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PM sensor development for on-board diagnosis of diesel particulate filter failures

J. Lavy, C.N. Millet, B. Réveillé, Abassi, L. Landry, Y. Creff
IFP Energies nouvelles,

F. Duault, S. Raquin
EFI Automotive

Contact : jacques.lavy@ifpen.fr

Environmental, ecological and health concerns result in tightening regulations of pollutant emissions from vehicle engines. In particular, diesel particulate filter (DPF) use is spreading with regard to particulate matter (PM) emission reduction. Regarding both US and EU legislation trends, it will be mandatory to monitor very low PM emissions to meet on-board diagnostic (OBD) requirements including DPF-malfunction detection. A PM sensor would here be entirely appropriate since the sensitivity of the current technology that is usually based on DPF pressure drop is too limited. Due to this increasing need, the development of various PM sensor technologies are currently under development.

Within the framework of the "CICLAMEN2" project, leaded by EFI Automotive and including EMSE, Renault Trucks, CTI and IFP Energies nouvelles, a PM sensor based on the resistive concept was developed. PM amount is calculated from the resistance measured between two electrodes, which decreases as conductive particles accumulate on the ceramic plate. After a certain period of soot loading, the PM sensor is able to regenerate itself by means of a heating resistance .
Soot deposition process plays a major role and the design of the sensor nozzle is one of the key elements to get accurate and robust response signal. 3D CFD simulation was performed to better understand the phenomena governing this process and to design a suitable sensor shield. It is important to avoid impact of large particles which disturb the sensor signal despite a very limited contribution to the soot mass, to get homogeneous particle deposition on the sensitive zone and to limit heat exchanges for a more efficient and faster regeneration.

The IFP-C3D software combining K-Epsilon RNG (Re-Normalized Group) turbulence model for fluid and lagrangian representation for particles was used. The spray liquid injection model was adapted for the particle representation. Turbulent dispersion appeared to have a predominant effect on the impact of particles below 5 µm, while inertia governed the impact of larger particles. Several shields were simulated to select the best trade-off between these two phenomena.

A specific particulate test rig was also developed to characterize and analyze the sensor response. For this new experimental set-up, a particle disperser was chosen rather than a particle generator. This approach allows to use various kinds of particles such as synthetic soot or soot recovered from an engine and to characterize the effect of the soot nature on the sensor response as well as flow velocity, temperature, soot concentration. Particle size measurement performed by SMPS allowed to check that the effect of the injection process in the PM test rig did not significantly modify the size of particles recovered from the engine: from 120 nm at engine outlet to 165 nm on the test rig, which was hence representative of conditions prevailing in an engine exhaust line.

A first evaluation of the PM sensor was made on both the engine bench and the PM test rig with soot recovered from the engine. The impact of soot concentration, velocity and temperature on the sensor resistance decrease with time was investigated.

The electronic unit was calibrated to regenerate the sensor once the resistance level of 1MΩ was reached. With this setting, the PM sensor sensitivity to soot concentration was characterized by analyzing the duration between each regeneration. As example, from 110 seconds for soot concentration of 11 mg/m^3, this duration increases up to 430 seconds when soot concentration is reduced to 4 mg/m^3. From the experimental data, we also calculated the soot quantity passing through the pipe during this regeneration duration. Effect of soot concentration and flow velocity was enhanced, leading to "corrective factor" set up and calibration. Similar tendency was observed for both particulate test rig and engine test rig results. Furthermore, correlation between experimental and 3D CFD results was made regarding the flow velocity effect.

PM sensor response according to soot mass flow rate was then analyzed and results from the particulate test rig fitted properly with results from an engine. This confirms the good representativeness of the particulate test rig and its potential to contribute to the development of such a PM sensor.

The PM sensor was finally evaluated on-board a vehicle at chassis dynamometer. For tail pipe soot emission of 9 mg/km, which is close to Euro 6c OBD thresholds limit of 12 mg/km, the PM sensor regenerated three times. We also noticed that the duration between the two last regenerations event occurring during the extra urban part of the cycle was shorter than during the urban part. This correlates with the higher soot quantity emitted during the accelerations of the extra urban cycle.

These results demonstrated the capability of such a sensor to be used as a micro DPF failure detector for future OBD requirements. To continue this work, a PM sensor model will be developed and validated from the overall experimental data obtained. DPF failure detection strategies will be also developed to be able to identified faulty and not faulty DPF during real vehicle life.

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PM sensor development for onboard diagnosis of diesel particulate filter failures

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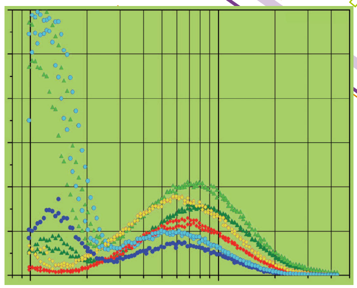
Zurich, 25-27th June, 2012



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Energies nouvelles

Outline

- Context, objectives and basics
- PM sensor design optimization by 3D-CFD
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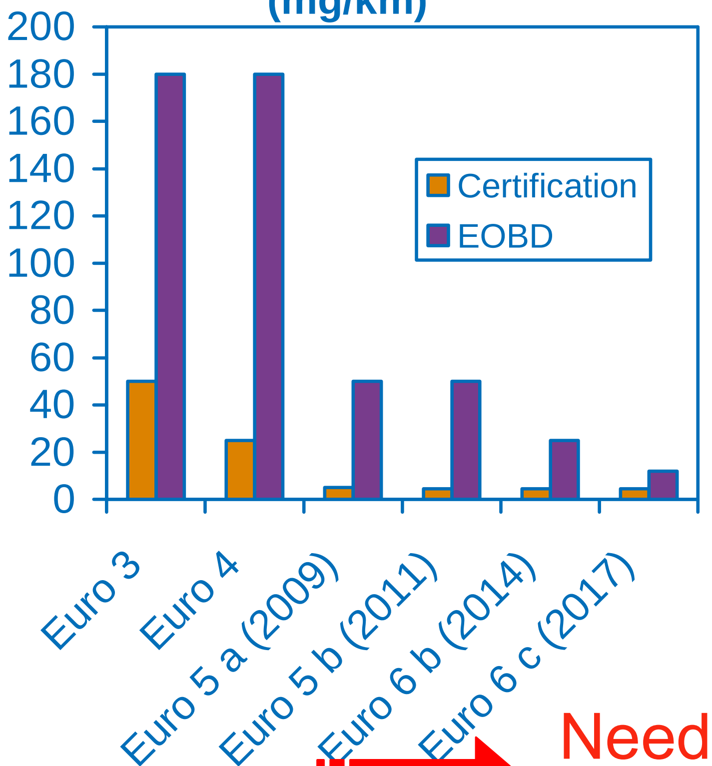
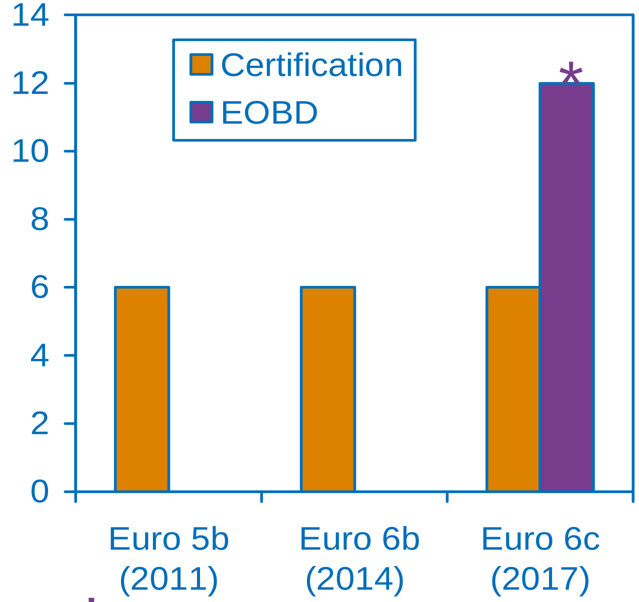
Particulate Matter
regulation evolution for Diesel PC in Europe

PM mass certification and EOBD threshold limits (mg/km)



PM number certification and EOBD threshold limits ($\#10^{11}$/km)

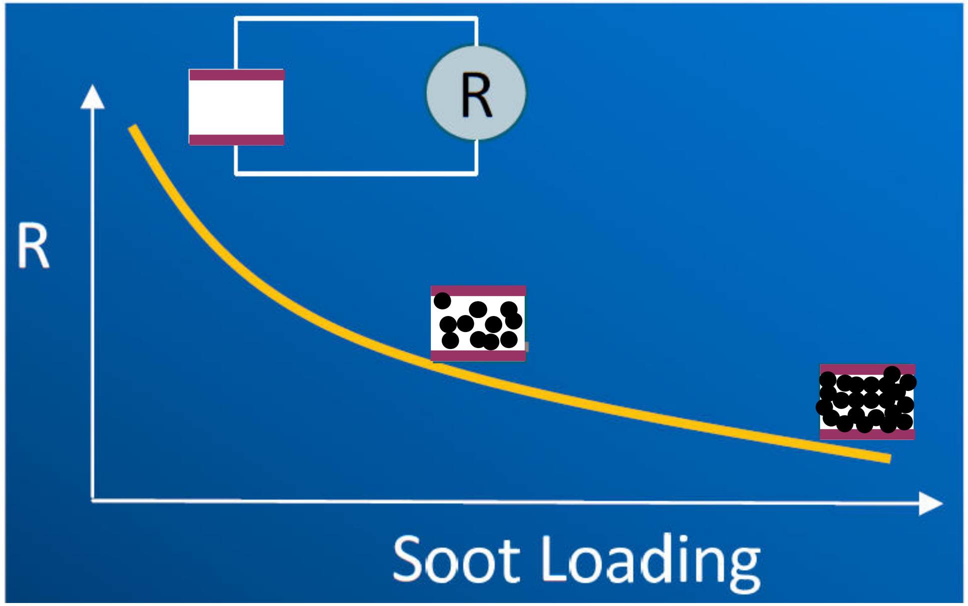


* To be assessed by sept 2014

Need for onboard soot sensors to comply with EOBD threshold limits in 2017

Basics of the resistive concept

Resistance decreases as conductive carbonaceous particulate accumulate

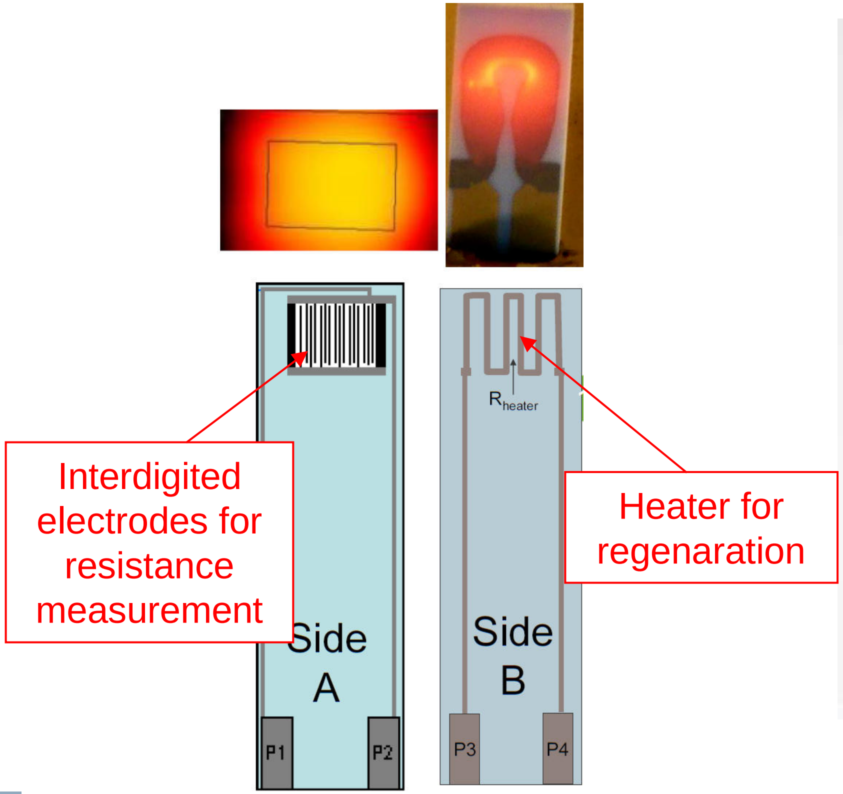


⇨ Accumulative process, regeneration needed

Sensor design

Sensitive element

Packaging & control unit



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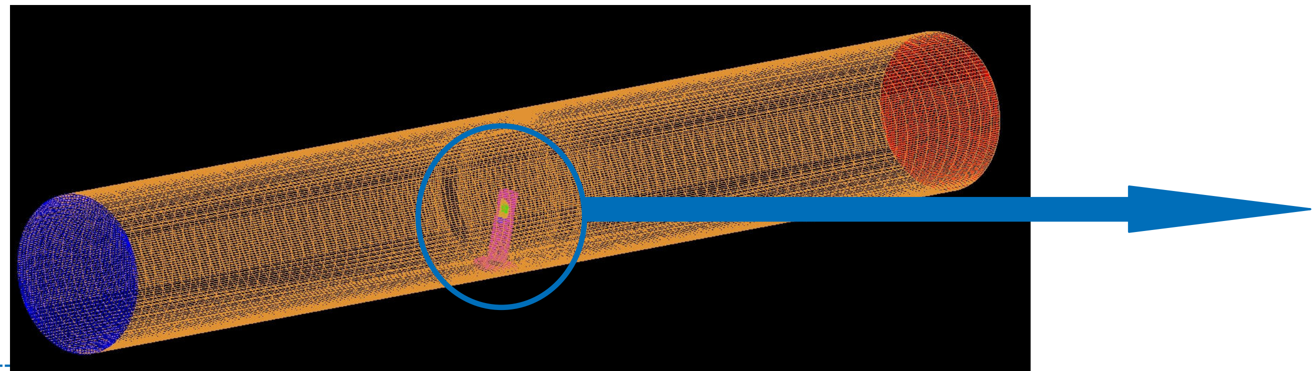
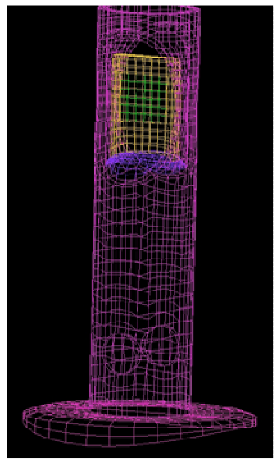
Sensor shield design optimization by 3D-CFD

- Objectives :
  - homogeneous particulate deposition
  - no large particulate impact
  - limited heat exchanges for efficient and fast regeneration

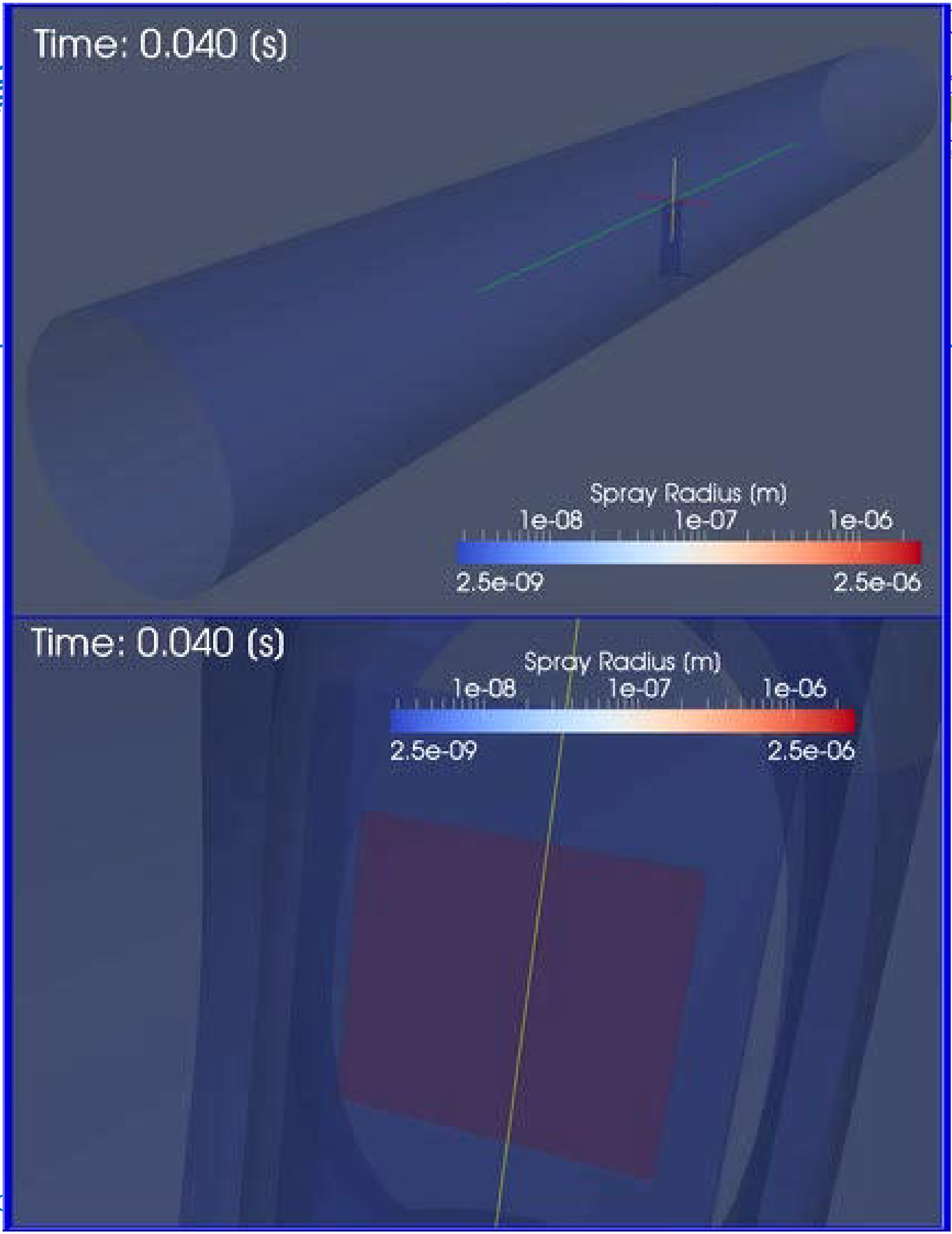
3D simulation by IFP-C3D

- K-Epsilon RNG turbulence model for fluid
- Lagrangian representation for particles
  - Based on spray liquid injection models (no evaporation)
  - Turbulent dispersion also taken into account for particles
  - Several particle sizes can be injected simultaneously
- 255 000 cells and 268 000 nodes
  - 64 processors → 25 to100 h (depending on flow conditions)





3D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Spray Radius (m)
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1e-07
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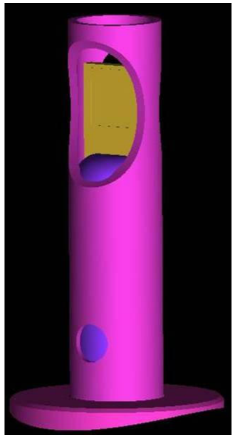

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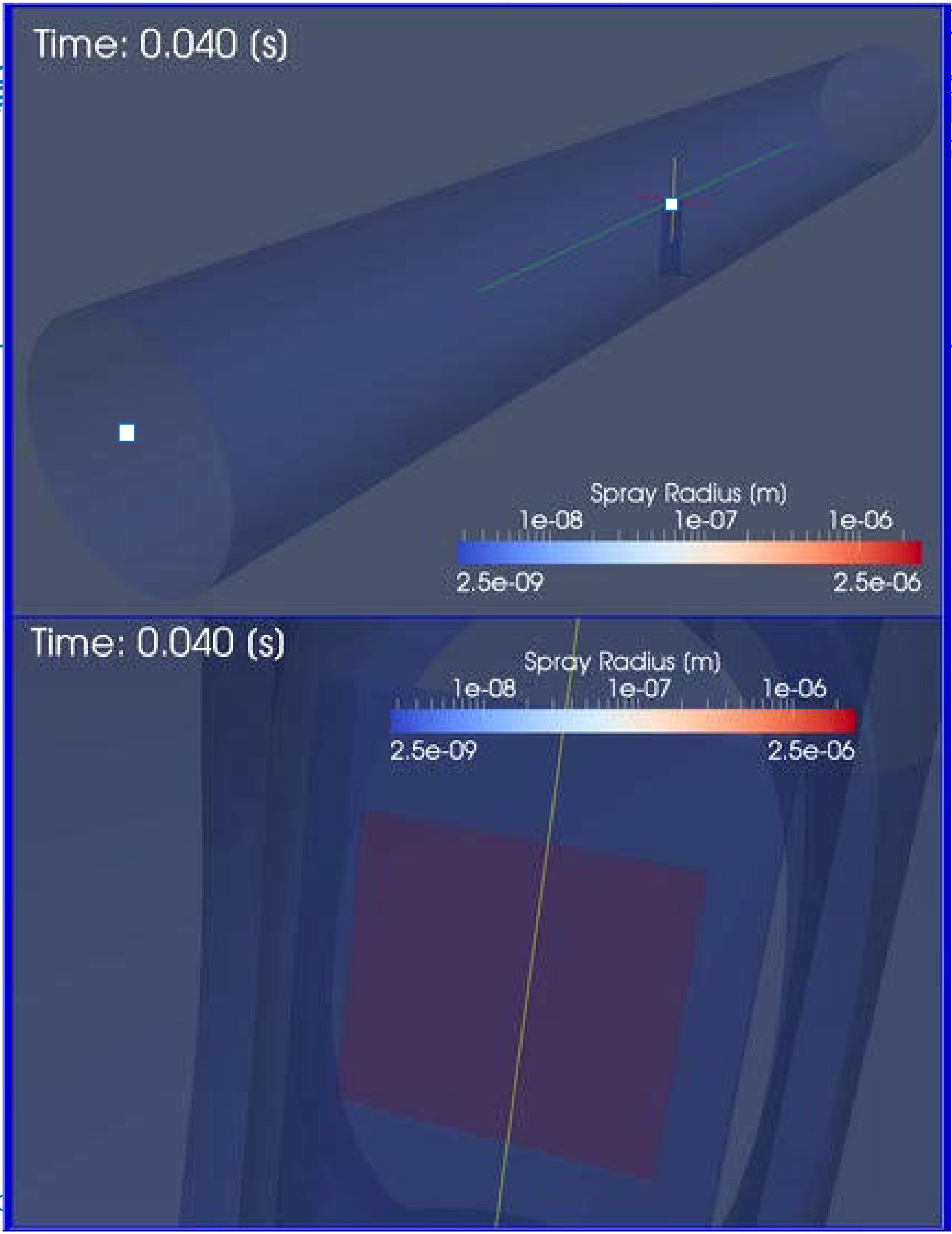
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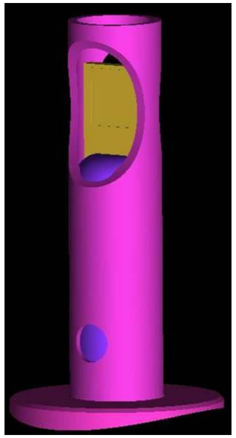
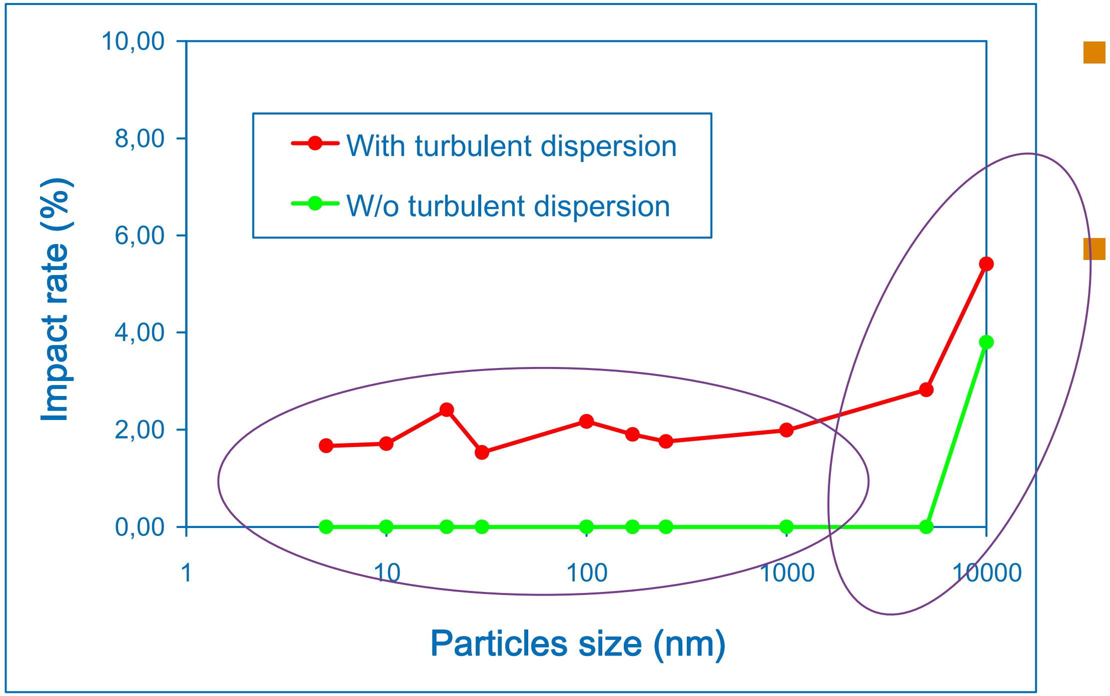


3D simulation by IFP-C3D

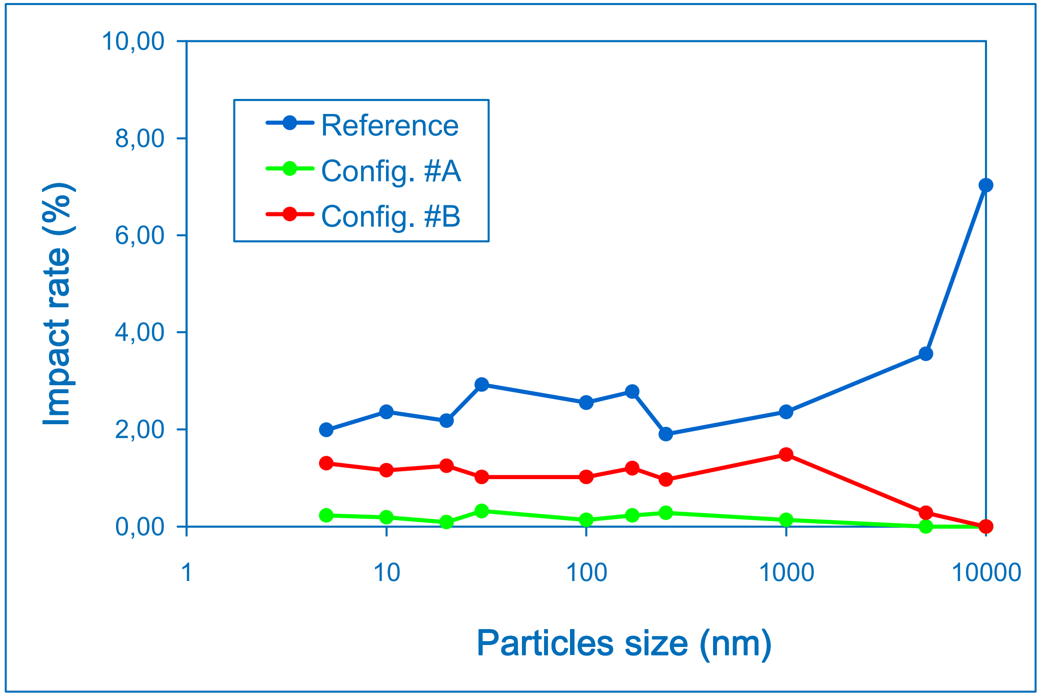
Turbulent dispersion and inertia effects



- Turbulent dispersion governs deposit of particles below *5 µm*
- Inertia governs deposit of particles above *5 µm*

3D simulation by IFP-C3

Sensor shield design optimization



- Reference design :
  - large particles impact a lot
- Config. #A :
  - no impact of large particles
  - limited impact rate for smaller sizes
- Config. #B :
  - no impact of large particles
  - impact rate remains significant for smaller sizes

Best experimental results with Config.#B

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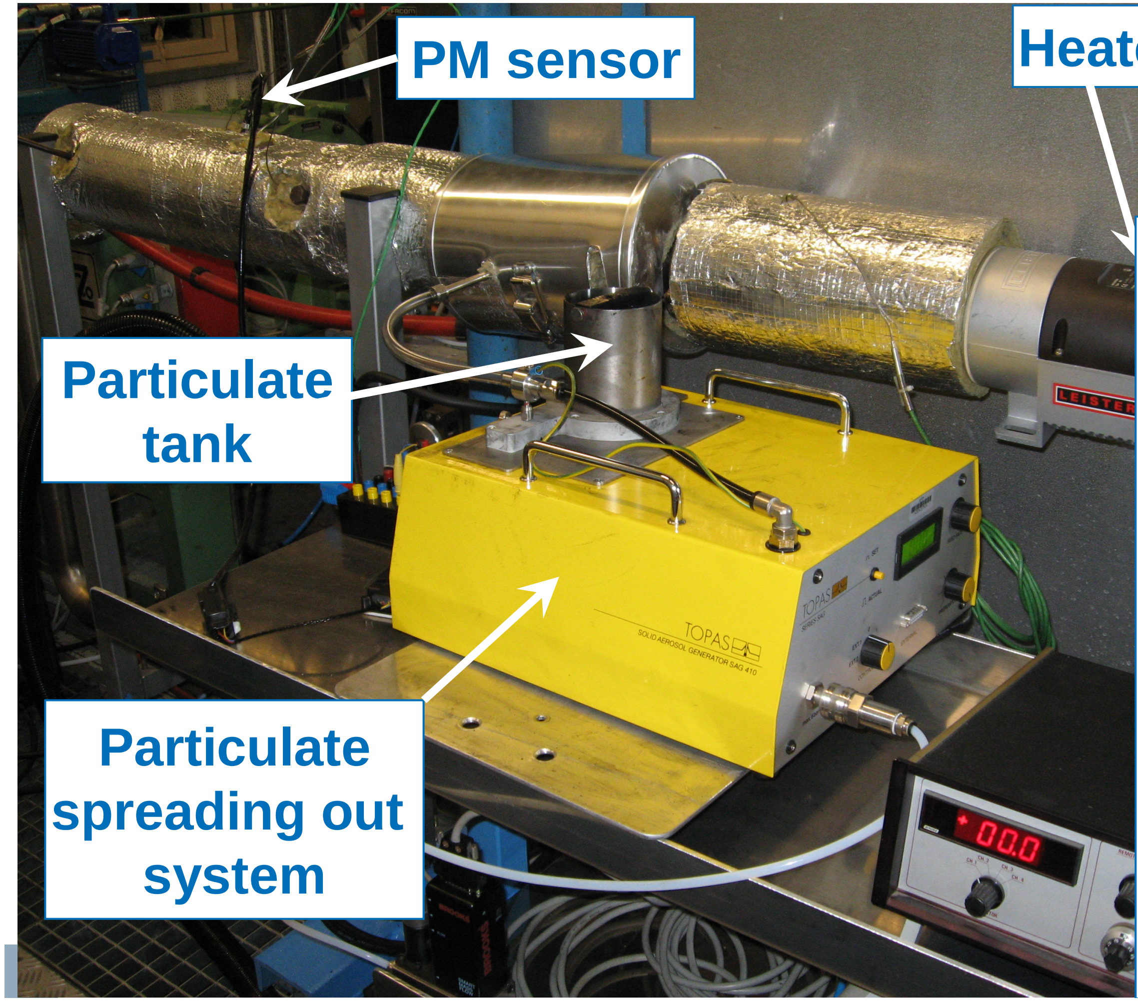
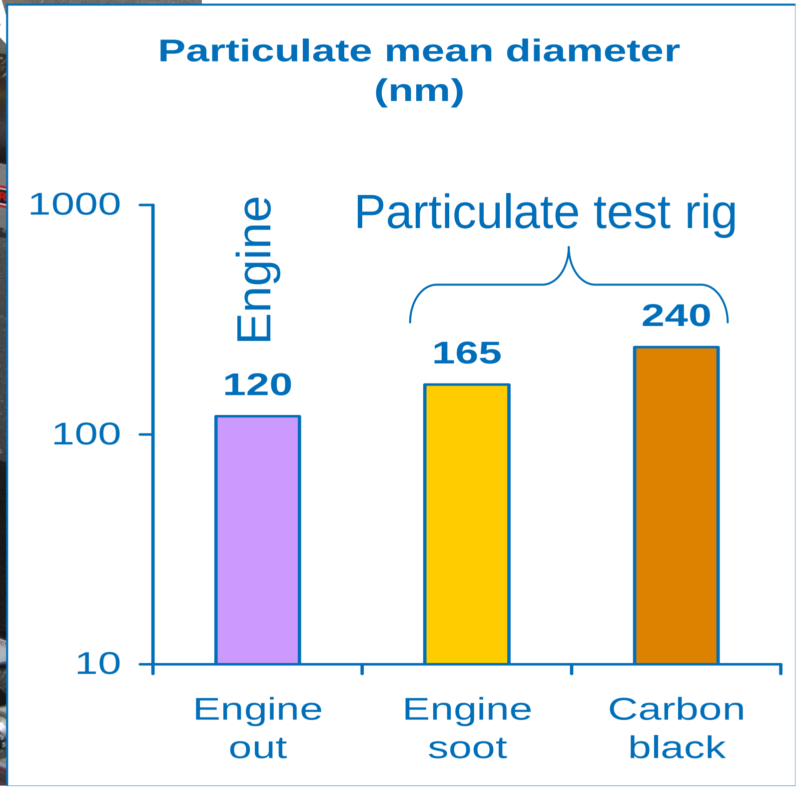
PM sensor response characterization

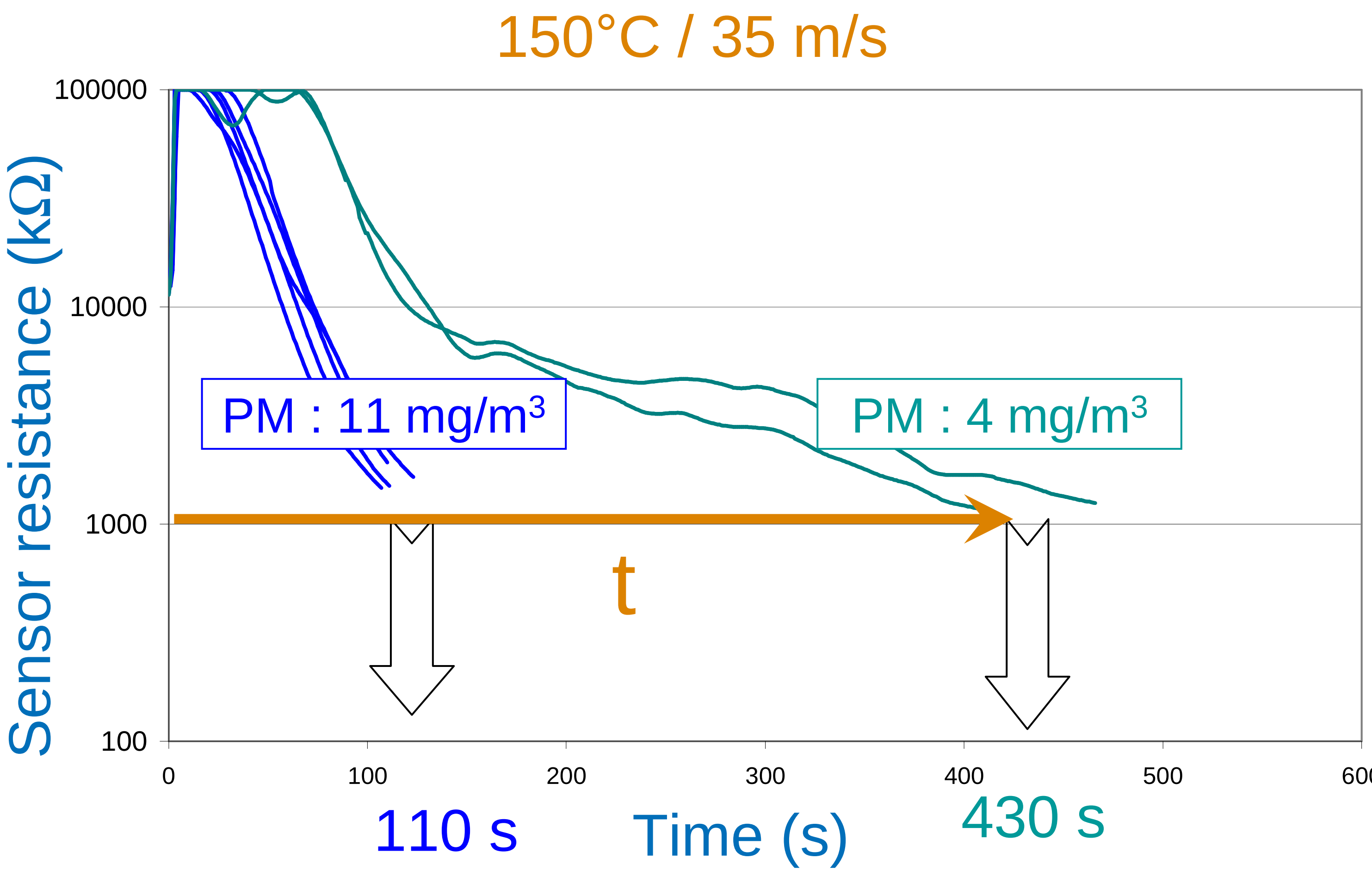
Specific particulate test rig



***Φ* : 39** mm
Flow rate : **0** → **350** m³/h
Flow velocity : **0** → **80** m/s
Temperature : **20°C** → **450** °C
PM concentration : **0** → **250** mg/m³

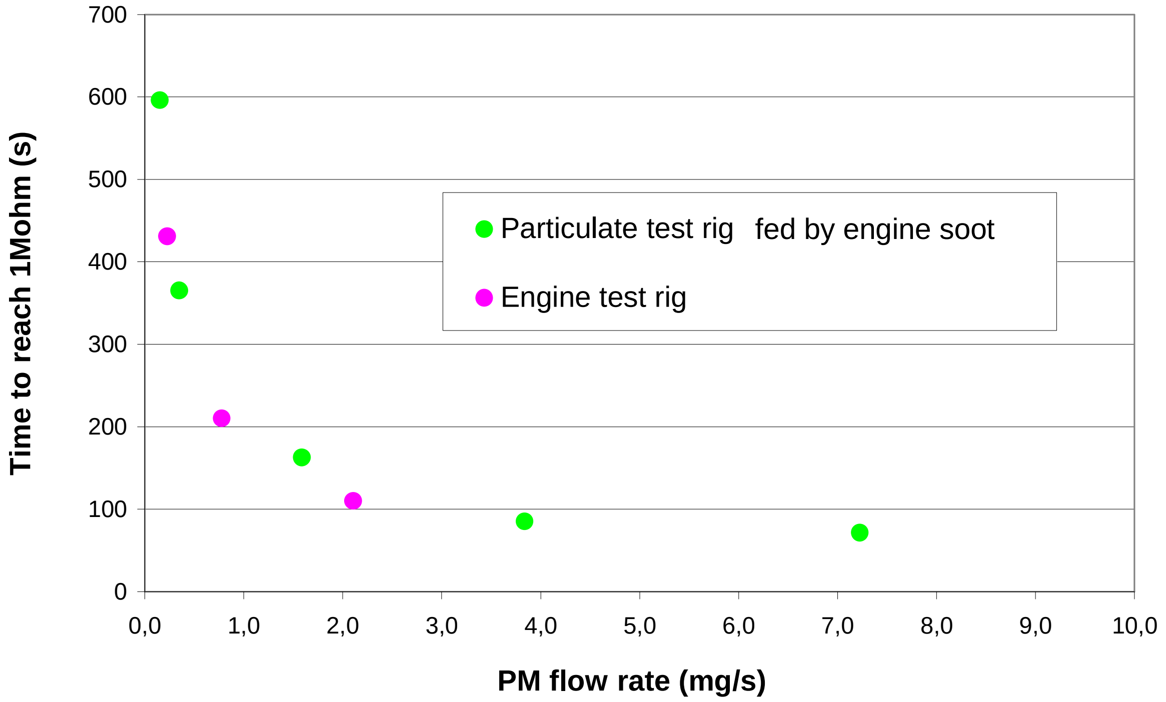


PM sensor response characterization



PM sensor response characterization

Engine and particulate test rig results comparison



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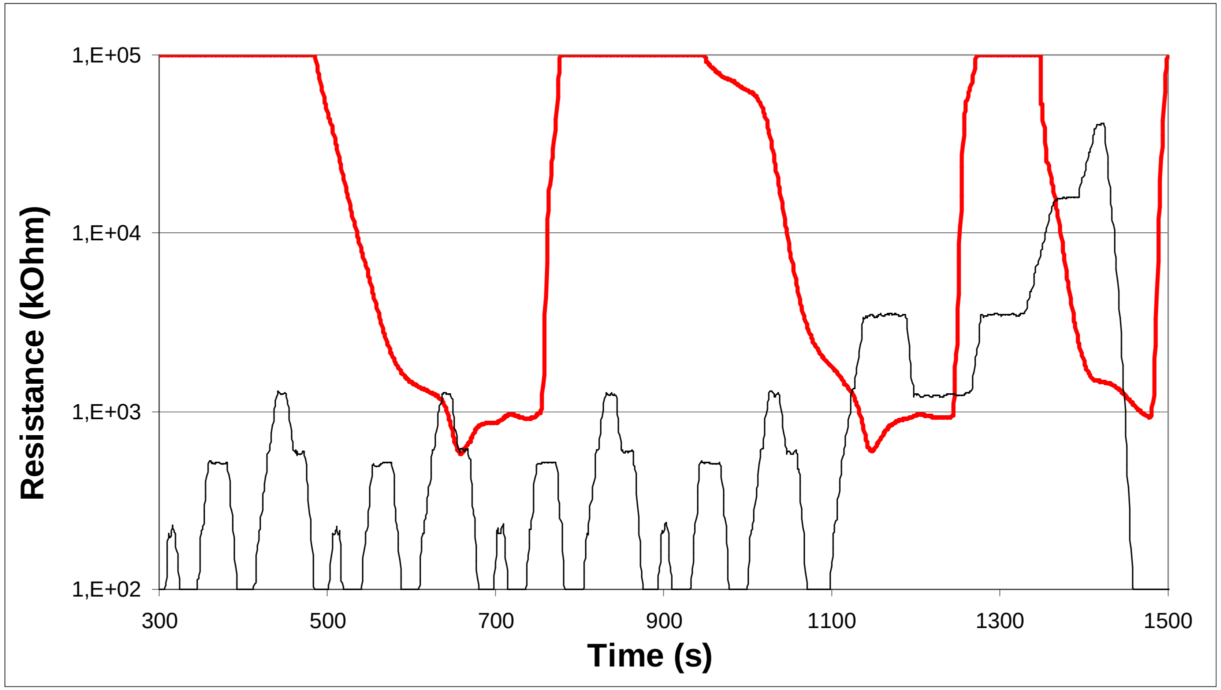
Vehicle evaluation



NEDC (hot)

PM : 9 mg/km

Sensor sensitivity confirmed by NEDC cycle at PM emission level close to most stringent OTL

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Conclusion

- Onboard resistive PM sensor developed
- 3D-CFD helped
  - to better understand particles deposit process
  - to optimize the sensor design
- A specific particulate test rig was developed
  - independent control of flow velocity, temperature, soot concentration and soot nature (synthetic soot or engine soot)
  - sensor response analysis and results in accordance with engine tests
  - high sensor sensitivity to low soot concentration
- PM sensor validation on vehicle
  - sensor sensitivity confirmed during NEDC cycle

➢ Resistive sensor adapted to future OBD threshold limits

Outlook

- Flow velocity, soot concentration and temperature effects analysis to define correcting factors in progress
- PM sensor model and DPF failure detection strategies set up
- Durability tests continuing (600 h, 2400 regenerations achieved so far on an engine) and poisoning robustness validation (from fuel and lubricant additives)
- Evaluation of PM sensor response to particulate number
  - Diesel engine
  - GDI engine (GPF developed to comply with future PN legislation)

Acknowledgments

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- To "CICLAMEN2" project partners

Tank you for your attention

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