FEATURE ARTICLE

The Development of PM Measurement Systems at Horiba

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Abstract

Much effort is being put into research and development aimed at reducing the particulate matter (PM) discharged by diesel engines. There is now a strong demand for developing technologies that will allow more accurate, continuous PM measurement. Horiba has been working for more than 20 years in the development and commercialization of PM measurement systems. In this report we review the various types of PM measurement technologies and provide an introduction to the latest PM measurement systems, such as the “micro-tunnel,” and the PM analyzer based on oxidization and reduction method.

1 Introduction

Because diesel engines have good thermal efficiency, much attention is directed toward the use of diesel engines as a means of preventing global warming. On the other hand, diesel engines also present a problem of pollution from particulate matter (PM) in the engine exhaust. The first step in making improvements to this element of diesel engine performance is the development of methods to accurately measure the PM mass emissions. At present, the officially prescribed method for measuring exhaust gas is to trap PM on a filter and measure the PM mass using a balance[1]. This method, however, does not allow for the dynamic measurement of generated PM, and therefore does not necessarily provide adequate information for engine research and development.

To solve this problem, Horiba has been working through trial and error for more than 20 years to develop continuous PM measurement methods that provide greater amounts of information. Although PM measurement technologies must deal with particular difficulties, such as the complexity of the mechanism of PM generation and composition, Horiba has proudly developed and fostered a variety of products that have proven highly useful to our customers.

2 PM Generation

In addition to gaseous substances, the discharge from diesel engines includes particulates in which micro-particles collect in catenoid or aggregated form. This matter is called particulate matter, and is mainly classified in three substances–soot, soluble organic fraction (SOF), and sulfate.

The main component of soot is carbon, and the soot is generated as a result of the incomplete combustion of fuel at high temperatures. SOF indicates components that remain after the burning of fuel or oil, and which dissolve in organic solvents. Sulfate, and sulfuric acid, are formed by a combustion reaction of the sulfur in fuel.

3 Dilution Sampling Systems

3.1 Full Tunnel

With the current official PM measurement method, exhaust gas is diluted and cooled to 52ºC (or lower) in a dilution tunnel through which clean air flows, and then a portion of the cooled exhaust gas is passed through a filter to collect the PM. The filter used to collect the PM is allowed to stabilize for at least one hour at a controlled temperature of approximately 25ºC and a relative humidity of 50%. The filter is weighed with a balance.

Mass of the PM is calculated from the difference between the weight of the filter before and after PM collection, and from the ratio of the sample passed through the filter to the total diluted flow.

Fig.1 shows the configuration of the total-volume dilution (full tunnel) system.

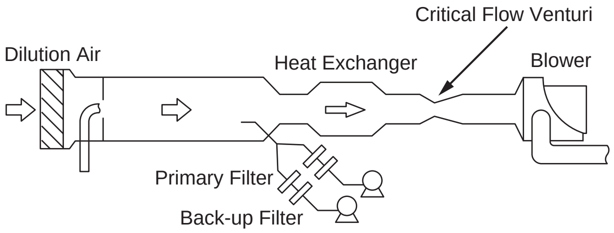

Fig.1 Full-tunnel PM Sampling System

3.2 Mini Tunnels and Macro Tunnels

When testing large engines with a full tunnel system, it is necessary to cool large quantities of exhaust gas to 52ºC or lower, so a very large tunnel must be used.

A smaller mini-tunnel system was developed based on the concept of dividing the exhaust gas into quantities of 1/10 to 1/100 of the total volume before introducing the gas to the tunnel. An even smaller micro-tunnel system has also been conceived based on the idea that it might be better to directly sample quantities of approximately 1/5000 of the total volume onto the filter, rather than dividing again the diluted sample prior to PM collection.

In order to introduce these new methods into practical application, it is very important to establish just how these methods correlate to the officially approved full tunnel method. To that end, Horiba has conducted extensive tests and validations in the development of its micro-tunnel system MDLT Series[2]. Fig.2 shows a PM sampling system that uses a micro-tunnel.

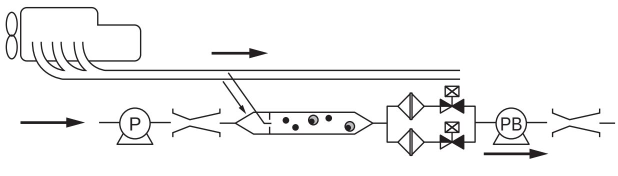

Fig.2 Micro-Tunnel PM Sampling System

4 The History of PM Measurement Method Development

With the official PM measurement method, PM is collected with a filter, then the total PM mass, including SOF, soot and sulfate, is measured. As such, with this method it is not possible to make real-time measurements of the exhaust conditions of an engine in operation, and this method also requires large-scale, high-cost equipment.

Horiba, as a manufacturer of exhaust gas measurement systems, has been working for more than 20 years in the research and development of various PM measurement methods that can overcome these problems.

4.1 Photo Acoustic Spectrometric Method

Our first undertaking in this area was the development of a photo acoustic spectrometric (PAS) method[3].

Fig.3 shows the operational flow of a continuous PM analyzer that uses the PAS method. The exhaust gas flow is split into two directions, one passing through a filter to remove the PM and then flowing to a measurement cell, and the other flowing directly to a measurement cell. When the measurement cells are irradiated by a CO_2 laser, the PM absorbs the laser light and generates sound waves. By calculating the difference in the strength of the sound waves from the two measurement cells, and by combining it with the flow rate of the exhaust gas, this system can continuously measure PM mass concentration.

This method is receiving attention as a continuous PM measurement method with fast response time. There are problems, however, with the correlativity of the results from this method and from the filter weighing method, as well as with the stability of the laser.

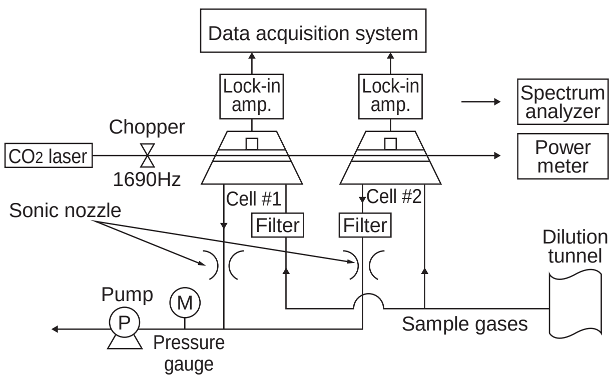

Fig.3 PM Continuous Measurement Using the Photo Acoustic Spectrometric Method

4.2 Electron Diffusibility Measurement

Electron diffusibility measurement (EDM) is a method for the selective continuous measurement of soot, which takes advantage of the high electron diffusibility properties of soot. The principle of EDM is shown in Fig. 4.

This method offers an advantage in that the equipment is relatively simple, but because it can only selectively detect soot, it is difficult to correlate the results of this method with those of the filter weighing method.

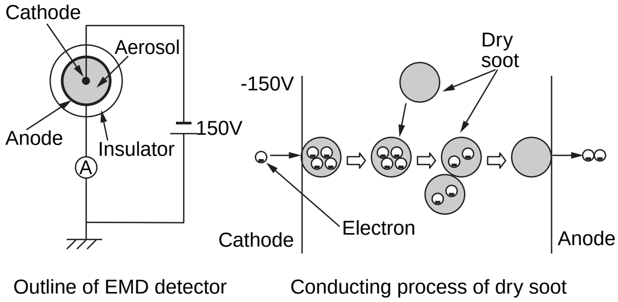

Fig.4 Principle of the EDM Method

4.3 Filter Combustion Method [4)]

This is a batch PM measurement method that uses a Bosch aspirator to sample exhaust gas directly from the exhaust pipe. A Bosch pump with a quartz filter draws in a continuous volume of exhaust gas, the PM that adheres to the filter undergoes complete combustion, and the mass of the PM is then calculated from the concentration of the CO_2 that develops during combustion.

Fig.5 shows the equipment configuration for this measurement method. This method correlates well with the tunnel method, but it is difficult to apply to continuous measurement.

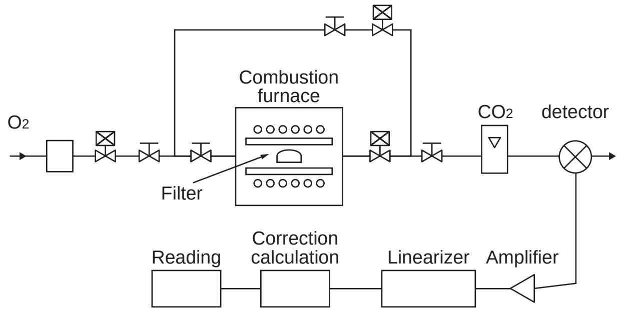

Fig.5 Filter Combustion Method

4.4 CO_2 Differential Method

This method was developed to meet the strong need for a means of continuously measuring PM. Fig.6 shows the measurement principle of the CO_2 differential method.

As with the PAS method, the sampled gas flow is split into two directions. The PM is removed from one sample flow, and then the gas sent to a combustion furnace. The other sample flow is sent directly to a combustion furnace. In the flow sent directly to the furnace, the PM components undergo complete combustion, generating CO_2, H_2O and SO_2. These gases are not generated during the combustion of the sample flow from which the PM was removed. The differences in the gas levels of the two sample flows indicate the PM. By measuring and calculating the individual concentrations of the CO_2, H_2O and SO_2, it is also possible to continuously measure soot, SOF and sulfate masses as well as the total PM. This is an extremely effective method for continuously measuring PM, however, it is difficult to improve sensitivity with this method.

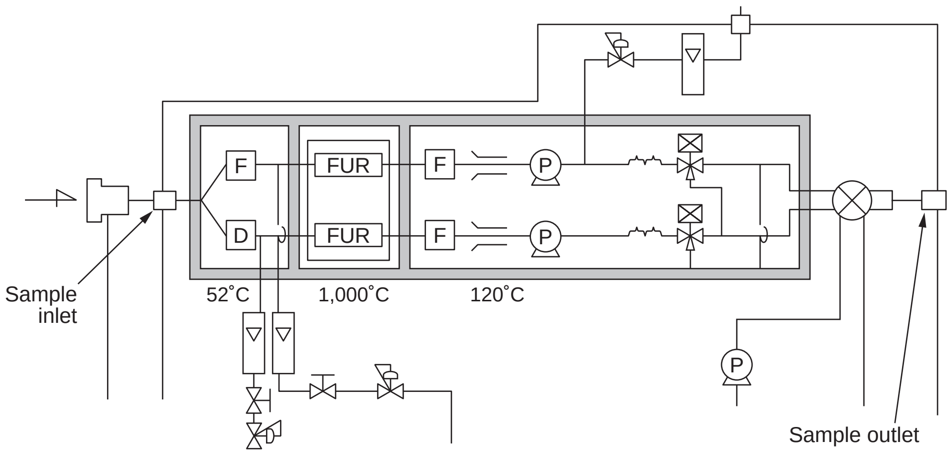

Fig.6 CO_2 Differential Method

4.5 Roll Filter Method

With this method, the PM is collected on a long, thin roll filter. After conditioned sufficiently, the PM is burned with a laser. The CO_2 gas concentration generated by the combustion is then used to continuously measure the PM (Fig.7).

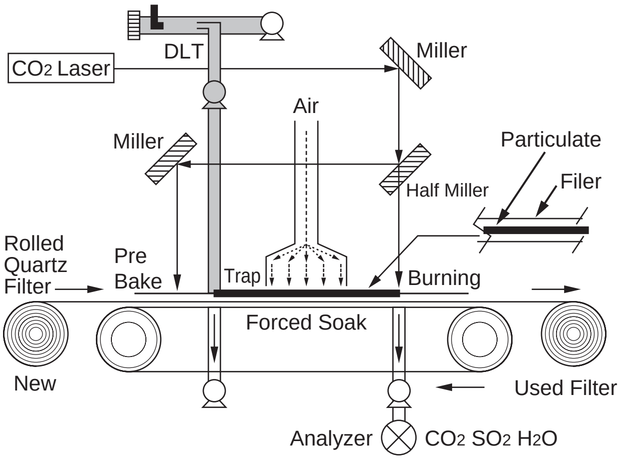

Fig.7 Roll Filter Method

5 Two Goals – Real-time Measurement and High Correlativity

Faced with difficulties such as changes in the market environment, not all of our ambitious efforts ended in success, but even our unsuccessful efforts provided valuable guidelines for the subsequent research and development of PM measurement systems. At Horiba, we eventually reached the conclusion that we needed to focus our development efforts on two methods – the flame ionization detection method, which places primary emphasis on real-time measurement, and the oxidization-reduction method, which offers high correlativity. Taking this direction of focused development, we have been able to successfully commercialize new PM measurement systems.

5.1 Flame Ionization Detection Method

With the flame ionization detection (FID) method, exhaust gas is burned by a hydrogen flame and the PM concentration calculated based on the ion current that develops during the burning. This method can continuously measure soot and SOF independently.

Fig.8 shows the flow of gas used with this method, as well as the signal outputs by the detectors, during diesel engine exhaust gas measurement.

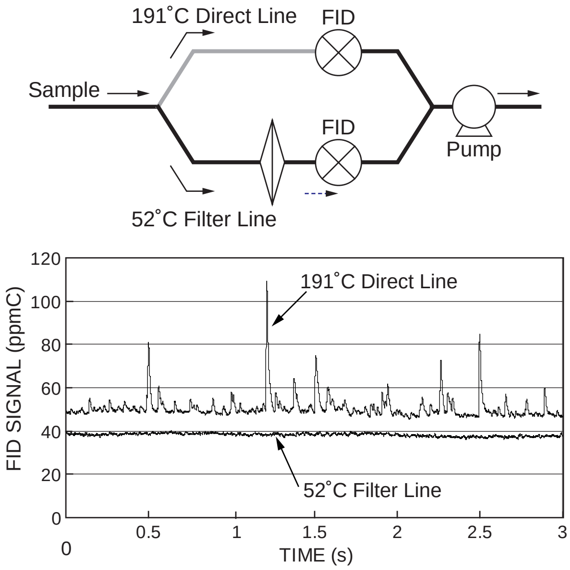

Fig.8 FID Sampling Flow and Detector Output Signal

The exhaust gas flow is split into two lines, one at 191ºC, and one with the temperature adjusted to 52ºC. For the 52ºC line, the solid components in the gas are removed by a filter, so only the gaseous components are fed to the FID. With the 191ºC line, the gas is fed directly to the FID.

The output from the 191ºC line includes a pulse signal. This signal is caused by carbon particles, and is proportional to the soot concentration. The difference in the base level of outputs from two lines, which is related to the amount of vaporized hydrocarbons under the each condition, correlates to the SOF concentration. Using both the filter weighing method and the FID method, measurements are made for various types of engines, and the measurement results used to calibrate the mass concentration scale.

Fig.9 shows the results of the continuous PM measurement of a diesel vehicle running on a chassis dynamometer. From the figure, we can see that both soot and SOF mass emissions vary with vehicle speed.

The MEXA-1220PM, a continuous PM that uses the FID method, has become quite popular as a measurement system that can quickly and easily collect data which is vital to engine research and development. For details about the MEXA-1220PM, please see the Readout issue No. 19[5].

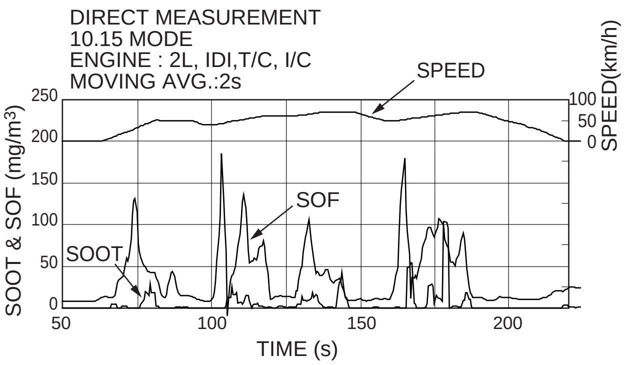

Fig.9 Measurement of Diesel Engine PM Mass Emission Using the FID Method

5.2 PM Measurement Using Vaporization, Thermal Decomposition, and Oxidization-Reduction Methods

As more and more advancements are made in the research and development of diesel engines, there is a rapidly growing need for the ability to measure even smaller PM quantities.

This method is based on the filtering method, but also makes use of nondispersive infrared gas analysis technology to achieve the measurement of ultramicro PM down to 0.2μg. As described in the detailed report, "MEXA-1370PM Super-Low-Mass PM Analyzer, " also in this issue of Readout, this method can independently measure soot, SOF and sulfate.

Fig.10 shows a comparison of results from vehicle measurements using this method and the filter weighing method. The figure shows the high correlativity of these two methods that exists even in the ultra-low mass range.

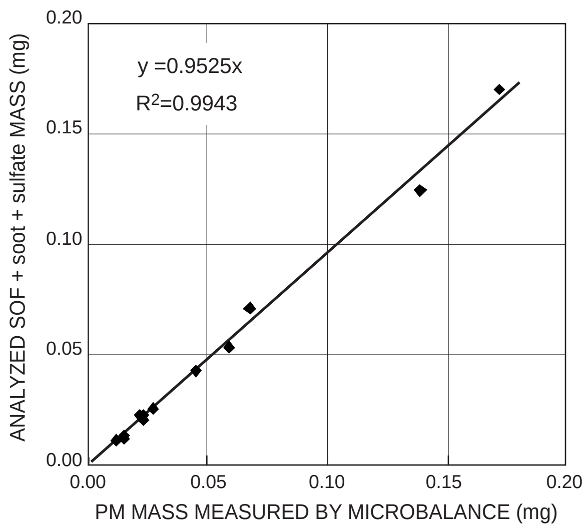

Fig.10 Correlation of the Vaporization, Oxidization-Reduction Method and the Filter Weighing Method

6 Conclusion

The reduction of PM in diesel exhaust gas is an urgent problem that requires immediate countermeasures. However, the complex composition and behavior of the PM have made it difficult to fully realize the technologies needed for accurate PM measurement.

Horiba has been working for many years on this problem, developing and testing a variety of technologies, with more than a few failures. However, by taking two different approaches, one focusing on continuous measurement and one focusing on ultra-high sensitivity measurement, we have been able to provide the market with measurement systems that can stand up to the demands of practical applications.

We anticipate that engine development will achieve extremely low levels of PM discharge, making it even more difficult to measure PM quantities. Still, we hope to continue making contributions to the development of clean engines as well as to the preservation of our natural environment through the establishment of even simpler, more effective PM measurement methods that are based on the technologies we have developed thus far.

References

1) United States Code of Federal Regulations 40, Part 86.
2) Yamagishi, Y. (1999). “Transient-Compatible MDLT-1302T Micro Tunnel”, Readout No. 19.
3) Osada, H., et al. (1982). “Real-time Measurement of Diesel Particulate Emissions by the PAS Method Using CO_2 Laser,” SAE paper 820461.
4) Yamazaki, H., et al. (1991). “A Study of Simplified Measurement Method for Diesel Particulate.” Society of Automotive Engineers of Japan, Preliminary Staff Report 911 1991-5.
5) Fukushima, H. (1999). “Continuous Measurement of Particulate Matter Using an Ionization Detector”, Readout No. 19.

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