New Particulate Matter Sensor for On-Board Diagnosis

Atsuo Kondo, Soji Yokoi, Takeshi Sakurai, Satoshi Nishikawa, Takashi Egami, Masahiro Tokuda and Takeshi Sakuma

NGK Insulators, Ltd.

INTRODUCTION

Diesel particulate filters have been widely used in diesel vehicles to remove PM from vehicle exhaust gas and to meet the requirements of existing legislation. EURO6 requires monitoring of the DPF system for malfunctions that may cause the tailpipe PM emissions to exceed the regulated levels. In accordance with EURO5, the delta pressure sensor has been used not only for DPF regeneration control, but also for OBD purposes. New measurement technology had been developed which enable a better monitoring of the function of a DPF.

Recently, several kinds of PM or soot sensor have been proposed to detect PM or soot directly. These include the resistive type which measures soot conductivity [1] [2], the single pole type which measures transient electrical signals in the exhaust flow, and the two pole type which has a similar structure to a spark plug.

BASIC CONCEPT

The proposed sensor detects the accumulation of soot. To detect the amount of soot, the sensor operates cyclically and in three sequential stages (Figure 1). In the first measurement stage, soot is forcibly collected using an electric field, and a thin soot layer is formed on the surface of the comb type detecting electrode. In the second stage, soot is naturally accumulated and detected by measuring electrostatic capacitance changes in the comb type detecting electrode. In the third stage, the accumulated soot is burned using a heater and the sensor returns to the first stage of the measurement.

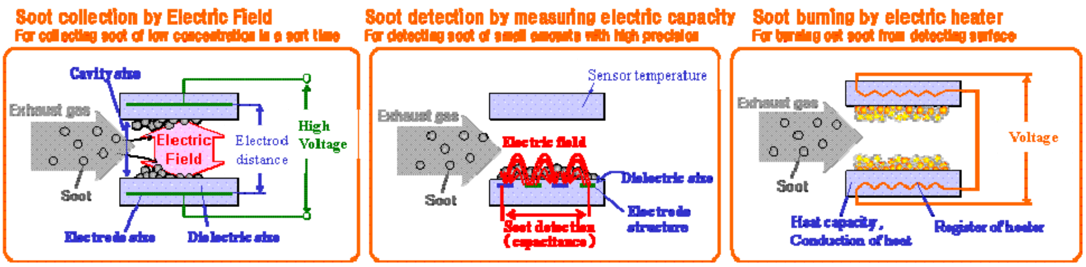

Figure 1 - Sensor operation stages

Figure 2 shows typical time series data of capacitance changes due to natural soot adhesion and forcible soot collection by electric field. Tests were performed on an engine at 1500 rpm / 80 Nm using a defective DPF with a high PM concentration of about 20 mg per cubic meter. The forcible soot collecting method was not initially used, in order to allow a comparison to be drawn with other methods.

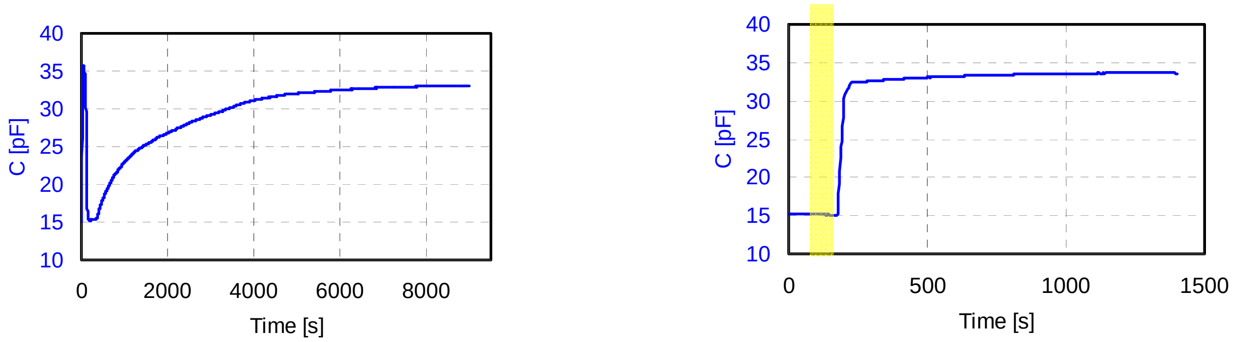

Figure 2- Soot collection by natural adhesion (left) and forcible soot collection by electric field (right)

The measured values uniformly increase over time and it takes a long time for the capacitance value to become saturated. A sensor with such low sensitivity cannot detect a defective DPF in one driving cycle.

Next, the proposed method with forcible soot collection was tested. During the combustion process in a diesel engine, PM, especially soot, is generated and electrically charged [3]. It adheres to the detecting electrode surface not only due to the anchor phenomenon, but also by electrostatic force. The horizontal electric field on the detecting surface forces soot to hit the surface at right angles. Figure 2 also shows the values detected using the forcible soot collection method. Because the capacitance value becomes saturated in a short time with high sensitivity, the horizontal scale is extended. An electric field was applied only as a trigger timed to soot detection (yellow zone only). After the electric field was switched off, the rate of capacitance increase was still much higher than that of natural adhesion. The new method not only reduced the detection time, but also changed the characteristics of the soot layer [4].

PROTOTYPE SENSOR STRUCTURE

The proposed sensor element is mainly made of ceramics and all electrodes are made of base metal, rather than noble metal. The functional patterns are made using ceramic tape casting and screen printing technology. The comb type detecting electrode is covered with an insulation layer. These patterns and base alumina material are fired at the same time in a furnace. The sensor element is connected by electric wires to the sensor control circuit. The capacitance measurement has been adopted because of its low temperature dependency in relation to the resistivity measurement [5].

The all-in-one prototype sensor control circuit applies the forcible collecting voltage, measures the capacitance value, controls the heater for burning soot and transmits sensor signals to the engine control unit via CAN-bus. The high voltage boost converter for forcible collecting has a small power capacity because the voltage is only applied among the element's dielectric and air. Therefore the Cockcroft-Walton generator was selected. The capacitance measurement range is very small at several Pico farads. An auto-balancing-bridge is used for measuring the impedance value and for sync-detecting to distinguish between the capacitance part and resistance part. The heater control circuit has a PWM-controlled output voltage and 4-wired heater resistance measurement. The CAN-bus communication is convenient for sensor development because the communication speed is high and the protocol is executed without a CPU procedure.

DESIGN IMPROVEMENT

The prototype sensor needs 2 kV as the high voltage trigger. Applying 2 kV is not, however, the preferred method because a long and wide sensor element is needed to secure the insulating distance in the sensor element. Also in order to maintain the insulating distance in the sensor body housing, the sensor element must be assembled in quite a complicated way. It is necessary to decrease the applied high voltage to around 500 V It is clear, however, that sensitivity also decreases as the applied voltage is reduced [5]. A new design was considered which would compensate for this decrease in sensitivity in order to allow for a reduction in the applied voltage.

To improve the sensitivity, the thickness of the insulation layer covering the comb type detecting electrodes was reduced from 50 microns (prototype) to 25 microns. By changing the insulation layer thickness, electrical flux lines from the comb type electrodes could easily pass through the conductive soot layer deposited on the insulation layer. This enabled an improvement in sensitivity. The sensitivity of the sensor also depends on the width of the gap between the pair of detecting electrodes. A small gap can give high sensitivity although the measurement range will be narrow. In contrast, a wide gap gives a wide measurement range with low sensitivity. There is an optimum gap width depending on the operation algorism. Another minor improvement is to place the edge of the comb type detecting electrode into the ceramic layers, because these edges include a large gap area which is less sensitive than the other consistent gap area.

TEST RESULTS

Figure 3 shows the OBD test results in the NEDC driving mode with the two defective DPFs controlling PM emissions. The forcible soot collection started at 505 seconds and an applied voltage of 2 kV and duration time of 1 minute was used in this experiment. After the collection period, prototype sensor signals from the two defective DPFs showed that capacitance values increased in proportion to the emission level in a short period of time, as mentioned above. There is a clear difference in the increase in capacitance values between the defective DPF at 1 times the regulation value and the defective DPF at 2 times the regulation value.

By improving the sensor design, the sensitivity is improved and it is easier to distinguish the defective DPF at 1 times the regulation value from the defective DPF at 2 times the regulation value. (The noise that appeared from zero seconds to 200 seconds in Figure 3 came from condensed water adhered to the comb type detecting electrodes.)

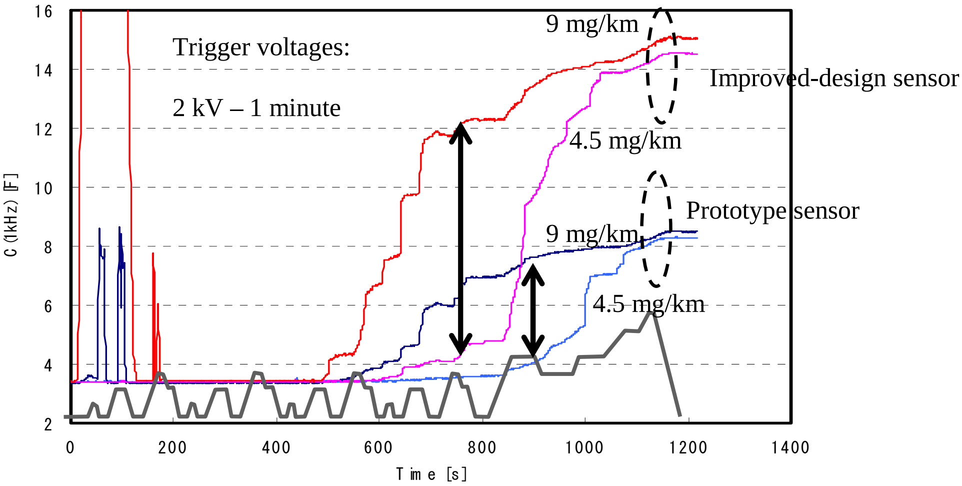

Figure 3 – Performance comparison between prototype sensor and new designed sensor in NEDC mode

CONCLUSIONS

New PM sensing technology will be required to meet future OBD regulations. The proposed forcible soot collection method, in which a thin soot layer forms on the detecting electrode, can significantly shorten the soot detection time compared with the natural collection method. The proposed sensor is mainly made of aluminium ceramics and all electrodes are made of base metal, rather than noble metal. The capacitance measurement has been adopted because of its low temperature dependency in relation to the resistivity measurement. The sensor signals are transmitted via CAN-bus to the engine ECU.

By improving the sensor element design, in the NEDC mode the sensor has sufficient sensitivity to detect a defective DPF in a short period of time with 2 kV trigger voltages. This design improvement has been applied to next generation PM sensors, which are small enough to use on board, and which have a trigger voltage of 500 volts or lower. The new PM sensor proposed in this paper has been developed based on this new concept and fundamental study of the soot adhering mechanism. It will be developed for commercial applications with particular emphasis on cost and OBD system requirements.

REFERENCE

[1] Ochs, T., Schittenhelm, H., Genssle, A., Kamp, B., “Particulate Matter Sensor for On-Board Diagnostics (OBD) of Diesel Particulate Filters (DPF),” presented at SAE World Congress, USA, 2010

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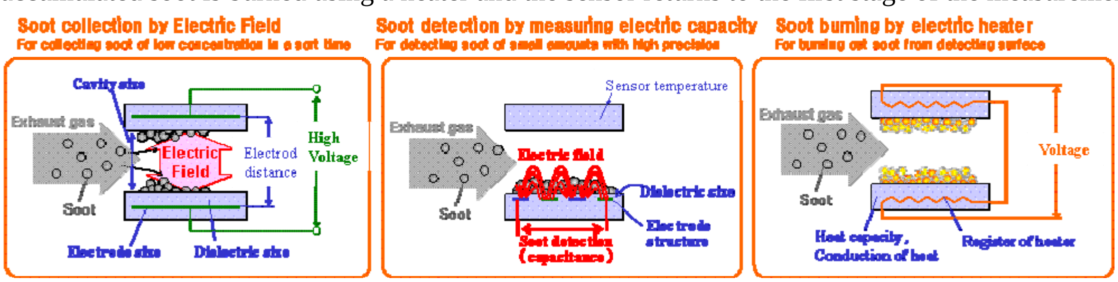

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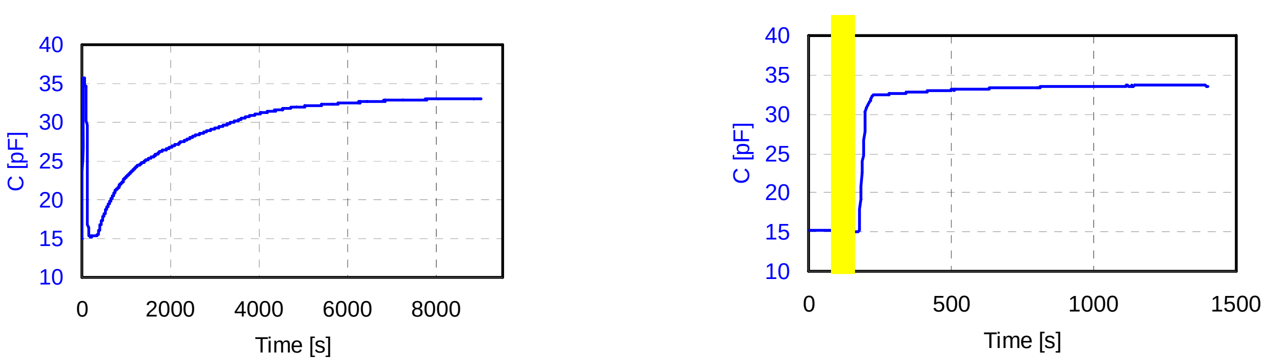

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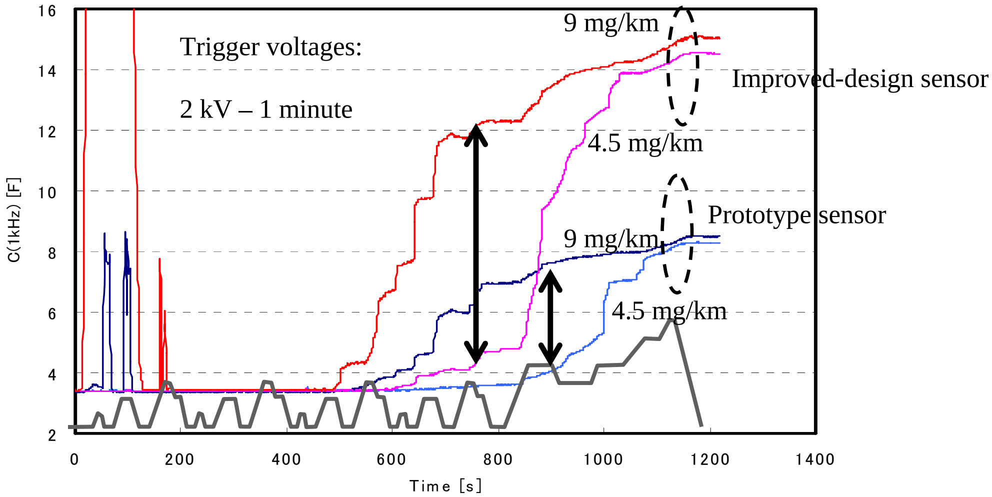

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NGK

15th ETH-Conference on Combustion Generated Nanoparticles 26th - 29th June, 2011

Contents

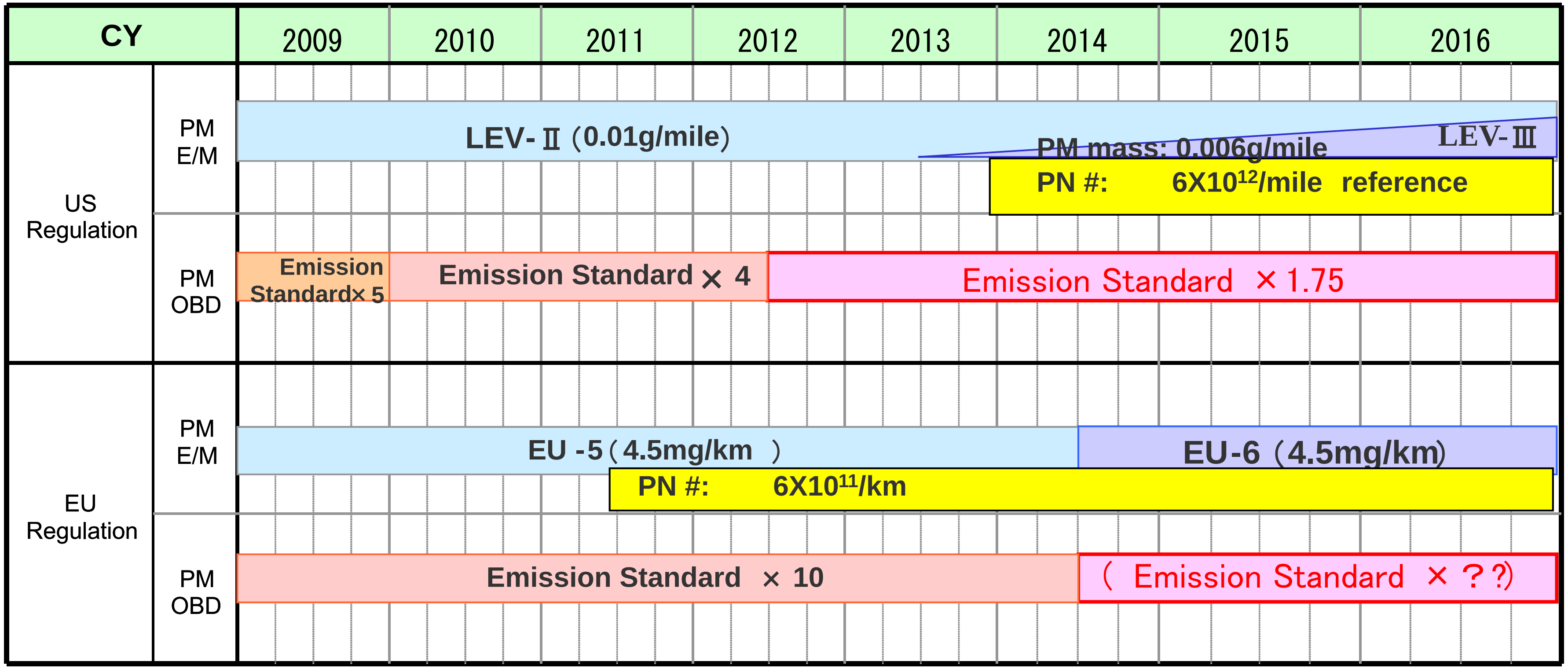
- Introduction
- Basic Concept & Feasibility Study
- Sensor Structure
- Performance
- Conclusion

Diesel emission control situation

- Diesel Particulate filters (DPF) are widely used.
  - To meet Euro-5 and Euro-6 PM weight regulation
  - In USA since US07

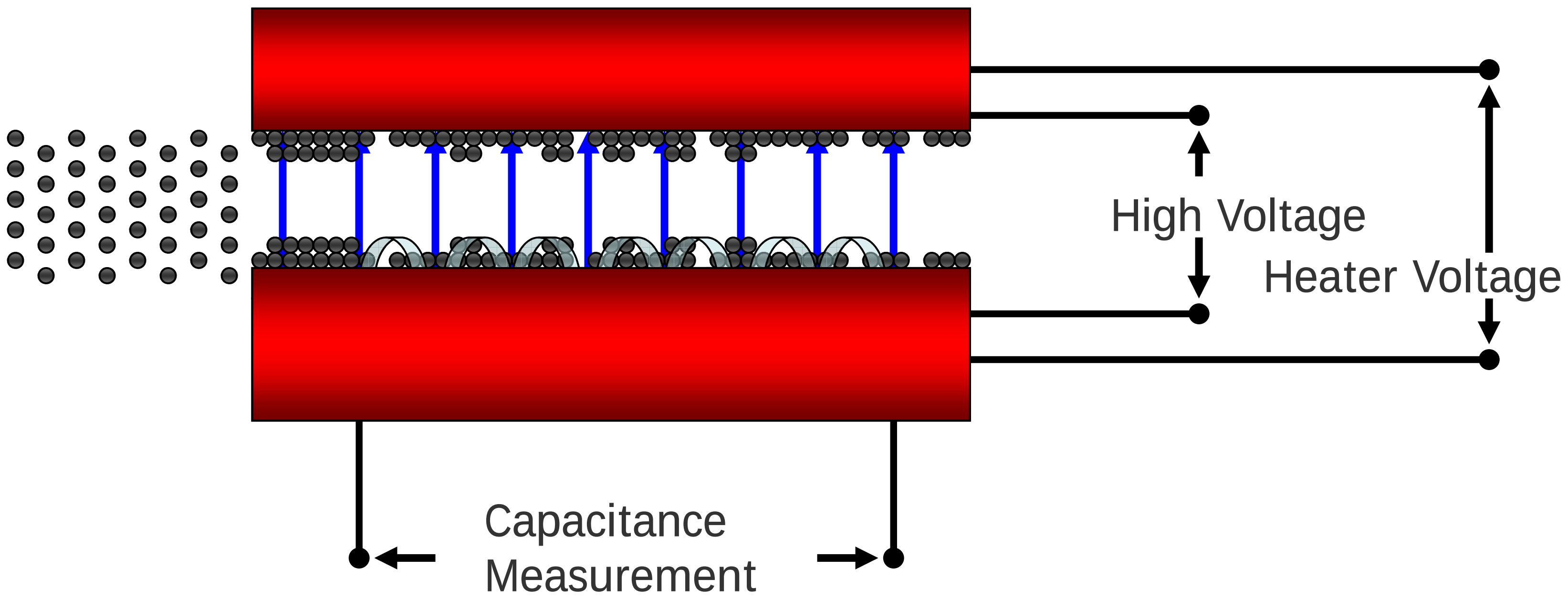
- Legislation requires On-Board Diagnostic (OBD) for DPF
  - DPF malfunction has to be detected.
  - NGK PM sensor has a potential to be use for OBD requirements.

Today's OBD legislation in US and EU

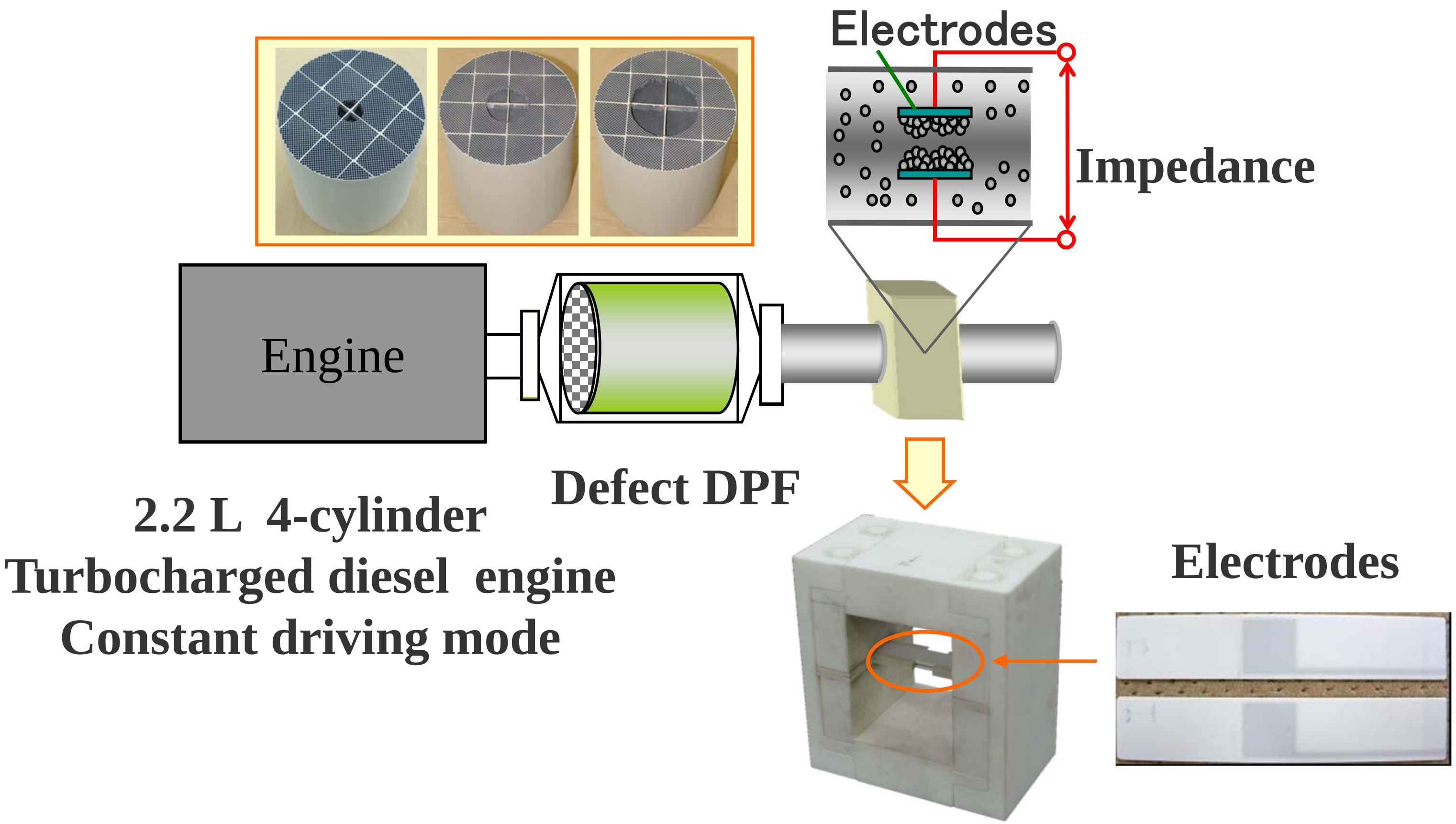


- US threshold LEVⅢ: x1.75
- EU threshold Today: X10

Basic concept of NGK PM sensor

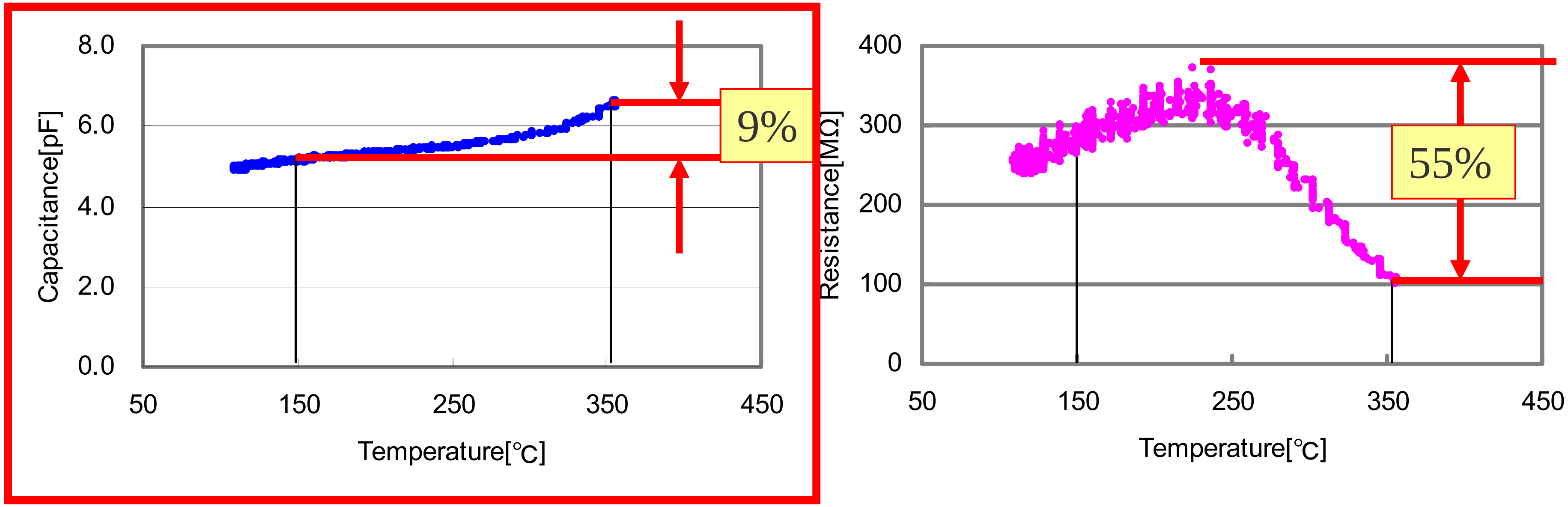


Feasibility Study



- PM emission is controlled by removing DPF plugs

Temperature Dependency with PM



- Capacitance measurement: 9 % variation
  - From 150 to 350 deg. C

Variation (%)

=(Cmax-Cmin)/(Cmax+Cmin)*100

- Resistance measurement: 55 % variation
  - From 150 to 350 deg. C

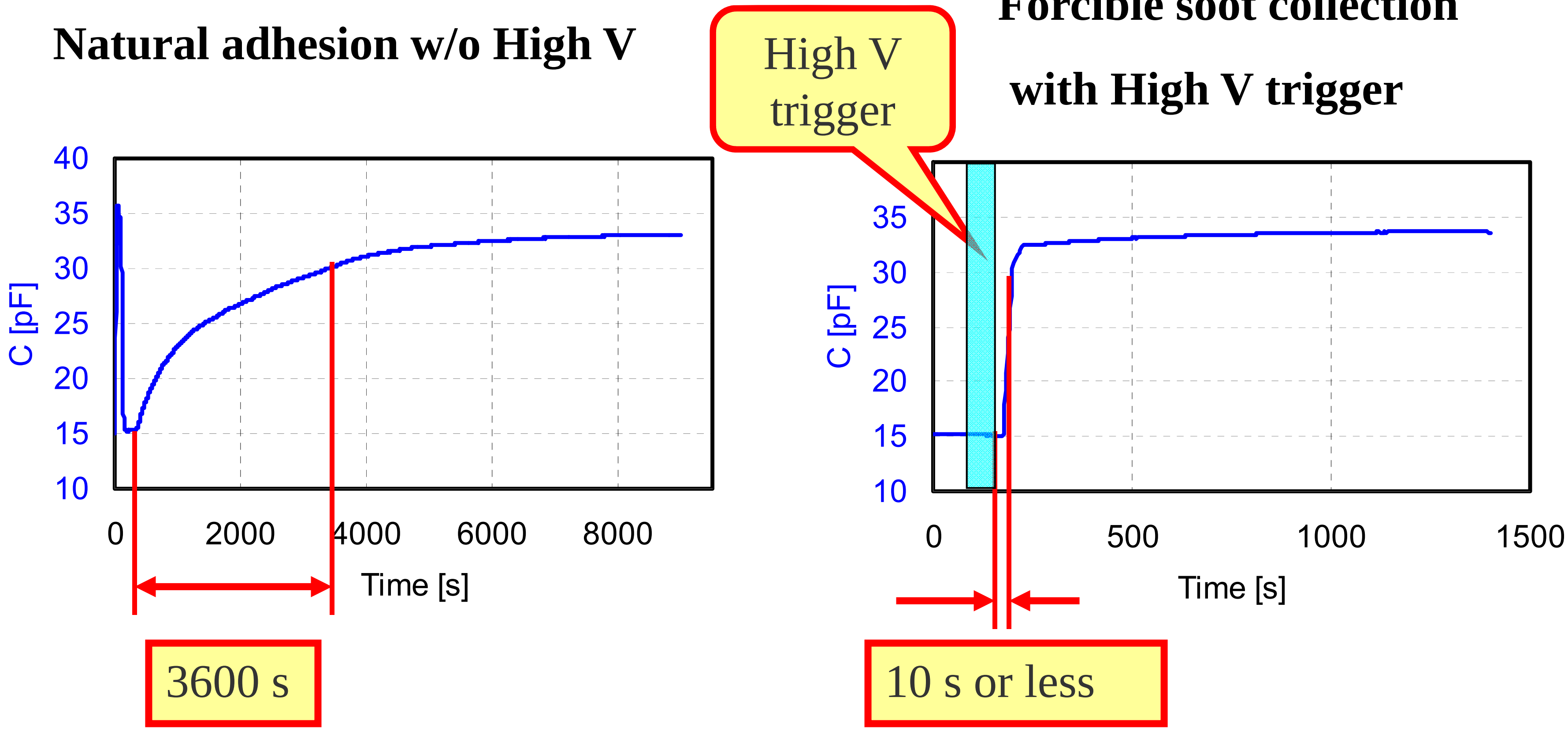
Variation (%)

=(Rmax-Rmin)/(Rmax+Rmin)*100

High Voltage Trigger

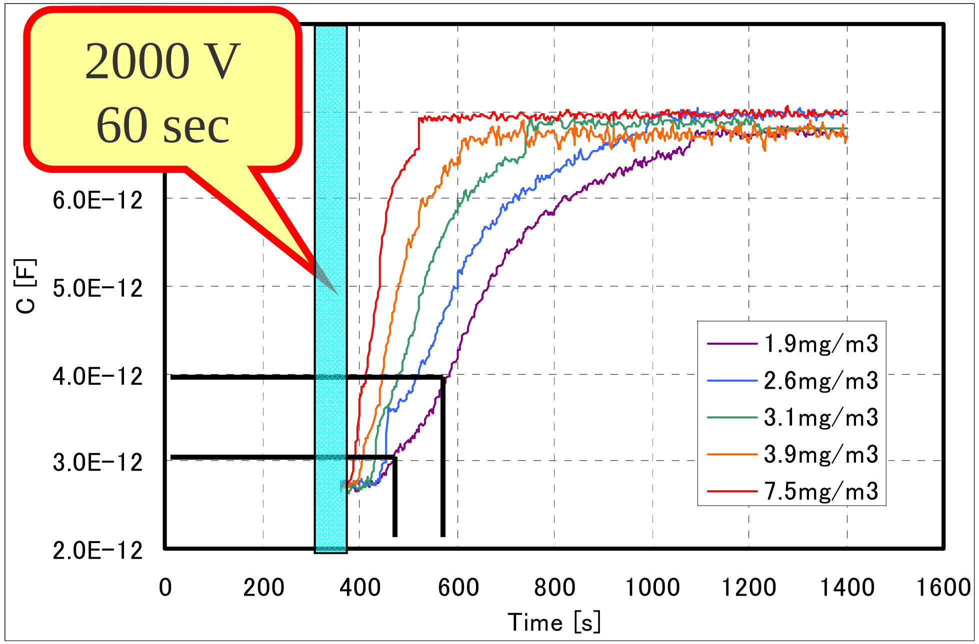
Natural adhesion w/o High V

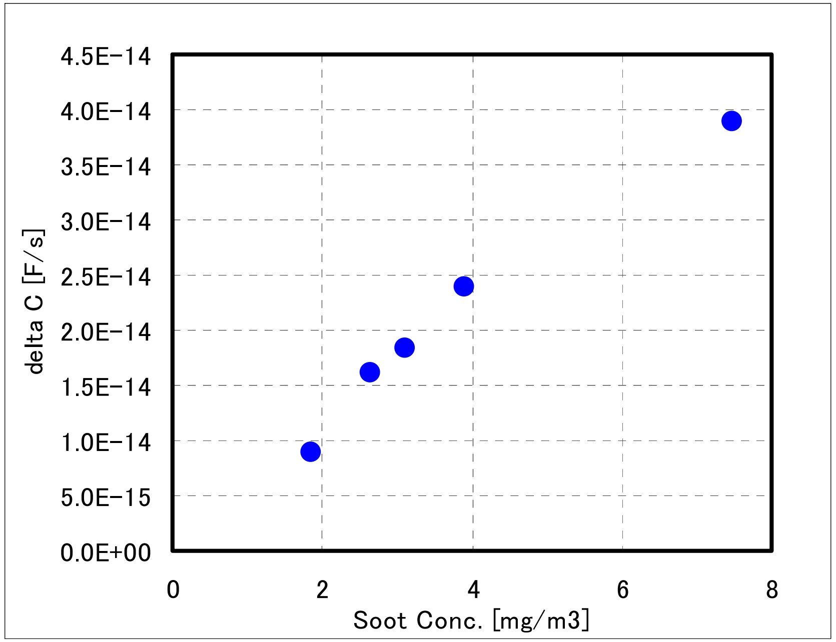
Forcible soot collection with High V trigger



- High voltage trigger improves response time!

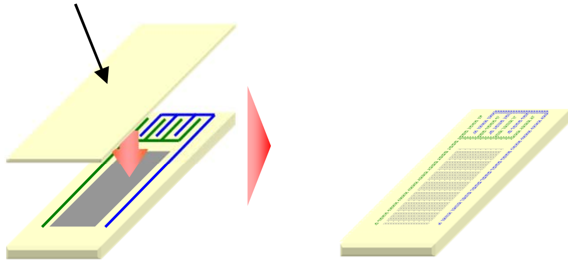
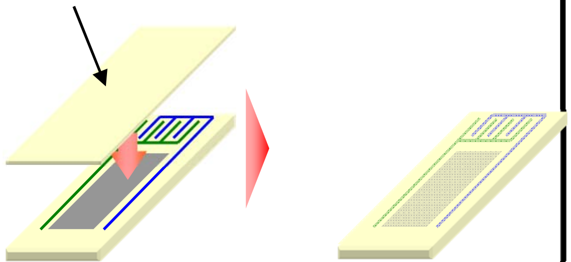
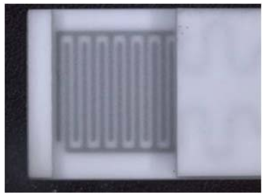
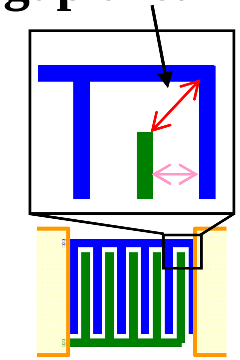
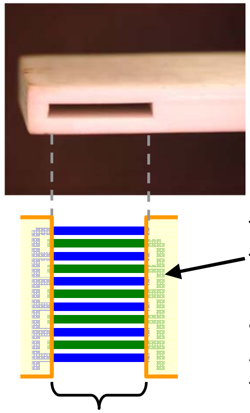
Soot concentration vs. delta C



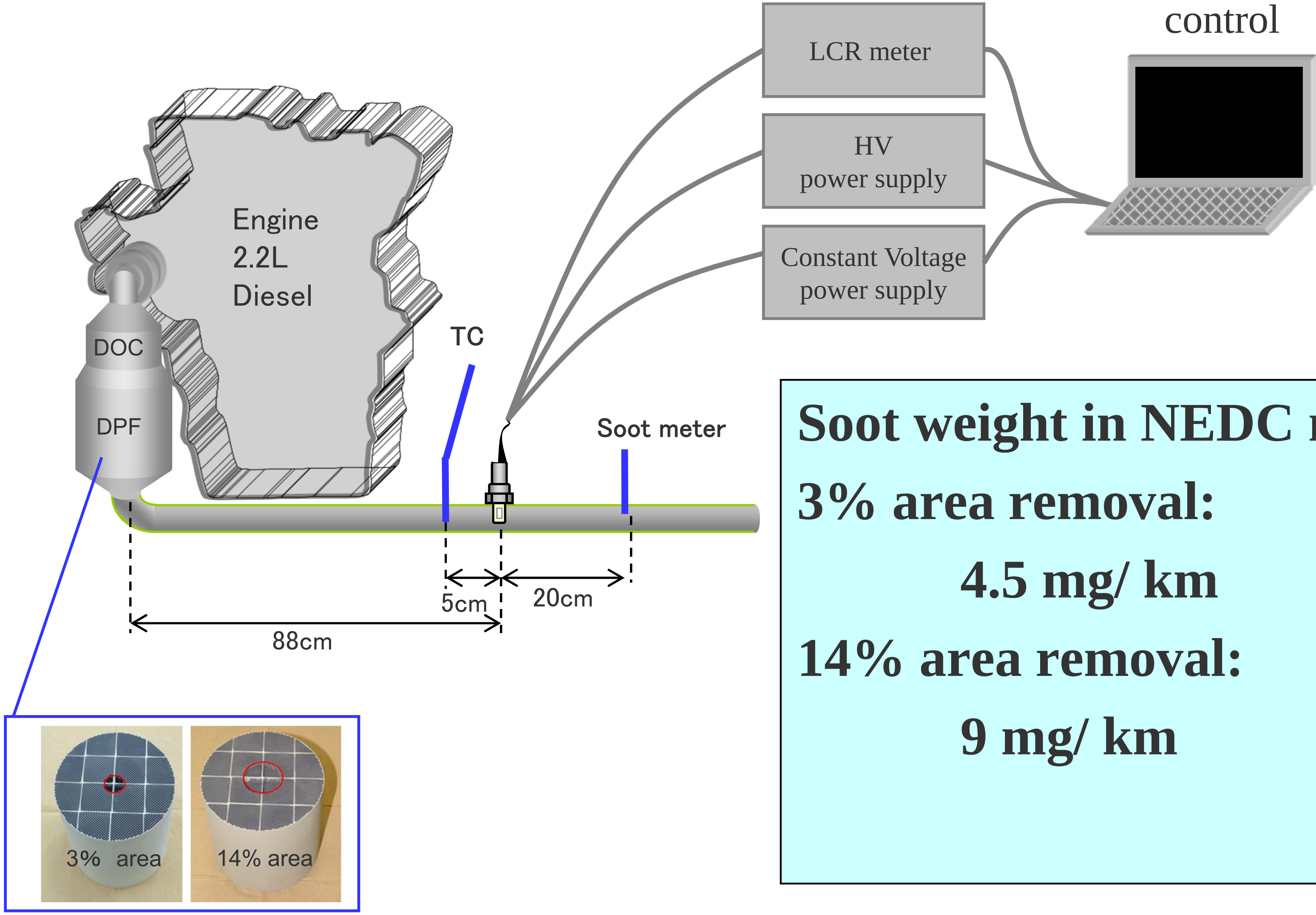


- Capacitance change in time was calculated. (=delta C)
- Soot concentration and delta C are well correlated.
- Capacitance is a good indication of soot concentration.

PM sensor design development

	First design	New design
Insulating layer	Insulating layer  50 microns	Insulating layer  <u>25 microns</u>
Gap area	Wide gap area  Cut model 	 Cavity Hiding wide gap area into ceramics

Engine test bench arrangement



Soot weight in NEDC mode

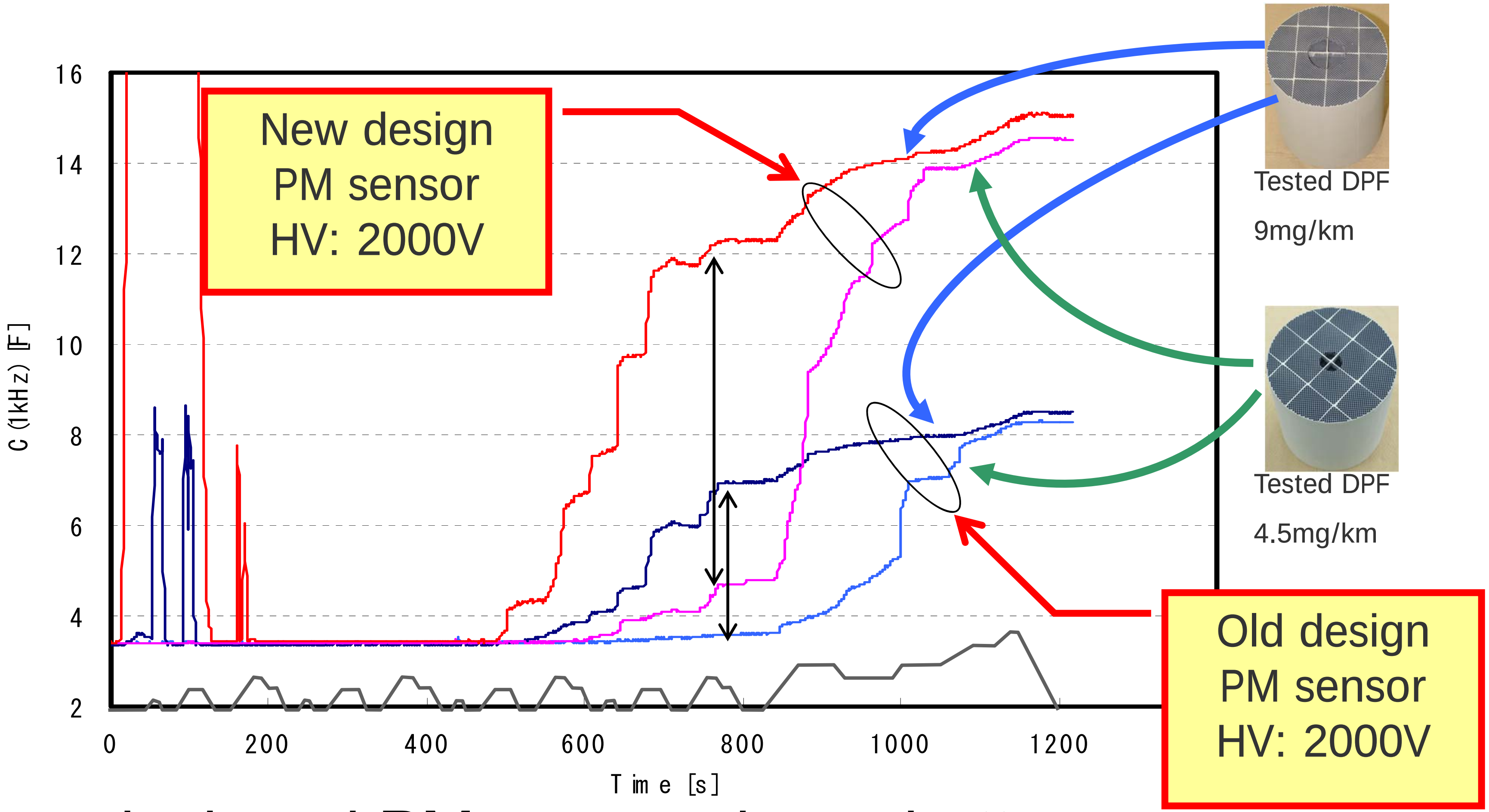
3% area removal:

4.5 mg/ km

14% area removal:

9 mg/ km

First and new design PM sensor tested under NEDC mode (2000 V)



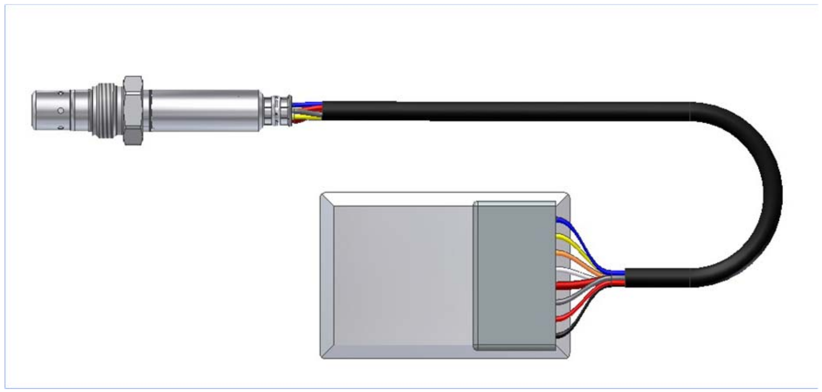
- New designed PM sensor shows better performance to distinguish 4.5 mg/km PM emission from 9.5 mg/km.

Summary of PM sensor design

PM sensor without protection cover

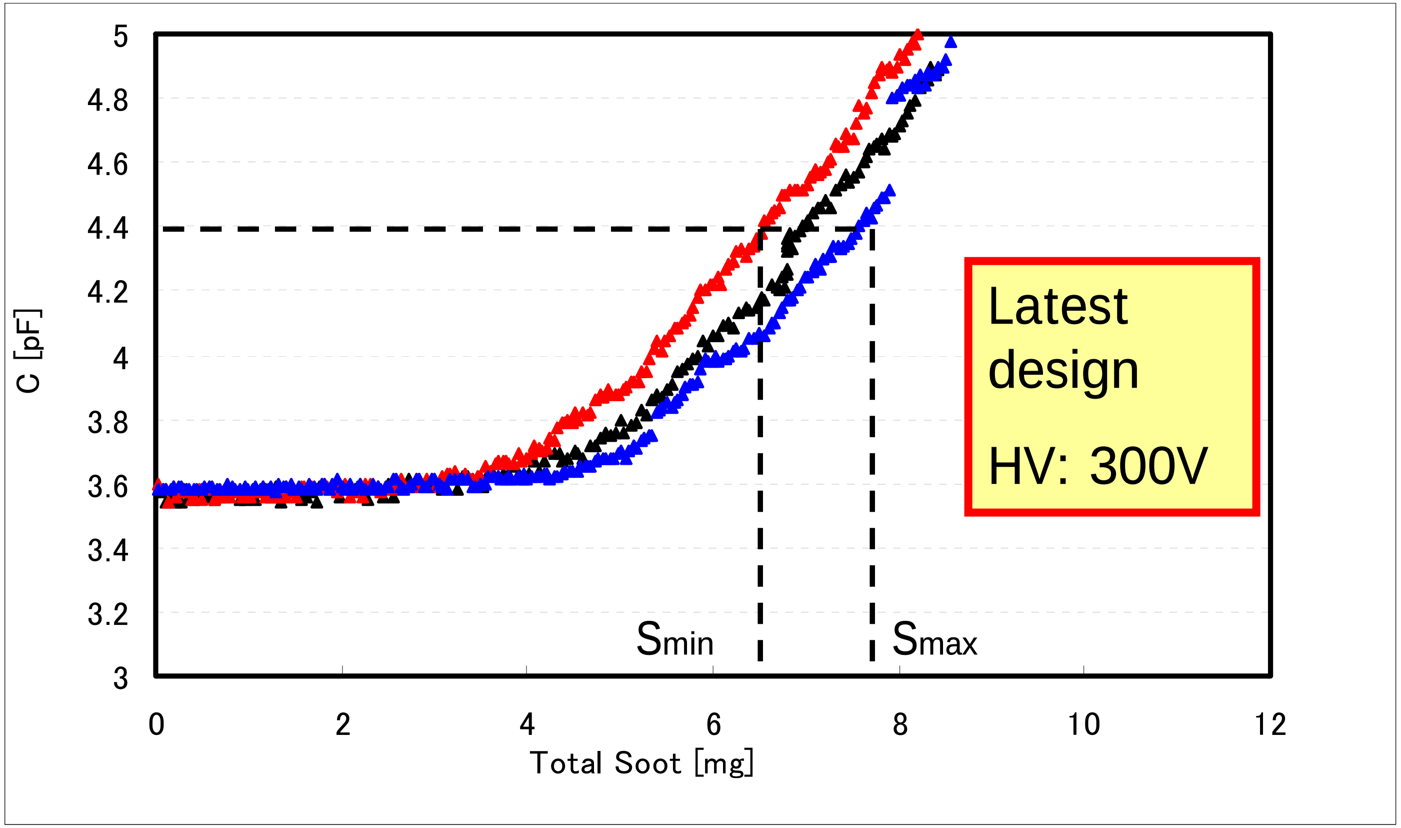
Prototype electric circuit board

(Size: 90 mm x 75 mm)



Final design concept under development

New design PM sensor tested under constant condition (300 V)



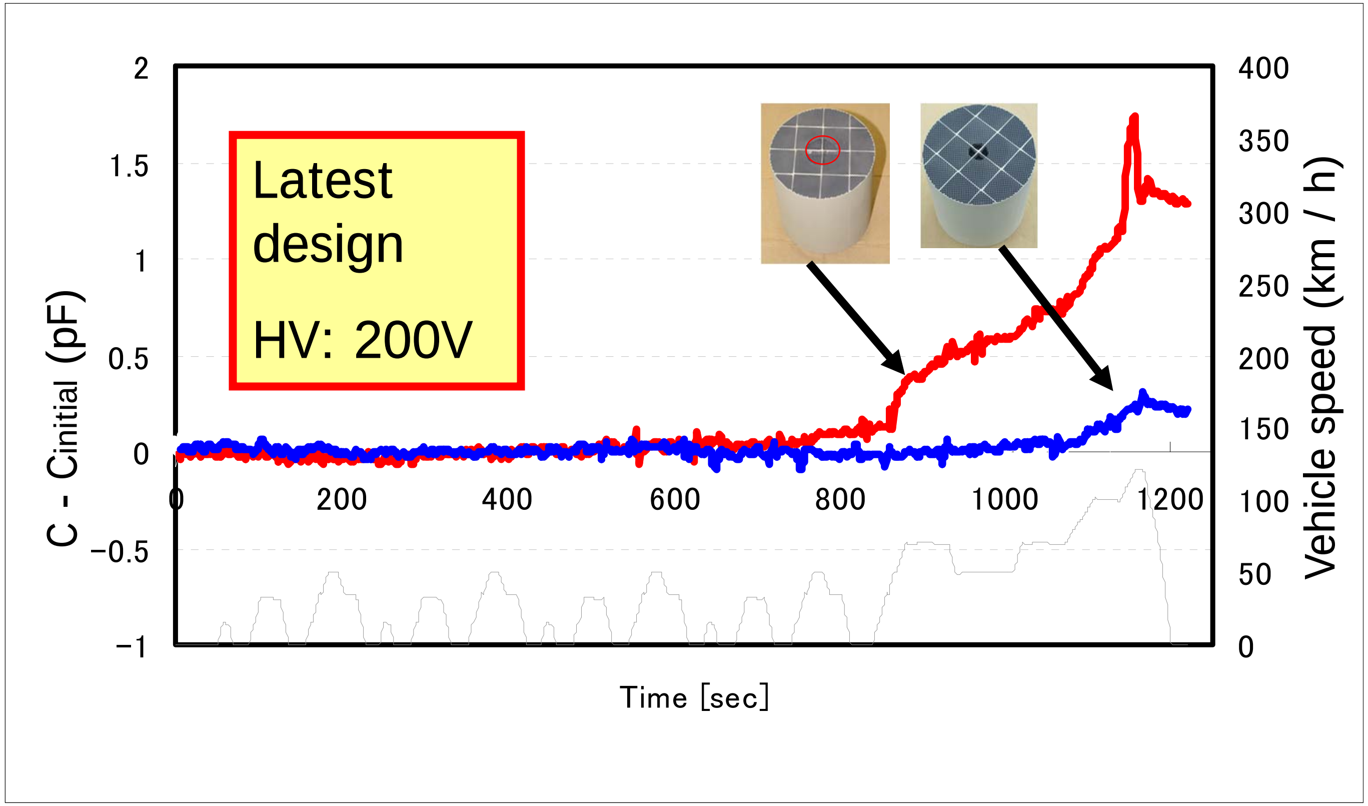
Engine condition:
1500rpm-40Nm
With Defective DPF

Soot varied from 1.9 to 3.1 mg/m3
Variation is normalized by total soot.

- Capacitance measurement: 7.8% variation within three measurement even low soot concentration.

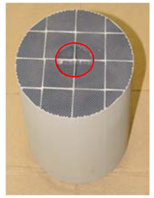
Variation (%)
=(Smax-Smin)/(Smax+Smin)*100

New design PM sensor tested under NEDC mode (200 V)



Engine condition:
NEDC mode
Defective DPF for
4.5mg /km at
NEDC

9.0mg /km at
NEDC



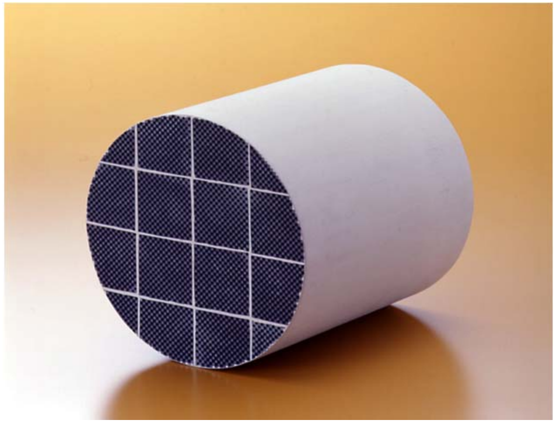
- Defective DPF with 4.5mg/km PM emission is still distinguishable from defective DPF with 9.0mg/km PM emission even 200V of high voltage.

Conclusion

- **Presented improved PM sensor can distinguish 4.5 mgs/km of PM emission from 9.0 mgs/km of it in NEDC mode.**
- **Capacitance measurement was chosen because of low temperature dependency of soot detection.**
- **Presented PM sensing technology with high voltage trigger can significantly shorten soot detection time.**
- **Small sized PM sensor, which is applicable for on-board, had been achieved by improving sensor structure and by decreasing high voltage.**

Thank you for your attention!

DIESEL PARTICULATE FILTER



HONEYCERAM®

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