

Smart Soot Sensor for Particulate Filter OBD

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ABSTRACT

In the frame of tighter emission requirements and environmental protection, future standards will soon lead to the use of an OBD soot sensor to monitor DPF leakage. Such a sensor will first be introduced in the US by MY 2015 and then in Europe for Euro 6.2 in 2017. The resistive ceramic sensing technology has been selected by most OEM as the most appropriate. The sensor collects the soot in a time cumulative manner and has an internal heater to clean the ceramic before each measurement sequence. The actual challenge of the hardware is to design a wide band collecting system with a high sensitivity and repeatability circuit processing. Electricfil has overcome major drawbacks of the resistive technology with an innovative sensor tip, with filtration features and a boosting electronic scheme. This sensor integrates internal diagnostic capability at power on and during operation.

But the most challenging task of the smart soot sensor is to be able to diagnose filter leakage whatever the driving condition are, smoother or tighter than the standard NEDC, FTP or WLTC cycles. The goal is to guarantee a robust detection of failure with no more than 1ppm false detection and no more than 100ppm of undetected leakage. In order to accommodate with OEM request and available database, Electricfil and IFPEN have developed two strategies, one assuming that the engine soot cartography is available and a second one without. Both predictive techniques have been simulated and show very good results. Intensive testing are on going to characterize the performances of these strategies on real time driving conditions with several vehicles.

The paper will describe the innovative hardware and software solutions and present the simulated and measured performances.

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INTRODUCTION

Despite Diesel Particle Filter has become a standard on diesel engines in most of worldwide countries, there is an increasing concern on human health. Since particles can deposit in the alveoli of human lungs it is in the public interest to have a high level of protection from these particles. The emission standards are lowering the allowed amount of particles emitted by the vehicle:

- California emission standards, the most stringent, are showing the path with proposal of 3mg/mi emission limit in 2021 and 1mg/mi goal in 2028 model year. The OBD

threshold limit (OTL) will be 1,7 times the emission limit by 2014 (1)

- European standard for Euro 6 and Euro VI have finally been approved with the respective OTL of 12 mg/km in 2017 and 25 mg/kWh in 2015 (2).

In the future new world harmonized light duty test cycle and real driving emission (RDE) tests will drive the pressure on cleaner vehicles.

Current DPF OBD is managed by differential pressure sensors, which sense the pressure drop within the DPF. Several studies (3, 4) have shown that this technology will



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Table 1. Electricfil's PM sensor targets

CRITERIA	REQUIREMENTS
Accuracy	1 ppm false detection 100 ppm non detection
Response Time	Detection on 2 nd NEDC Confirmation on the 3 rd cycle
Max regeneration power	6A max peak 24 W
Max regeneration time	30s @ whatever the flow conditions are
Internal OBD features	Open circuit Short circuit Plausibility Gain, offset, voltage range
Lifetime	200 000km

not be able to meet the stricter regulations applicable after 2015-2017. In the frame of tighter emission standards, Electricfil initiated the development of a soot sensor for OBD purpose five years ago (5, 6, 7, 8.). The sensor located downstream of the DPF collects the soot in a time cumulative manner so as to monitor any leakage. It contains its own software for signal processing and cleaning strategy and transmits to the engine control unit (ECU) a signal of OTL compliance.

OBD REQUIREMENTS AND CHALLENGES

The lowered soot OBD threshold will require the use of a soot sensor after the DPF. This sensor will perform the soot measurement and process the information so as to provide to the ECU "high level information" relative to DPF leakage. For such processing the sensor will also request some information about the engine operating conditions from the ECU.

The diagnostic of exceeding threshold limit must be guaranteed during certification phases on a succession of maximum 3 NEDC cycles and also in driving conditions with minimum frequency defined by the IUPR standard (In Use Performance Ratio). The challenge is therefore to design a robust OBD sensor for both certification cycle and real driving conditions whatever the driving conditions. The OTL is a fixed value, but due to physical uncertainties and tolerances, a statistical approach has to be considered. Hence, the main challenge of the DPF diagnostic strategy is to detect all faulty DPF while minimizing false detections (of good DPF).

The sensor with the embedded strategy must provide a quick and robust DPF status. A DPF diagnostic strategy failure in real life driving conditions would be to consider a faulty DPF as good or to consider a good DPF as faulty. Moreover the sensor must withstand very harsh environment conditions (temperature, vibrations,...) and must not be affected by ash, rust, moisture, acids,...

Following a wide customer survey, ELECTRICFIL is working on below specification for typical light duty application:

SOOT MODULE HARDWARE

The Electricfil sensor's is based on the resistive technology: on an insulating substrate, the soot is collected between two platinum interdigitated electrodes. When there is no soot on the sensor, the resistance measured between the electrodes is close to the one of the substrate. When the soot is collected on the sensitive window, the resistance is decreasing. A heater is placed on the sensor in order to burn the soot and repeat multiple measures in a row.

Although the measuring principle of is very simple, this technology has to overcome some challenges:

- Withstand the exhaust environment
- Regeneration in any case of temperature and flow
- Resist to at least 100 000 regenerations
- Insensitivity to big particles blown off of the exhaust tube
- Insensitivity to position

Mechanical of the Sensor

The soot sensor is an exhaust sensor comparable to a NOx sensor; it is composed by a ceramic sensitive element inserted in a body made of different stainless steel alloys and a sensor control module (SCM) that manages the sensor and communicates with the ECU of the vehicle.

The [Figure 1](#) shows a drawing of the sensor and 3Ds of the sensor and the SCM.

The ceramic sensitive element of the sensor is protected from breakage thanks to the tip which has a plane area that orientates the sensor in the boss. The ceramic substrate is placed and hold in the tip thanks to different bids. A glass sealing insures the tightness between the exhaust environment and the connection area. The tip is laser welded to the rear tube and a rubber gasket insures the tightness between the outside environment and the connection area. In the connection area, a ceramic connector and stainless steel

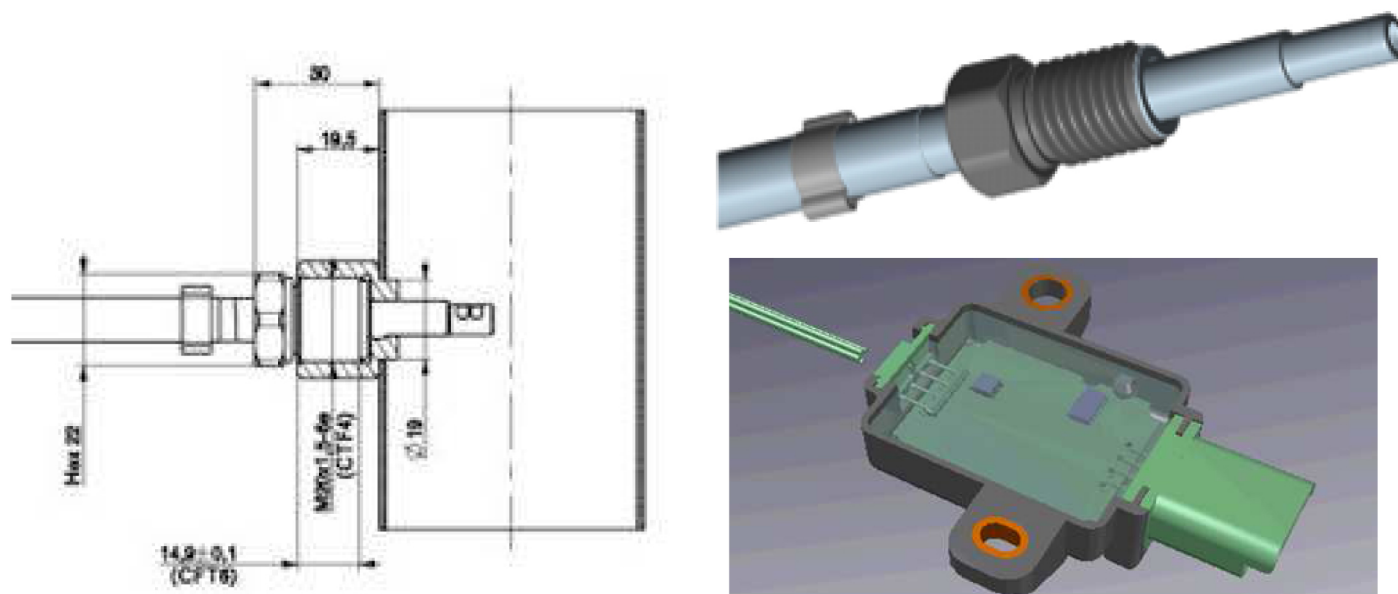


Figure 1. Drawing of the sensor and 3Ds of the sensor and the sensor control module (SCM)

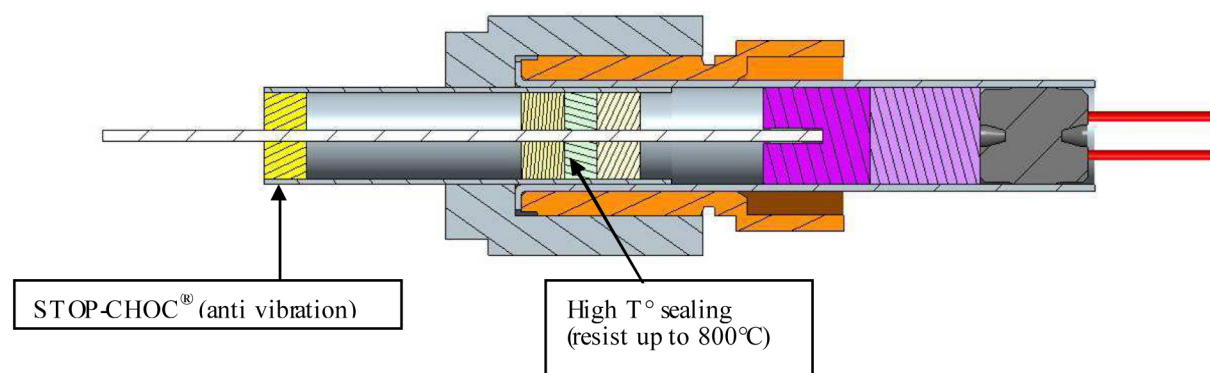


Figure 2. Internal design of the sensor

terminals apply a mechanical contact on the track pads. The packaging is designed to withstand the severe exhaust environment (three patents deposited and one already accepted WO/2011/004121).

The SCM, a 50×45 mm box, hosts different strategies that manage the sensor such as regeneration strategy, measuring strategy, dew point strategy, sensor diagnostics, communication with the ECU thanks to CAN bus... and even a DPF diagnostic.

Regeneration of the Sensor

Regeneration is a necessary step in a measuring cycle. This enables the sensor to be cleaned and ready for a new measurement cycle, burning the soot that has been collected on the sensitive element. A platinum track (heater) is screen printed on the sensor substrate in order to complete this step. This is an operation during which it is impossible to measure soot in the exhaust tube, in a consequence, the regeneration

duration must be as short as possible. Of course the regeneration strategy is of high importance because it guarantees the temperature target and controls when starting the regeneration and when stopping it, but the hardest work here was to design a robust heater that requires as less power as possible.

In order to minimize the regeneration time and the power needed to complete a regeneration it is possible to:

Apply a homogeneous temperature high enough to burn the soot on the sensitive element

→ the heater has to be very well designed

Apply a very high temperature

→ the substrate has to withstand very high mechanical stress

Decrease the substrate mass

→ the substrate has to be well designed and the sensitive element has to be taken into consideration in order to keep the same area and thus the same response time

Table 2. Thermal-mechanical-electrical model input data

Ambient temperature	120°C
Initial substrate temperature	160°C
Exchange coefficient between exhaust gas and substrate	350 W/(m².K) (@30m/s)
Substrate thermal conductivity	24,7W(m.K)
Substrate density	3720 kg/m³
Substrate specific heat	880 J/(kg.K)
Substrate Young modulus	303.10⁹ Pa
Substrate Poisson modulus	0,21
Substrate thermal expansion coefficient	8,2.10⁶ K⁻¹
Heater resistivity @ 25°C	1,3.10⁶ Ω.m
Heater thermal resistivity variation	0,0026 K⁻¹



Figure 3. Temperature cartography (a) of the “optimized design” and (b) of the “design 1”

Decrease the cooling of the substrate by the exhaust flow (forced convection coefficient)

→ the tip of the sensor has to be well designed
Thus one main topic of the sensor conception is to design a heater that enables a quick regeneration, insuring a very high robustness of the sensitive element.

Of course it is impossible to test experimentally all these parameters independently. So we have simulated the thermal-mechanical-electrical behavior of the sensitive element to optimize the sensor regeneration. We used the COMSOL software to do this study with the following input data:

Different parameters were studied in order to find the best heater design according to the following output data:

- Von Mises stress
- Thermal homogeneity
- Heating efficiency

Simulation results of the optimized heaters in temperature homogeneity (optimized design) and in power consumption (design 1) are shown on Figure 3, Figure 4, Figure 5:

The Figure 3 and Figure 4 shows very good temperature homogeneity and very low temperature amplitude in the sensitive area (30°C) which is a very good result. Von Mises stresses are localized on the sides of the substrate and well spread on a consequent length of the substrate. This helps to

decrease the maximum stress caused by the thermal expansion of the substrate and in a consequence, this improves the robustness of the sensitive element to regeneration steps.

Current density level in the optimized design is very homogeneous (around 500MA/m²) and this avoid hot points on the substrate that could fuse the heater track or produce cracks in the substrate. On the contrary, the current density level in the “design 1” shows a lot of red areas that could explain eventual crack on a prototype.

The table 3 summarizes the main output results of the simulations for the optimized design.

Table 3. Main output results of the heater simulations

Width of the substrate (mm)	5
Thickness of the substrate (mm)	1
Sensitive element T (°C)	668-637
Input voltage (V)	11.8
Σ max (MPa)	150
Max current density (MA/m²)	1260
Max power density (GW/m3)	1030



Figure 4. Von Mises stress cartography (a) of the “optimized design” and (b) of the “design 1”



Figure 5. Current density cartography (a) of the “optimized design” and (b) of the “design 1”

Once the optimizations have been done by simulation, the two simulated designs have been tested on a hot air test bench in order to characterize their robustness. The first design was simulated with the aim to be able to achieve the regeneration with the lowest power while the conception of the “optimized design” was thought in order to be the most robust.

According to some OEM specifications, the sensor has to be able to regenerate more than 100 000 times in its life. In order to test this characteristic a typical regeneration condition has been chosen (120°C / 16m/s) and samples of both designs were placed on the test rig. The sensors were programmed to regenerate every 30 seconds. The Figure 6 shows a typical regeneration cycle and the Table 4 the main endurance results.

It turns out that the design 1, which is the most efficient one in terms of power consumption, is not robust enough to comply with the most stringent OEM specifications while the “optimized” is far better. The new objective is to test the sensors until the breakage or 200 000 cycles and to do Weibull analysis with 30 “optimized design” parts.

Design of the Sensor Tip

The sensor tip plays a role in two main functions of the sensor: measuring and regeneration.

Regeneration: As it has been described in this article the exchange coefficient between exhaust gas and substrate is an important parameter. In other words the cooling of the substrate by the exhaust flow is of high importance and the design of the tip has to minimize this cooling.

Measuring: The maximum amount of soot has to enter in contact with the sensitive area in order to minimize the response time of the sensor. The tip has to maximize the particle flow. But also, the sensor has to measure only particles from the engine and not particles that have been stocked on the exhaust tube and blown off by a sudden high flow for example. This kind of “big” particles whose mean diameter is above 5µm can make the sensor signal drop in a second whereas it is not representative of the particles distribution and hence introduce dispersion in the measure. The tip has to select the particle size.

Minimize the cooling and maximize the particle flow seems to be antinomic. However, the design found has overcome the challenge to find the best compromise in terms of flow but also to filter the so called “big particles”.

It is possible to find in the literature some granulometric analysis of the soot at the engine out or at the tail pipe of a modern diesel engine. The Figure 7 is an example of such analysis. Most of the particles have a diameter between 10nm and 300nm with a peak at 70nm.

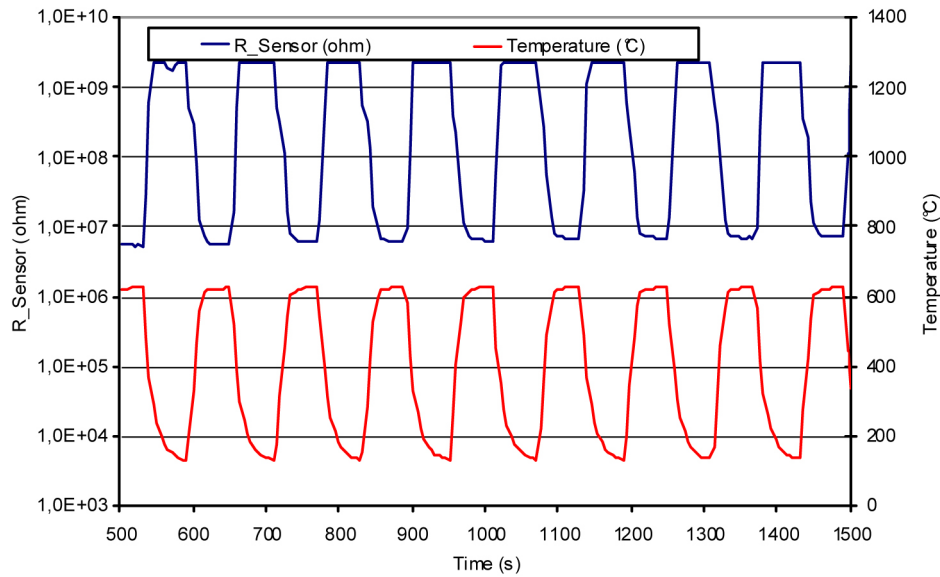


Figure 6. Typical regeneration cycle

Table 4. Sensors endurance results

	Design 1			Optimized design		
Sensor ID	C6	C3	C4	A7	C7	C8
Number of regeneration cycles	5430 (broken)	12163(broken)	11550 (broken)	44838 (broken)	114590 (still in test)	120493 (still in test)
						B5 (still in test)

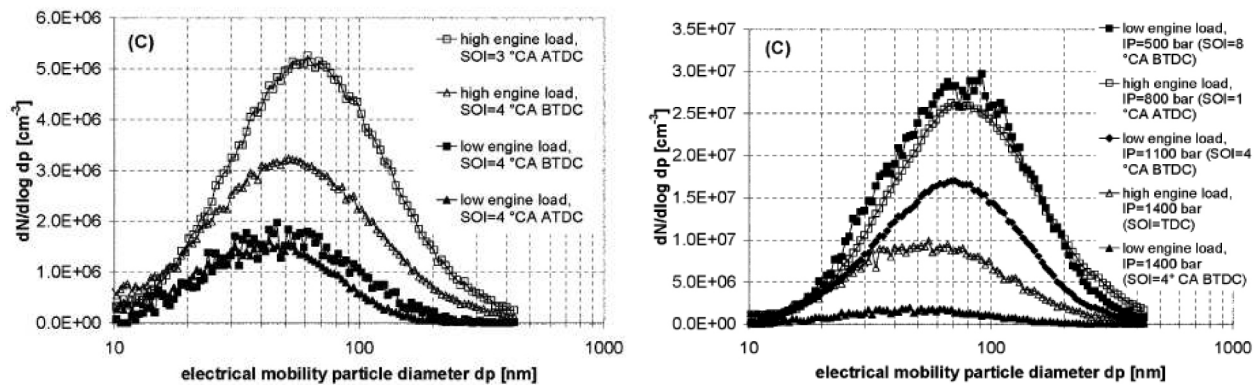


Figure 7. Particulate number size distributions (SMPS) at engine out in function of diverse parameters (9)

Hence the sensor tip has to filter particles whose mean diameter is above 500nm.

The Ansys Fluent software was used to simulate the soot behavior in the vicinity of the sensitive element as function of the flow velocity, the soot diameter and different tip designs.

The tip concept designed is a tip with “reverse” collecting windows. The substrate is protected by a shield without opening upstream of the substrate and the sensitive area is on the downstream side of the substrate. The exhaust gas are

sucked up in the sensor tip with a reduced velocity and according to their mass, thus their diameter, the particles too. The Figure 8 shows the result of a simulation with the optimized tip in terms of stationary velocity field. The tip diameter is 7mm, the sensitive element 5mm.

From the stationary velocity fields and the density of the particles, soot concentration fields as function of the flow velocity and the size of the particles were simulated. The Figure 9 shows an example of these simulations.

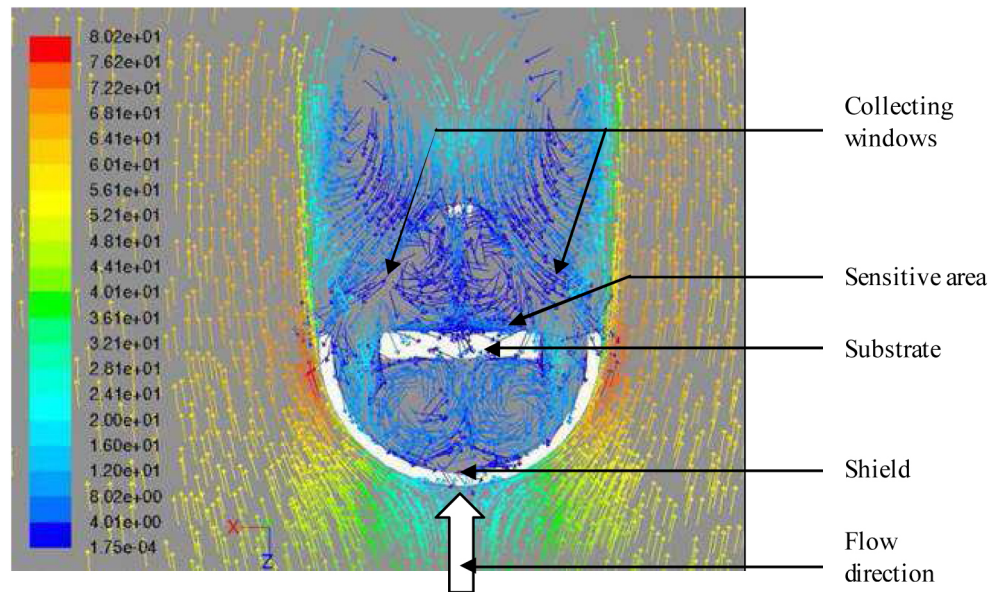


Figure 8. Stationary velocity field around the sensor optimized tip

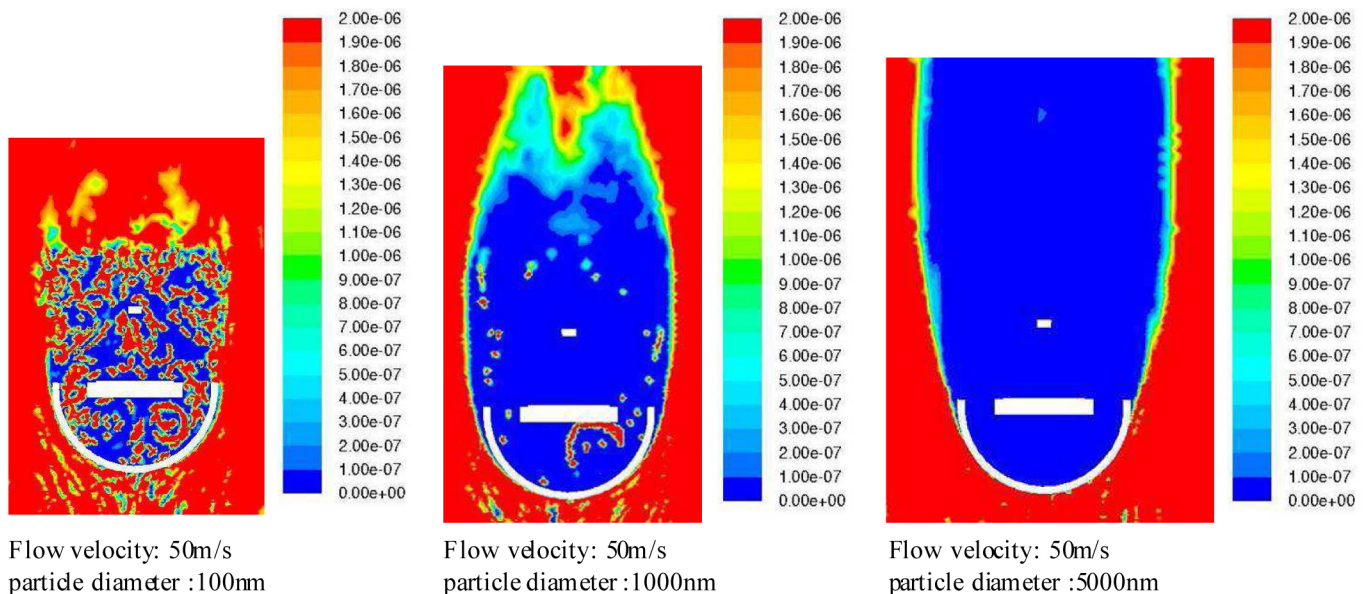


Figure 9. Soot concentration field in the vicinity of the sensitive element with a flow velocity of 50m/s

All the results are summarized in the [Figure 10](#) that describes the soot concentration in the vicinity of the sensitive element as a function of the particle size at different flow velocities

The [Figure 10](#) shows the great advantage of such a design. Indeed only the particles below $1\mu\text{m}$ can be collected on the sensitive element. A supplementary advantage is that this tip offers to the substrate a protection against droplets that could induce cracks in the substrate while the heater would be on and against some pollution such as some ash or rust particles. Finally, as the collecting windows are large (in the range of the mm), it is impossible that soot can clog the sensor tip.

The exchange coefficient between exhaust gas and substrate with this tip and with a flow of 30m/s was calculated at $350 \text{ W}/(\text{m}^2\cdot\text{K})$ and in consequence is in concordance with the results described in the regeneration part of this article. The sensor is able to regenerate in 30 seconds with such a tip and the “optimized design” heater.

As it could have been expected, the response time of the sensor was not good at all with a simple potential divider with a supply voltage of 5 volts but with a much higher supply voltage, the response time became very good. The [Figure 11](#) shows the evolution of the sensor response time