

In-Situ Real-Time Fuel Consumption Measurement Using Raw Exhaust Flow Meter and Zirconia AFR Sensor

Masanobu Akita, Hiroshi Nakamura and Masayuki Adachi
Horiba, Ltd.

ABSTRACT

Fuel efficiency is one of the most important parameters in advanced vehicles. Therefore, the measurement of fuel consumption in-situ and in real-time is obviously demanded in development and evaluation processes of new engines and vehicles. This paper describes a new concept for measuring fuel consumption in real-time, which utilizing raw exhaust gas flow rate and exhaust air-to-fuel ratio (AFR). The AFR is defined as the mass ratio of air and fuel supplied to the engine, and the mass flow rate of exhaust gas can be regarded as the summation of the mass flow rate of air and fuel. This means the fuel consumption can be calculated from exhaust flow rate and AFR.

To realize in-situ, real-time measurement, we used an ultrasonic exhaust flow meter which can measure a wide flow range accurately with no pressure loss, and a fast response zirconia sensor which can be installed onto the exhaust pipe directly without any sampling system. This exhaust flow-AFR method has the advantage that the real-time fuel consumption can be easily obtained without delay time by these in-situ measuring devices which can be installed at the almost same location.

Integrated fuel consumption by this method showed good correlations with conventional methods, i.e. the carbon balance method and the fuel flow method. Furthermore, in the transient tests including engine start and fuel cutting operation, it showed sufficient response for real-time analysis. The results suggest that this method has a significant potential for measuring fuel consumption in-situ and in real-time.

CITATION: Akita, M., Nakamura, H. and Adachi, M., "In-Situ Real-Time Fuel Consumption Measurement Using Raw Exhaust Flow Meter and Zirconia AFR Sensor," *SAE Int. J. Commer. Veh.* 6(1):2013, doi:10.4271/2013-01-1058.

1. INTRODUCTION

The improvement of fuel efficiency is one of the most important issues in the R&D of powertrain systems, and the real-time fuel consumption must be analyzed correctly to optimize the engine operation under transient driving conditions.

Generally, real-time fuel consumption is measured by fuel flow method, where a fuel flow meter is directly installed in the fuel line of engine in a test facility.[1] However, it is difficult to install a fuel flow meter in a completed vehicle which typically includes a complex fuel system.

A carbon balance method using a constant volume sampler (CVS), in which concentration of CO₂, CO and HC in diluted exhaust gas is measured respectively, is also generally used; however, the response time of measured fuel consumption may not be short enough and may be unstable due to the change of exhaust flow rate and mixing influence during rapid transient engine operations.

More accurate fuel consumption may be obtained if it is measured by a non-sampling method, with fast response, and that places no extraneous load on the engine.

This paper discusses a method of real time fuel consumption measurement achieved by a raw exhaust flow meter and an AFR sensor.

2. EXPERIMENTAL EQUIPMENT

2-1. Ultrasonic Exhaust Gas Flow Meter

Various methods are available to determine exhaust gas flow. [2] In this study, in order to obtain a fast response, an ultrasonic exhaust gas flow meter was utilized in the measurement system. The main advantages of the ultrasonic flow meter are:

- High accuracy,
- Wide measurement range,
- No pressure loss, and

- No influence from gas composition and density.

Figure 1 shows the principle of the ultrasonic flow meter. Special ultrasonic transducers which can be used in high temperature gas were utilized for the measurement. The ultrasonic transducers were installed on opposite side of an exhaust pipe each other. An electronic controller generated ultrasonic pulses which were transmitted both upstream and downstream, while the propagation time for the pulse to traverse the pipe was measured.

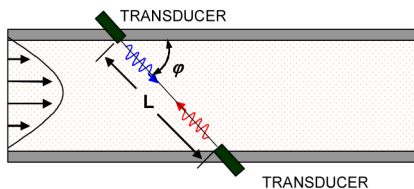


Figure 1. Principle of ultrasonic exhaust gas flow meter

When gas is flowing in the pipe, the propagation time is different between two directions. The propagation times are expressed as follows:

$$t_{dn} = \frac{L}{c + v(t) \cos \varphi} \quad (1)$$

$$t_{up} = \frac{L}{c - v(t) \cos \varphi} \quad (2)$$

where

- t_{dn} is propagation time in downstream direction [s];
- t_{up} is propagation time in upstream direction [s];
- L is distance between each transducer [m];
- C is sound velocity [m/s];
- $v(t)$ is exhaust gas velocity at time t [m/s];
- φ is ultrasonic propagation angle against flow direction [degree].

Equation (1) and (2) can be deformed as shown in equation (3) and (4).

$$c = \frac{L}{t_{dn}} - v(t) \cos \varphi \quad (3)$$

$$c = \frac{L}{t_{up}} + v(t) \cos \varphi \quad (4)$$

By eliminating sound velocity c from these equations, the exhaust gas velocity is expressed as equation (5).

$$v(t) = \frac{L}{2 \cos \varphi} \times \left(\frac{1}{t_{dn}} - \frac{1}{t_{up}} \right) \quad (5)$$

This means that the measured value of exhaust gas velocity is independent of sound velocity.

Exhaust volume flow rate at standard condition is calculated from the exhaust gas velocity and the diameter of the exhaust pipe.

$$q_{\text{vew}}(t) = k_{\text{profile}} \times A \times v(t) \times \frac{T_0}{T(t)} \times \frac{P(t)}{P_0} \quad (6)$$

where

$q_{\text{vew}}(t)$ is exhaust volume flow rate at standard condition [m³/min];

k_{profile} is correction coefficient for the ununiformity of gas velocity and/or temperature in exhaust pipe;

A is the cross-section area of exhaust pipe [m²];

T_0 is temperature at standard condition [K];

$T(t)$ is temperature of exhaust gas [K];

$P(t)$ is the absolute pressure of exhaust gas [kPa];

P_0 is absolute pressure at standard condition [kPa].

In this study, the coefficient k_{profile} was determined by comparing the exhaust flow rate by the ultrasonic flow meter with that by a smooth approach orifice (SAO) flow meter as a reference. Also, the effect of exhaust gas temperature on sensor itself was compensated separately. The specifications of the ultrasonic flow meter are summarized in table 1.

Table 1. Specifications of ultrasonic exhaust gas flow meter

Items	Specifications	Notes
Accuracy of flow rate	±3% of readings	0.06 to 0.1[m ³ /min]
	±2% of readings	0.1 to 0.4[m ³ /min]
	±1% of readings	0.4 to 10[m ³ /min]
Response time	No more than 0.5[ms]	T90
Pressure loss	No more than 1.0[kPa]	Maxium flow condition
Output rate	10[Hz]	



Figure 2. Ultrasonic exhaust gas flow meter

2-2. Zirconia AFR Sensor

As a fast response and non-sampling method, a zirconia (ZrO_2) sensor was adopted to measure AFR. Figure 3 shows the configuration of the ZrO_2 AFR sensor.

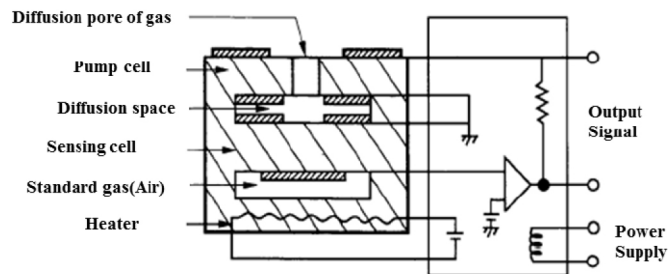


Figure 3. Configuration schematic of zirconia AFR sensor

Sample gas diffuses into a diffusion space through a pore on sensor surface. The inside sensing-cell monitors the difference voltage between both side of the cell, i.e., reference gas side and sample gas side. The pumping-cell controls the current so that the difference voltage becomes constant at the same value with the case of stoichiometric fuel combustion. That is, under lean combustion conditions, the excess O_2 in the diffusion space is pumped out. By contrast, deficient O_2 is pumped in under rich conditions, being mainly supplied by reduction of CO_2 .

The pumping current is expressed as equation (7).

$$I_p = \frac{n \times F \times S \times P}{R \times T \times L} \times D_{\text{O}_2} \times C_{\text{O}_2} \quad (7)$$

where

- I_p is pumping current [A];
- n is electric charge number related to an electrode reaction process (= 4);
- F is faraday constant;
- S is the cross-sectional area of gas diffusion pore;
- P is pressure;
- R is gas constant;
- T is temperature;
- L is length of the gas diffusion pore;
- D_{O_2} is the diffusion coefficient of oxygen;
- C_{O_2} is oxygen concentration.

This means that the excess and deficiency of O_2 can be known from the pumping current. The AFR can be determined by comparing such O_2 condition with that in stoichiometric combustion and it shows linear characteristic. The specifications of the AFR sensor used in this study are summarized in table 2.

Table 2. Specifications of zirconia AFR sensor

Items	Specifications	Notes
Accuracy of AFR	± 0.3	9.5 to stoichiometric point
	± 0.1	stoichiometric point
	± 0.3	stoichiometric point to 20
	± 0.7	20.01 to 30
Response time	± 1.0	30.01 to 40
	Typical 80[ms]	



Figure 4. Zirconia AFR sensor

2-3. Setup of the Equipment for In-Situ Fuel Consumption Measurement

Figure 5 shows the experimental setup for the in-situ fuel consumption measurement. The ultrasonic sensor was basically installed at the tailpipe end of the test vehicles. The ZrO_2 sensor should be also installed at the tailpipe, as close as possible to minimize delay time and gas density difference between the sensors. On the other hand, the ZrO_2 sensor installed at upstream close to the ultrasonic sensor may give a flow disturbance effect. Therefore, the ZrO_2 sensor was located at 10 times the straight pipe diameter upstream of the ultrasonic sensor.

The outlet of the ultrasonic flow meter is connected to a CVS, which serves as a reference measurement system to evaluate the correlation.

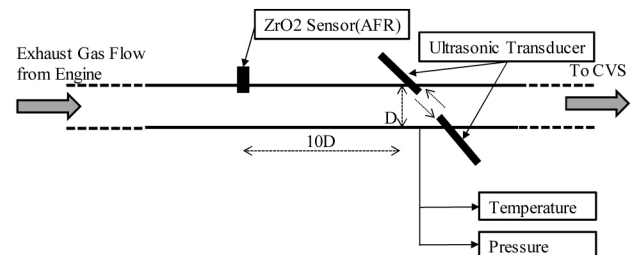


Figure 5. Experimental setup for in-situ fuel consumption measurement