Experimental study of partial regeneration

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ABSTRACT

It is well known that diesel particulate filters can be subjected to incomplete regeneration which can lead to DFP failure when a severe regeneration follows many partial regenerations. The following study concentrates on C-DPF (Catalysed Diesel Particulate Filter) filters made of R-SiC (Recrystallized Silicon Carbide) and aims at studying the soot distribution in the filter as a function of regeneration efficiency. The soot distribution is deduced from a radial velocity profile at the rear of the filter determined using a specific test bench.

First, an experimental protocol has been designed to produce a controlled partial regeneration. This protocol allows us to obtain the desired regeneration efficiency. To measure the velocity profiles at the filter outlet a specific test bench has been designed and built.

Test results do not show a direct linear correlation between the pressure drop efficiency (ratio of the total pressure loss of the filter before regeneration on the pressure loss after regeneration) and the mass efficiency (ratio of the soot mass after regeneration on the soot mass before regeneration) during partial regenerations. On the contrary a very good linear correlation between the mean velocity and the mass regeneration efficiency has been observed.

Moreover, it could also be observed that more the regeneration efficiency increases and more the radial distribution of remaining soot in the filter is homogeneous. Consequently, regeneration is better where the filter is more loaded. This result shows that partial regeneration in the case of a controlled regeneration tends to homogenize the distribution of soot in the radial direction and thus to not concentrate soot which are not regenerated.

Then, we have observed that the correlation between the mean velocity and the remaining soot mass after partial regeneration is very different from that obtained during loading. Thus, loading a filter completely then emptying it partially does not give the same result as loading it partially. So, it seems that the protocol of partial regeneration that we did it modifies the distribution of soot inside the filter. Thus, to have a more accurate explanation of this phenomenon, a better knowledge of the axial soot distribution is necessary.

INTRODUCTION

Today, catalysed diesel particulate filter (C-DPF) technology seems to be the most promising solution to deal with the future emission standard requirements for diesel vehicles. This system can reduce totally soot, CO and HC. Diesel particulate filters, in real world-driving, are often submitted to incomplete regeneration. These incomplete regenerations could be dangerous for filter integrity because the remaining soot in the channels may be non-uniform. This non-uniform distribution and especially the density of remaining soots and a change of their physicochemical composition can cause local important temperature gradients and thus break the filter. So, a very good comprehension of this phenomenon is necessary.

Currently, numerical and experimental studies about loading and complete regeneration are well-known. On the other hand, experimental studies which allow to visualize and to quantify the soot distribution after a partial regeneration are not very widespread. However, theoretical studies are more common.

So, we have created a system which allows us to observe the localization, in the radial direction of the C-DPF, of soot after the loading or the remaining soot after a controlled partial regeneration.

Experimental study of partial regeneration

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SAINT-GOBAIN CREE *
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"10th ETH Conference on Combustion Generated Nanoparticles"

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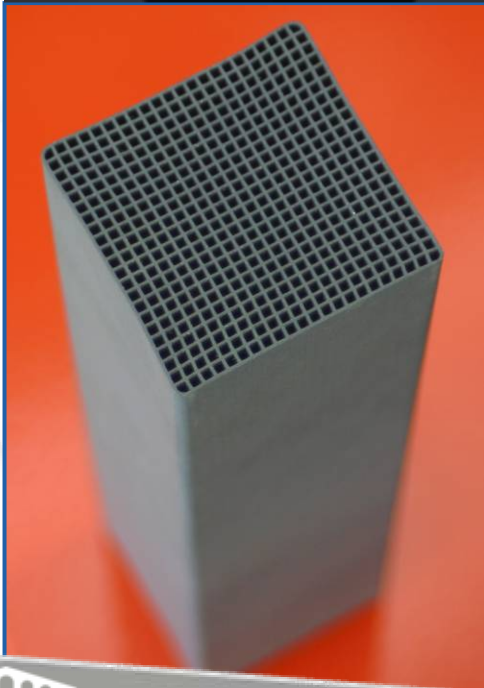
Experimental study of partial regeneration

- Context
- Experimental setup
- Results
  - Loading
  - Partial regeneration
- Conclusions
- Work in progress



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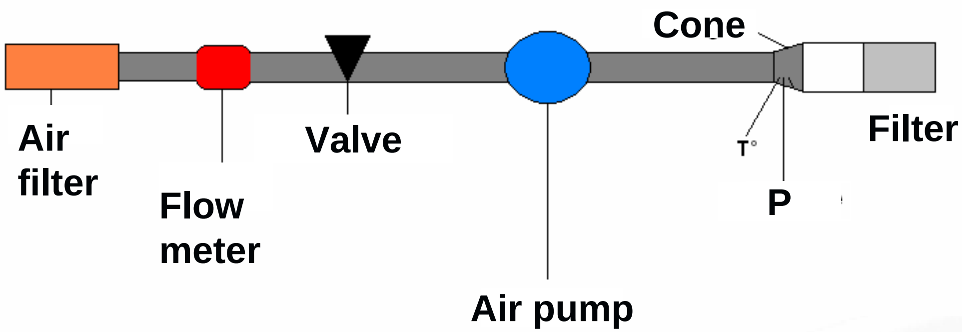
Why partial regeneration?

- Real-world driving → May induce incomplete regeneration
- Nature of soot: soot is not oxidized → modified
  - Density (SAE: 2002-01-0957)
  - Chemical and physical composition (SAE: 2003-01-0833)
- Several regenerations → Strong local temperature gradients
  - Dangerous for the filter integrity : cracks, failures
- A better understanding of partial regeneration is required
  - Soot distribution before partial regeneration
  - Soot distribution after partial regeneration

Experimental setup: device

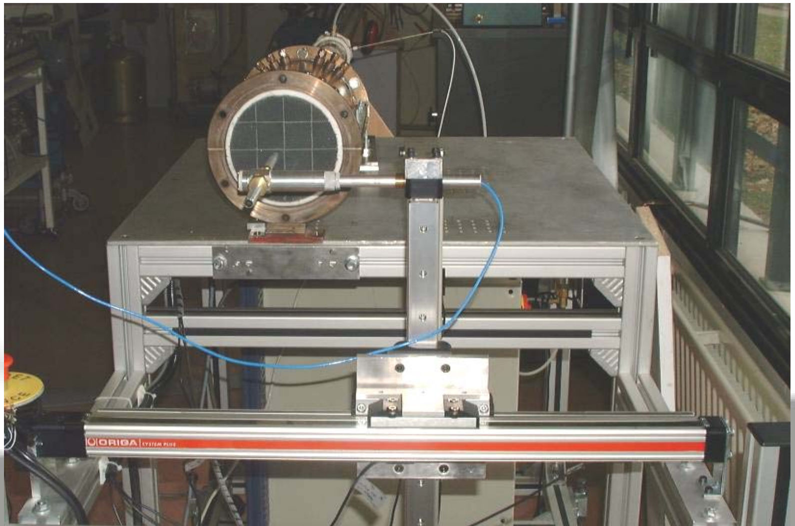
Bench for flow measurements

- Determination of **velocity profiles** at the rear of the DPF.
- Determination in the radial direction of the **localization of soot** oxidation, soot loading …



Automated device

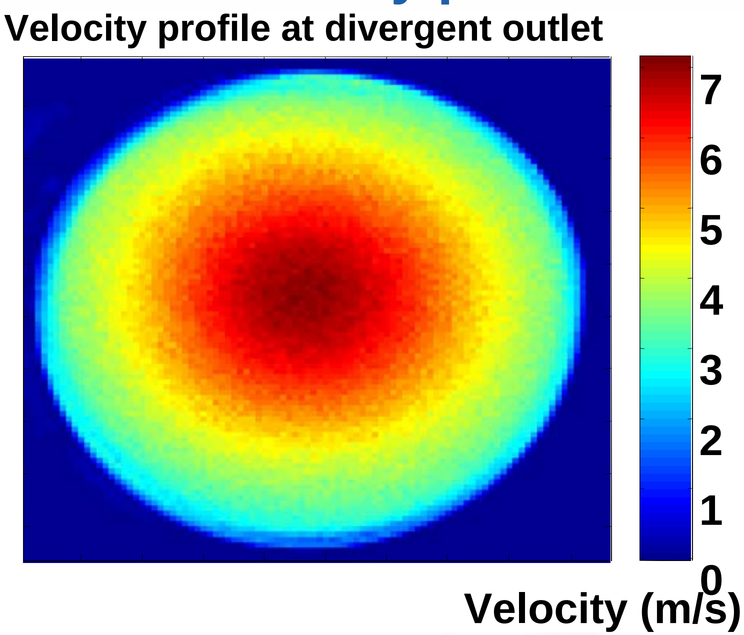
Anemometer diameter: 9mm

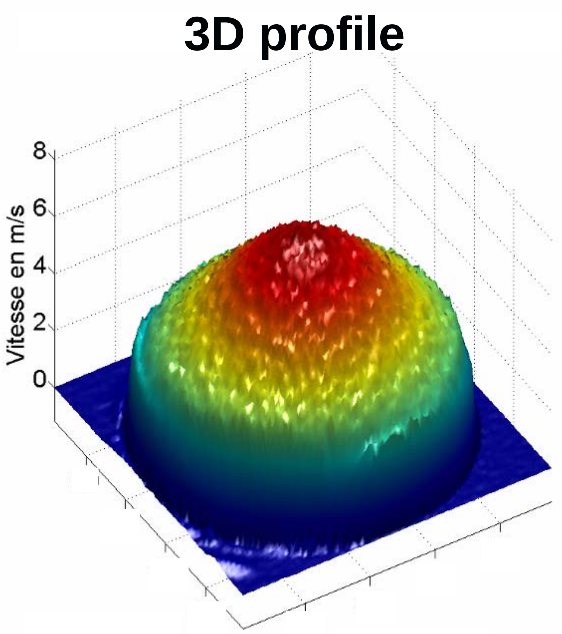


Experimental setup : Validation

Validation of flow rate

- Velocity profile at the rear face of the divergent





✓ Dome like profile

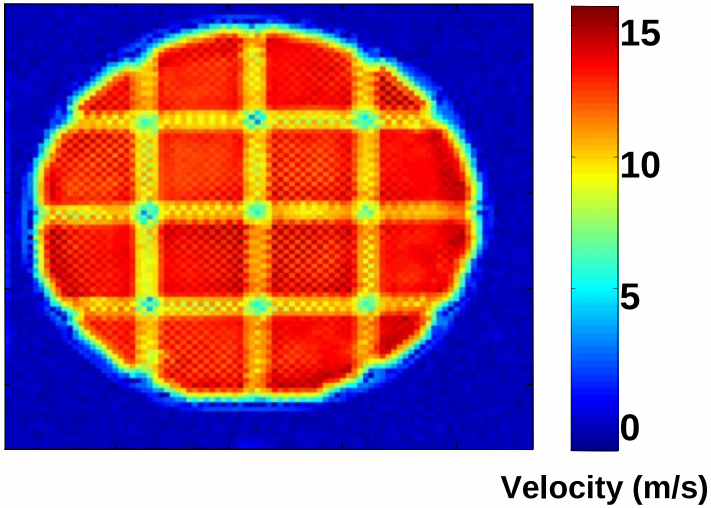
✓ Error of 3% between measured and calculated flow rate

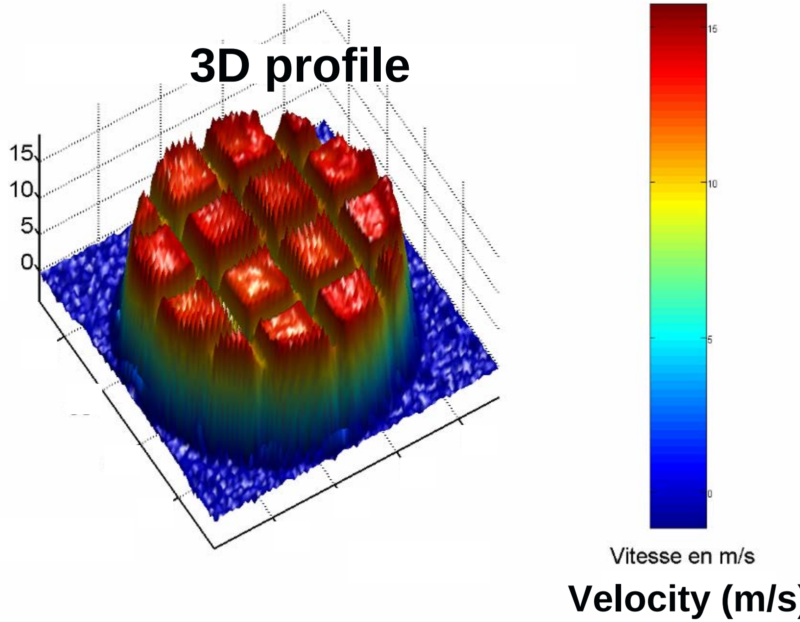
- ✓ Flow rate measured with a flow meter
- ✓ Calculated flow rate : $\int VdS$

Experimental setup: Validation

Velocity field with empty filter

Velocity profile at DPF outlet : no soot

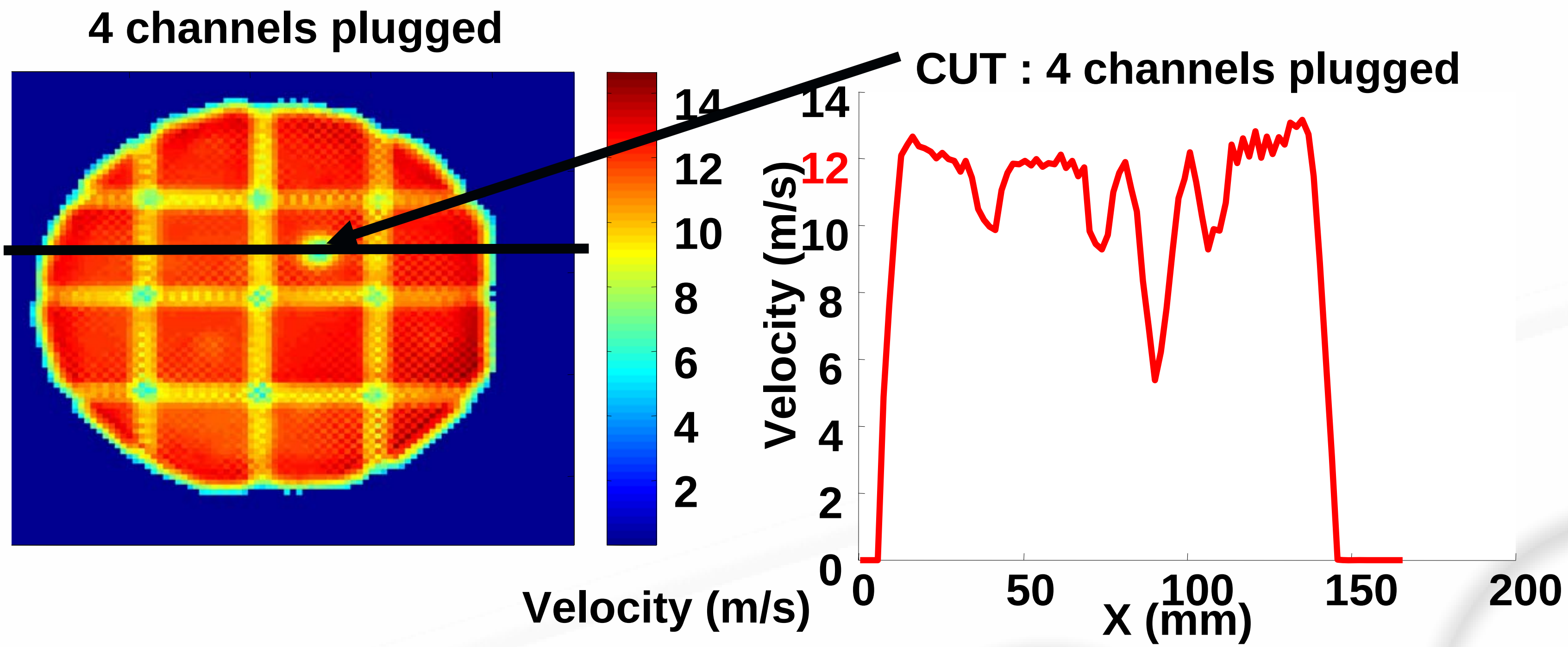




- Uniform flow
- At the filter, we can observe:
  - Contour of the filter
  - Unit elements
  - Inter unit elements cement
  - Open and closed channels

Experimental setup: Validation

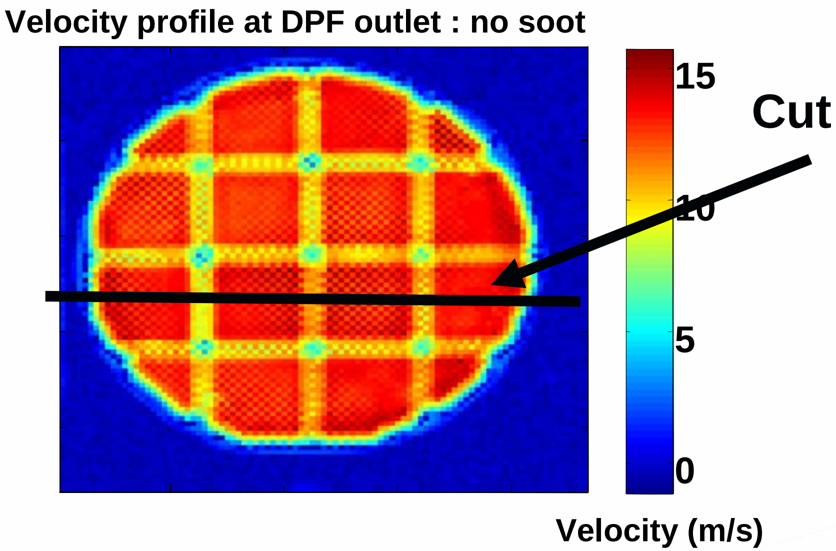
- **Velocity field with 4 channels plugged**

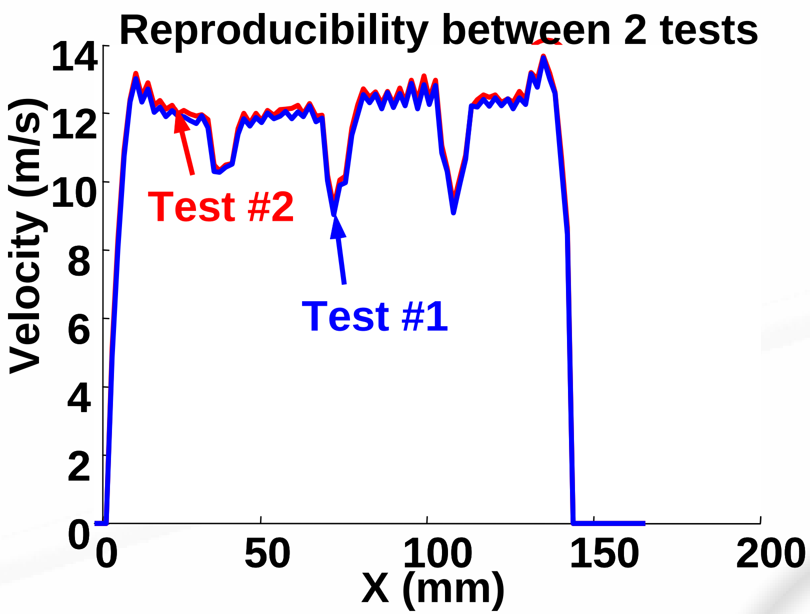


  - Measured velocity in plugged area decreases from 12 to 5 m/s
- **Velocity field with 1 channel plugged**
  - Measured velocity in plugged area decreases from 12 to 9 m/s
- **Anemometer acts as a spatial low pass filter**

Experimental setup: Validation

Reproducibility tests

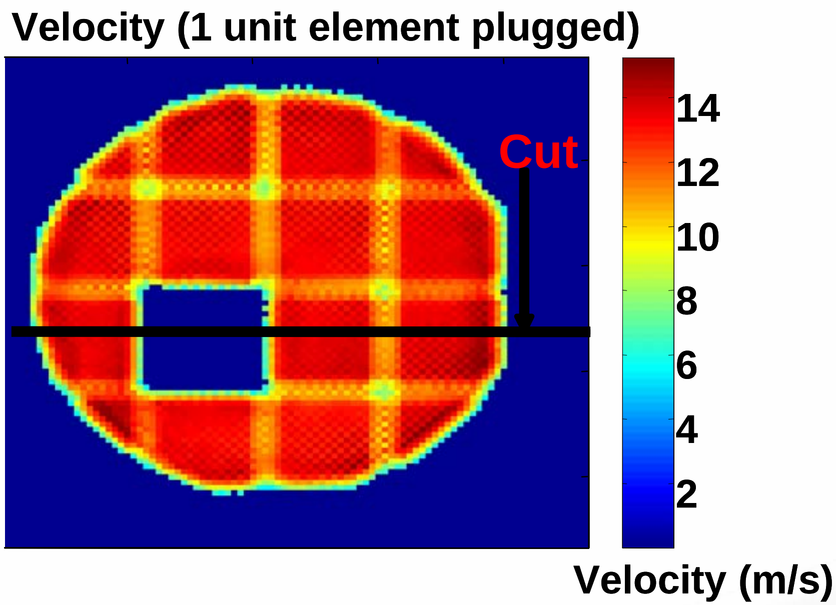


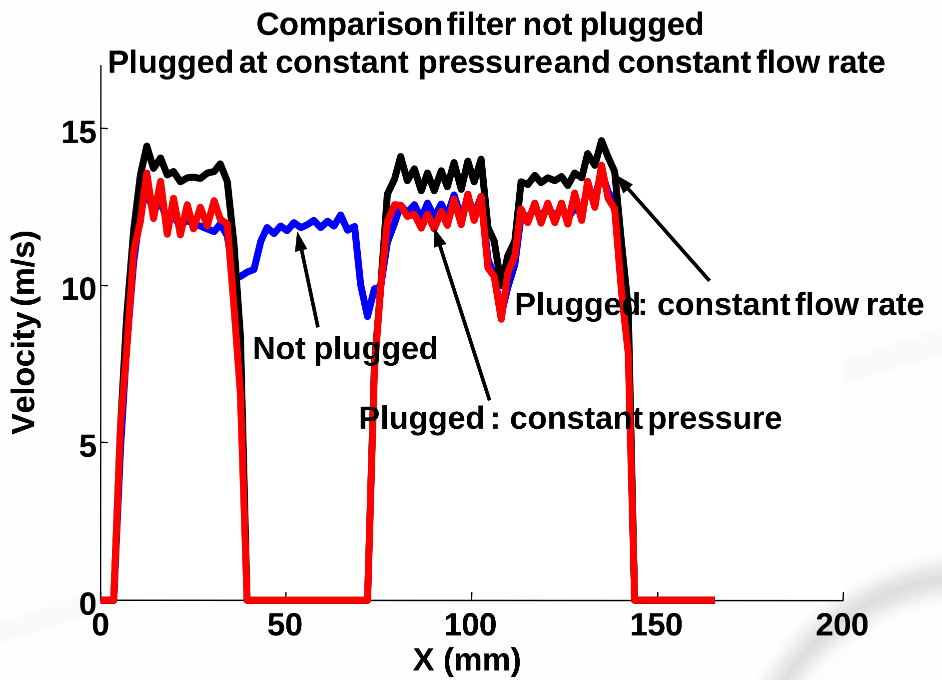


➢ Very good reproducibility between 2 tests (error less than 2%)

Experimental setup: operating conditions

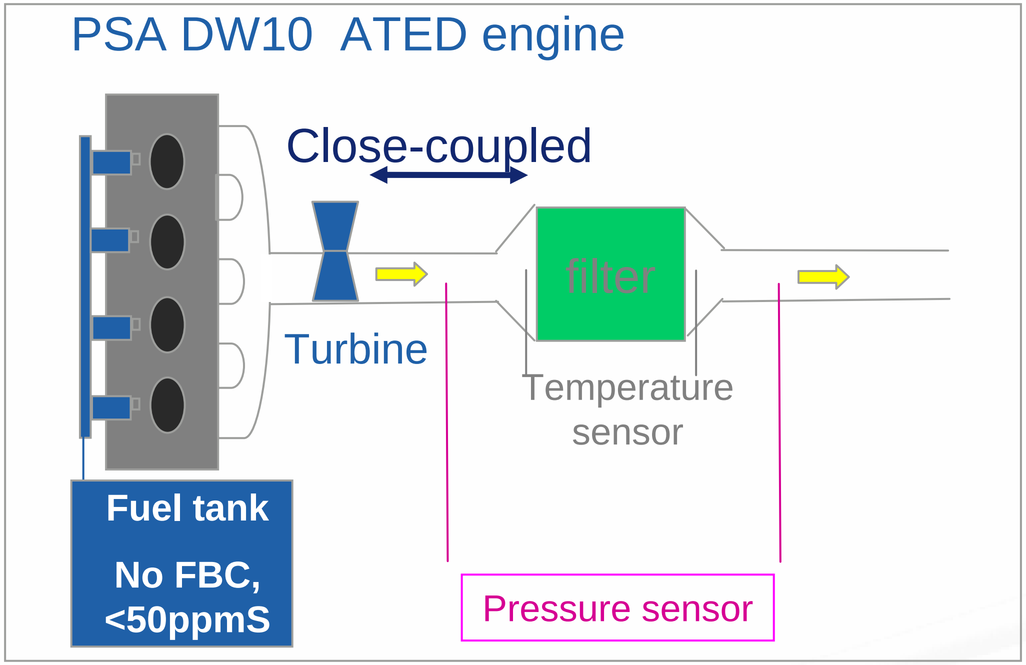
Constant pressure vs. Constant flow rate





- **Constant flow rate : an offset of velocity can be observed**
- **Constant pressure: very good superposition of velocities: Easier comparison of empty, loaded or partially regenerated filters (no flow compensation effect)**

Engine Bench configuration



Filter characteristics

	Filter
Material	RSiC
Coating	40 g/ft^3 Pt
Geometry	Square
Cells density (CPSI)	311
Wall thickness (µm)	280
Diameter*Length	5,66'' x 6''

Experimental device : Engine bench

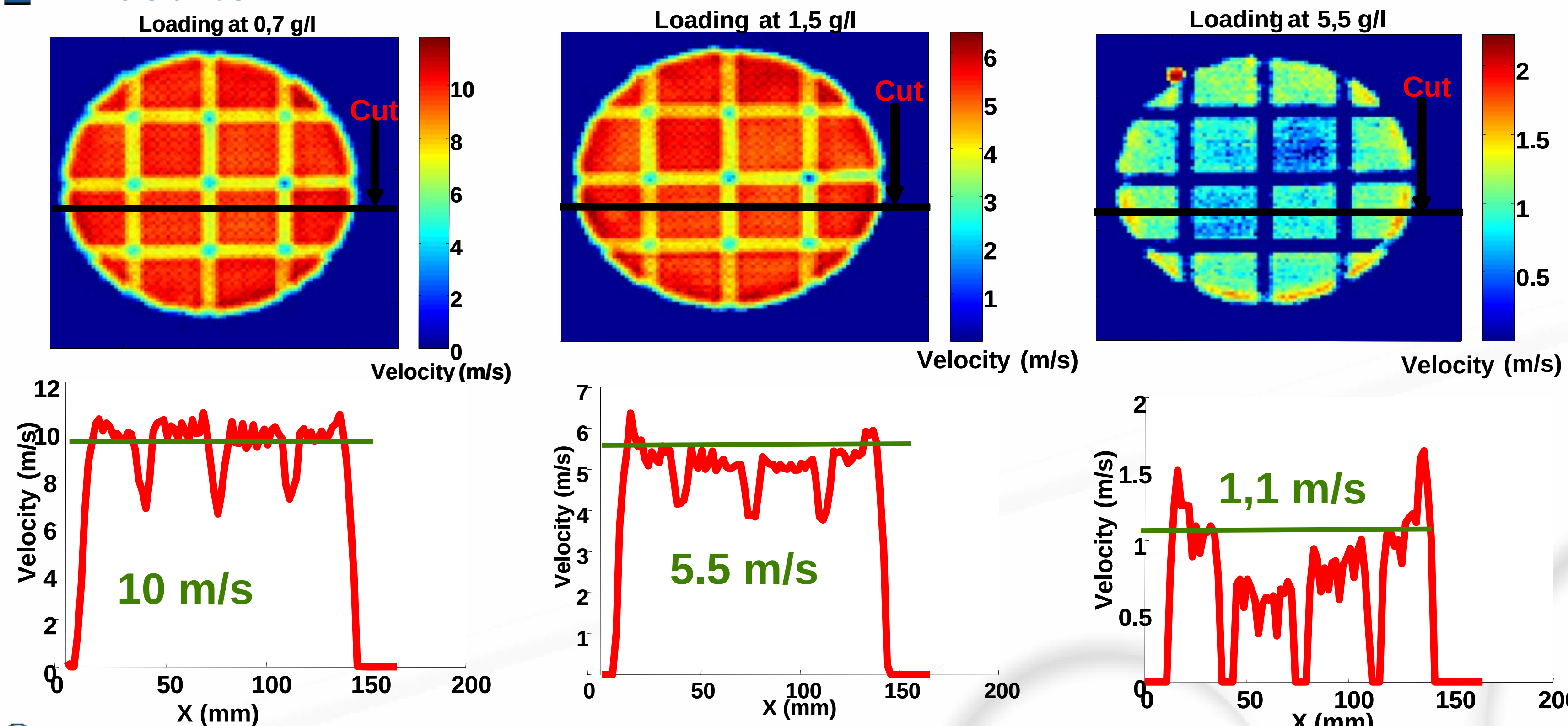
- ✓Passenger cars Diesel engine 2.0L, direct injection
- ✓Post-injection to increase exhaust gas temperature
- ✓Fuel: less than 50 ppm of S

Results: Loading

Protocol

- 3000 rpm, 50 Nm, flow rate 250 kg/h, exhaust gas temperature 250°C

Results:

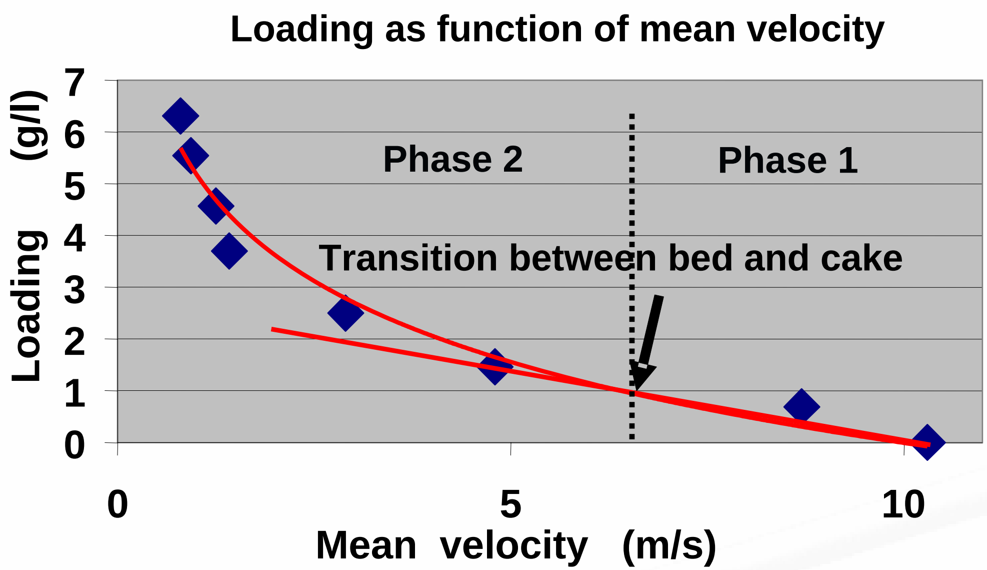


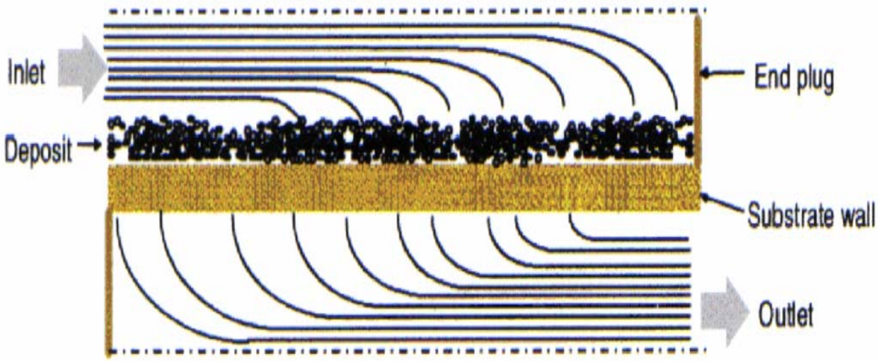
Velocity profile

- Initially completely uniform profile
- A slight increase of the amount of soot at the center of the filter is observed at higher loadings
  - This is due to the cone in front of the filter : Diverging angle more than 40°

Results: Loading

- Loading as function of mean velocity at the rear of the filter





- 2 phases :
  - First phase (linear) → Soot bed loading mode
  - Second phase (exponential) → Soot cake loading mode
- Transition from bed to cake filtration
  - Exact position has to be determined

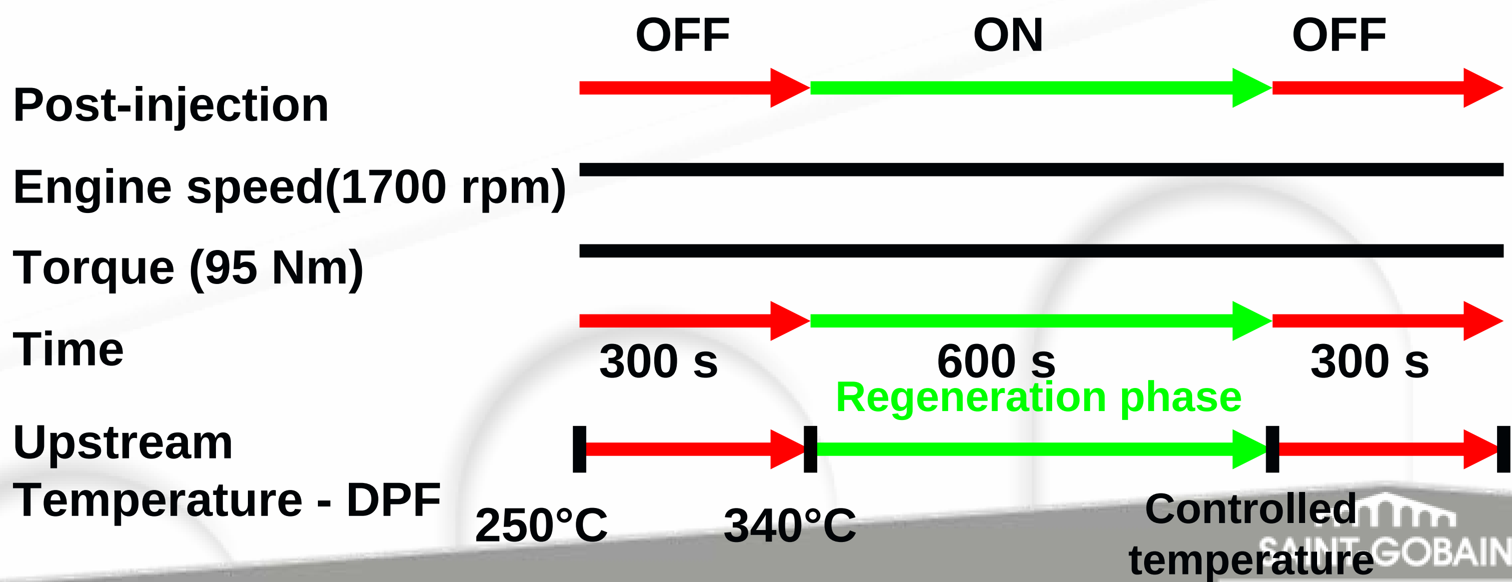
Partial regeneration: operating conditions

Protocol

- Loading at 7 g/l
- Controlled partial regeneration
- Weighing of filter
- Velocity profile measurement

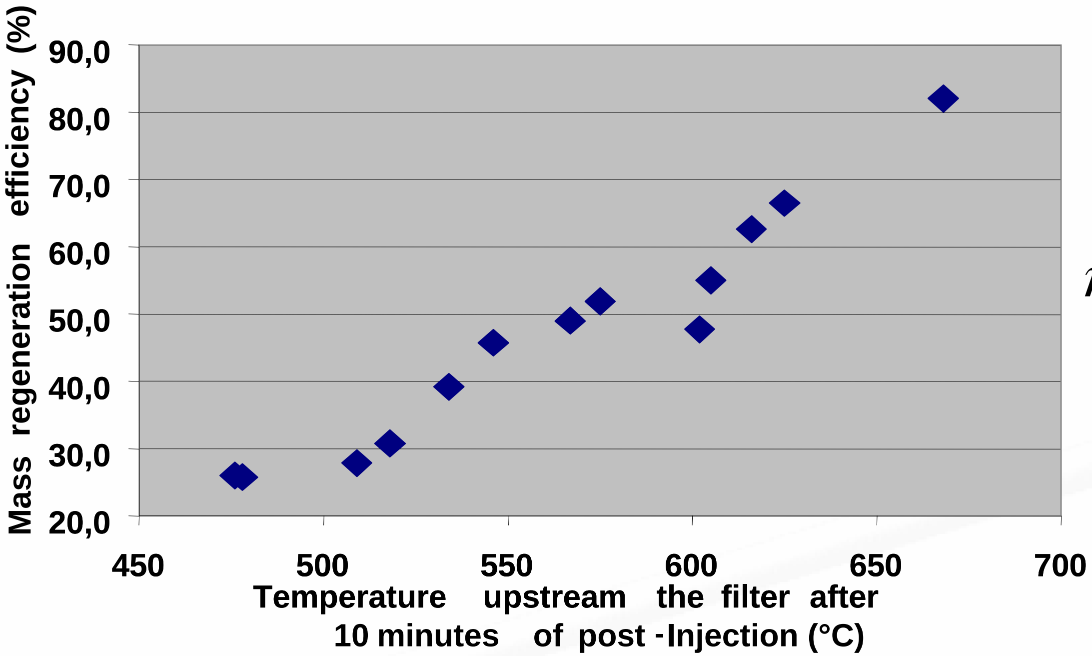
Operating point

- Corresponds to real-world driving condition at 90 km/h



Partial regeneration: Results

- Regeneration efficiency as a function of upstream temperature of the DPF



Mass regeneration efficiency:

$$\eta = \frac{M.loaded - M.regenerated}{M.Loaded - M.empty}$$

- Very good reproducibility (not displayed)
- Fraction of oxidized soot can be controlled by temperature

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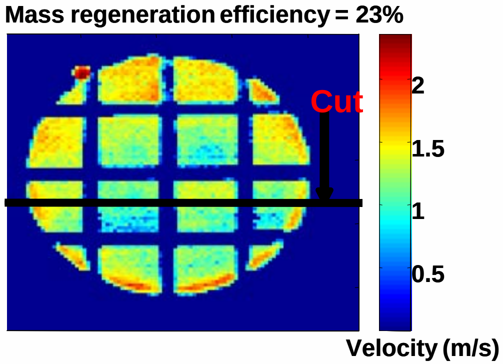
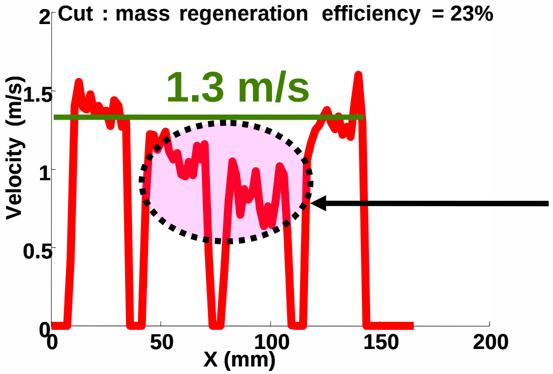
Partial regeneration: Results

Velocity profiles:

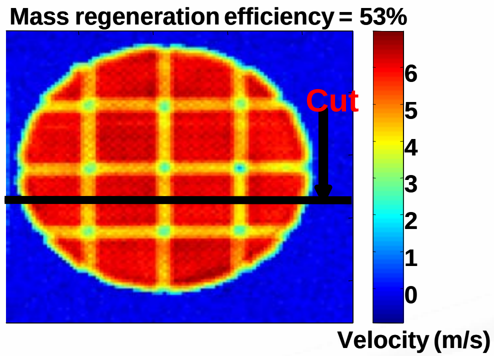
23%

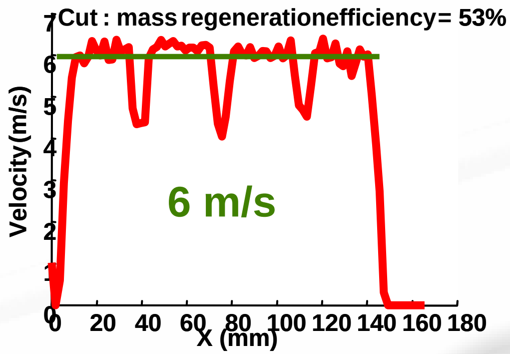




- Beginning of oxidation of soot where the filter is the most loaded

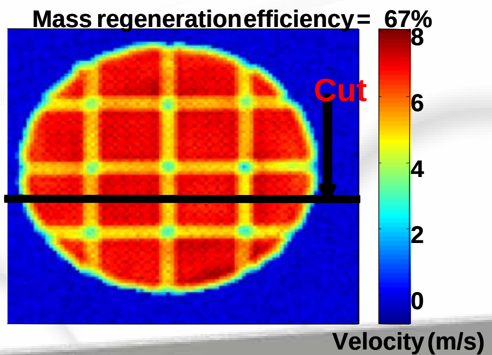
53%

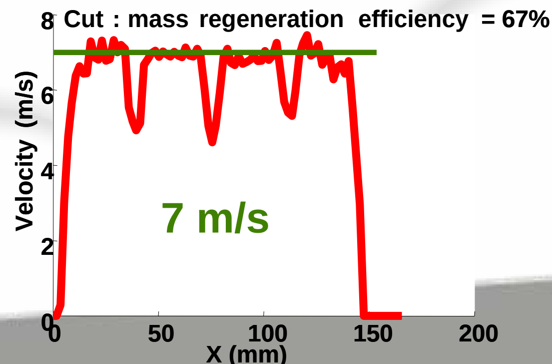




- Remaining soot distribution tends to be uniform quickly (30% of mass efficiency)

67%

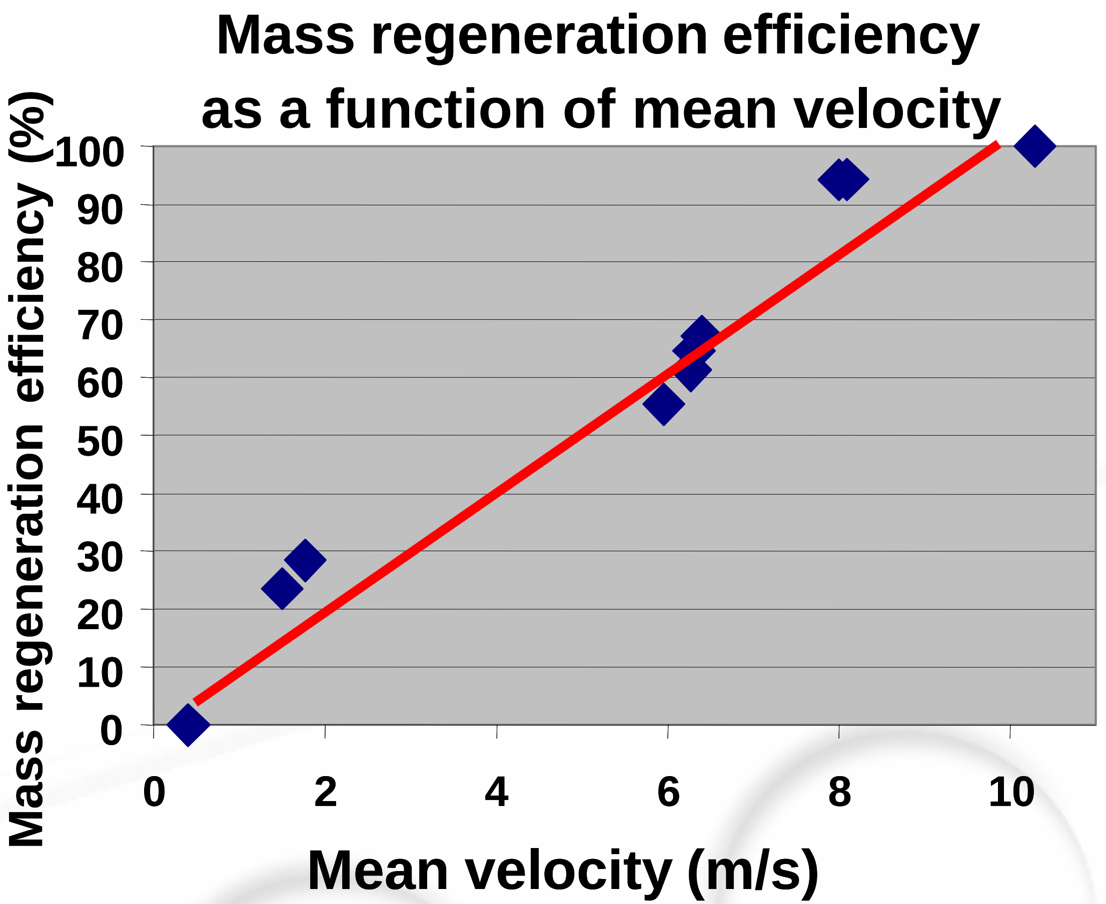




- As soon as remaining soot is uniformly distributed → Soot continues to burn uniformly

Partial regeneration

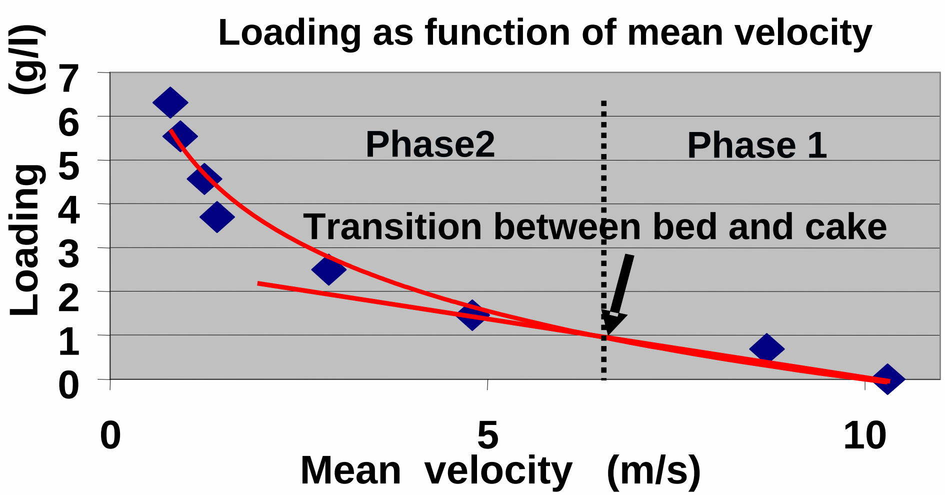
- Mass regeneration efficiency as a function of mean velocity

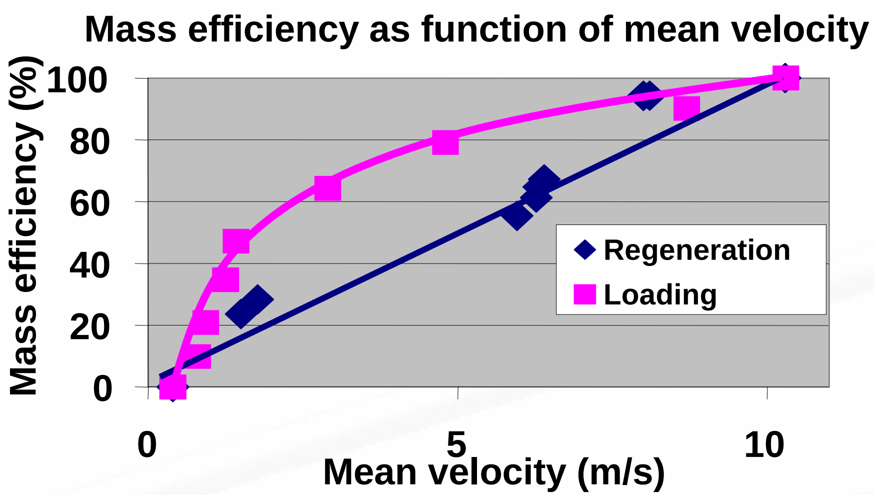


- Linear evolution between mass regeneration efficiency and mean velocity

Synthesis: regeneration-loading

Comparison of regeneration and loading





- Loading and regeneration display different behavior
- Longitudinal Soot deposition is uniform during loading

  (PhD Thesis B. Bouteiller 2006)
- Question raised: Where does soot burn?
  - At first in the bed?
  - Longitudinal non-uniformity?

Conclusions (1)

- **Experimental setup**
  - Experimental apparatus which measures **the radial velocity** at the filter outlet has been set up
  - Provides a good **accuracy** which allows to see **open and closed channels**
- **Loading**
  - Radial soot distribution is almost **homogeneous**
  - **Nonlinear** evolution of mean velocity
  - Determination of **« cake » - « bed » filtration transition ?**
- **Regeneration: With our protocol**
  - protocol → **Control** of the **regeneration efficiency**
  - **Remaining soot** tends rapidly to be **uniformly distributed in radial direction**
  - **Linear** evolution of the velocity profile

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Conclusions (2)

- **Quasi - homogeneous loading and regeneration in radial direction**
  - **One single channel is representative of the complete filter**
  - **Single channel modeling is representative of the entire filter**

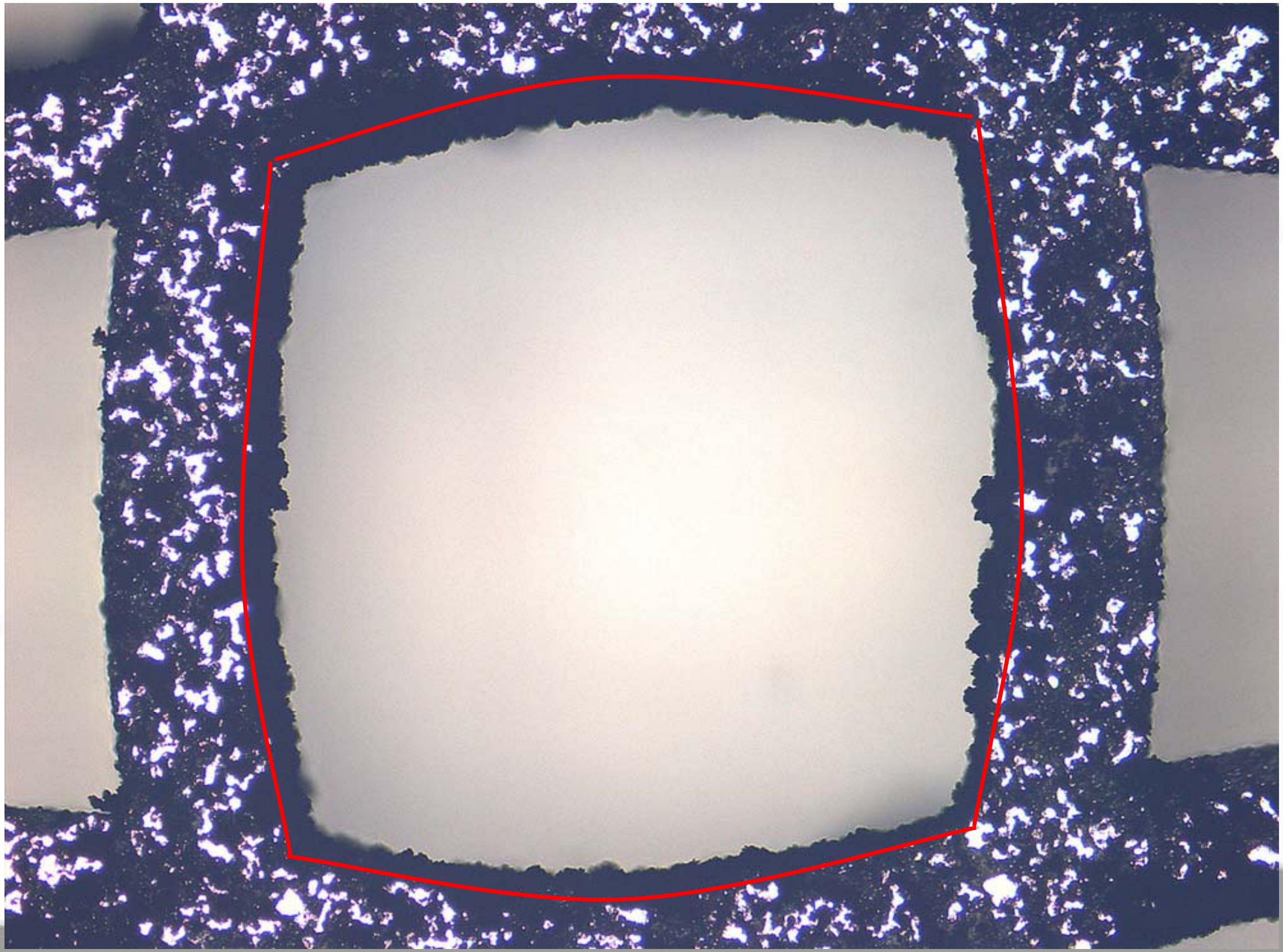
- **Comparison: Loading - Regeneration**
  - **Velocity as a function of soot mass at the rear of the filter during loading and regeneration are completely different. What occurs?**
    - Need to study soot distribution in longitudinal direction
    - Need to visualize the behavior of soot in (bed) and on (cake) the wall during regeneration

Work in progress

- **Visualization of soot oxidation in a single unit element**
  - **One single channel is representative**
  - **Longitudinal soot oxidation profile**
    - Unit element cut in 7 parts
    - Microscopic observation of soot thickness in each cross section

Work in progress

- Visualization of soot oxidation in a single unit element
  - Longitudinal direction
  - Bed and cake visualization

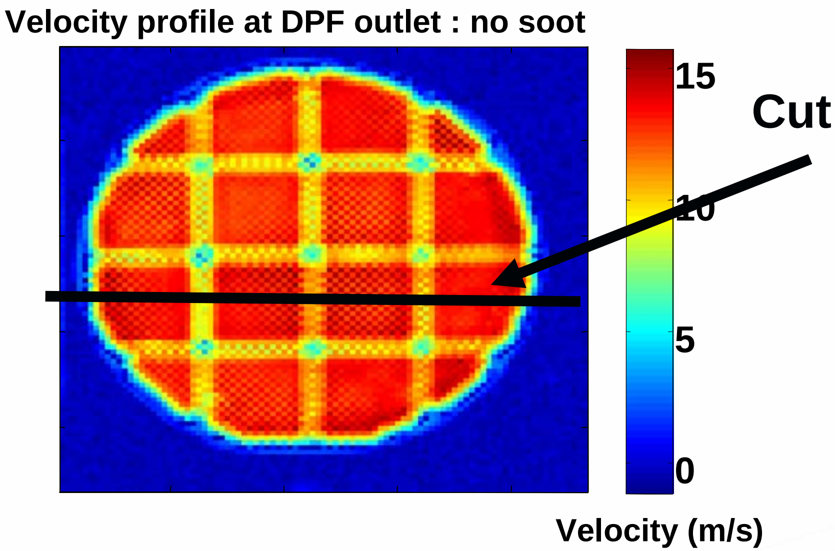


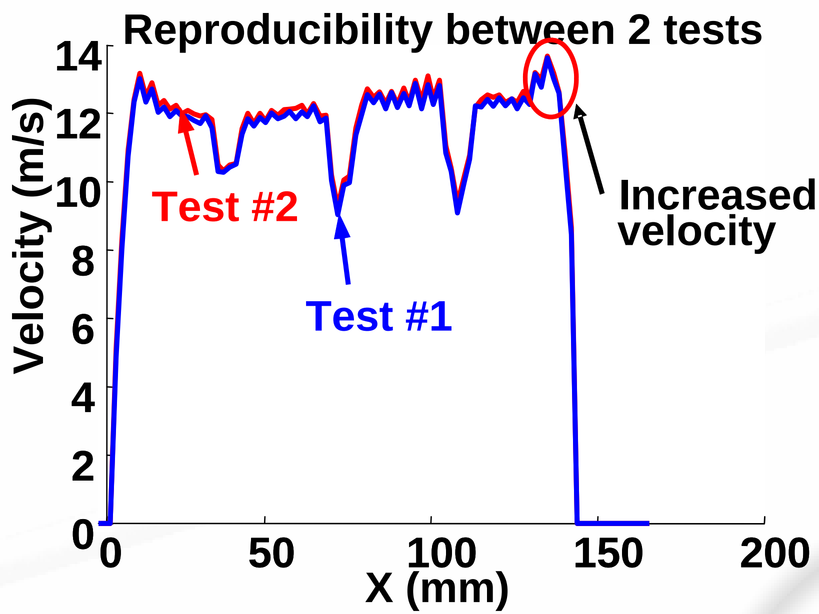
Thank you for your attention

- **L.M.E. Université Orléans (France)**
  - Dr. Alain Charlet
  - Nicolas Dumuis
  - Pr. Pascal Higelin
- **Saint-Gobain C.R.E.E.**
  - Patrick Girot
  - Vincent Gleize
  - Anthony Briot

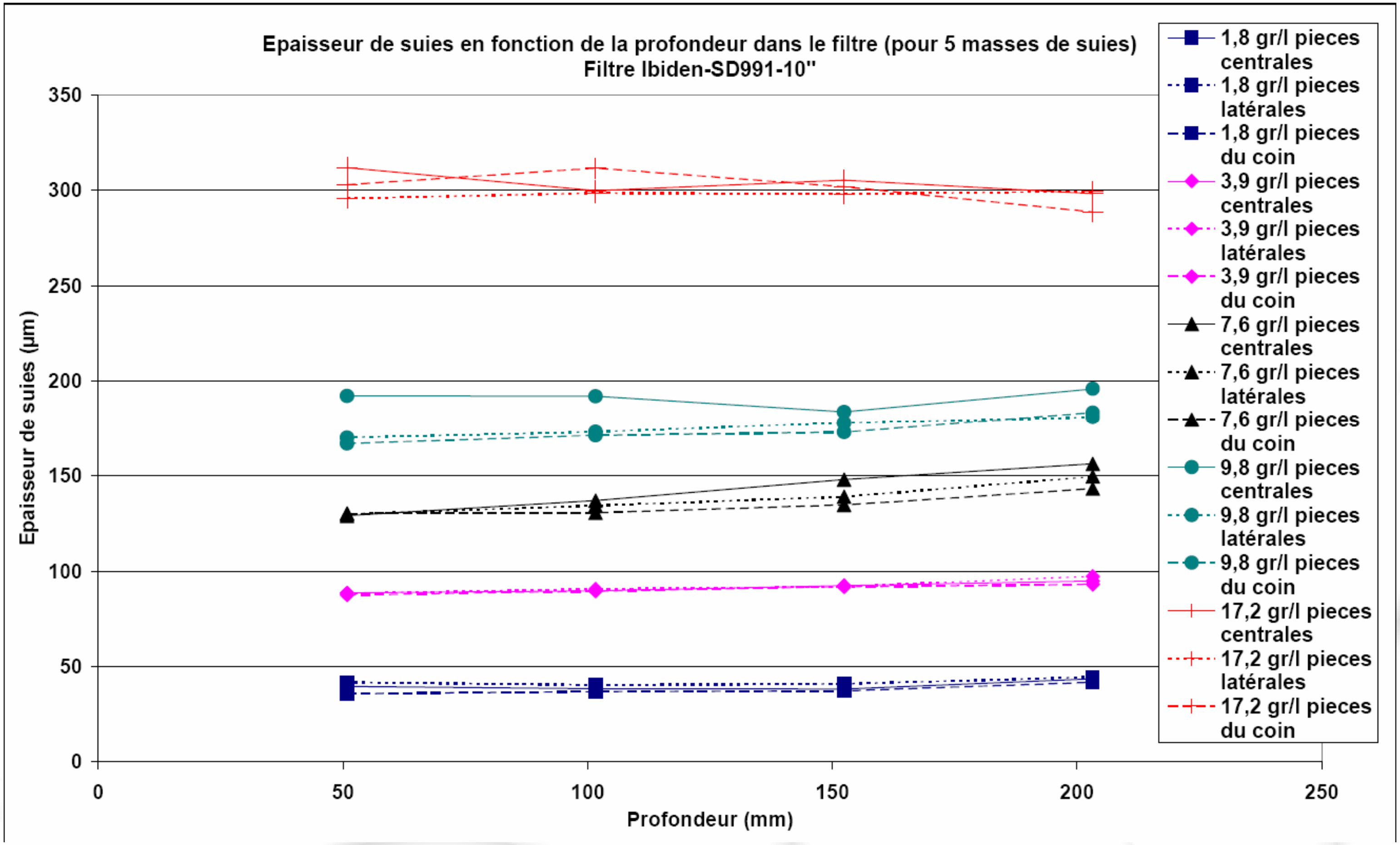
Experimental setup: Validation

Reproducibility tests





- Increase of the velocity at the periphery of the filter
- Very good reproducibility between 2 tests (error less than 2%)


Epaisseur de suies en fonction de la profondeur dans le filtre (pour 5 masses de suies)
Filtre Ibiden-SD991-10"
Epaisseur de suies (µm)
Profondeur (mm)
0
50
100
150
200
250
300
350
1,8 gr/l pieces centrales
1,8 gr/l pieces latérales
1,8 gr/l pieces du coin
3,9 gr/l pieces centrales
3,9 gr/l pieces latérales
3,9 gr/l pieces du coin
7,6 gr/l pieces centrales
7,6 gr/l pieces latérales
7,6 gr/l pieces du coin
9,8 gr/l pieces centrales
9,8 gr/l pieces latérales
9,8 gr/l pieces du coin
17,2 gr/l pieces centrales
17,2 gr/l pieces latérales
17,2 gr/l pieces du coin