Development of a Next Generation Opacimeter by using the Light Scattering and the Light Extinction Method for Periodic Technical Inspection Use

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Introduction

Diesel particulate filters (DPFs) have usually ability to remove near 100 % of particulate matter (PM) in engine exhaust. If the filtration efficiency of DPF deteriorates, the periodic technical inspection (PTI) emission test must detect it. However, current use opacimeters for PTI have not enough sensitivity to differentiate between DPF with and without faults.

Recently, next generation opacimeters based on laser light scattering photometry (LLSP) are developing. The LLSP takes about 100 times more sensitive than current use opacimeter based on light extinction method. However, a standard calibration procedure of the LLSP is not established.

This study is intended to develop a next generation opacimeter equipped with the LLSP and the light extinction method for PTI use.

Developed opacimeter

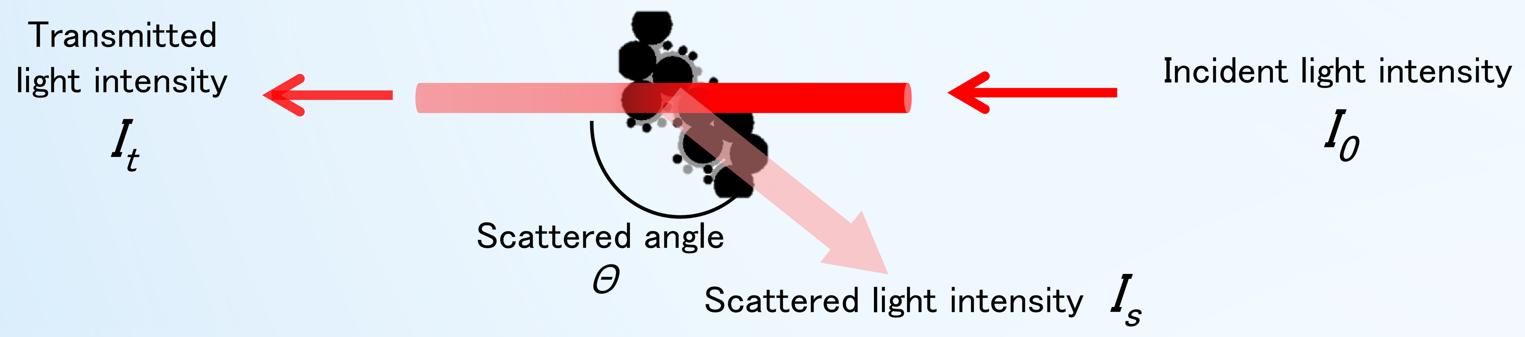
Key feature: 2 methods in 1 instrument

The LLSP is suitable for low PM concentration and the light extinction method is suitable for high PM concentration. Thus, the two methods in one instrument makes applicability not only to latest DPF-equipped vehicles but conventional high-emitting vehicles.

The light extinction method measures light extinction coefficient (k-value), and serves the calibration of LLSP as the k-value reference. Consequently, another reference instrument such as reference opacimeter is not required for the calibration of LLSP.

Principles

When a collimated light beam irradiates soot aggregate in exhaust, soot aggregate extinguishes and scatters the incident light.



Schematic of light extinction and scattering caused by a soot aggregate

k-value measured by ***the extinction method*** is defined as same as a current opacimeter.

$$k = -\frac{\ln \tau}{L}\alpha$$

where, τ is the transmittance(I_t/I_0), L is the optical length[m], and α is a conversion coefficient; The k-value measured by 650nm light is converted to the k-value under condition of 560nm.

k-value measured by ***scattering method (LLSP)*** is calculated by next equation.

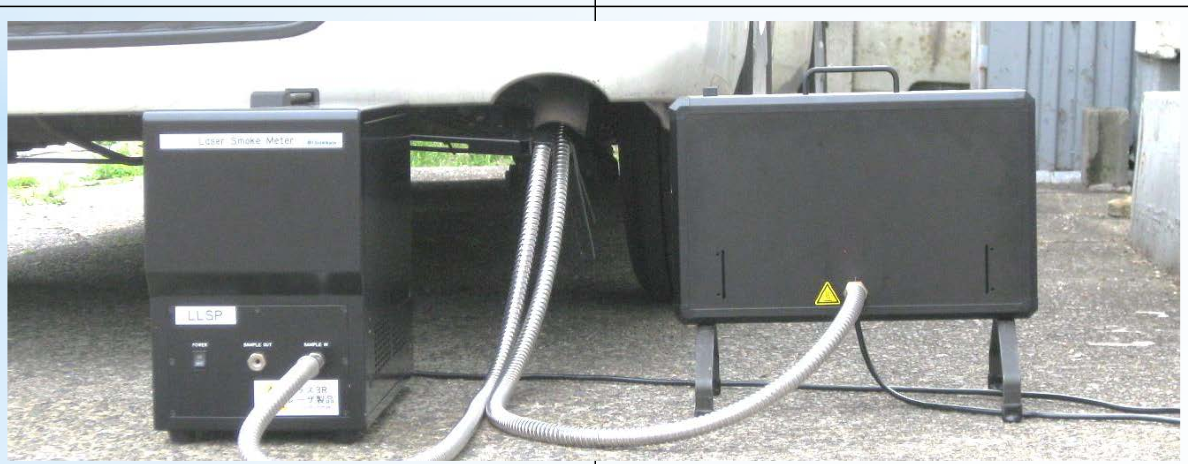
$$k = A \times I_S$$

where, A is a proportionally coefficient. Each instrument has an own coefficient A required to calibrate, respectively.

Specifications

The developed opacimeter adopts some modification as well as addition of the LLSP.

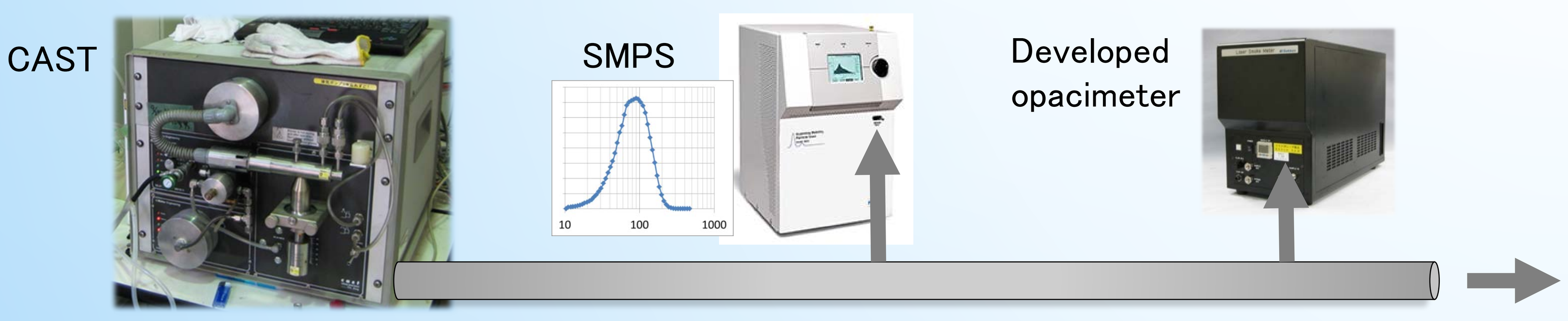
- Red laser of 650nm : Low NO_2 interruption compared with green LED of 560nm.
- Filtered reference air: Zero level calibration referred to particle free air.
- Sampling pump: Response time independent on exhaust pressure.

Product name	GSM-600 (developed opacimeter)	GSM-200 (current opacimeter)
Exterior		
Principle	Light extinction and scattering	Light extinction
Light source	Laser 650nm	Green LED
Optical length	0.147m (extinction)	0.185m
Zero reference	Filtered air	Surrounding air
Sampling	Active flow (pump)	Passive flow
Certification	-	PTI regulation in Japan

Experimental

Calibration system

Soot particles generated by a CAST (Matter Engineering) are introduced to a particle spectrometer (SMPS 3034, TSI) and the developed opacimeter. SMSP measures particle size distribution to investigate an effect of particle size on scattering intensity. The correlation of scattered light intensity and k-value is calibrated at the developed opacimeter. Reference k-value based on the extinction method measured by the developed opacimeter results in simplification of the calibration system.



Schematic of calibration system

Test vehicles

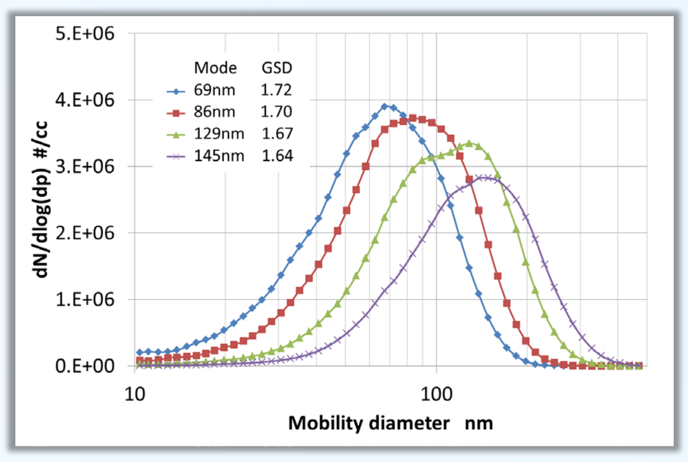
		
Vehicle type	Diesel commercial van, GVW<3500kg	
Engine type	L4, 3L, Direct injection, Turbo with inter cooler	
After treatment	DOC	DOC+DPF
Emission regulation	JAPAN new short term (2003)	JAPAN new long term (2005)

Results

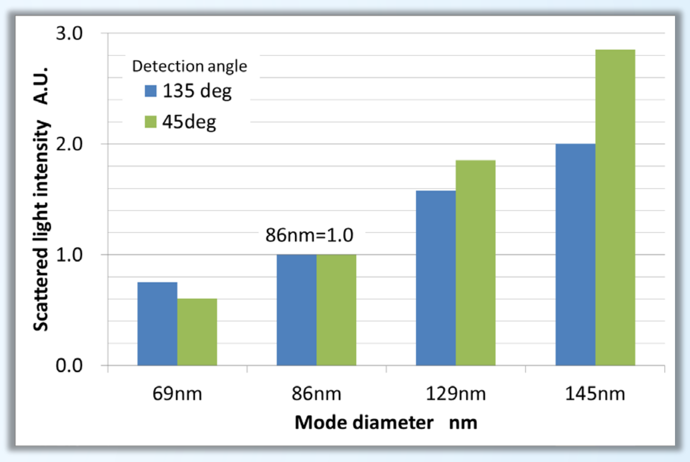
Correlation of scattered light intensity and k-value

The LLSP is required to calibrate a correlation of scattered light intensity and k-value by using actual particles. Particles generated by a CAST were introduced to the developed opacimeter. The k-value was measured by the extinction method and scattered light intensities were measured at scattered angle of 45 and 135deg. The larger particle size, higher scattered intensity at fixed k-value. Backward scattering angle of 135deg was less affected by particle size compared with forward scattering angle of 45deg. As a result, the effect of particle size on scattered light intensity is considered to be compensated by simultaneous measurement of scattered light intensities at two angles.

However, the developed opacimeter measured scattered light intensity at only angle of 135deg in view of the cost and calibration procedure. The correlation of scattered light intensity and k-value was calibrated at particle size distribution with the mode-diameter of 86nm.



Distributions of particle size generated by a CAST

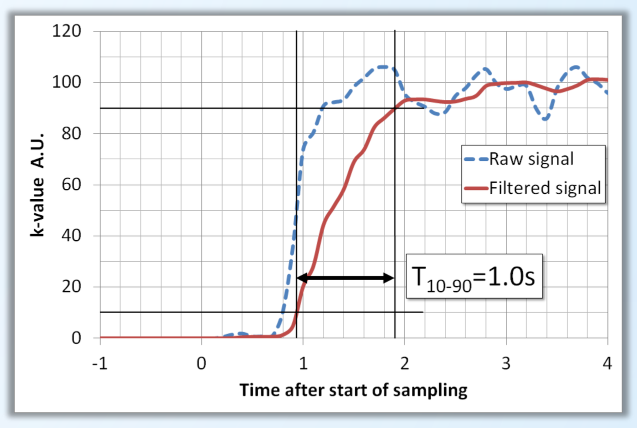


Effect of particle size on scattered light intensity

Response

The PM emission test in the PTI is conducted by free acceleration, i.e. transient measurement. Therefore measured peak k-value is affected largely by the response time of the instrument.

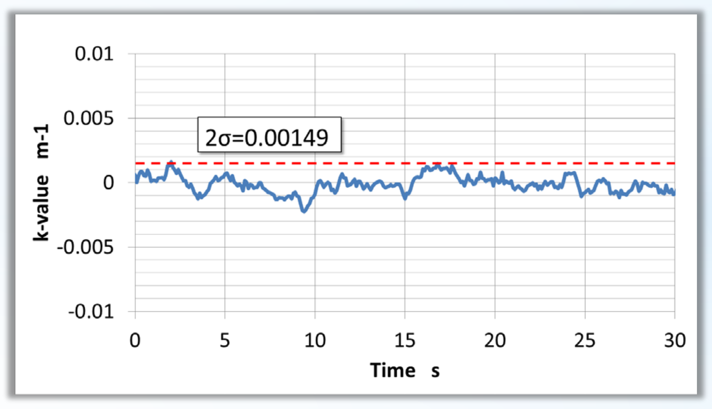
The developed opacimeter is equipped a first order low-pass filter, and the time constant of the filter was adjusted experimentally so that the filtered signal raise time 10-90% is 1.0 second.



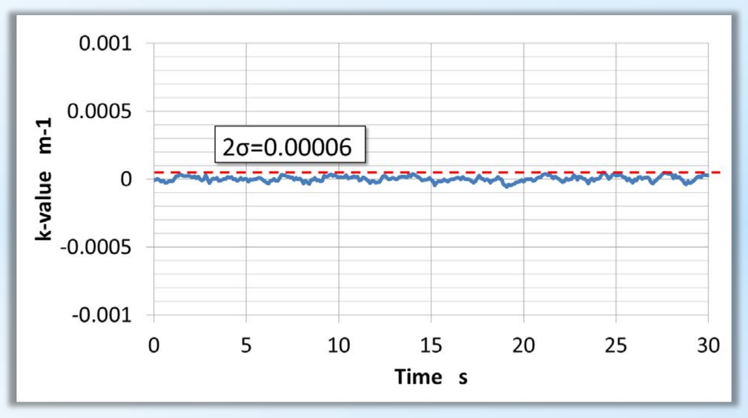
Time histories of normalized up-slope of k-value

Detection limits

Detection limit was defined as a value two times the standard deviation of output signal for particle free air measurement over 30 seconds. This value is considered to represent the noise level of the detection system. The detection limits of the extinction method and the LLSP were 0.00149m^{-1} and 0.00006m^{-1}, respectively.



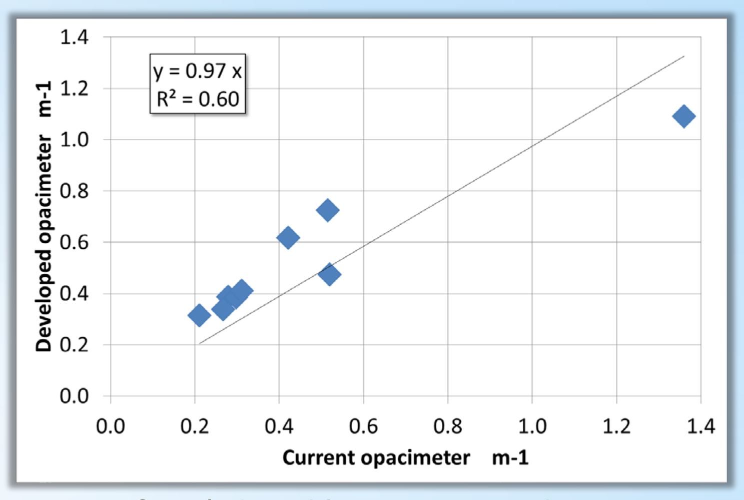
The output signal of the extinction method for particle free air



The output signal of the LLSP for particle free air

Compatibility with the current opacimeter

Compatibility with a current opacimeter was investigated by free acceleration test of the vehicle without a DPF. The developed opacimeter executed as extinction mode on this test. In accordance with the PTI regulation, peak value of measured k-value were plotted. A rough correlation was confirmed. The deviation of k-value is considered to result from the difference in the response characteristics between the developed and current opacimeter.

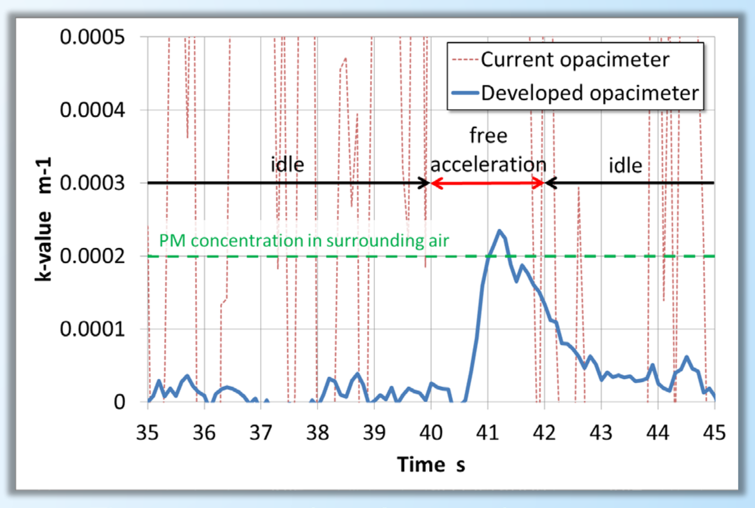


Correlation with a current opacimeter

Sensitivity for DPF-equipped vehicle

A free acceleration test of the vehicle with a DPF was conducted. The developed opacimeter executed as LLSP mode and successfully detected PM emission synchronized to free acceleration operation. The developed opacimeter refers filtered air as the zero reference, and makes possible to detect PM concentration around surrounding air.

The signal to noise ratio of the current opacimeter is too low to detect PM emission of k<0.001m^{-1}.



The output signals at free acceleration test

Conclusions

- The detection limits of the extinction method and the LLSP were 0.00149m^{-1} and 0.00006m^{-1}, respectively.
- At the vehicle without a DPF, k-value measured by the extinction method on the developed opacimeter was confirmed to have a correlation with that of by a current opacimeter.
- At the vehicle with a DPF, the LLSP on the developed opacimeter could detect PM emission of k<0.001m^{-1}.

Future works

- Evaluation of the correlation with a current opacimeter and the developed opacimeter in various vehicles.
- More examination of the two scattered angles sensing for particle size compensation.
- Development of a simplified calibrator for on-site calibration.

Acknowledgement

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