ECN Workshop 1 - Hydraulic Characterization

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Summary of the Hydraulic Characterization Working Group Session

The hydraulic characterization group has two main objectives: first to provide accurate data to the community concerning rate of injection, spray momentum and hydraulic coefficient; and second, to compare the measurements between facilities and estimate the eventual difference between injectors. The first part explained the difference related to the measurement of the mass flow, Sandia and CMT both provided data in this respect, using two different approaches: the Bosch "long tube" method for CMT and the mass adjusted rate of momentum for Sandia. Higher oscillations have been observed and analyzed for the long tube method when compared to the ROI measured by Sandia. The analysis showed that the oscillations were generated by an axial translation of the injector thus compressing the testing fluid section of the rate meter, which has been correlated with needle motion measured at Argonne. The momentum flux has been measured by CMT, Sandia and CAT. Both CAT and CMT have the sensor placed orthogonally to the spray while the spray hits the sensor at a 30^{o} angle in Sandia's facilities. The measurements showed good agreement between facilities and injectors except for 210678 that presents higher rate of momentum. An analysis of the oscillations recorded by the pressure transducer placed on the feeding line demonstrated the influence of the length of this line, but more interestingly, it has been observed that the amplitude of the fluctuations was related to the injection system upstream (e.g. high-pressure pump, lines and regulation device). Finally, a complete analysis of the measurements has been carried out by changing injection and discharge pressures to hydraulically characterize the injectors through C_d, C_a, C_v as well as the effective velocity and diameter.

Conclusions

The conclusions drawn for the hydraulic characterization session were that pretty good agreement between research institutes as well as similarities in the way of measuring these parameters. One concern has been pointed out though, injector 210678 showed higher rate of momentum according to CAT compared to the other injectors of the set. The vibration analysis performed to understand where the oscillations on ROI came from revealed that the fluctuations on ROI and momentum signals were similar and related to a displacement of the needle and injector. If no experiment is possible and since all the nozzles in the ECN are (should be) very similar, the best way to obtain the injected mass and spray momentum can be achieved using the dimensionless coefficients (C_d, C_v, C_a) that should be close for all nozzles (210678?). If a difference in diameter is observed, it has been seen to affect strongly the discharge coefficient C_d and the area coefficient C_a but not to influence the velocity coefficient C_v, this must be affected by an injection pressure problem though. To obtain mass flow rate from spray force measurement the following formula should be applied before adjusting the injected mass:

$$\dot{m}_f \propto \sqrt{\dot{M}_f}$$

Discussions

The first comment made after this session was the lack of data concerning direct measurement of the injection rate as it does not require expensive installation, only CMT directly measure the ROI and Sandia measured it indirectly. The Bosch "long tube" method proved not to be appropriate to generate an exact rate of injection for modelers due to the high oscillations present on the signal. Injector 210678 must be sent to Sandia for further analysis of the possible higher spray momentum (compared to other injectors of the same family). Spray momentum measured at CMT and CAT showed similar features and pointed out a possible sensor resonance at Sandia. There is a need for experimentalists to provide accurate injection rate signal to modelers as this is the starting point of the process and the impact on later results is huge. Raul Payri (CMT) said he would discuss about generating a "virual" injection rate with the other members of the injection group when back in Valencia.

Experimental uncertainties

When it comes to hydraulic characterization, the errors or uncertainties on the experimental side come from different sources. When talking about uncertainties, a difference shall be made in this case between precision and accuracy of the experiments. Starting with the precision, mounting the injector several times in the test rigs (either flow rate meter or spray momentum facility) may lead to slightly different results. Specific analysis has been carried out to address this and showed that the maximum deviation was about 1% (corresponding to spray momentum, this value for injection rate is about 0.6%), which is in agreement with previous studies performed at CMT. Concerning the accuracy of the experiments, care must be taken to what kind of measurements we are looking at. For instance, rate of injection when measured by the Bosch "long tube" method presents large oscillations, which have been analyzed and are now known to be an artifact of the experimental technique. The transient regions cannot be taken as recorded and displayed; either for momentum or mass flow rate, signal filtering and experimental arrangement may shift the signals away from the reality of the physical process. Finally, the maximum uncertainty of the measurement for the steady period (value) of the injection has been estimated to be below 4% for both experimental techniques.

Recommendations and bottom line

The first recommendation concerning the hydraulic characterization is that every injector should be tested as some differences have been seen within this set of "identical" injectors. The hydraulic characterization is a necessary step for the experimentalists as it provides important data to the modelers and slight variations may induce important differences in mixing and combustion. Care must be taken when performing hydraulic characterization, because although injection rate and spray momentum are two essential parameters, they require expertise to be carried out correctly. Additional efforts are needed in this field as the diagnostics are not able to provide precise and accurate enough data for model predictions. The design of a "best guess" for the injection rate has been taken by CMT (Dr. Jaime Gimeno is working on a "virtual" injection rate) and should be discussed by the ECN participants before releasing the information.

ECN Workshop: Injector's hydraulic characterization

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ECN Workshop, May 13 and 14 2011

Ventura, CA

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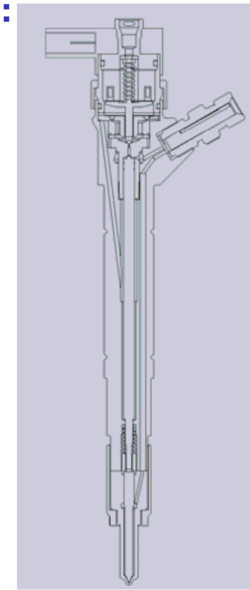
Spray A conditions

- **Rate of Injection and spray momentum are performed to hydraulically characterize the injector:**
  - Bosch CRI 2.4 (solenoid actuated)
  - Single-hole orifice (several units)
  - Geometric nominal diameter: 0.090 mm
  - Conical shape: KS 1.5/86
- **Specific testing conditions:**
  - Injection pressure: 150 Mpa
  - Discharge pressure: 6.0 MPa
  - Injection duration: 1500 μs (ET adjusted)
  - Injector temperature: 343 K (controlled)



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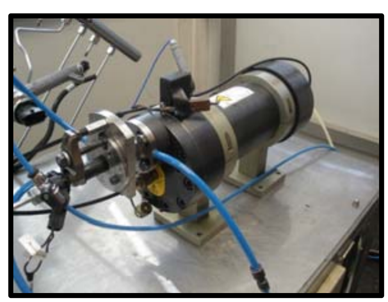
ROI measurement at CMT

- ROI measurements have been performed with a system using the Bosch method (IAV commercial hardware)
- Injection pressure is regulated upstream the rail to damp pressure oscillations induced by the pump
- Electric signal to command the injector is generated by a Genotec (I_{open} = 18 A (450μs), I_{hold} = 12 A)
- **Measurements methodology:**

  A pressure transducer records the ROI in an anechoic tube filled with the fuel injected

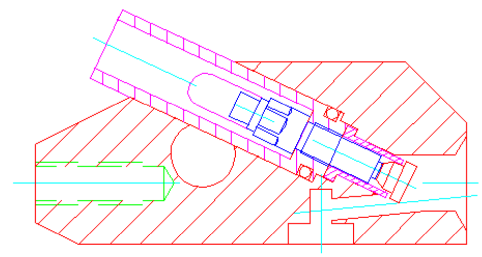
  Total amount of fuel injected in each stroke measured with a gravimetric balance to adjust the ROI signal

  Average over at least 25 cycles, shot-to-shot deviation below 1%

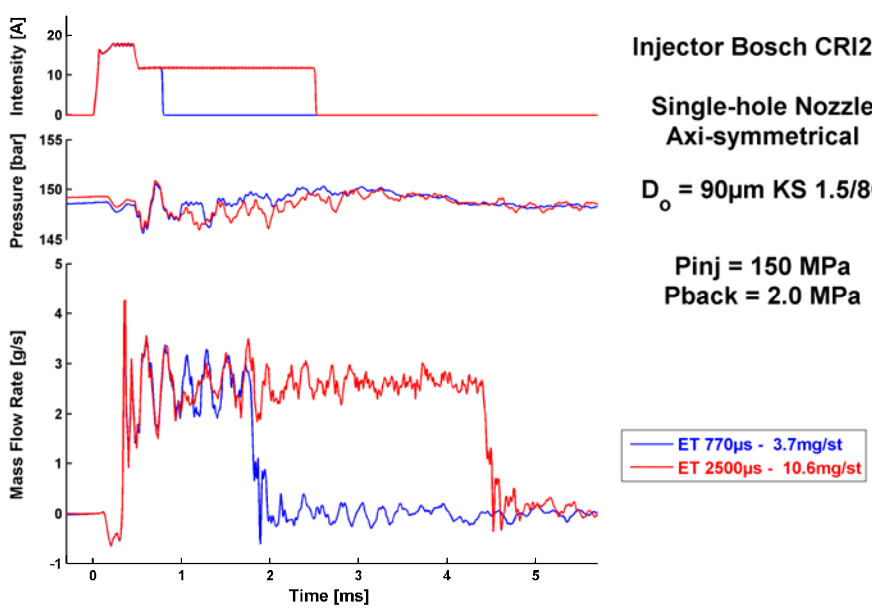


Hydraulic measurement at Sandia

- The injection system uses the specifications of the "Spray A" with a 22 cc Common-Rail and a 24 cm line connected to the injector
- Injection pressure is generated and regulated directly by the oleo-pneumatic pump (different from a standard common rail that is used at CMT)
- Spray momentum is measured in a time domain by a force transducer placed at a 30º angle
- The rate of injection is obtained by collecting the total injected mass by stroke assuming similar momentum and ROI shapes



ROI results



Injector Bosch CRI2.4

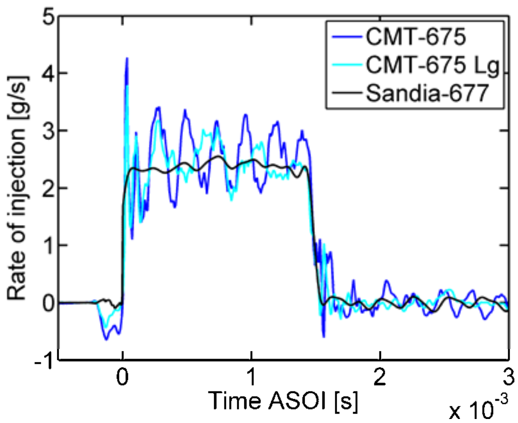
Single-hole Nozzle
Axi-symmetrical

D_o = 90µm KS 1.5/86

Pinj = 150 MPa
Pback = 2.0 MPa

ROI Comparison

- Injection rate of two similar nozzles at two institutions: Mean ROI of 675 slightly higher than 677
- This graph confronts two different measurement methodologies: Bosch (long tube) method vs. Mass adjusted momentum flux



- Higher oscillations with Bosch method (further analysis later)
- Average mass flow rates are of the same order (2.62 vs. 2.45 g/s)
- Longer injection line affect ROI oscillations but mean value holds

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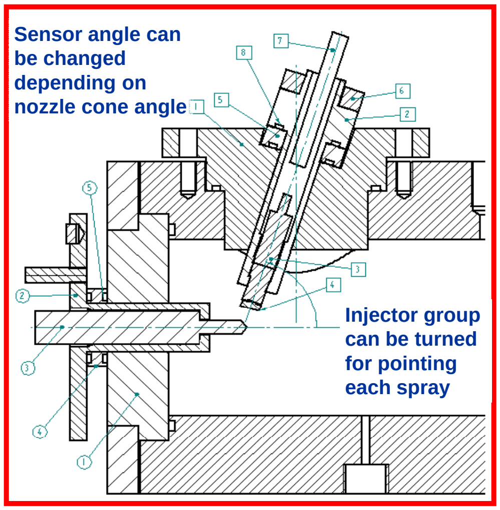
Spray Momentum test rig (CMT)

- **Main features:**
  - Piezo-electric sensor: Force sensor which directly measures the momentum flux



- Pressurized with gas N_2 (CMT & CAT), ambient air (Sandia)
- Actual testing pressure condition inside the chamber (CMT & CAT)
- Sensor perpendicular to spray (CMT & CAT) or at 30º (Sandia)
- Spray impinges on a ceramic shield attached to the sensor

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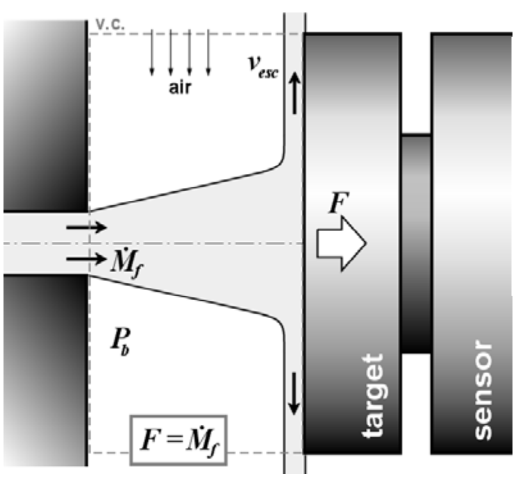
Spray Momentum measurements



$$\dot{M}_f = \dot{m}_f \cdot u_o$$

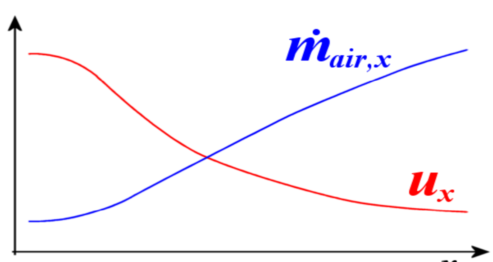
$$\dot{M}_x = \left(\dot{m}_f + \dot{m}_{a,x}\right) \cdot u_x$$

- **Momentum tests assumptions:**
  - Incoming air velocity perpendicular to axis

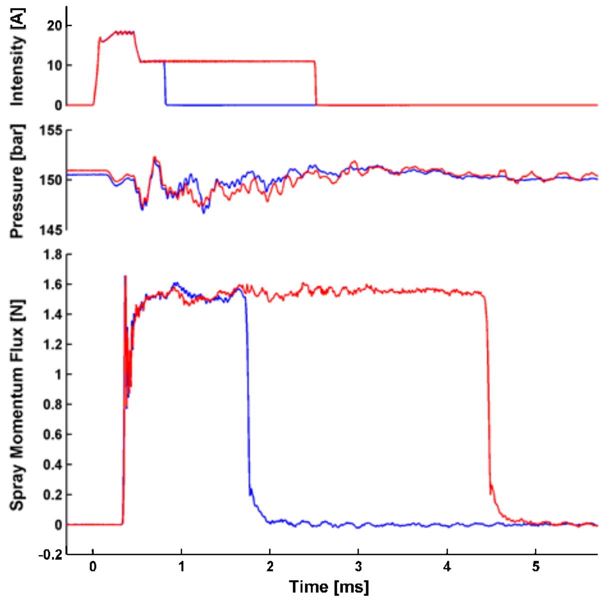
$$\dot{M}_f = \dot{M}_x$$

Momentum is conserved in axial direction

- **Momentum does not depend on:**
  - Chamber pressure or density
  - Measurement distance from orifice



Spray Momentum results



Injector Bosch CRI2.4

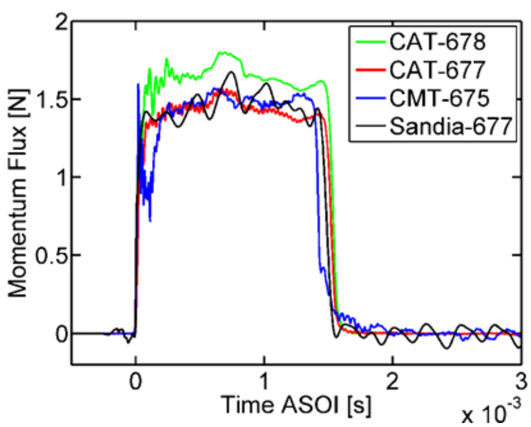
Single-hole Nozzle
Axi-symmetrical

D_o = 90µm KS 1.5/86

Pinj = 150 MPa
Pback = 2.0 MPa

Momentum comparison

- Similar momentum between 677 measured at CAT and Sandia when compared to 675 measured at CMT
- Injector 678 (CAT) presents higher momentum (up to 15 % higher) than the others



- Transients are widely affected by experimental arrangements
- Signal from Sandia presents different oscillations than those measured by CMT and CAT
- Measuring spray momentum with an angle seems to affect the recorded signals

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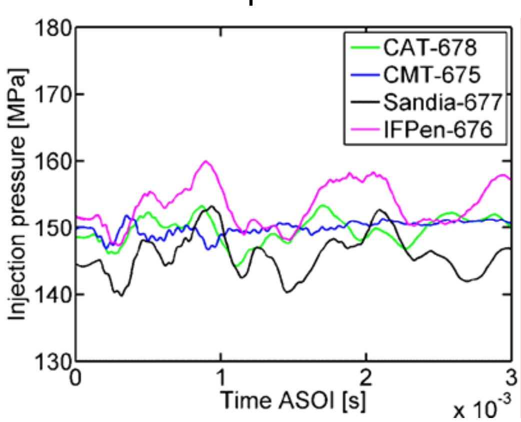
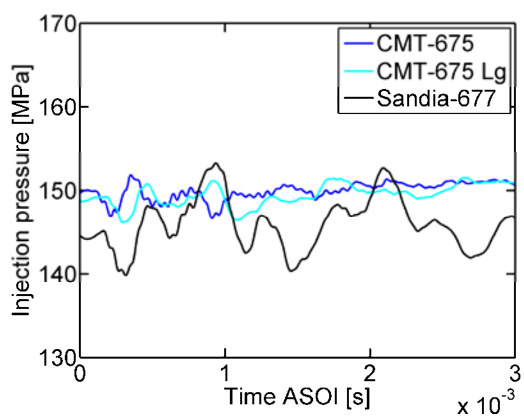
Comparison of injection pressure

- Amplitude of injection pressure oscillations varies from facility to facility, even with similar Common Rail and rail-to-injector line
- CMT's 30 cm long line seems to resemble more original Spray A setup at Sandia in terms of oscillation features while amplitude is not affected





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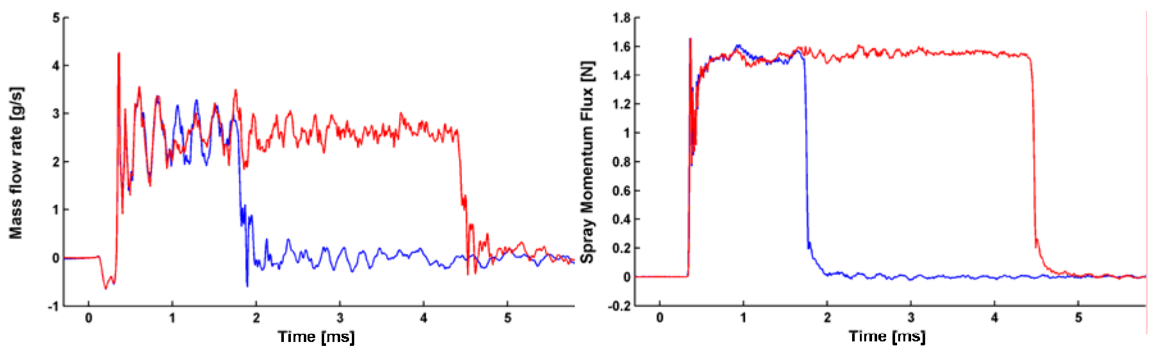
Oscillations on ROI

- **ROI of ECN injector presents important oscillations**
  - This is the result of a displacement of the injector and it has been observed on spray momentum too
  - This displacement has been measured by placing an accelerometer (motion sensor) on the injector

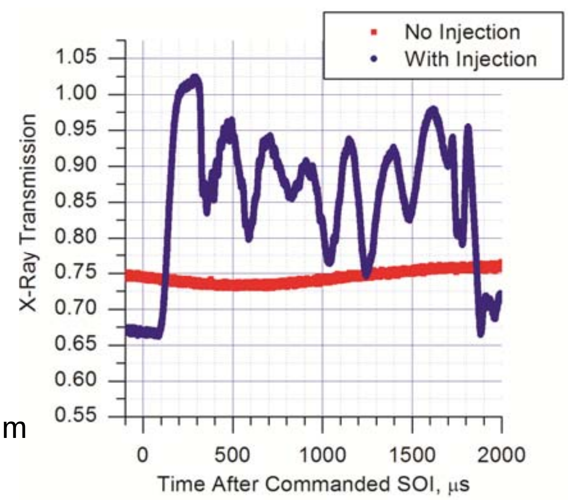


Acoustic analysis

- **The fluid hammer due to fuel-fuel or gas-fuel contact leads to pressure waves in the tip:**
  - ROI and SM frequencies depend on injection pressure in the first part of the injection (related to speed of sound)
  - The system needle-rod-fluid makes this frequency to increase until its natural one and resonates → Injector moves
  - The complex system (Injector as well) keeps vibrating until the end of the electronic command of the solenoid → Control volume closes: Oscillations are damped out
  - Similar frequencies appear on both injection rate and spray momentum measurements at frequencies around 6-7 KHz (confirmed by accelerometer motion sensor)
  - The important oscillations seen on ROI at CMT are due to the displacement of the injector, acting like a piston in the testing volume where the pressure is recorded (volume filled with fuel)

Additional results from Argonne

- X-ray measurements confirmed the displacement of the injector when injecting
- Low frequency oscillations are observed on the no-injection signal, this is the result of pressure pulsations from the rail
- This plot is for "Spray A" condition with a 750 µs electronic command and 2.08 MPa discharge pressure
- Frequency of the same order to that revealed by CMT's experiments on ROI, momentum and motion sensor signals



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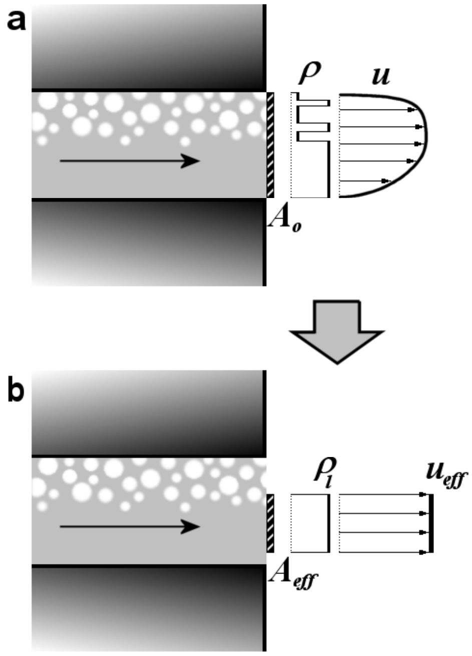
HYDRAULIC CHARACTERIZATION

- **Determination of effective velocity, area and hydraulic coefficients:**
  - Spray momentum measurements: Spray force $\left(\dot{M}_f\right)$
  - Rate of injection measurements: Mass flow rate $\left(\dot{m}_f\right)$
- **Mean values at maximum needle lift of momentum and mass flow rate**
  - 5 injection pressures: 50, 100, 150, 180 and 200 Mpa
  - Different discharge pressures (densities) can be done to observe cavitating phenomenon (not in Spray "A" nozzle)
  - Long energizing time to get the steady part of the injection (2500 μs)
  - Data are analyzed together to evaluate the effective area, velocities and hydraulic coefficients

ANALYSIS PRINCIPLE (1/2)



$$\dot{m}_f = \int_{A_o} \rho \cdot u \cdot dA$$

$$\dot{M}_f = \int_{A_o} \rho \cdot u^2 \cdot dA$$

$$\dot{m}_f = \rho_l \cdot u_{eff} \cdot A_{eff}$$

$$\dot{M}_f = \rho_l \cdot u_{eff}^{\,2} \cdot A_{eff}$$

$$u_{eff} = \frac{\dot{M}_f}{\dot{m}_f}$$

$$A_{eff} = \frac{\dot{m}_f^{\,2}}{\rho_l \cdot \dot{M}_f}$$

ANALYSIS PRINCIPLE (2/2)

- Effective velocity and area can be calculated from spray momentum and mass flow rate
- Velocity and area coefficients can be obtained using theoretical velocity and real outlet geometric area

$$u_{eff} = \frac{\dot{M}_f}{\dot{m}_f} \Rightarrow C_v = \frac{u_{eff}}{u_{th}} \qquad C_d = \frac{\dot{m}_f}{A_{geo} \cdot \rho_f \cdot u_{th}}$$

$$A_{eff} = \frac{\dot{m}_f^{\,2}}{\rho_f \cdot \dot{M}_f} \Rightarrow C_a = \frac{A_{eff}}{A_{geo}} \qquad C_d = C_v \cdot C_a$$

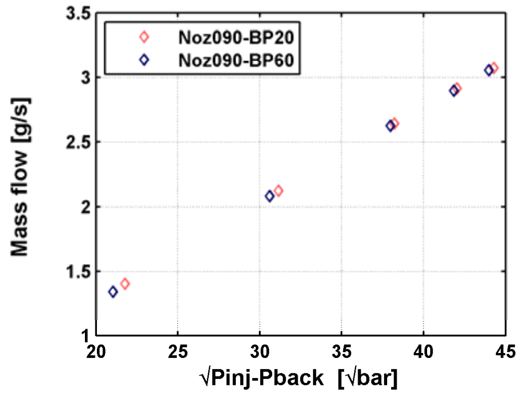
- **Velocity calculation uncertainties:**
  - Mass flow and momentum flux are measured under different conditions (ROI measurements are performed injecting into liquid fuel while Momentum in gas N_2)

MASS FLOW RATE (nozzle 675)

- **Mean mass flow at maximum needle lift is proportional to the square root of the pressure drop:**

$$\dot{m}_f = \overbrace{C_v \cdot C_a \cdot A_{geo} \cdot \sqrt{2\rho_f}}^{\approx \text{ constant}} \cdot \sqrt{\Delta P}$$

- **Mass flow should be linear to $\sqrt{\Delta P}$ without collapsing**

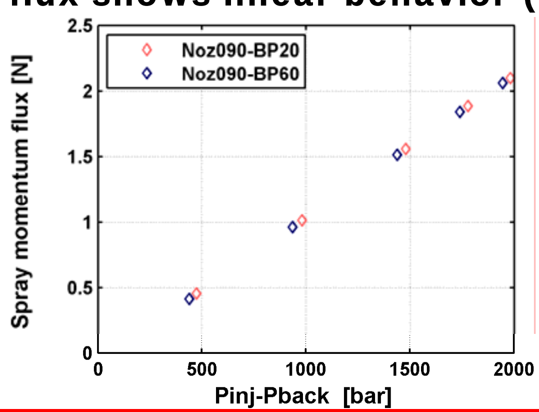


MOMENTUM FLUX (nozzle 675)

- **Mean momentum flux at maximum needle lift is directly proportional to the pressure drop:**

$$\dot{M}_f = \overbrace{C_v^2 \cdot C_a \cdot A_{geo}}^{\approx \text{ constant}} \cdot 2 \cdot \Delta P$$

- **Momentum flux shows linear behavior (as expected)**



Data recompilation

- **Spray A - Hydraulic characterization: Single hole nozzle CRI2.4 90μm KS1.5/86): Nozzle 675**
  - Injected mass: 3.62 mg/st (P_{inj} =150 MPa - P_b =6.0 MPa)
  - Stabilized mass flow rate: 2.62 g/s
  - Stabilized momentum flux: 1.52 N
  - Effective diameter: 89 μm
  - Effective velocity: 580 m/s
  - Discharge coefficient: C_d = 0.90
  - Area coefficient: C_a = 0.98
  - Velocity coefficient: C_v = 0.92
  - Momentum coefficient: C_m = 0.83

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Conclusions I

- The results between research centers showed agreement and similarity concerning measuring methodology
- One injector (678) measured by CAT revealed higher momentum flux than the others from the ECN set
- Direct ROI measurements have only been performed at CMT with the Bosch (long tube) method
- The vibration analysis revealed that the oscillations on ROI and momentum signals were similar and related to a displacement of the injector
- The recorded injection rate signal is affected by the measurement method since the displacement of the injector is amplified in the rate meter
- The overall uncertainty on ROI and spray momentum for the injector tested has been evaluated to be below 4% with a standard deviation around 3%

Conclusions II

- Spray momentum has been repeated after dismantling the nozzle on injector 675 and provided results within the uncertainty (relative difference below 2%)
- Since all the nozzles in the ECN are very similar, the best way to obtain the injected mass and spray momentum come from using the non-dimensional coefficients (C_d, C_v, C_a) that should be very similar for all nozzles
- To obtain mass flow rate from spray force measurement the following formula should be applied before adjusting the injected mass

$$\dot{m}_f \propto \sqrt{\dot{M}_f}$$

- More information http://www.cmt.upv.es/ECN.aspx

- Using spray momentum flux measurements to understand the influence of diesel nozzle geometry on spray characteristics, Fuel 84, p. 551-561, 2005.
- A new methodology for correcting the signal cumulative phenomenon on injection rate measurements Experimental techniques. Volumen: 32 (1) pp. 46-49, 2008.

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Discussions and questions

ECN Workshop, May 13 and 14 2011

Ventura, CA