Transition Region Exhaust Gas Measurement Using High-Speed Response Laser Equipment

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Mitsubishi Heavy Industries, Ltd. (MHI), has developed a compact laser exhaust gas measurement device that can directly measure the gas temperature and concentration at high speed in engine pipes for furnace monitoring applications such as boilers and refuse incinerators. In this report, we describe the equipment and show, using case studies, how new insights have been provided by using it for exhaust gas measurement during transient operation of test bench engines or vehicles, in situations where data are difficult to obtain with conventional equipment. We also show the effectiveness of this equipment in the development of engine and exhaust gas treatment systems.

1. Introduction

MHI has been involved in developing laser-based measurement technologies for gas concentration and temperature in furnaces for applications such as boilers and refuse incinerators.[1,2] As this measurement technology is a noncontact method, real-time measurement is possible, avoiding the delays inherent in measurements based on gas sampling. We are currently adapting this technology for use in engine exhaust measurements in automobile applications. This has required two new advances: improvement of the response time to the millisecond range, and development of a sensor that could be directly attached to the exhaust pipe of an automobile.

In this report, we describe our high-speed response engine exhaust gas measurement equipment, which includes these two developments. We also show how this equipment can be used effectively in engine development by obtaining information not easily obtained by conventional equipment in the case of transient engine conditions in which the engine load changes rapidly.

2. Laser engine exhaust gas measurement equipment

The current laser exhaust gas measurement equipment is based on laser absorption spectroscopy technology, which derives the gas concentration and temperature from the optical absorption at a specific wavelength. The actual measurement of concentration and temperature in the exhaust gas is obtained by the analysis of laser light falling on the measurement sensor (measurement cell) after passing through the exhaust gas. The sensor is attached directly to the exhaust pipe with optical fiber as shown in **Fig. 1**, and the analysis takes place in the main equipment component.

MHI has commercialized both high-speed and high-accuracy measurement equipment using different control and analysis methodologies with the same laser absorption spectroscopy principle.

2.1 Equipment overview

(1) High-speed response laser exhaust gas measurement equipment

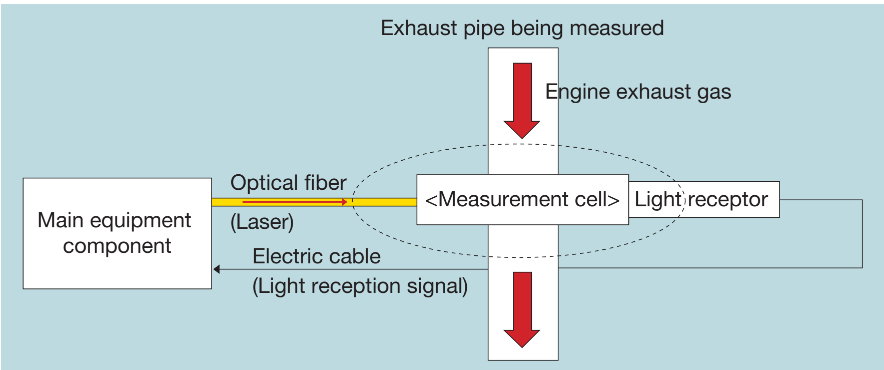

Fig. 1 Laser exhaust gas measurement equipment
Typical equipment system used for measurement of gas in a pipe.

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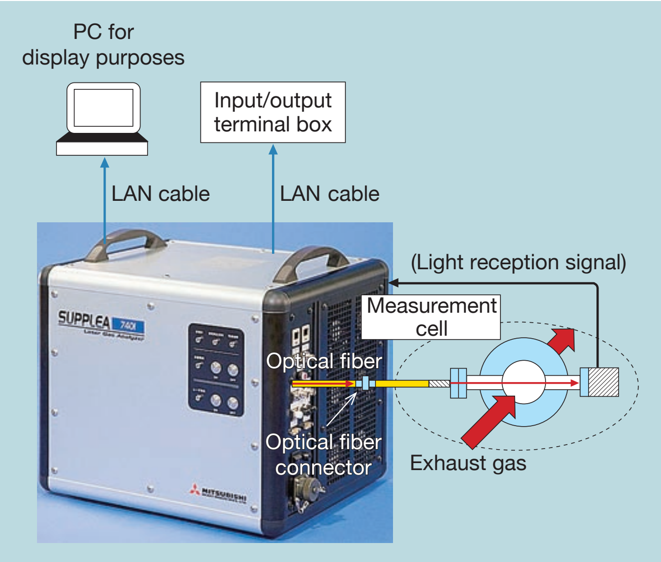

Fig. 2 Super prompt laser exhaust gas analyzer (SUPPLEA)
This has a very fast measurement time of 1 ms, and can simultaneously measure the gas temperature and concentrations of H_2O, CO, CO_2, CH_4, and O_2.

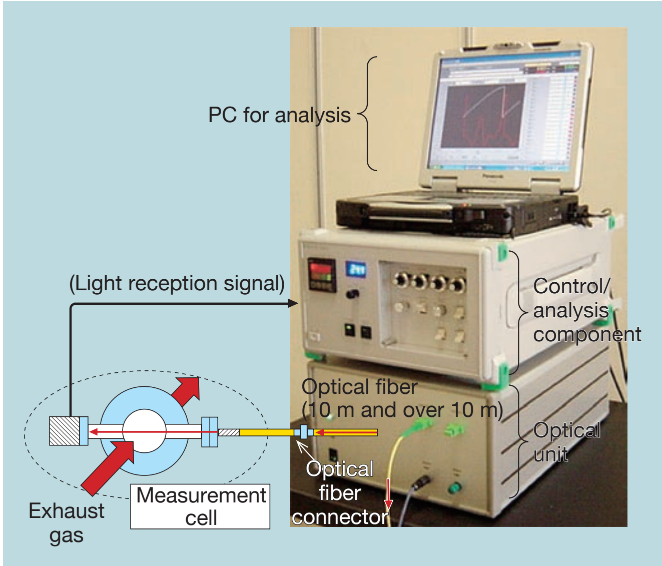

Fig. 3 High-accuracy/super prompt laser exhaust gas analyzer (TDLAS)
This device can measure the parts-per-million constituent concentrations of NOx and NH_3 at two points simultaneously with a response time of 100 ms or less.

Figure 2 shows a schematic of the Super Prompt Laser Exhaust gas Analyzer (SUPPLEA). This high-speed equipment consists of the measurement cell attached directly to the exhaust pipe, the main equipment component, and a personal computer (PC) for analysis and display. It simultaneously measures the exhaust gas temperature and the concentrations of the gas components (e.g., H_2O, CO, CO_2, CH_4, and O_2) with a time resolution of 1 ms. This equipment is used mainly in situations where the quantity of solid particulates is low, such as in engine exhaust gas.

(2) High-speed response/high accuracy laser exhaust gas measurement equipment

Figure 3 shows a schematic of the Tunable Diode Laser Absorption Spectroscopy (TDLAS) device that can perform high-speed measurements of minor gas components such as ammonia (NH_3) or nitrogen oxide (NOx) at the parts-per-million level. This equipment also consists of a measurement cell attached directly to the exhaust pipe, the main equipment component, and a PC for analysis and display, and has a measurement time of 100 ms or less.

This equipment is used mainly for the measurement of diesel engine exhaust gas because it is affected very little by solid particulates. It is also possible to measure the gas concentrations at two points such as before and after the exhaust emission control catalyst, with one set of equipment.

Table 1 summarizes the features of both types of equipment.

2.2 Measurement cell

While there are various configurations corresponding to different pipe sizes, they all use the two typical types of measurement cell.

(1) Multipath cell

This cell can be installed directly into an existing flange because the sensor is very thin, as shown in **Fig. 4.**[3] It has a pair of mirrors configured to achieve multiple reflections

Table 1 General specifications for MHI's laser exhaust gas measurement equipment

Product name	1.SUPPLEA*1	2.TDLAS*2
Features	• Super-fast responsiveness (1 ms) • Simultaneous measurement of multi-constituent concentrations (% level) and temperature • Measurement at 1 point	• High-speed responsiveness (100 ms) • High-accuracy measurement of single constituent concentration (ppm level) • Simultaneous measurement at 2 points
Application	• Gasoline engine exhaust gas • Exhaust gas after diesel particle filter (environment without solid particulates)	• Diesel engine exhaust gas • Gasoline engine exhaust gas (not affected by solid particulates)
Details	• Measures H_2O, CO, CO_2, CH_4, and O_2 simultaneously • Measurement range of gas temperature: 150–800°C	• Measures one of the following at a time: NH_3, NO, NO_2, N_2O, or others
Measurement principle	Laser absorption spectroscopy (high-speed wavelength scan and change detection)	Laser absorption spectroscopy (Wavelength modulation method)

*1: SUPer Prompt Laser Exhaust gas Analyzer *2: Tunable Diode Laser Absorption Spectroscopy

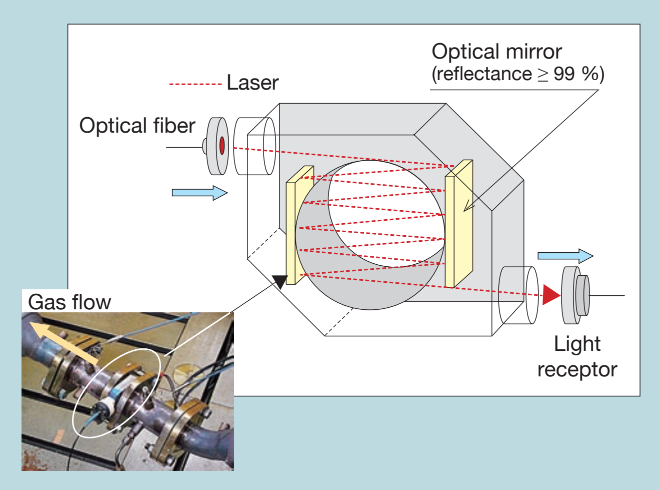

Fig. 4 Multi-path cell[3]
As the sensor is very thin, it can be attached directly to the flange of an existing pipe.

so that laser light is transmitted to every part of the pipe cross section. This has the following advantages: the average cross-section value can be obtained without being affected by the distribution of the concentration or temperature in the pipe, and the optical path length can be increased to improve the measurement sensitivity.

However, contamination of the mirrors is a problem since the exhaust gas and the mirrors are in direct contact with each other. Therefore, this sensor is suitable mainly for the measurement of gasoline engine exhaust, or diesel engine exhaust downstream from the diesel particle filter, where few solid particulates exist.

(2) Single-path cell with air purge system

Figure 5 shows a single-path cell with an air purging system. This cell permits maintenance-free measurement by eliminating the optical parts that are in direct contact with the exhaust gas, and by injecting purging gas to prevent the accumulation of contaminants on the window. However, the cell is larger and thicker than the multiple-reflection type, and some modification of the pipes may be required for some installations. This type of sensor is used mainly for the measurement of diesel engine exhaust gas.

The cell shown in Fig. 5 (a) is for a small-diameter pipe of approximately 50 mm or less, while that shown in Fig. 5 (b) is for a larger-diameter pipe of 115 mm or more.

3. Case study of automobile exhaust gas measurement

Here we discuss a case study of exhaust gas measurement using this equipment with an automobile under transient operating conditions, such as those in which the load changes rapidly. Usually, exhaust gas measurement under such conditions is difficult with conventional methods. We also describe the effectiveness of this equipment in the development of engines and vehicles.

3.1 Example of measurement results from passenger car chassis dynamo test

The chassis dynamo test of a passenger car can be easily performed with conventional sampling instruments. However, because the responsiveness of conventional instruments is as slow as several seconds and the gas sampling equipment must be near the engine, measurement at the tail-pipe is often used, even if there is a delay from the actual engine behavior. This makes it difficult to evaluate the engine behavior accurately under transient conditions.

On the other hand, the laser exhaust gas measurement

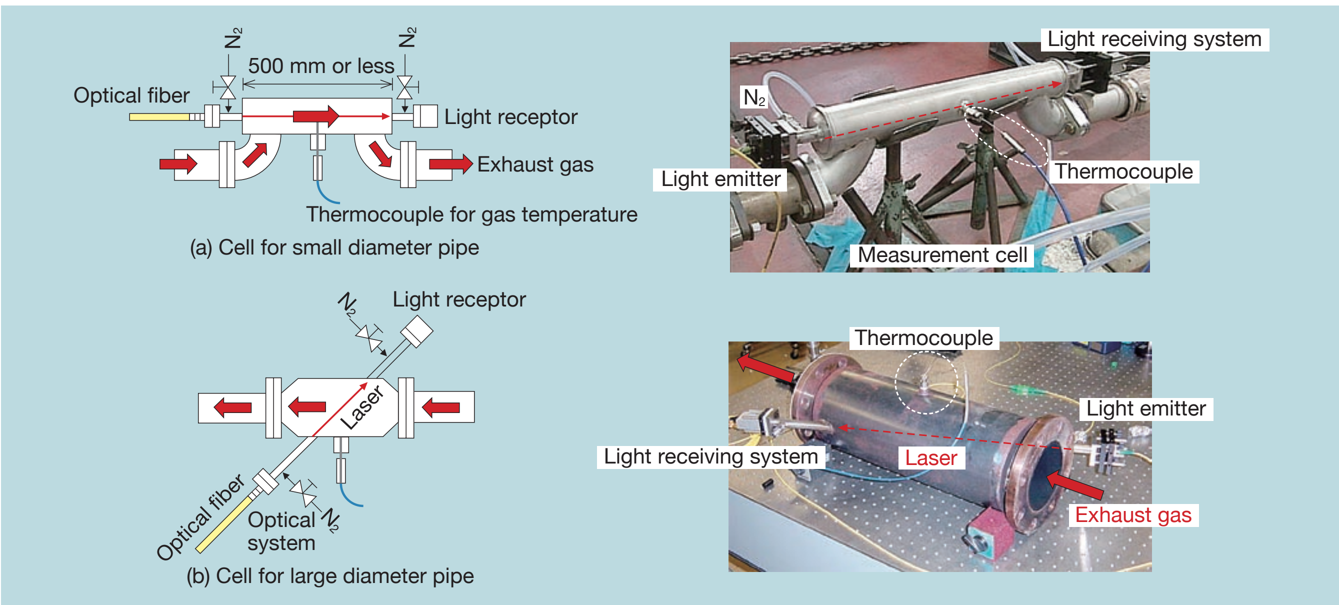

Fig. 5 Single path cell with air purging system
Even in the presence of particulates, maintenance-free measurement is possible for (a) small diameter pipes and (b) large diameter pipes.

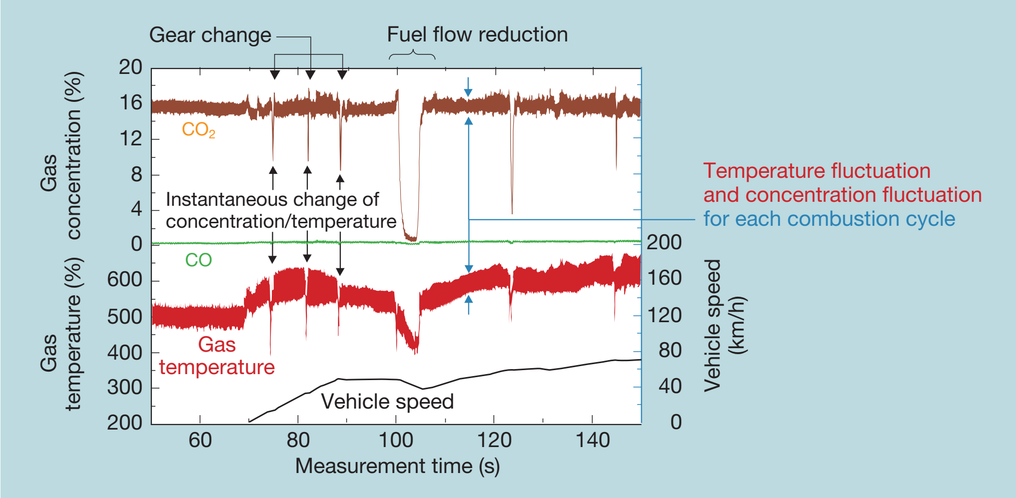

Fig. 6 Example of rapid exhaust gas measurement during mode driving test
Combustion fluctuation for each cycle can be measured, and the effect of instantaneous transient phenomena such as gear changes and fuel flow reduction can be observed.

equipment developed by MHI has a very short measurement time, and the measurement cell can be easily installed at any arbitrary location along the tailpipe without any modification to the pipe. This makes it easy to capture information in the transient region of engine operation during the chassis dynamo test.

Figure 6 shows an example of laser exhaust gas measurement at the exhaust manifold outlet for 10–15 driving modes on the chassis dynamo. Transient phenomena relating to engine control are clearly recorded, including the instantaneous changes of gas concentration and temperature corresponding to slight changes of throttle setting due to gear changes or variations in fuel flow. At first glance, it would seem that the CO_2 concentration and gas temperatures fluctuate widely. However detailed analysis reveals that these fluctuations are directly related to the combustion cycle of each piston.

Thus, high-speed transient phenomena and the fluctuation of each combustion cycle can be easily measured with this equipment even with the chassis dynamo test. This can contribute to faster development or upgrading of vehicles so they run more cleanly with better fuel efficiency.

3.2 Understanding the amount of gas overlap flow on an engine test bench

One type of current engine control stabilizes combustion by increasing the overlap of the inlet and outlet valves in high load regions and returning some portion of the exhaust gas to the intake in the form of overlap flow.

The objective of the example shown here is to verify whether the amount of exhaust gas that enters the intake (i.e., the amount of overlap flow) can be determined by high-speed measurement of the CO_2 concentration using SUPPLEA in the air intake between the intake manifold and the intake port during the bench test of a gasoline engine.

Figure 7[3] illustrates the measurement results. This graph shows crank angles on the horizontal axis and CO_2 concentration in the intake gas on the vertical axis as a function of the crank angle. Notes (1)–(5) in the figure show the degree of overlap of the inlet and outlet valves; as the numerical value increases, the amount of overlap increases. We observed that there is very little CO_2 in the intake gas under the condition of (1) without overlap, and that the CO_2 concentration increases rapidly, and its peak appears earlier, as the overlap increases.

Since this overlap flow can now be measured in real time, as opposed to with a numerical simulation only, it is possible to measure/control the optimal overlap amount based on actual measurement results.

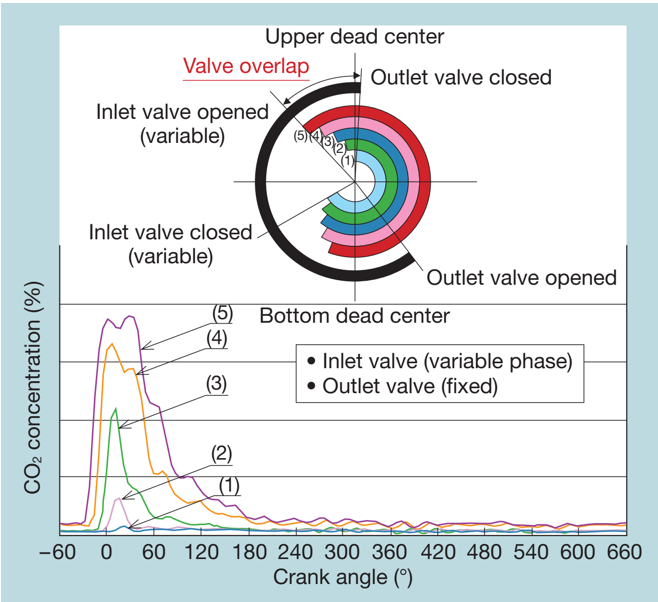

Fig. 7 Measurement of the overlap flow rate as a function of overlap amount of inlet valve/outlet valve [3]
High-level engine combustion control is simple because the overlap flow rate of exhaust gas to the intake side can be measured in real time.

This example shows that our equipment makes it possible to adjust advanced engine combustion controls simply and easily.

3.3 NH_3 concentration measurement in a diesel passenger car

Urea selective catalytic reduction systems help improve the control of diesel emissions. In this type of system, it is important to control the optimal injection volume of NH_3 as a function of the amount of NOx generated. NH_3 also plays an important role in the de-nitrification (deNOx) of NOx storage catalyst.

Since NH_3 is a substance with strong absorptive properties, accurate measurement of its concentration is difficult using gas sampling. This is particularly so in a case in which the concentration changes rapidly (transient region of concentration change), and the response delay with the sampling method makes detecting changes very difficult.

Therefore, we describe a case study in which TDLAS is used to measure the concentration of NH_3 in diesel exhaust gas. We recorded the quantitative results and responsiveness of measuring the NH_3 concentration in the exhaust gas at the tail pipe of a diesel passenger car using TDLAS with a single path-cell and air purge system, and compared these to the results obtained using the gas sampling method.

During the test, exhaust gas containing NH_3 of a certain concentration was first measured to confirm that the measurement values using both methods were the same. After that, the measurement results were compared while driving the car under conditions in which the amount of NH_3 generated changed in sharp spikes (i.e., rich spike condition).

Figure 8 shows the measurement example with the NH_3 concentration (upper graph) and the signal for NH_3 production (lower graph) as a function of time; the NH_3 is produced during the spike signal. This equipment can measure the change of NH_3 concentration synchronized with the spike signal while conventional instruments hardly register the change at all.

Thus, while conventional instruments lack responsiveness for the evaluation/control of the deNOx system above, the MHI equipment can easily evaluate and control the system. This will help accelerate the development of more advanced deNOx systems.

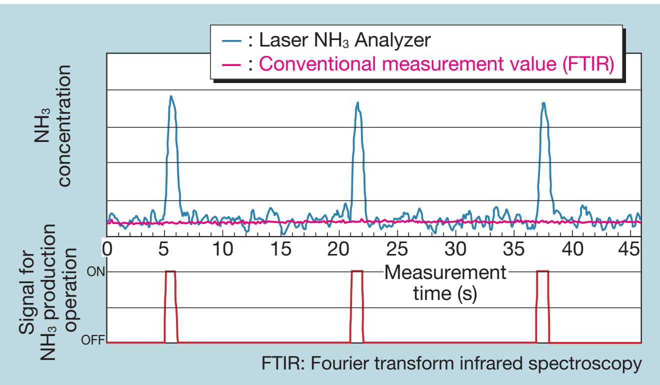

Fig. 8 Measuring ammonia production during a rich spike
More advanced deNOx systems can be designed and controlled using laser measurement equipment to measure prompt NH_3 change.

4. Conclusion

MHI has developed compact laser exhaust gas measurement equipment that can measure engine exhaust gas at high-speed.

(1) High-speed response laser exhaust gas measurement equipment (SUPPLEA)
- Simultaneous measurement can be achieved for gas temperature and concentrations of H_2O, CO, CO_2, CH_4, O_2 with a response speed of 1 ms.
- One set of equipment measures one location.

(2) High-accuracy laser exhaust gas measurement equipment (TDLAS)
- Concentration can be measured with high-accuracy on a parts-per-million level with a responsiveness of 100 ms or less.
- One set of equipment can simultaneously measure two points, such as before and after the catalyst.

MHI intends to assist customers in their product development by providing this equipment in order to help them understand various phenomena that cannot be investigated conventionally. This includes the following:

(1) High-speed phenomena that are otherwise difficult to observe, such as the change of concentration and temperature for each cycle of the engine combustion process.

(2) Changes of NH3 concentration that are difficult to detect by sampling measurement; this is very important in the development of future exhaust gas treatment systems.

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