Feature Article

Application

Direct Fuel Consumption Measurement using Fuel Flowmeter

Takashi MATSUYAMA

Yuki ITOGA

Influenced by the trend toward reducing greenhouse gases represented by Kyoto Protocol, provisions on fuel consumption standard is stricter every year in transportation sector as regulations directly contributing to reduction of exhaust gases. As a result, efforts of automobile manufacturers to reduce fuel consumption are made more actively and quickly and therefore the technical development to realize low fuel consumption requires such a fuel consumption measurement system that enables highly accurate measurement. This article introduces our fuel flowmeter which satisfies the request for direct fuel consumption measurement with high accuracy and the important points to fuel consumption measurement at the viewpoints of sensor and measurement system.

Introduction

Automotive vehicles and internal combustion (IC) engines are a source of CO_2 emission which is a greenhouse gas. For example, 18% out of the total CO2 emission in Japan is emitted from transport sources (Figure 1). For this reason, CO_2 emissions from engine and vehicles have recently been regulated around the world. The CO_2 emission from IC engines is determined by the carbon content of the fuel also by the fuel consumption, so fuel consumption reduction is essential for the reduction of CO_2 emissions. To that end, there's been an increase in development into the technology for more accurate fuel consumption measurement.

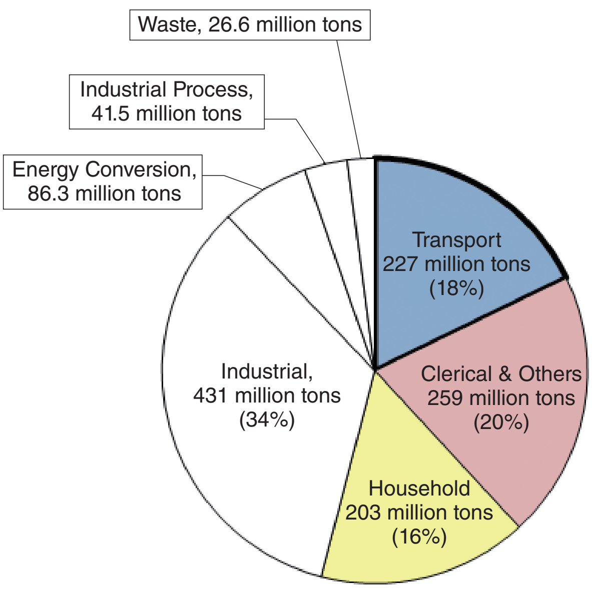


Figure 1 CO_2 Emissions of the transport Sector (Japan. 2012)
Source: Ministry of Land, Infrastructure, Transport and Tourism

Several methods are used to measure fuel consumption. One of the methods is to measure the fuel consumed by engine directly by means of a flow meter. The degree of accuracy required for the fuel flow meter can be estimated as follows. If a heavy duty vehicle with a 10 litre engine is tested in JE05 test cycle, the fuel consumption could be estimated at 3.6 kg approximately. This is equivalent to a mass flow rate at 7.1 kg/h approximately. Considering that a change of 1% has significant implications for fuel consumption certification, it can be seen that a variation of 0.07 kg/ should be readily determined.

In order to meet the need for such high accuracy fuel flow measurement, HORIBA has introduced a Coriolis flow meter based system, the FQ-2200CR. In this paper, the techniques applied within the FQ-2200CR are described.

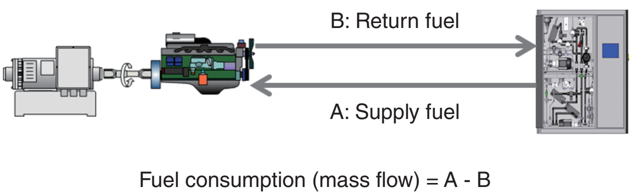


Figure 2 Concept of fuel flow measurement by fuel flow meter

Overview of Fuel Flow Meter FQ-2200CR

Configuration

The concept of the new fuel flow measurement system is shown in Figure 2. The amount of fuel consumed in unit time i.e. the flow rate, is calculated as the difference between fuel supplied to the engine and the return fuel from the engine. In this method, fuel consumption can be measured continuously in real time. In reality, it is very difficult to apply such a fuel flow meter in a vehicle. Therefore it is commonly used for fuel consumption measurement in engine testing for development and certification.

The schematic diagram of the FQ-2200CR is shown in Figure 3. FQ-2200CR measures fuel flow by using a mass flow sensor based on the Coriolis principle. The operating principle and features of the Coriolis flow meter will be described later in this paper. The area surrounded by blue line is located inside of FQ-2200CR. In Figure 3, "A" is measuring portion where Coriolis flow meter is installed. "B" is conditioning section to regulate the temperature and pressure of the fuel which is supplied to the engine. "C" is the engine whose fuel flow rate is to be measured.

Concept and features of the Coriolis flow meter

The Coriolis flow meter used in FQ-2200CR has two

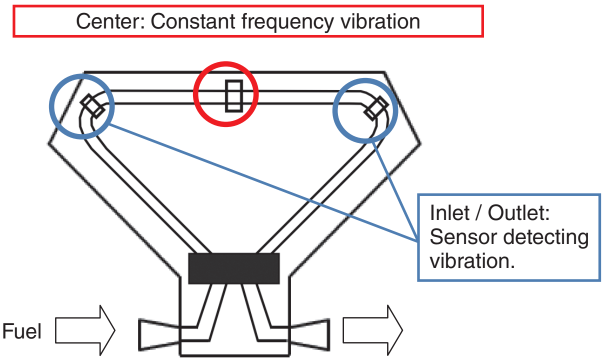


Figure 4 Coriolis flow meter

loops which are made from a single pipe and the two loops are configured in parallel position each other. Figure 4 is the schematic view of Coriolis flow meter in the direction perpendicular to the loops. Constant frequency vibration is applied at the center of the loops using a coil. Vibration sensors are installed on both ends, inlet and outlet, to measure pipe vibration.

The fuel flow measurement principle of the Coriolis flow meter is shown in Figure 5. In the case of "(a)", no fuel is flowing in the loops and the vibration phases between two loops are the same. In contrast, in the case of "(b)", fuel is flowing in the loops. In this case, vibration between two sensors has phase difference (ΔT). The phase difference is caused by the force called "Coriolis force" which is generated when vibration is applied to the direction perpendicular to the pipe where fluid is flowing. The magnitude of the Coriolis force depends on the mass flow rate in the pipe, so the mass flow rate can be determined from the phase time difference.

As the Coriolis measures mass flow, there is no need to measure fuel density, which is required if "volume" flow measurement is used. Generally speaking, it is difficult for the Coriolis flow meter measure repeatably ar low flow

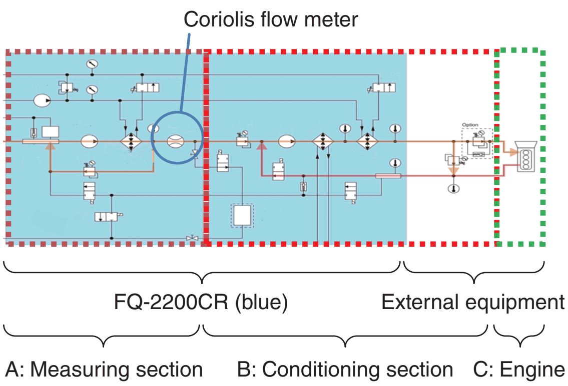


Figure 3 FQ-2200CR fuel flow mesurement schematic diagram

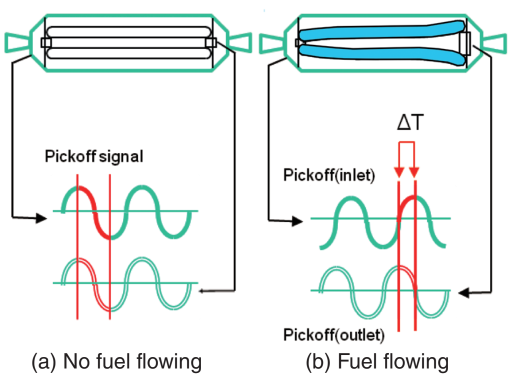


Figure 5 Coriolis flow meter principle

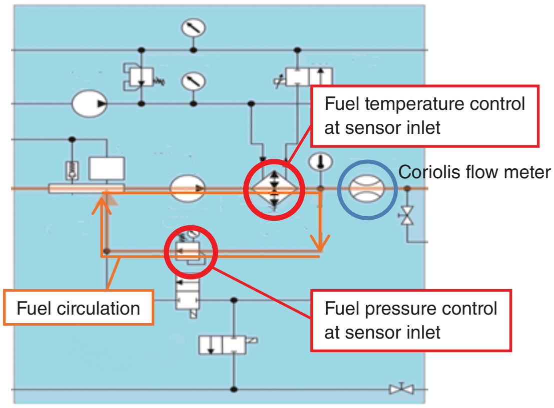


Figure 6 Inhibition of influence of temperature and pressure in the Coriolis meter

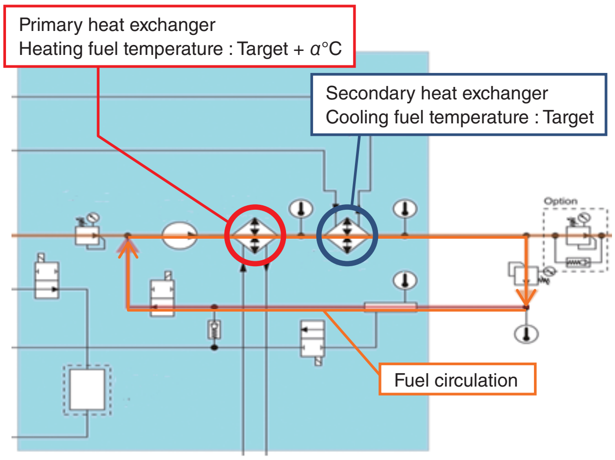


Figure 7 Reduction of temperature / pressure effect in pre-conditioning section

rates. The HORIBA Group has applied a unique technique in the FQ-2200CR to solve the problem as described below.

Measurement Repeatability Improvement

In order to improve the measurement repeatability of the Coriolis fuel flow meter system, not only is the condition of the Coriolis flow meter itself important but also the performance of the fuel conditioning section that supplied fuel to the engine.

Condition control in flow rate measuring portion

The sensor output from the Coriolis flow meter can be affected by the fluctuation of temperature and pressure of the fuel flowing in the meter. Key points to reduce the effects are shown in Figure 6. As shown, the fuel circulation circuit is configured at the inlet of Coriolis flow meter to control the fuel pressure and temperature by using a pressure regulator and heat exchanger, respectively. By setting the fuel condition to be the same when in measure mode as it was during the zero-point calibration mode, the influence of fuel temperature and pressure to the sensor output is suppressed.

The vibration of the sensor also affects the output of Coriolis flow meter. As mentioned above, the Coriolis flow meter vibrates the pipes to measure the mass flow rate. If the pipes resonate with pulsation of fuel flowing in pipe or from vibration coming from outside of the system, measurement accuracy can be affected. So, the use of flexible pipe is partly used to cut off the vibration from fuel pump or from outside of the system, and vibration insulation countermeasures have been also applied to the Coriolis flow meter.

Fuel control in the pre-conditioning section

When the fuel flow rate is measured by Coriolis flow meter, there is a small inner volume in the pre-conditioning section (in pipe, regulator and so on) which is connected between engine and Coriolis flow meter. If the inner volume is changed by temperature, or fuel density is changed by temperature and/or pressure, the response time of Coriolis flow meter to measure the fuel consumed by engine can be affected. Then, measurement repeatability of fuel flow rate determination is affected. The countermeasures in the pre-conditioning section for the temperature and/or pressure effect are shown in Figure 7. In the FQ-2200CR, the temperature of fuel which is supplied to the engine is stabilized by using fuel circulation. Two sets of heat exchangers are used for temperature control. First, fuel temperature is heated to target temperature + α°C by primary heat exchange and then it is cooled to target temperature by secondary heat exchanger, whereα°C is constant. The two step process enable precise control of fuel temperature.

Effect of temperature change in pre-conditioning section

In this paragraph, the effect in the pre-conditioning section is described when fuel temperature is changed. One of the examples of the output of the FQ-2200CR when fuel temperature is changed rapidly is shown in Figure 8. Fuel flow rate is constant and target temperature is changed from 25°C to 27°C (case (a)) and from 25°C to 23°C (case (b)). In both cases, fuel flow rate is changed as -0.075 kg/h or +0.06 kg/h during fuel temperature changing in 100 sec. After temperature is stabilized, the output returns to the same level as before the temperature was changed.

One of the causes of the symptom mentioned above is

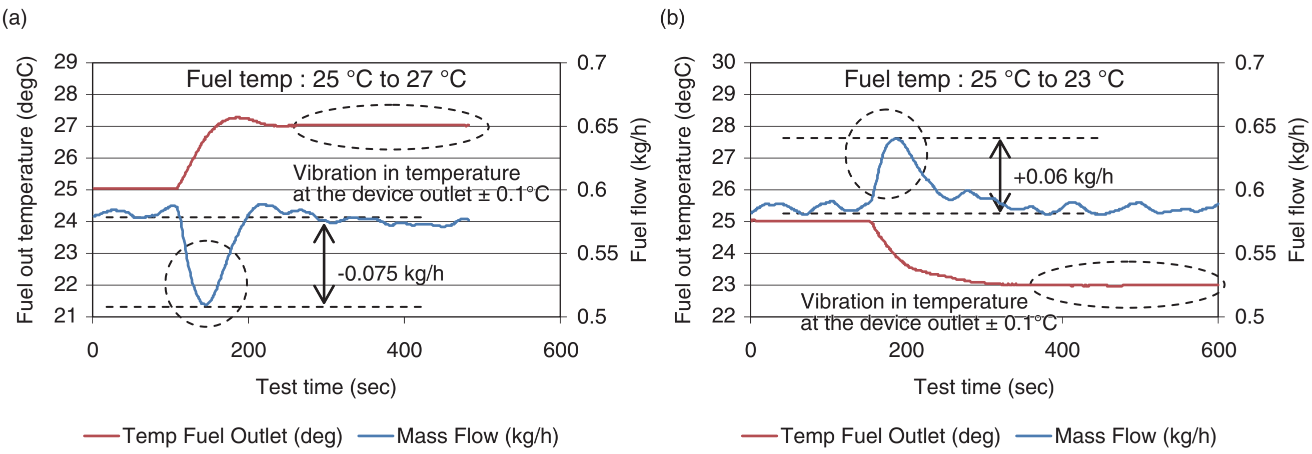


Figure 8 Mass flow rate when fuel temperature is changed

thought to be the inner volume change in regulator, PR4, in pre-conditioning section (Figure 9), which is caused by temperature change. Operation of the regulator and the forces within it are shown in Figure 10. When fuel flow rate is zero, the fuel flow path in the regulator is closed by range spring (a). When fuel is flowing with pressure regulated, range spring is pushed up by another spring in the bottom, the fuel flow path is opened and diaphragm is also pushed up to the fuel flow path. The spring force as well as the stiffness of the range spring (made of carbon steel) and diaphragm is affected by the temperature. Therefore, if the fuel temperature is rapidly changed from 25°C to 23°C, the force which attempts to return the diaphragm and range spring to the original position is generated (c). As a result, shape of diaphragm is close to the static condition (a) and inner volume of regulator is increased. The fluctuation of fuel flow rate when temperature is decreased (Figure 8b) can be caused by the fuel which is flowing into the increased inner volume. Therefore, in order to minimize the error, it is necessary to reduce the fuel temperature change when fuel flow rate is measured. As shown in Figure 9, the fuel temperature is regulated in the range of ±0.1°C by using heat exchanger and regulator in fuel circulation in the FQ-2200CR.

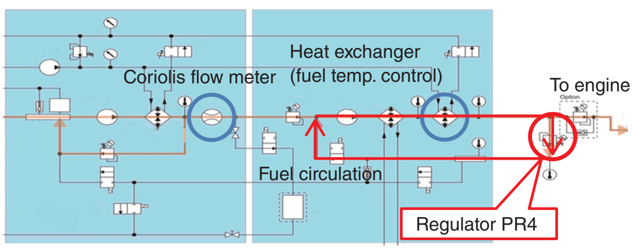
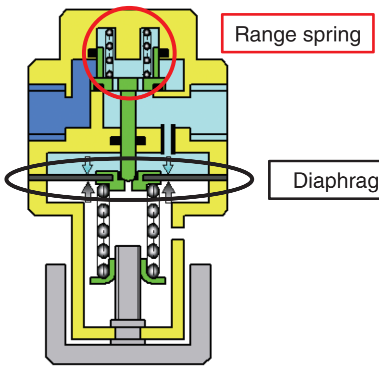
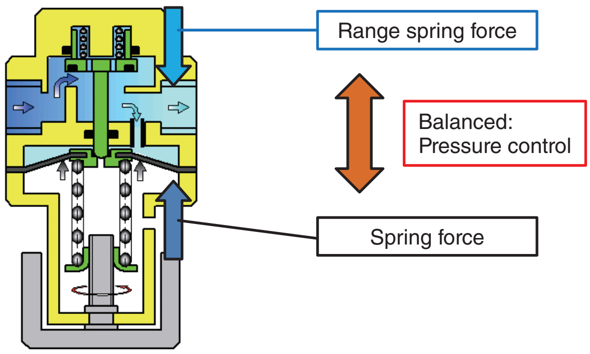


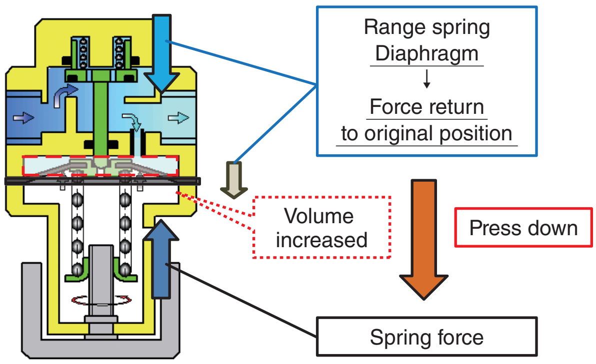
Figure 9 Fuel temperature effect in regulator (preprocess portion)



(a) : No fuel flowing

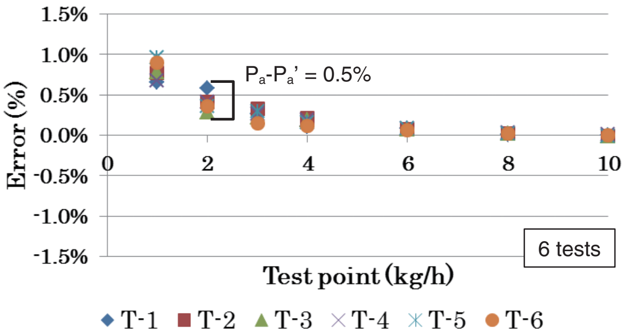


(b) : Fuel flowing (pressure control)

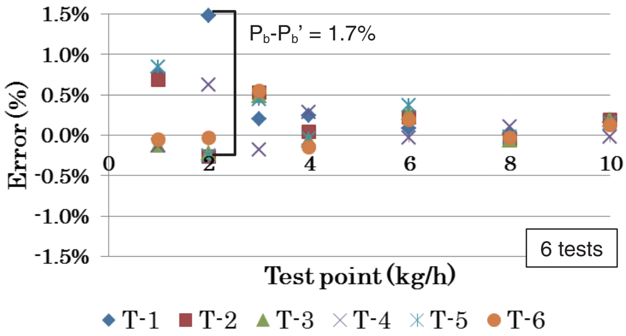


(c) : Fuel temperature is decreased from condition (b)

Figure 10 Regulator operation



(a) with temperature control (ordinary operation)



(b) without temperature control

Figure 11　Flow rate accuracy

Measurement Repeatability of the FQ-2200CR

Examples of the results of flow rate accuracy with the FQ-2200CR are shown in Figure 11. The validation method is shown in detail in Figure 12 and Figure 13. The horizontal axis is the mass flow rate measured by a reference Coriolis flow meter, and the vertical axis is the measurement difference between the reference Coriolis flow meter and the FQ-2200CR (%). The results in ordinary operation with the repeatability improvement mentioned above are shown in (a), and the results without repeatability improvement are shown in (b). In the case of (b) without the repeatability improvement, the difference between max value P and min value P' is large when flow rate is small. On the other hand, it is confirmed that repeatability is improved very much in the case (a), with the repeatability improvement since the difference between max value P and min value P' is small in the range from 1 kg/h to 10 kg/h.

The flow diagram of the validation system for flow rate accuracy used in Figure 11 is shown in Figure 12, and the concept is shown in Figure 13. A Coriolis flow meter and electric balance are used as reference equipment to

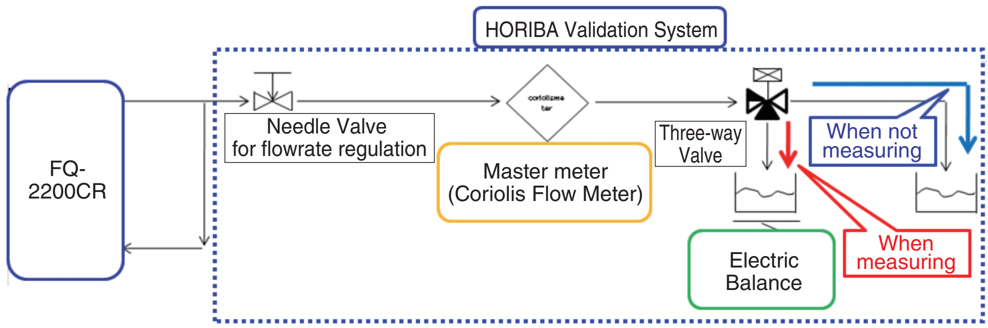


Figure 12　Flow diagram of validation system for flow rate accuracy

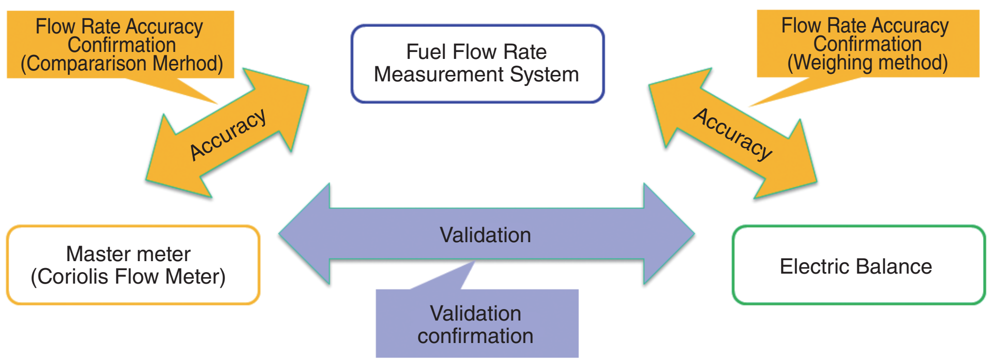


Figure 13　Flow rate accuracy validation

validate system accuracy. The evaluation method with reference Coriolis flow meter is the “Comparison Method”, which directly compares output (mass flow rate) from the system to be evaluated with output from the reference Coriolis flow meter. Since two Coriolis flow meters are connected for the validation, the validation system is designed to avoid mutual interference by vibration. On the other hand, fuel is put in a pan on the electric balance with buoyancy adjustment only when flow rate is measured. The validation method is the “Weighing method”, which compares integrated flow value by the system to be evaluated with the mass measured by electric balance. Thus, two references are used to ensure the accuracy of the flow rate measurement and the validity of the test at the same time and, therefore, the reliability of FQ-2200CR is ensured.

Conclusion

This paper describes the improvement of measurement repeatability applied in the FQ-2200CR using the Coriolis flow meter, which can be used for directly determining the fuel consumption of the engine. We are confident in the system as a real-time fuel consumption measurement tool with high precision will help in making engine R&D more effective as well as in shortening its development time. In future, through the provision of higher performance and more reliable fuel flow measurement, we will continue to contribute to the measurement of the performance of the internal combustion engine and vehicle.

Takashi MATSUYAMA
Automotive Measurement System Design Dept.
Engineering Center
Research & Development Division
HORIBA, Ltd.

Yuki ITOGA
Automotive Measurement System Design Dept.
Engineering Center
Research & Development Division
HORIBA, Ltd.