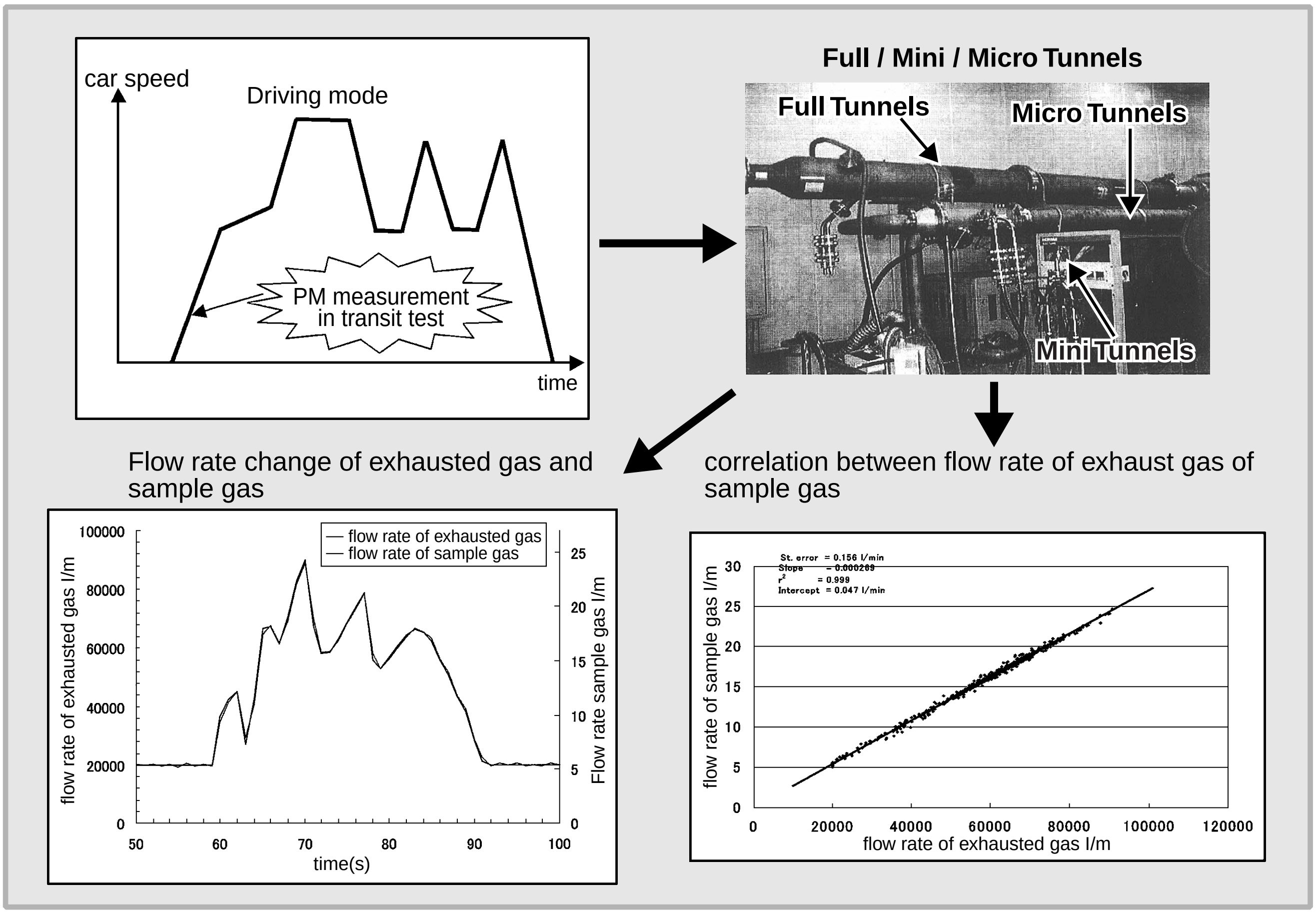
FEATURE ARTICLE

The MDLT-1302T Partial-Flow Dilution Tunnel for Transient Test Cycle PM Sampling

Yutaka Yamagishi



Abstract

The current steady-state test cycles used to measure particulate matter (PM) in engine exhaust will be replaced by transient test cycles in near future. Horiba has recently developed a PM sampling system using a partial flow dilution method, the MDLT-1302T, to perform sampling during transient test cycles. The MDLT-1302T has been evaluated using a heavy-duty diesel engine operating under the Euro Transient Cycle (ETC) and Feaeral Test Procedure (FTP) transient cycle, and the results prove that a fast flow control has been achieved with a response time of less than 0.5 second. This paper describes the performance of the MDLT-1302T and the technical challenges encountered during its development.

1 Introduction

This paper describes the performance of the MDLT-1302T partial-flow dilution tunnel, a system that will allow highly reliable particulate matter emissions measurements of diesel engine exhaust when diesel engines are tested under the transient test cycles that will soon be required by law.

When a diesel engine is driven under simulated road conditions, condensed carbon particles and high-boiling-point hydrocarbons emitted from the tailpipe generate particulate matter (PM). To measure PM emissions during simulated driving conditions in the laboratory, a dilution tunnel is used. Until recently, only full dilution tunnels can be used to operate effectively when the engine was operated under transient test cycles and partial flow tunnels could not apply to transient testing. The new transient test regulations place additional demands on dilution sampling system which shall be met by fast response flow control systems, if partial flow samplling method was used for required transient cycles.

2 Problems of the Dilution Tunnel and Transient Test Cycle

PM measurement has previously used a full flow dilution tunnel where the entire amount of engine exhaust gas is collected and made available for sampling. However, under this sampling method the size of the dilution tunnel depended on the exhaust gas volume: the greater the volume of exhaust gas from the test engine, the larger the dilution tunnel system must be. The partial-flow dilution tunnel eliminates this problem by permitting sampling of a part of the total exhaust flow. The partial-flow dilution tunnel system first separates the flow of engine exhaust by a constant split ratio before the exhaust stream is fed into the dilution tunnel. The dilution tunnel dilutes and cools the exhaust gas using dilution air. Then the diluted exhaust passes through filters after the tunnel to prepare for PM sampling. The following equation shows the relationship of the engine exhaust gas flow-rate and the diluted exhaust gas flow-rate:

$$r = \frac{G_{exh}}{G_{tot} - G_{dil}} = \frac{G_{exh}}{G_{sam}} = \text{const.} \text{-------} (1)$$

$$G_{sam} = G_{tot} - G_{dil}$$

Where G_{exh} : Total flow-rate of engine exhaust gas
G_{tot} : Flow-rate of diluted exhaust gas
G_{dil} : Flow-rate of dilution air
r : Split ratio
G_{sam} : Flow-rate of engine exhaust gas to be sampled

As shown in equation (1), to maintain a constant diluted exhaust flow-rate (G_{tot}), it is necessary to control the dilution air flow-rate (G_{dil}) at an early stage before the engine exhaust gas flow (G_{exh}) changes rapidly. Thus, high-speed measurement and control of the dilution air flow is required for the partial-flow dilution tunnel if it is to operate under transient test cycle.

3 Early Development

Our approach to developing the MDLT-1302T partial-flow dilution tunnel started with improvements made to dilution tunnels used for steady-state emissions testing. We began by making improvements in the speed of measurement and control for steady-state test cycles. Fig.1 provides a schematic of the a dilution tunnel used in steady-state cycle PM emissions tests.

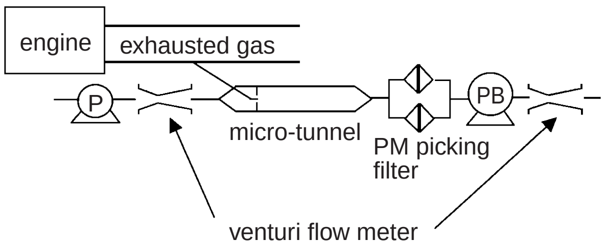


Fig.1 Flow Schematic of the Dilution Tunnel for a Steady-State Test Cycle

3.1 Venturi Flow Meter

Horiba's dilution tunnel uses highly accurate venturi flow meters that are free from errors caused by differences in the densities of the many different gaseous components of the sample, especially CO_2 and H_2O. The density of engine exhaust gas is nearly constant and thus does not present measurement problems when venturi flowmeters are used.

As shown in Fig.2, the venturi flow meter has a configuration where the diameter sharply decreases from the inlet to the throat and gradually expands towards outlet. Here the flow-rate measurement is based on the proportional relationship of the velocity of the gas and the square root of the differential pressure caused by two different velocities of the gas-the pressure at the inlet and the pressure at the throat. Because the equation relies on the square root of the pressure differential, measurements using a venturi flow meter are more accurate at high flow-rates. Chart 3 shows a measurement accuracy curve that illustrates this point.

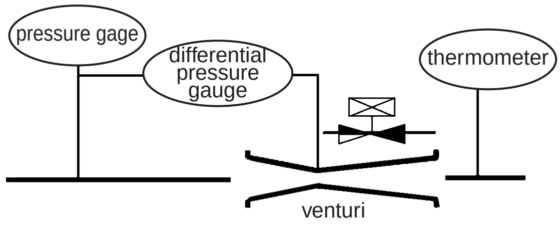


Fig.2 Configuration of the Venturi Flow Meter

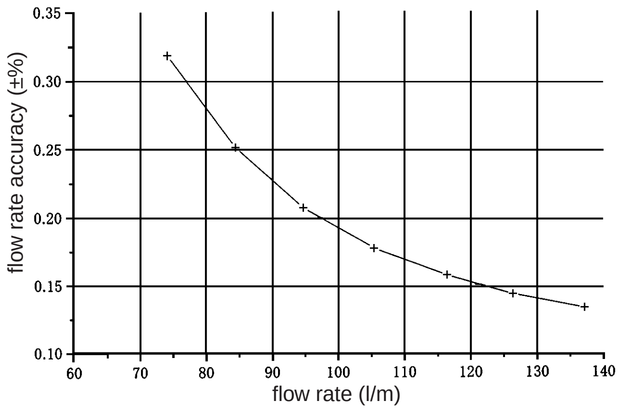


Fig.3 Measurement Accuracy of the Venturi Flow Meter

3.2 Partial-Flow Sampling by the Blower Pump and Predictive Control

In the partial-flow dilution tunnel system, the diluted exhaust flow rate is maintained by controlling the rotation speed of the pump installed after the tunnel and PM sampling filter. Because moving a large flow of air generates a large inertia, if a large-volume pump is used to control the flow of dilution air a response delay is unavoidable. This is why different types of blowers are used. Control of the dilution air requires fast response to control inputs so the dilution air pump uses a low-inertia vortex blower. The diluted exhaust flow does not require such a fast response, so a positive displacement root blower is used.

Fig.4 shows a typical step response of dilution air flow-control when a venturi flow meter is used with a vortex blower. Here the delay time (T_d) is approximately 0.4 second and the response time at 90% of indication (T_{90}) is only 0.5 second.

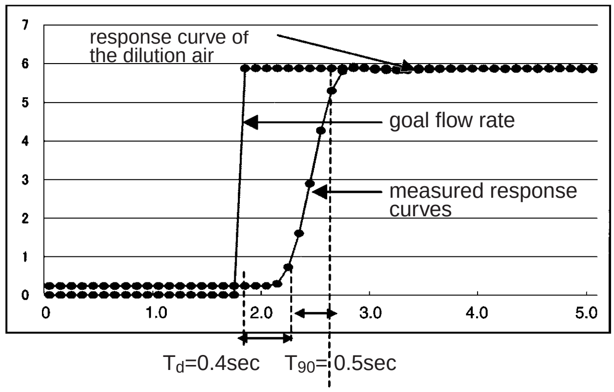


Fig. 4 The Step Response of Flow Control Using the Air Blower

Because the exhaust gas flow rate from the tested engine varies rapidly but gradually than the step change, a response time of 0.5 second for T_{90} is an acceptable result in use.

However, the delay time (T_d) needs a further improvement. The predictive control method is used in this purpose. Under this method the test engine performs a certain simulated driving cycle before PM sampling begins. This allows collection of time sequence data on the exhaust gas flow. Based on this data, the actual PM test is performed using the delay-time correction thus derived. Fig.5 shows that this method reduces sampling error to 5% or less.

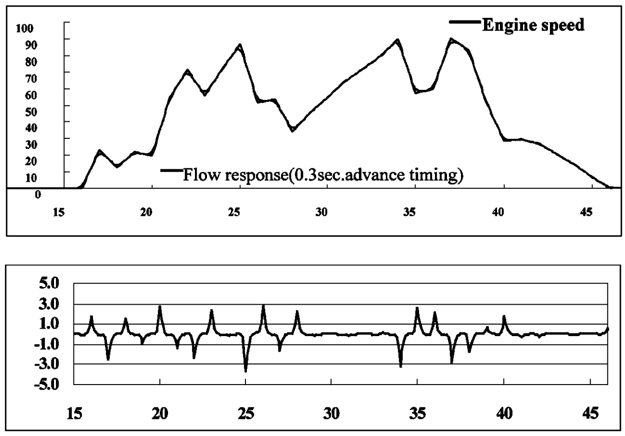


Fig.5 Flow Control Error by the Predictive Control Method

4 Further Speed-Up …Development of MDLT-1302T…

To satisfy the need for fast flow-rate control, Horiba has developed the MDLT-1302T partial-flow dilution tunnel for use with transient test cycles. Fig.6 shows a flow schematic of the MDLT-1302T. The following paragraphs discuss some of the new technologies applied in developing this new dilution tunnel.

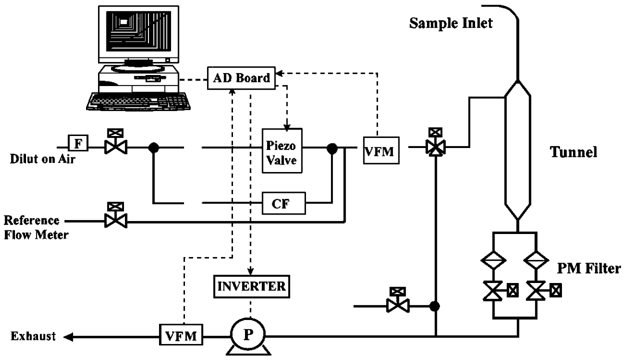


Fig.6 Flow Schematic for the MDLT-1302T

4.1 Fast Response Dilution Air Flow Control by Piezo Valve

The two major factors that affect delay in performing accurate measurement during a transient cycle are: 1) the time delay between the sampling of exhaust gas and its measurement and; 2) the delay in the flow control of the dilution tunnel. The first factor can be corrected by using a predictive control method as discussed in section 3.2. Overcoming the problems posed by the second factor, i.e., speeding up the response time of the dilution tunnel flow control, is discussed in the following paragraphs.

The first approach replaced the vortex blower rotation control method with a new flow control method that uses a supply of compressed air controlled by a piezo-electric valve. This idea came from a design for a hot-wire type mass flow controller that used a control valve. Such devices are in common use, although their accuracy and response speed were not satisfactory for use in our application.

The innovative method developed by Horiba combines a piezo-valve with a venturi flow meter. In addition to this, by using a critical flow orifice (CFO) with the piezo-valve, the response time can be reduced significantly. As shown in Fig.7, these approaches contribute to dramatic improvement of the step response to 0.2 second for both T_d and T_{90}.

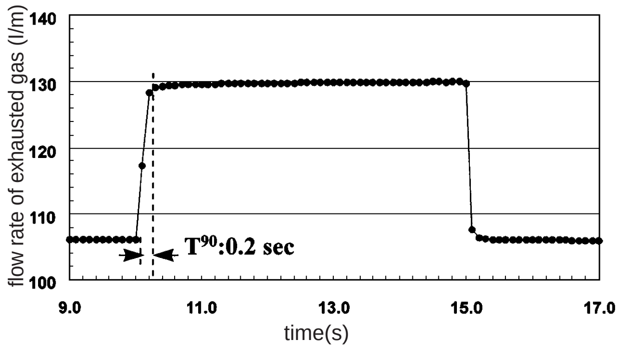


Fig.7 The Step Response of Flow-control Using the Piezo-Valve

4.2 Flow-Control Electronics

To achieve fast-response flow control, all elements must perform at high-speed-the signal processing and control system, as well as the flow meter and flow control device. The electronics system is vitally important. It must perform virtually instantaneous flow-rate computations using the analog signals from differential pressure sensors of the venturi flow meters as well as target flow-rate values and controller feedback signals. For example, the piezo-valve has a characteristic hysteresis. The valve-opening signal voltage supplied to the piezo element is variable. To permit adjustments to the timing of signals controlling the piezo-valve, a closed-loop control system with variable target voltage is required.

Modern control theory requires that the control signal be faster than the target response time by one order of magnitude. To meet this requirement we made our flow control response time target within 200 ms, and concentrated our efforts toward minimizing delays from processes such as A/D conversion, flow operation, and D/A conversion. This produced a control loop with a notably high speed of 20 ms.

5 Evaluation of Transient Response in the MDLT-1302T

Fig.8 shows a flow rate change of diesel engine exhaust gas and sample gas during a Euro Transient Cycle (ETC) test. Fig.9 shows the correlation between two flows when measured second-by-second throughout the 1800-second duration of the ETC test. The sampling flow-rate shown here is obtained from the diluted exhaust gas flow-rate and dilution air flow-rate in equation 1 in section 2. As is obvious from Fig.8, the exhaust gas sample flow into the tunnel takes only 0.2 second to catch up to the exhaust gas flow rate (input). The correlation factor between these two flows is 0.998 (refer to Fig.9), which shows that a reliable proportional control is successfully achieved. The result of this evaluation clearly indicates that the MDLT-1302T provides steady performance with minimum delay time and fast response. The MDLT-1320T is especially useful in measuring exhaust gas in cold-start tests. This performance is also supported (see Fig.10) by the evaluation of operation in mode 10.15 test cycle used in Japan.

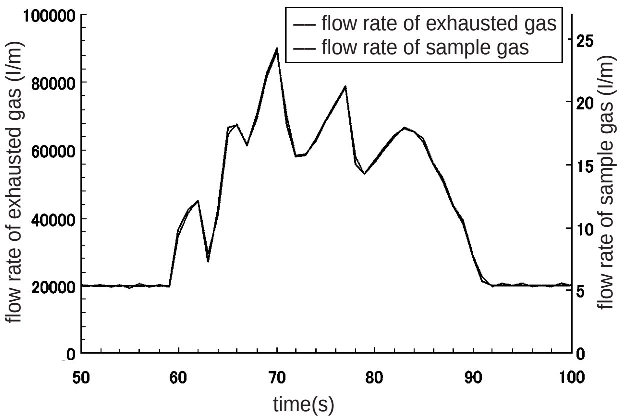


Fig.8 The Flow Rate Change of Engine Exhaust Gas and Sample Gas in the ETC Mode Transit-Time

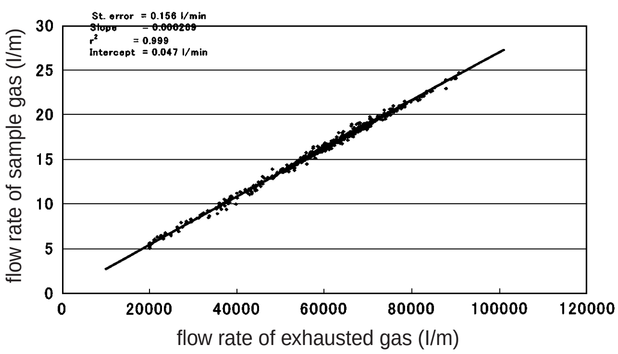


Fig.9 The Correlation of Engine Exhaust Gas Flow Rate and Sample Gas in the ETC Mode Transit-Time

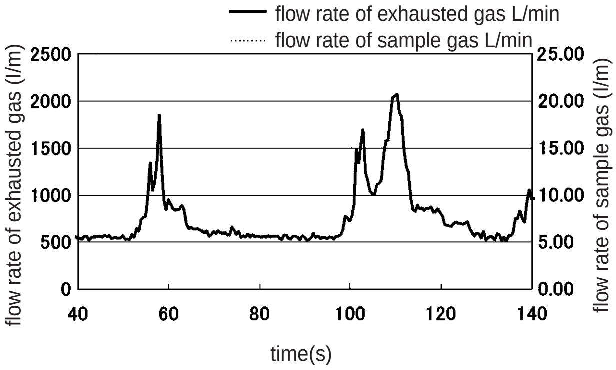


Fig.10 The Flow Rate Change of Engine Emission Gas and Sample Gas in Mode 10/15 Transit-Time

6 Configuration of the MDLT-1302T

Fig.11 shows an overview of the MDLT-1302T. The system is made up of the model DLT-1302 dilution tunnel (set-up inside the engine emission test laboratory), the model DLS-2300 dilution flow control unit, and a set of operator and indicator panels to be installed in the operation room. The control unit containing the venturi flow meters and piezo-valve is included in the 19-inch rack. The connection between the engine exhaust pipe and the dilution tunnel inlet is made with a heated transfer tube less than 1.5m in length. A supply of compressed air is required for the dilution air. The operator and indicator panel provides buttons for setting the basic operation conditions such as input of the engine exhaust gas flow rate, switch between real-time input control or predictive control, and selection of dilution air control mode. Momentary flow and integrated flow can also be indicated. The external controls also allow operation and momentary flow output.

Fig.10 The MDLT-1302T Partial-Dilution Tunnel for Transient Test Cycle PM Sampling

7 Conclusion

The adoption of the transient test cycle has created new performance requirements for diesel engine PM emissions measurement systems. As the result of our fundamental experiments and studies, Horiba has developed the MDLT-1302T the first among the competitors, to meet the measurement needs of the transient test cycle. We encountered a number of challenges in the our development process and have overcome each problem through our teamwork with electrical, mechanical, and software experts. As the MDLT-1302T product is evaluated and challenged by customers in the field, we plan to continue our effort improve the state of the art of emissions measurement.

Yutaka Yamagishi

Manager

Emission Analysis R&D Dept.

Horiba, Ltd.