle-to-cycle injection rate instabilities arose for short current energizing time

Cycle-to-cycle dispersions of the fuel injection pressure in the AVL gauge meter for commercial ECU – P_{inj} = 100 MPa



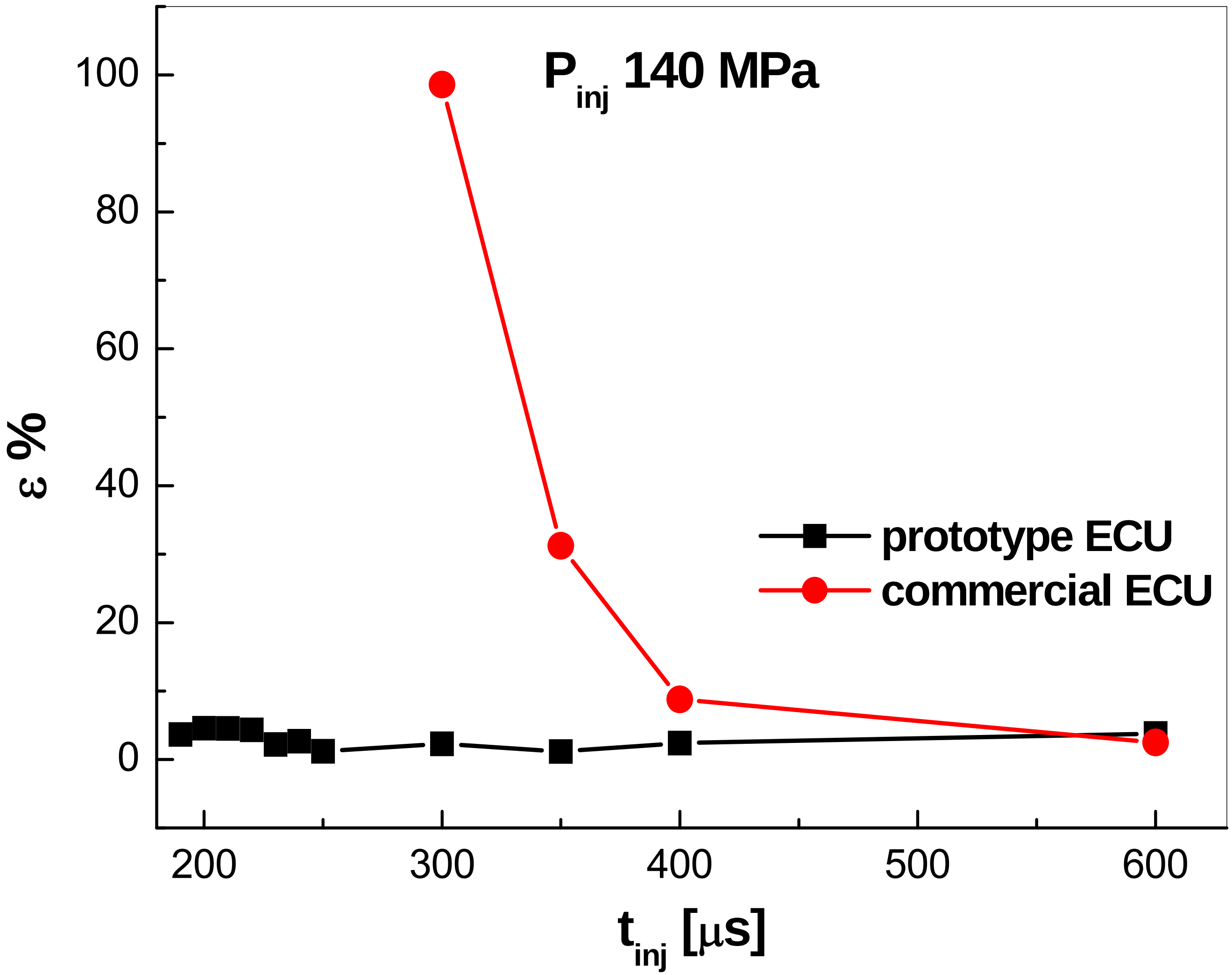
The percentage error decreases from the value 100 at 300 μs to 3.8 at 600 μs

Cycle-to-cycle pressure dispersions in the AVL gauge meter for prototype ECU – P_{inj} = 100 MPa



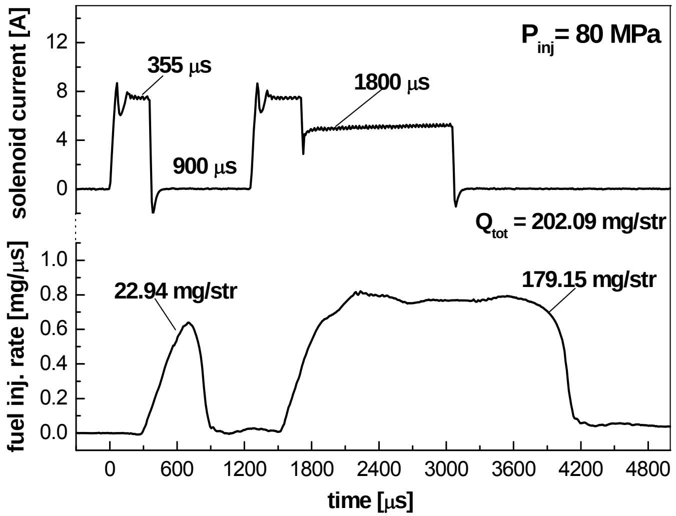
Stable values have been obtained with the injection apparatus driven by the prototype ECU.

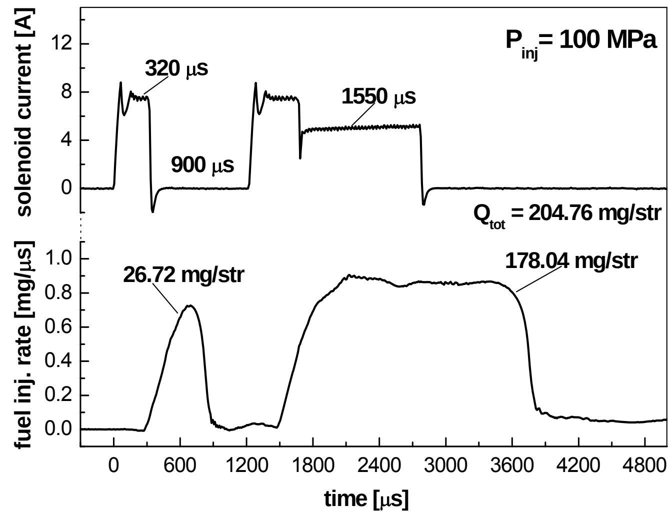
ε% of the delivered quantities for the fuelling system driven by prototype and commercial ECUs

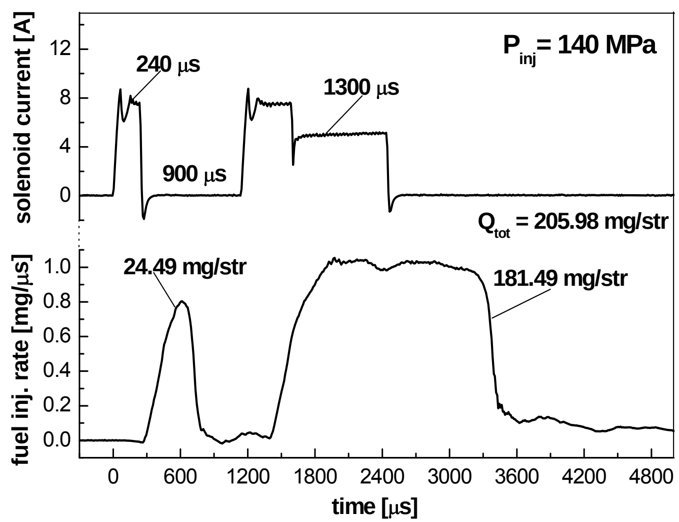


A fine stability has been found for the prototype ECU down to 190 μs

Energizing currents and injection rate profiles acquired by fuel injection meter



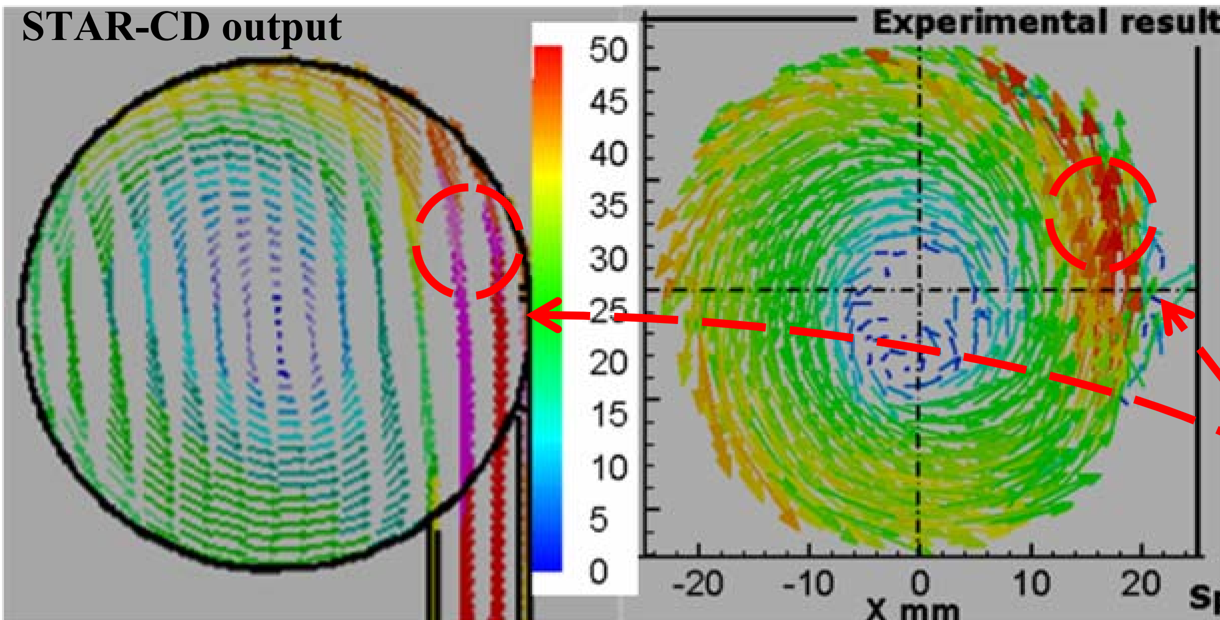




PIV Results

IN-CYLINDER FLOW FIELD

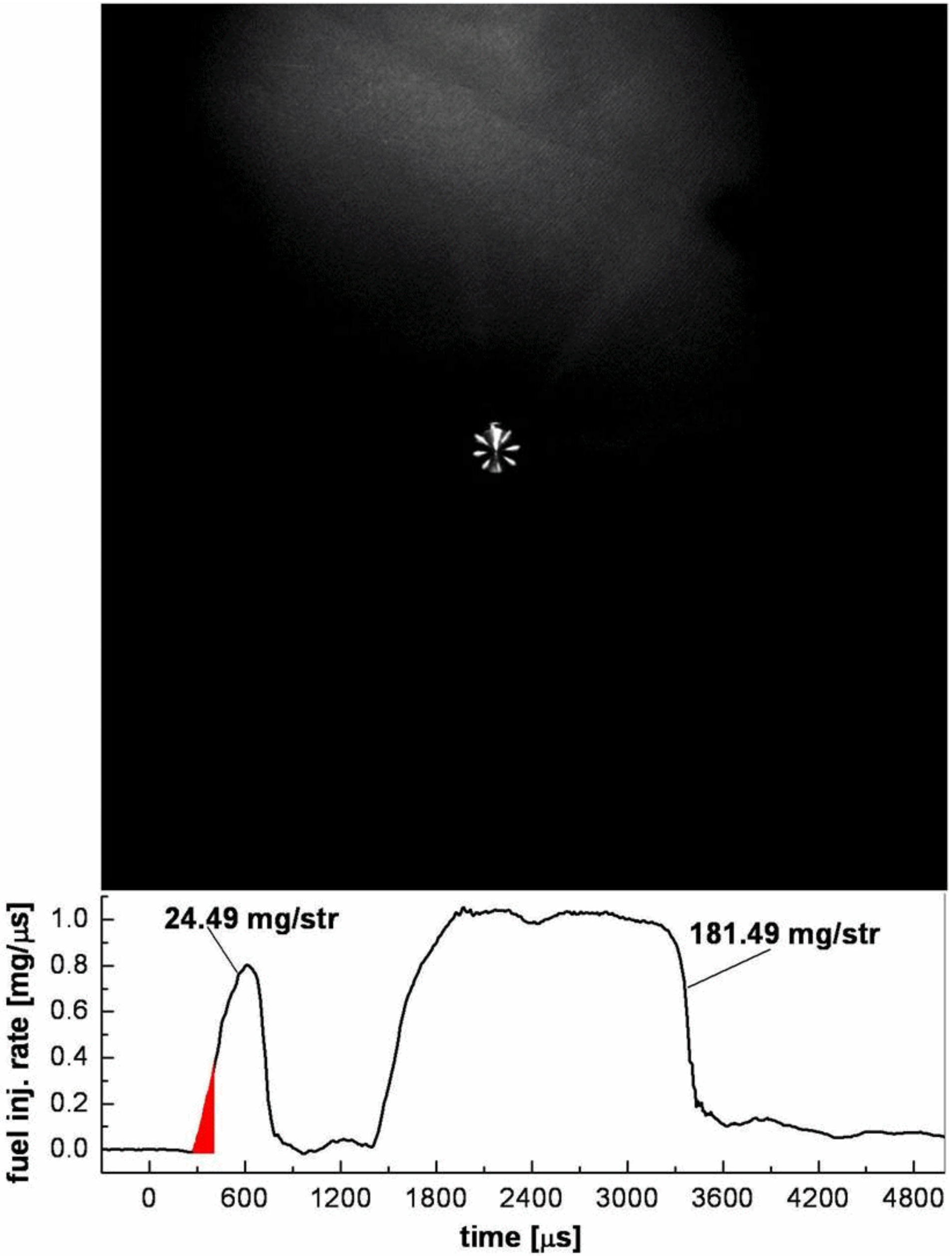
Comparison between STAR-CD output and PIV data of air velocity vector distribution at 25° c.a. BTDC. Measurements have been taken using diesel droplets as tracer sprayed inside the combustion chamber.



The two distributions are roughly the same

Moving away from the outlet zone, the velocity lightly decreases showing a relative maximum, at the combustion chamber periphery, of about 40 m/s

SPRAY EVOLUTION CHARACTERIZATION

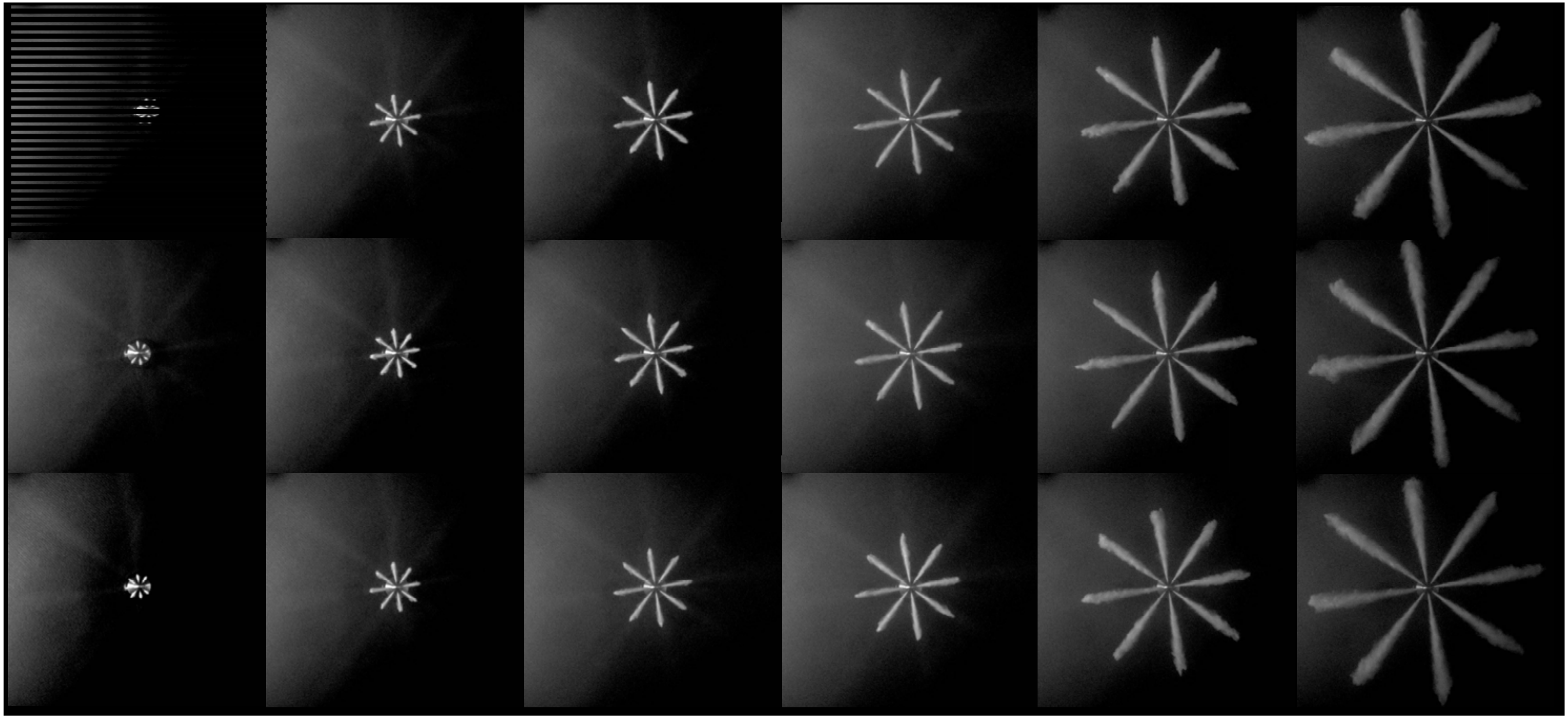


Non evaporative conditions

$$P_{inj} = 140\ \text{MPa}$$
$$\rho_{ch} = 17\ \text{kg/m}^3$$

NON EVAPORATIVE CONDITIONS

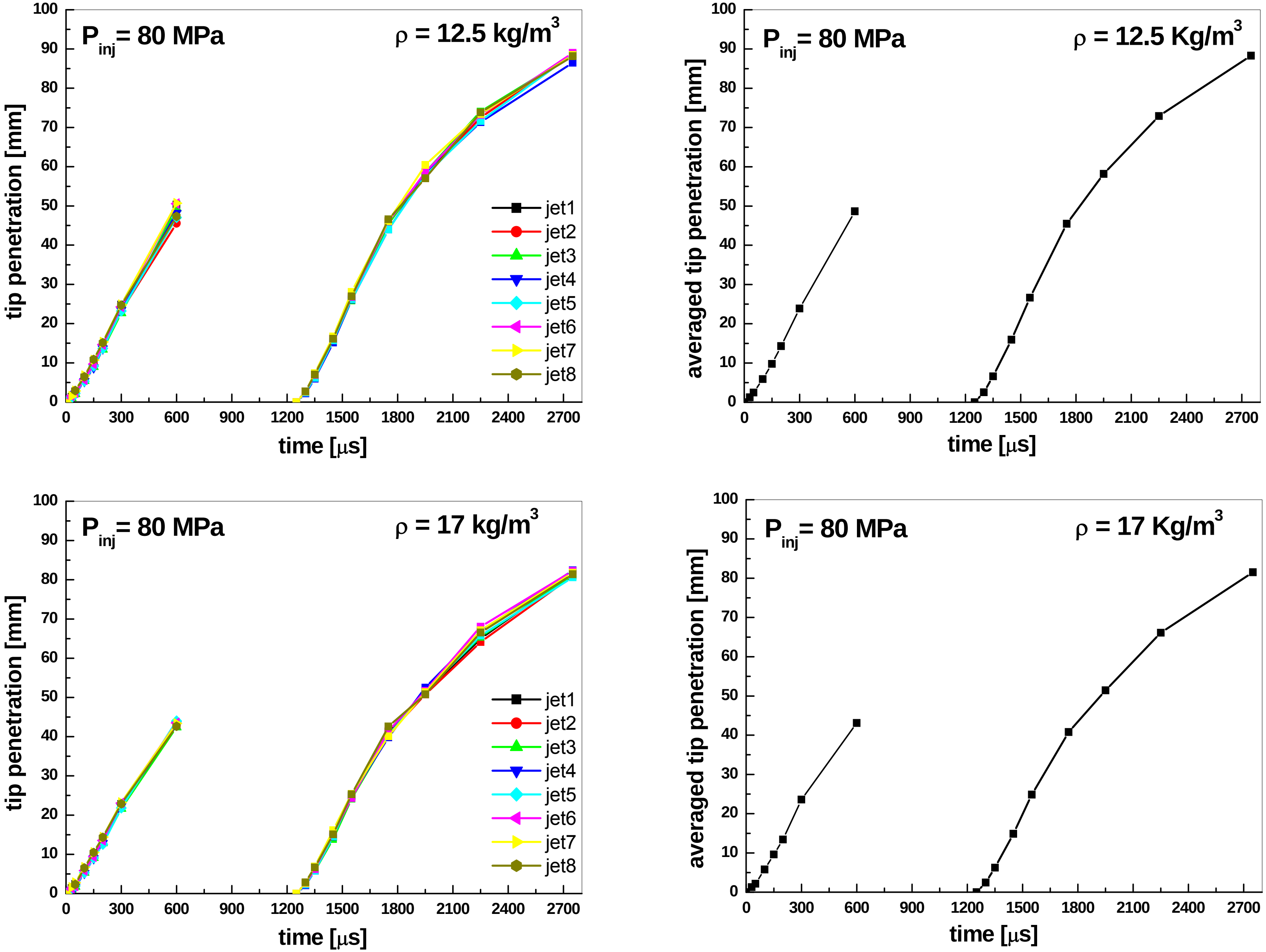
P_{inj}= 140 MPa; ρ_{ch}= 17 kg/m^3



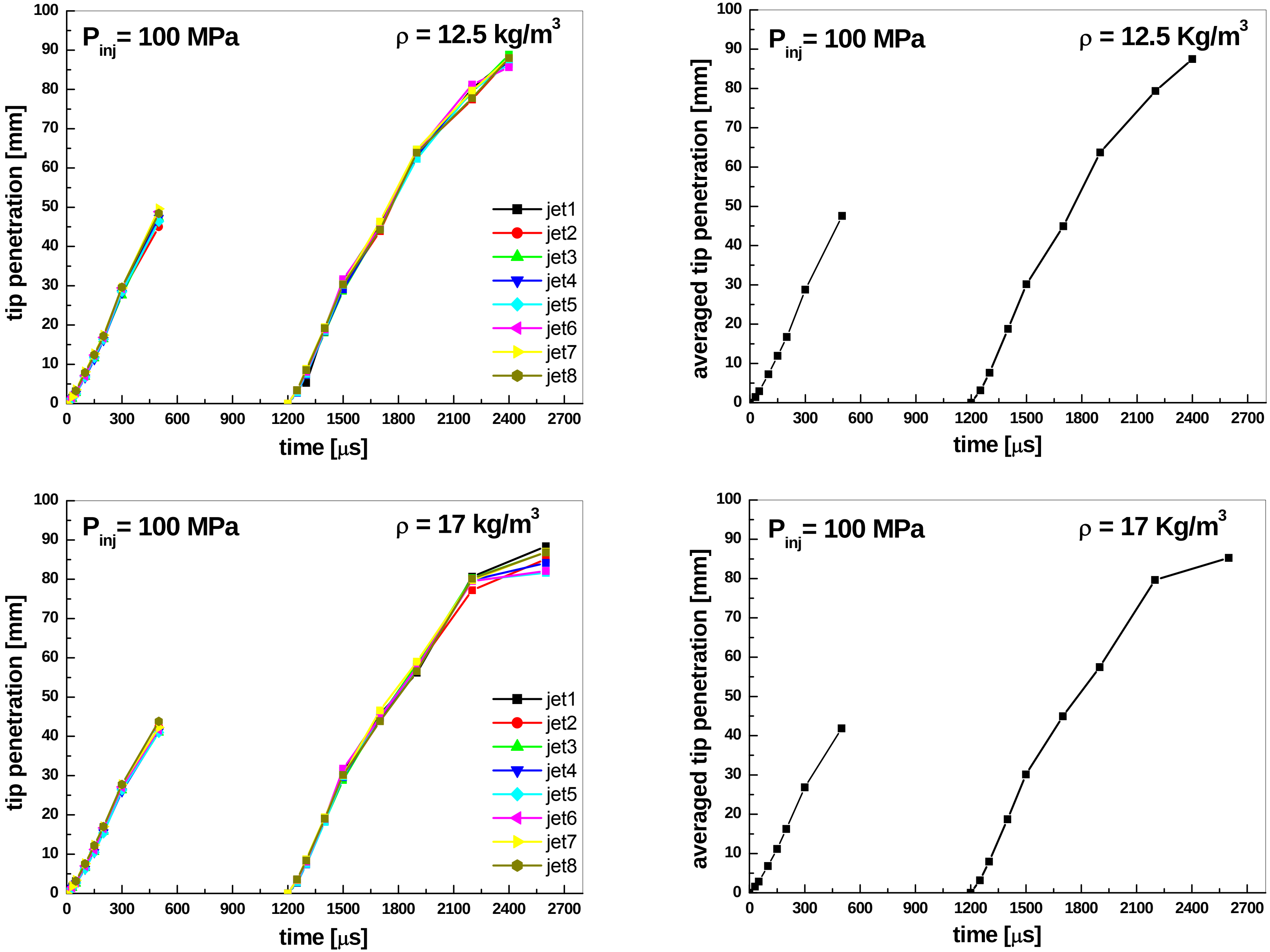
t_{inj}= 50 μs | t_{inj}= 100 μs | t_{inj}= 150 μs | t_{inj}= 200 μs | t_{inj}= 300 μs | t_{inj}= 450 μs

The fuel structure shows a uniform behaviour for each jet indicative of a good stability of the injection process also for small amount of delivered fuel

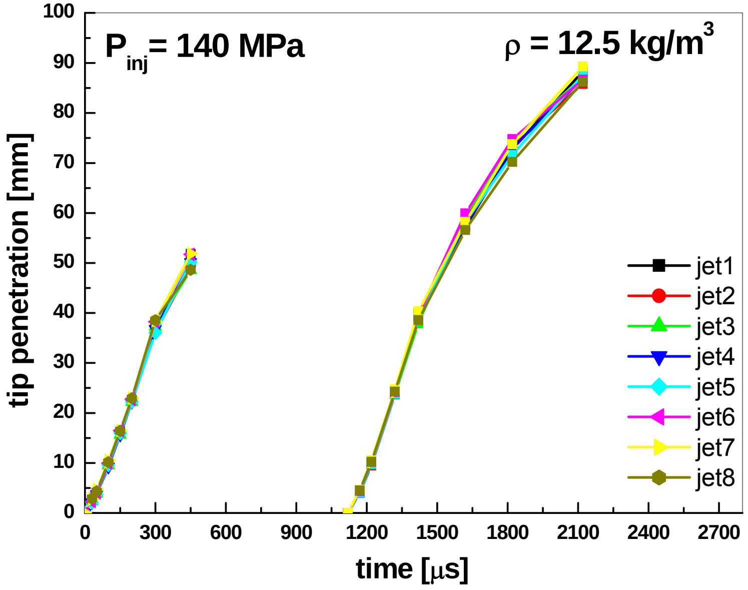
Non evaporative spray tip penetrations - 1

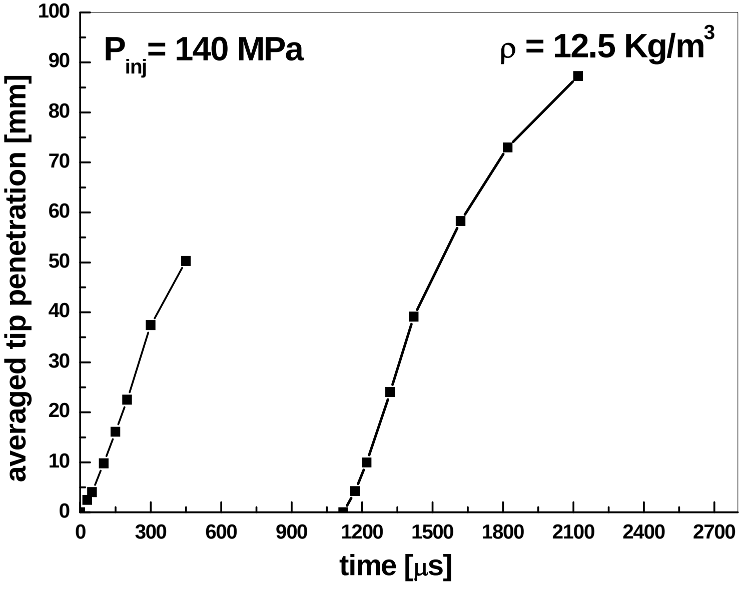


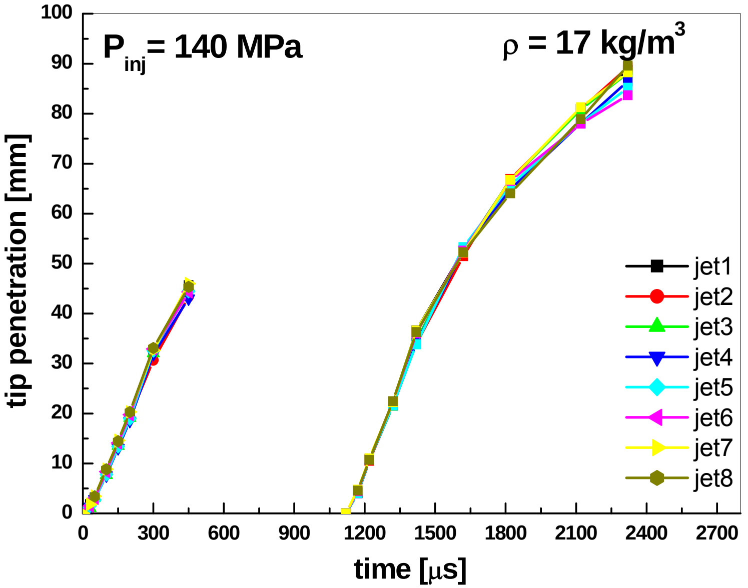
Non evaporative spray tip penetrations - 2

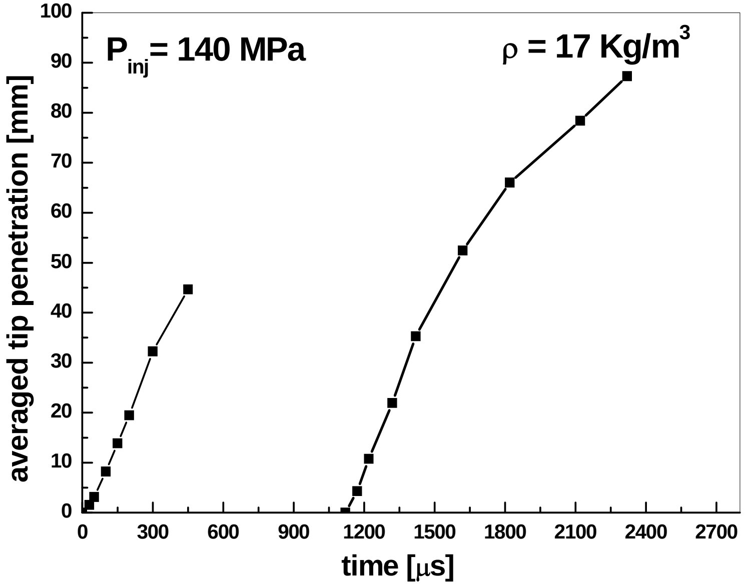


Non evaporative spray tip penetrations - 3

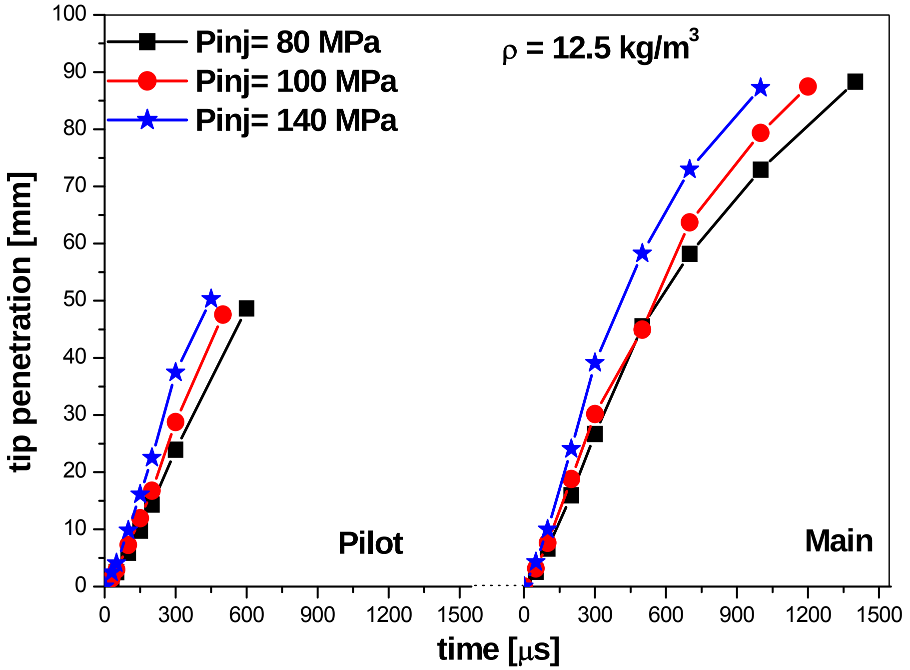


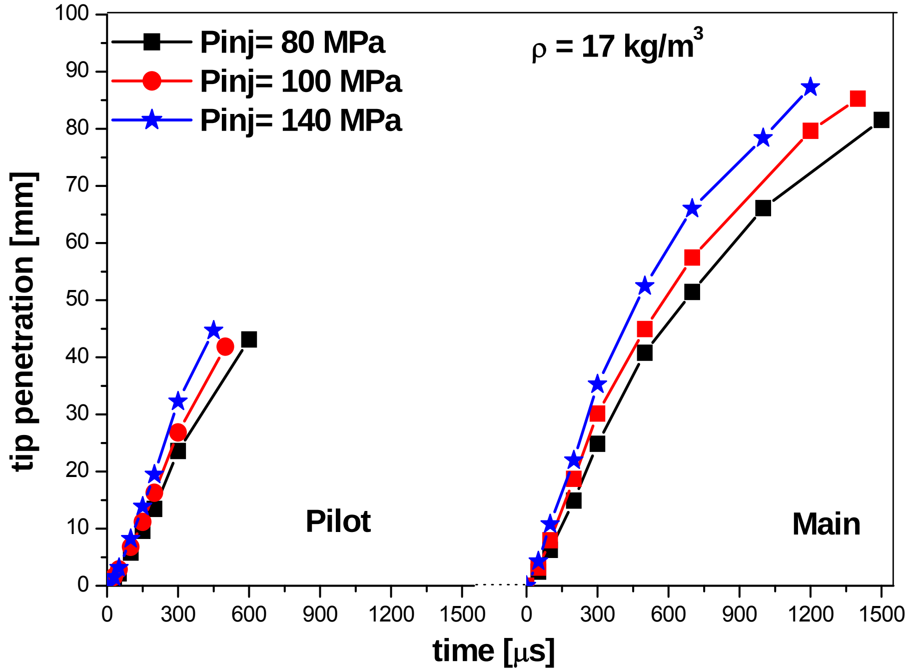


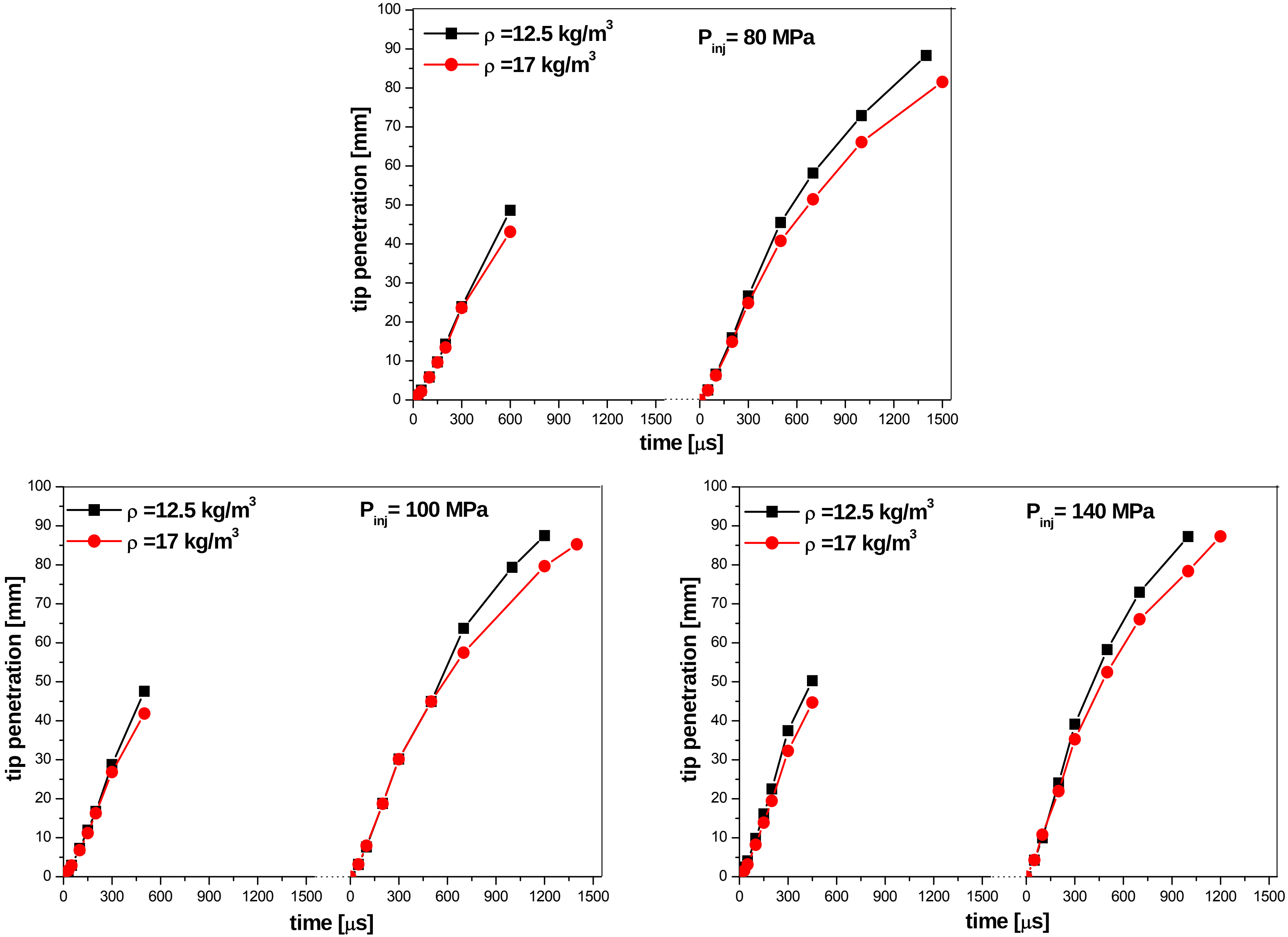




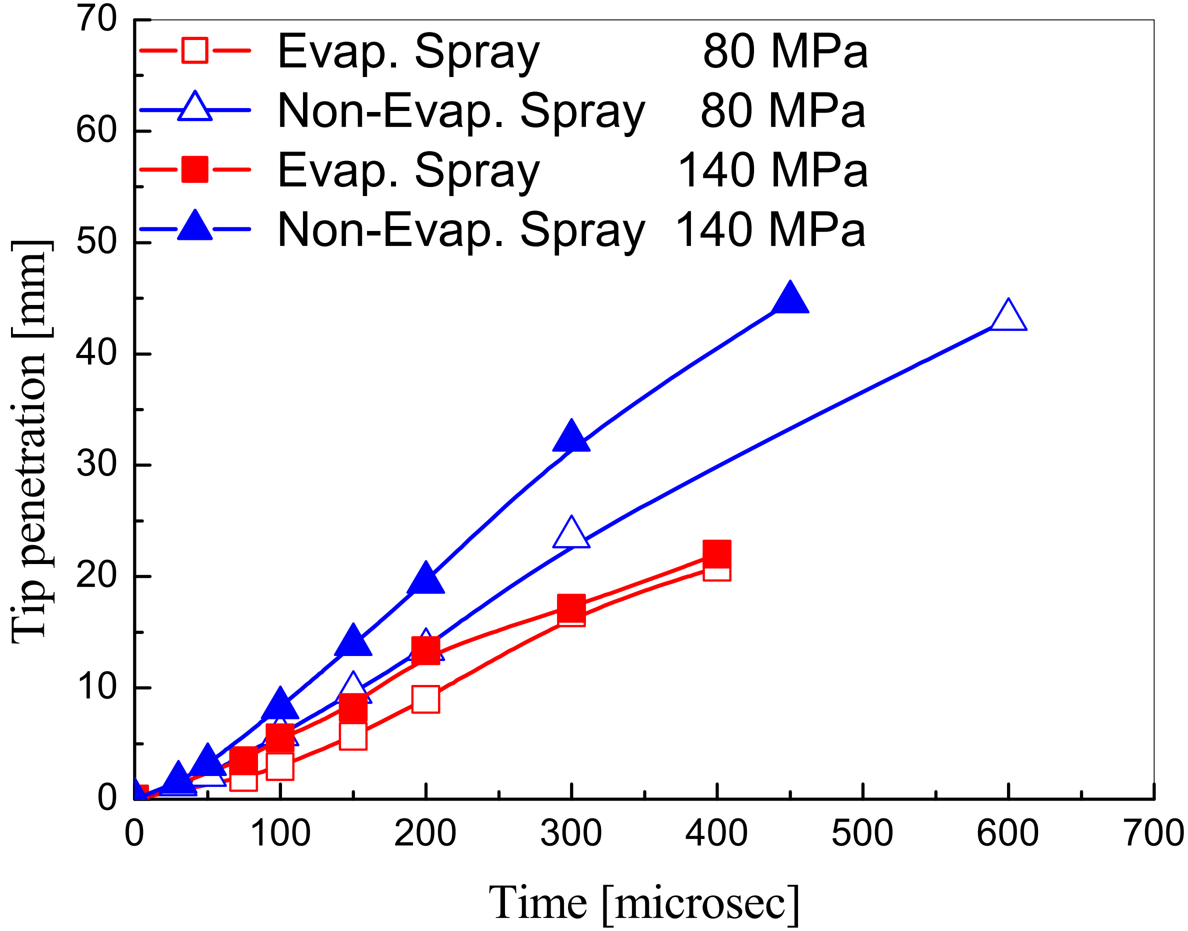
Non evaporative spray tip penetrations at the investigated injection pressures






ρ =12.5 kg/m^3
ρ =17 kg/m^3
P_{inj}= 80 MPa
P_{inj}= 100 MPa
P_{inj}= 140 MPa
tip penetration [mm]
time [μs]

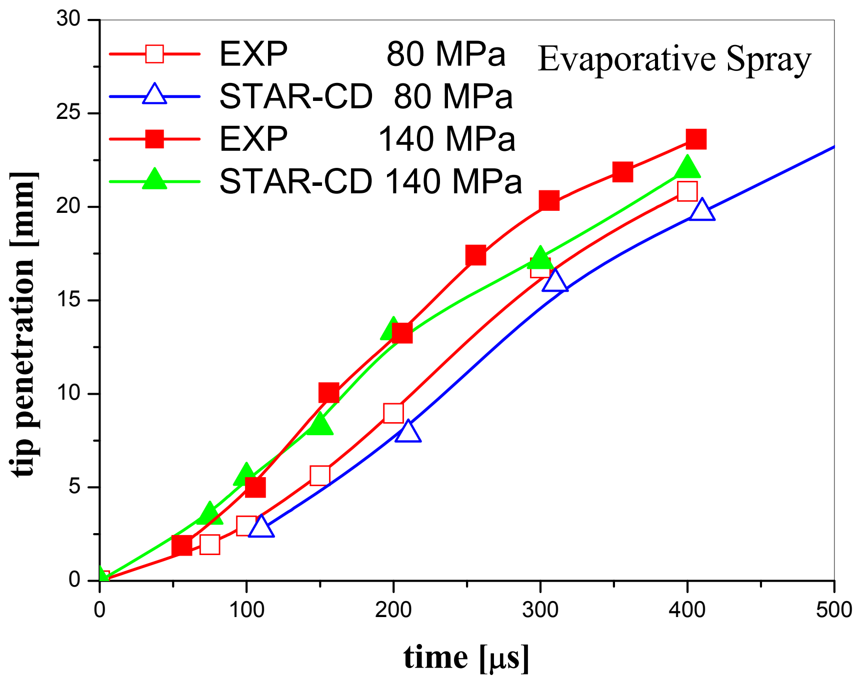
Comparison of spray tip penetration under evaporative and non evaporative conditions



The penetrations of the jets, in non evaporative conditions, are longer than evaporative ones denoting an evaporation process on boundaries and front of the tip

SPRAY MODEL VALIDATION

- **Fuel spray is modelled by using Huh-Gosman atomization model, while Reitz-Diwakar models has been used for secondary break-up**
- **Test-case results are evaluated in terms of spray penetration and spray shape evolution by qualitative comparison with the imaging technique results.**



A good agreement can be observed between computed and measured tip penetrations.

CONCLUSIONS

An experimental and numerical investigation has been carried out on the processes of fuel injection and spray formation from a CR apparatus for heavy duty diesel engines.

Significant cycle-to-cycle injection rate instabilities have been highlighted for pulse duration shorter than 400 μs, using the commercial ECU; a fine stability has been found for the prototype ECU down to 190 μs.

The jets penetrations, in non evaporative conditions, are longer than evaporative ones denoting an evaporation process on the boundaries of the tip.

Computation and experiment comparisons agree fairly for the liquid spray penetrations in the combustion chamber.

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THANK YOU FOR YOUR ATTENTION

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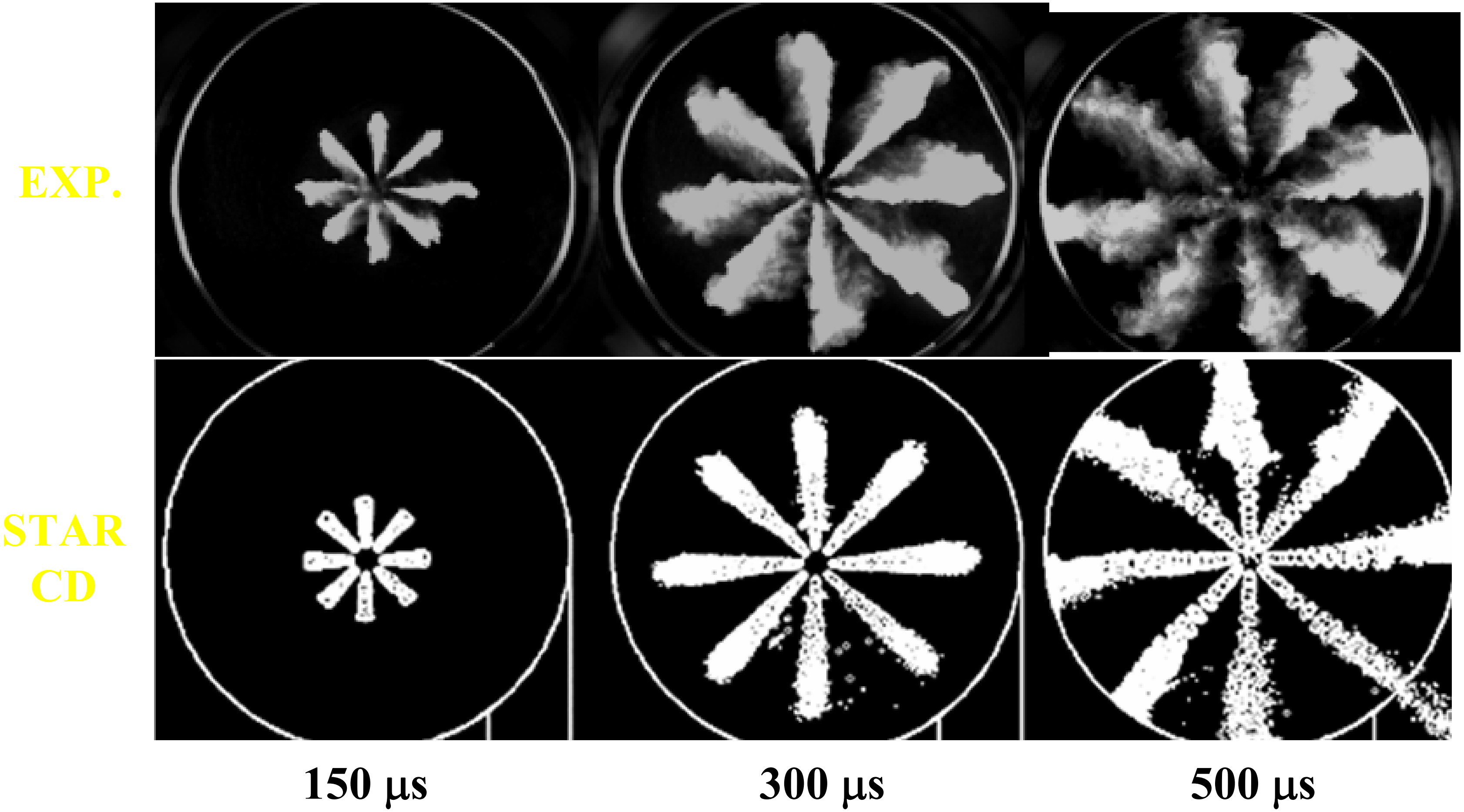
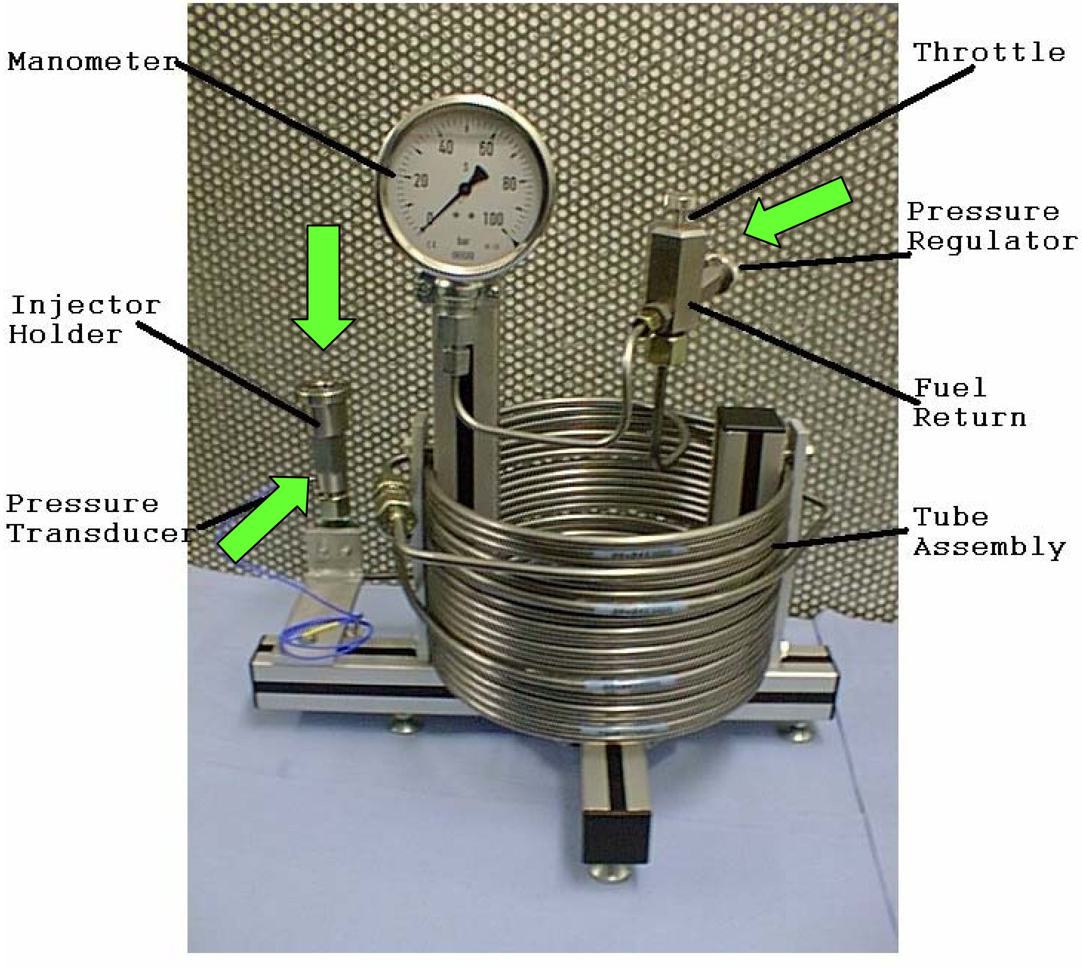
Pilot injection sequence obtained by the experimental single-shot image (top row) and the STAR-CD code (bottom row) injecting the fuel at 25° c.a. ATDC.



The comparison shows a large-scale agreement between computations and experiments mainly for the liquid spray penetration but some details related to detached clusters of particles are not captured by the code.

Injection Rate Meter



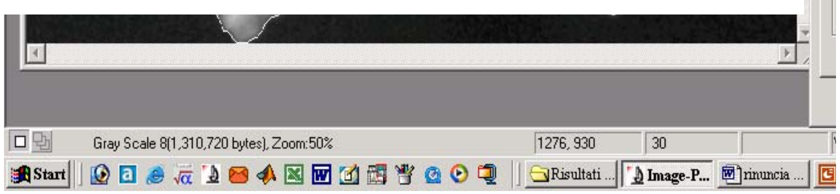
$$q = \frac{p \cdot A_{tube} \cdot 10^5}{a \cdot \rho}$$

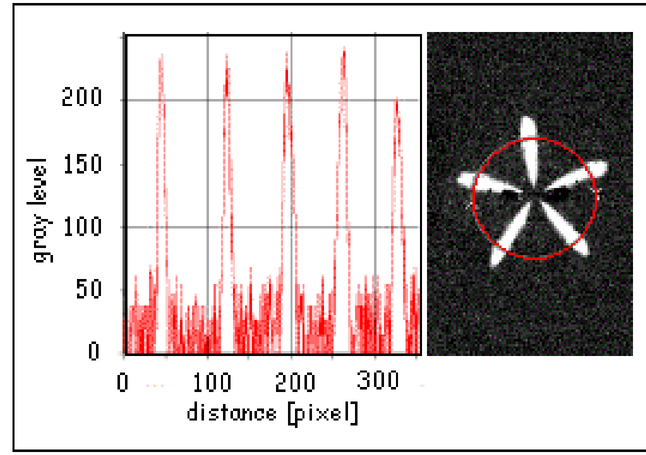
Images Processing

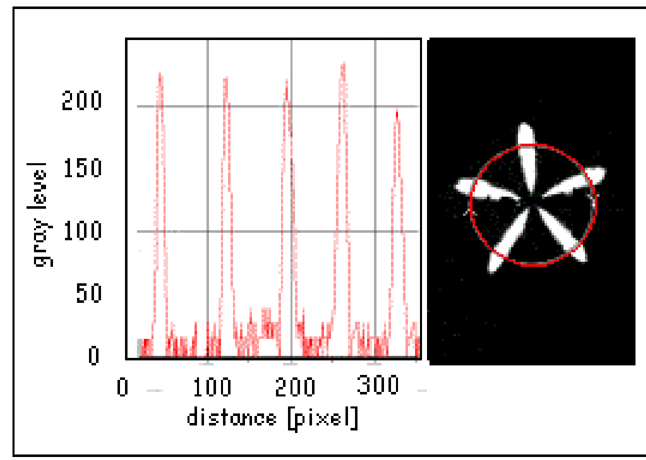
The processing procedure has been divided into:

- ➢Background subtraction
- ➢Image filtering
- ➢Fuel spray edges determination

A median filter has been applied to remove impulse noise from the spray image







The sprays images have been proce
Image Pro Plus to extract the main

Histograms of gray levels before (top) and after (bottom) the filter application

In-cylinder pressure signal for a two-stroke, loop-scavenged motored diesel engine, 3000 cm^3 displ. and 10.1:1 c.r.