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Fuel Consumption Monitoring System Using Control Signal and Characteristic Correlations of Fuel Injector

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Abstract

Objectives of this study are (i) to investigate characteristics of a fuel injector and to establish the characteristic correlation for correcting the fuel injection rate calculated from the control signal of a fuel injector, and (ii) to design and fabricate the fuel consumption monitoring system by measuring the control signal of a fuel injector in conjunction with considering the obtained characteristic correlation to enhance accuracy of the measured fuel consumption rate. The characteristics of a fuel injector (maximum fuel injection rate of 270 cm^3/min), e.g., engine speeds, percentages of injector's duty cycle, and pressure differences between fuel rail and intake manifold, were experimentally investigated on a test set in the laboratory. The study found that when the engine speed increased, the fuel injection rate increased. When the percentages of injector's duty cycle increased, the increasing ratio was less than the one-to-one increasing ratio as a case of the ideal. Moreover, when the pressure difference increased, the fuel injection rate increased. After that, the fuel consumption monitoring system was designed and fabricated based on the Arduino Mega 2560 microcontroller. Trip distance was measured by a GPS module. The real-time fuel consumption rate could be shown on a LCD display. All recorded data were stored onto a SD card for further data analysis. Finally, the on-road-test validation was conducted by on the 2011 Mitsubishi Triton installed with the 4-cylinder gasoline engine with total displacement of 2,351 cm^3. It was found from that the average discrepancy of the measured fuel volume was ± 1.88% compared to the actual fuel volume obtained by measuring a decreasing volume of consumed fuel.

Keywords: Fuel Consumption Monitoring System; Fuel Injector Control Signal; Fuel Injector Characteristic; Microcontroller; Fuel Injection System.

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1. Introduction

Fuel consumption monitoring system is justified to be one of the most necessary systems installed in recent vehicles. Drivers are informed and guided by the system in order to drive with higher fuel efficiency. Although recent vehicles have been installed with the system from manufacturers, huge numbers of vehicles do not have this system on board. Installation of a fuel consumption monitoring system that directly measures flow rate of the fuel is a convenient choice but it cannot be acceptable because this may cause failure to the fuel system and danger since a fuel supply line must be cut and reconnected. Some post-installed meters measure an opening angle of a throttle valve and convert into the fuel consumption rate. However, this technique causes relatively high discrepancy since engine load is not directly depended on the throttle valve's opening angle. In order to create a new system with high accuracy and reliability, an idea to design and fabricate the fuel consumption monitoring system by measuring percentages of duty cycle (%DC) and frequency of injector pulse signal generated by the electronic control unit (ECU), has been proposed. Fuel injection rate in a specified time is calculated from the measured control signal. In conjunction with the vehicle velocity obtained from the global positioning system (GPS) module, the fuel consumption rate in a unit of kilometer per liter (km/liter) can be determined. Although this technique has higher accuracy than some other techniques because the fuel consumption is directly obtained from the signal that actually controls an operation of the engine's fuel injector; however, the past studies reported that the characteristic of a fuel injector such as structure of the fuel injector, %DC, pressure difference between a fuel rail and an intake manifold (DP), fuel temperature, flow pattern of intake air, heterogeneous fuel and air mixture, etc. [1]-[5] are the major factor that causes the actual fuel injection rate to diverge from the one corresponding to the injector's control signal. Therefore, in order to enhance the accuracy and the reliability of the fuel consumption monitoring system using fuel injector's control signal, the characteristics of fuel injector are always needed to be considered simultaneously.

From aforementioned reason, it became the significance of this study with two main objectives that are (i) to investigate characteristics of a fuel injector and to establish the characteristic correlation for correcting the fuel injection rate calculated from the control signal of a fuel injector, and (ii) to design and fabricate the fuel consumption monitoring system by measuring the control signal of a fuel injector in conjunction with considering the obtained characteristic correlation to enhance accuracy of the measured fuel consumption rate.

Obtained results will be useful in several ways, such as; researchers on the fuel system obtain basic knowledge about effects of characteristics of a fuel injector on the actual fuel injection rate, manufacturers of the fuel consumption metering system gain initial model for developing the system with higher accuracy, and vehicle owners have the higher accuracy fuel consumption metering system and the system will be used as an important tool to adjust their driving behavior and to reduce fuel usage correctly and efficiently.

2. Experimental Setups and Procedures

2.1 Investigation on Characteristics of Fuel Injector and Establishment of Characteristic Correlation

The characteristics of a fuel injector experimentally investigated in this study consisted of (i) engine speeds, (ii) %DC, and (iii) pressure difference between a fuel rail and an intake manifold (ΔP) these is actually used in the spark-ignition (SI) engine. A laboratory-scaled test set was designed and made to be able to simulate the vehicle's fuel system. Components of the test set are schematically depicted as shown in **Fig. 1** and the details are as follow.

(1) A fuel tank made from stainless steel had capacity of 28.7 liter. (2) A twelve-volt direct-current fuel pump taken from the 2011 Mitsubishi Triton was installed inside of the fuel tank to pressurize and supply the fuel through (3) a fuel filter to (4) a fuel rail, which was particularly made from stainless steel. Inner diameter and length of the fuel rail was 20 mm and 150 mm, respectively. The outlet of the fuel rail was connected to (5) a fuel pressure regulator (Flex, Super Pro V.2) that was used for controlling the ΔP to be constant. A hole with a diameter of 14 mm was drilled at the middle of the fuel rail for installing

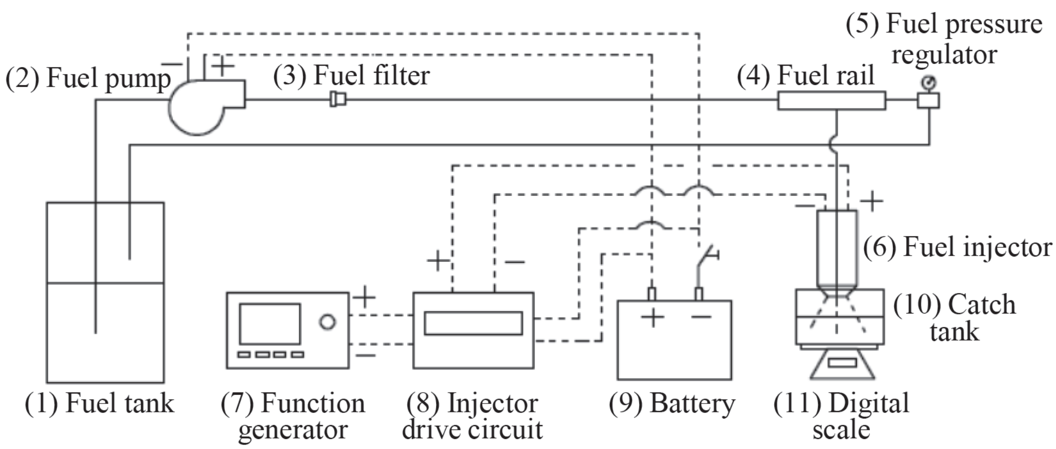

Fig. 1 Experimental setup for investigating the characteristics of fuel injector.

(6) a fuel injector (Bosch, maximum fuel injection rate of 270 cm^3/min) taken from the 4-cylinder gasoline engine with total displacement of 2,351 cm^3 in the 2011 Mitsubishi Triton (Engine model 4G64). The fuel injector in this test was the same model as installed in the engine of the vehicle used in the on-road test as in the Section 2.3. Square-wave pulse signal to control operation of the fuel injector was generated by (7) a function generator (DDS Function Generator, SG1003) with output frequency range from 0.1 Hz to 3 MHz, and accuracy of frequency and amplitude was ± 5×10^{-6} Hz and ± 10% (1 kHz, 20 $V_{p\text{-}p}$), respectively. The fuel injector's control signal corresponded to various engine speeds could be simulated by adjusting the frequency of the signal from the function generator. Moreover, the %DC of the signal could be directly set on the function generator. Voltage of the generated signal was increased to be enough to control the fuel injector by (8) an injector drive circuit and (9) a battery (GS, 46B24R-MF, 12 VDC, 45 Ah). Control signal passed through wires to a connector of the fuel injector. Fuel injection rate was calculated after the fuel injected into (10) a catch tank in a specified time was weighed by (11) a digital scale (Radwag, WLC 1/A2, resolution 0.01 g, accuracy ± 0.03 g).

Experimental procedure for investigating the characteristics of the fuel injector started after the fuel tank was fully filled with the gasoline (octane number of 91). The ΔP was initially defined and set by the fuel pressure regulator. Frequency and pulse width corresponding to the engine speed and the %DC needed to be investigated were adjusted by the function generator. For a 4-stroke engine, the fuel injector injected the fuel one time per 720° of the crank angle; therefore, the frequency and the pulse width of the control signal could be determined by equation (1) and (2) respectively.

$$f = \frac{N}{2 \times 60} \tag{1}$$

$$PW = \frac{\%DC}{100} \times T = \frac{\%DC}{100 \times f} \tag{2}$$

Where

f = the frequency of the fuel injector's control signal (Hz)

N = the engine speed (rpm)

PW = the pulse width of the fuel injector's control signal (s)

T = the period of the fuel injector's control signal (s).

After the fuel was supplied, the fuel injected within period of one minute was weighed and divided by the density of the fuel at 25 °C, which was the same as the surrounding temperature, to be the fuel injection rate per minute. The procedure was repeatedly conducted for 5 replications in order to increase the reliability of the data. All obtained fuel injection rates were averaged to be the representative result affected by a certain variable parameter. Finally, the engine speed, the %DC, and the ΔP were changed and aforementioned procedure was conducted until all variable parameters as listed in the scope were completely investigated.

When effects of the characteristics of the fuel injector on the fuel injection rate were achieved, the characteristic correlation to correct the fuel injection rate measured from the fuel injector's control signal could be consequently established by means of the least square curve fitting. The correlation was programmed onto the fuel consumption monitoring system in order to enhance accuracy of measured fuel consumption rates.

2.2 Design and Fabrication on Fuel Consumption Monitoring System

Major components of the fuel consumption monitoring system are shown in **Fig. 2** and details are listed as follows.

(1) A microcontroller (Arduino, Mega 2560) was used as a central processor of the system. Electrical power was supplied by separated power storage to prevent interference from the engine. Since voltage of the fuel injector's control signal in the tested vehicle varied in a range between 2 and 14 V, which was higher than the maximum voltage of 12 V that the microcontroller properly operated, the voltage of the measured control signal was regulated to be the logic TTL signal or the pulse signal with voltage fluctuating between 0 and 5 V by (2) a voltage regulator (Sila, MM-DCIN V2.0). Velocity and position coordinates of the tested vehicle were obtained from (3) a global positioning system (GPS) module (ETT, ET-Mini GPS). After the microcontroller processed the measured control signal and velocity in conjunction with the characteristic correlation, the measured and calculated data were shown in (4) a LCD display with 4 lines of 20 characters. A case of the display could be attached onto a windshield in a position that a driver could clearly observe. In addition, the system also functioned as a data logger as the measured and calculated data could be stored in the SD card by using of (5) a SD card module (Adafruit, Data logging shield) with real time clock (RTC) for further data analyses.

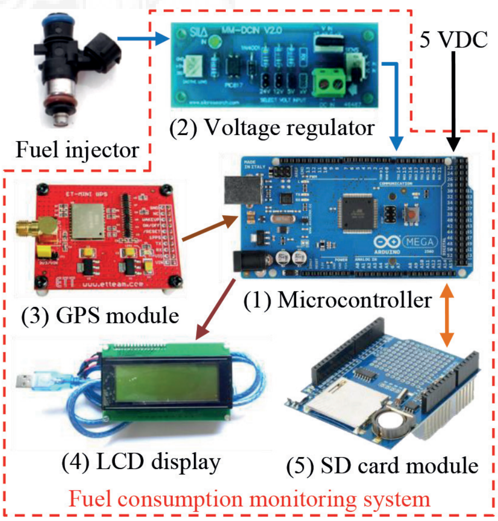

Fig. 2 Components of the fuel consumption monitoring system

Procedure that the system measured, processed, and displayed the data is as follows. (i) Readiness of each component was checked. (ii) From the velocity that the GPS module sent to the microcontroller once a second, distance that the tested vehicle ran within one second, or the velocity in one second, could be calculated by equation (3). (iii) The fuel injector's control signal being in a pattern of the square wave, as shown in **Fig. 3,** was measured and interpreted. Pulse width (PW) or the time duration that the control signal commanded the fuel injector to inject the fuel could be found by time difference between an increase and a decrease in the voltage of the signal as shown by the point A and B, respectively. Period (T) of the control signal wave was determined from the time difference between two adjacent points of an increase in the voltage as shown by the point A and C, respectively. Consequently, the engine speed and the %DC were determined as expressed in equation (4) and (5), respectively. (iv) The characteristic correlation established by the procedure described in the Section 2.1 and as expressed in the Section 3.1.4 was substituted by the engine speed and the %DC and then the fuel injection rate (FI) was figured out. After that, the fuel consumption rate (FC) during a certain second was calculated from Equation (6) and was sent to be shown on the LCD display. (v) The measured and calculated data were stored on the SD card. (vi) The system repeatedly conducted the step (ii) to (v) until the tested vehicle reached the end of a trip. If the average button located on the meter was pushed, the average fuel consumption rate (FC_{avg}) and the fuel volume (FV) along the trip could be found from equation (7) and (8), respectively and they were displayed for 5 s before the system turned off itself.

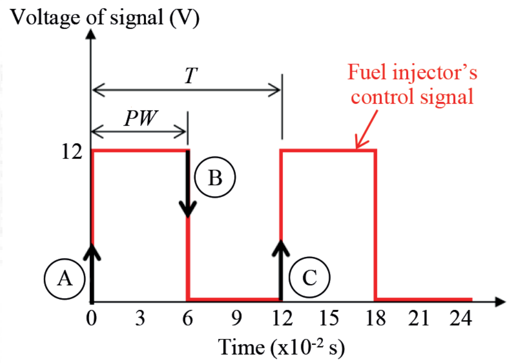

Fig. 3 Measurement on fuel injector's control signal

$$v = \frac{V}{3,600} \tag{3}$$

$$N = \frac{2\times 60}{T} \tag{4}$$

$$\%DC = \frac{PW}{T}\times 100 \tag{5}$$

$$FC = n_{inj} \times \frac{60,000\times v}{FI} \tag{6}$$

$$FC_{avg} = n_{inj} \times \frac{60,000\times v_{avg}}{FI_{avg}} \tag{7}$$

$$FV = \frac{v_{avg}t}{FC_{avg}} \tag{8}$$

Where

V = the velocity of the vehicle (km/h)

v = the velocity of the vehicle in one second (km/s)
FI = the fuel injection rate (cm^3/min)
FC = the fuel consumption rate (km/liter)
n_{inj} = number of fuel injectors installed on the engine (injectors)
FV = the fuel volume (liter)
t = the total time duration entire the trip (s)

The fuel consumption monitoring system was fabricated by installing the microcontroller, voltage regulator, GPS module, and SD card module into the transparent acrylic box that was called as the meter unit. The front side of the meter unit had a port for power input from the battery, an input port for a cable connecting to the fuel injector's control signal cable, an output port for sending data to the LCD display, and an antenna port for GPS module. A push switch for showing the average fuel consumption along a trip was located on the top side of the meter unit. The meter unit is shown in **Fig. 4.**

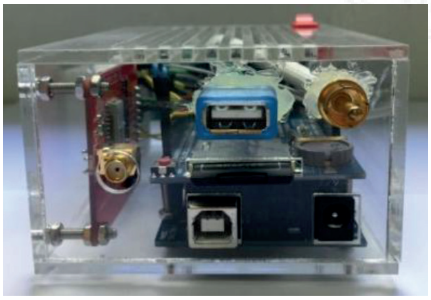

Fig. 4 The meter unit

2.3 On-Road Test and Verification

The test to verify reliability of the fuel consumption monitoring system was carried on selected public roads in Chiang Mai, Thailand with total distance of 38 km. Processed data shown in the display consisted of (i) the fuel consumption rate (km/liter), (ii) fuel injection rate (cm^3/s), and (iii) velocity of the tested vehicle (km/h) as shown in **Fig. 5.** Meanwhile, all measured and calculated data were continuously stored on the SD card.

Fig. 5 Reported data on the display during on-road test

The test procedure is as follows. (i) The fuel, which was gasoline with the octane number of 91, was filled in a fuel tank until the topmost level reached the reference mark at the filling tube. (ii) The test began after the system was turned on and the tested vehicle was driven along the selected route in the real-world situation. (iii) When the tested vehicle reached the end of the route, the tank was fully refueled to reach the reference mark as before. The volume of re-filling fuel was identical to actual volume of the fuel consumed along the test. (iv) The test was repeated conducted for 3 rounds. (v) Accuracy and reliability of the system was determined by comparison between fuel volume obtained from the system by measuring the fuel injector's control signal and calculating the characteristic correlation (FV) and actual volume of consumed fuel (FV_{act}). And (vi) the fuel volumes obtained from the system with (FV) and without (FV_{ideal}) consideration on the characteristic correlation were compared to point out importance of the consideration on the characteristic of the fuel injector in conjunction with the measurement on the fuel consumption from the fuel injector's control signal.

3. Results and Discussion

3.1 Effects of Characteristics of Fuel Injector on Fuel Injection Rate and Characteristic Correlation

3.1.1 Effect of engine speeds on fuel injection rate

From the experimental investigation of the test rig, when the engine speed increased from 1,000 to 6,000 rpm, the fuel injection rate continuously increased in linear function for each constant %DC and ΔP as shown in the **Fig. 6.**

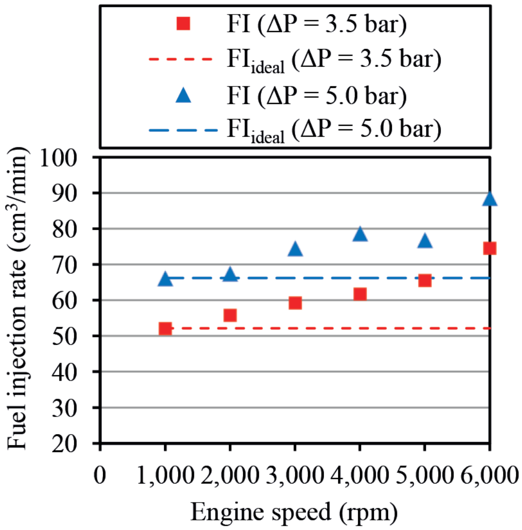

Fig. 6 Effect of engine speeds on the fuel injection rate

However, when ideal fuel injection of the fuel injector is considered, it is found that the fuel injection rate is always constant entire engine speed range at certain %DC and DP. This fact can be explained by following example. At the engine speed of 2,000 rpm, although frequency of the fuel injection is more than that of the engine speed of 1,000 rpm for twice, time duration that the fuel injected at the engine speed of 2,000 rpm is less than that of the engine speed of 1,000 rpm for a half, considered with the same %DC and ΔP. In the light of this reason, sum of the fuel volume injected in a specified time must be the same entire the engine speed range. Aforementioned experimental results are not agreed with the trend of the ideal fuel injection rate - the measured fuel injection rate will be less than the actual one.

The discrepancy of the fuel injection rate occurs due to delaying of the fuel injector's needle during closing phase, which is caused by the inertia of the needle and spring inside the injector [6]. When the fuel injector's control signal is turned off, the needle cannot close the fuel injector instantly. This causes excessive volume of the fuel to be injected continuously during movement of the needle until it reaches the fully close position. Thus, the actual fuel injection volume is more than the volume corresponding to the pattern of the fuel injector's control signal. Moreover, the discrepancy increases as an increase in the engine speed according to the accumulate discrepancy from higher frequency of the closing phases of the fuel injector. This is well agreed with the results obtained from the previous study [7].

3.1.2 Effect of percentages of duty cycle on fuel injection rate

When the %DC increased the fuel injection rate continuously increased in linear function for each constant engine speed and ΔP as shown in **Fig. 7.**

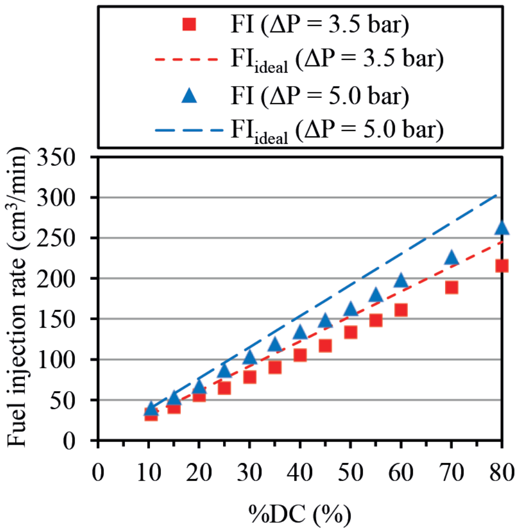

Fig. 7 Effect of percentages of duty cycle onthe fuel injection rate

Nevertheless, when ideal fuel injection of the fuel injector is considered, it is found that the fuel injection rate is always a direct proportion to the %DC with one-to-one ratio at certain engine speed and ΔDP, e.g., the fuel injection rate at the %DC of 40% must be twice of the rate at the %DC of 20%, considered with the same engine speed and ΔP. This is because the time duration that the fuel injects in a case of the %DC of 40% is a double of the duration in a case of the %DC of 20%. The trend of the ideal fuel injection rate is not agreed with the aforementioned experimental results -the measured fuel injection rate will be more than the actual one.

The discrepancy of the fuel injection rate occurs due to the cavitation effect appearing in the fuel passage inside of the fuel injector. The cavitation is bubbles that are induced to be occurred near the injector's nozzle tip during movement of the injector's needle [8]. The cavitation obstructs the fuel flow during the injection phase. Thus, the actual fuel injection volume is less than the volume corresponding to the pattern of the fuel injector's control signal. In addition, the discrepancy increases as an increase in the %DC according to the accumulate discrepancy from longer duration of the injection phase of the fuel injector. This trend is well agreed with the results obtained from the previous study [7].

3.1.3 Effect of pressure differences on fuel injection rate

It was found from the experiments that when the ΔP increased, the fuel injection rate increased for each constant engine speed and %DC as shown in **Fig. 8.**

However, since the ideal fuel injection rate according to the ΔP could not be found in this study, an ideal line to determine discrepancy of the actual fuel injection rate deviating from the ideal rate is unable to be plotted.

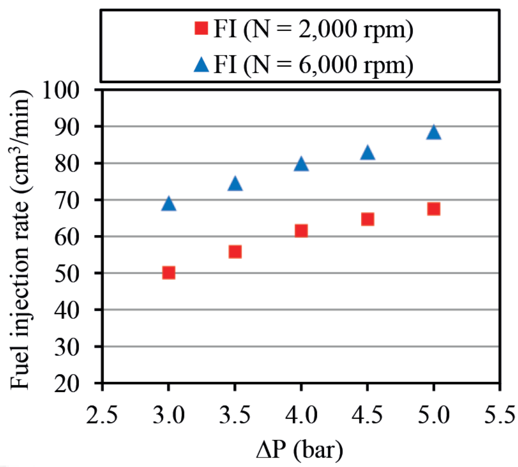

Fig. 8 Effect of pressure differences on the fuel injection rate

3.1.4 Establishment of characteristic correlation

From the tests, all results were plotted on the three-dimension coordinates. The horizontal axes on the plane x-y were the engine speed and the %DC, respectively. The vertical axis or the z-axis was the fuel injection rate, which was quantitatively presented by gradient colors. The results were separated to different layers according to the ΔP ascending from the lowest layer with the lowest ΔP of 3.0 bar as shown in **Fig. 9.** The characteristic correlations affected by the engine speed and the %DC were established by means of the least squares fitting method and separated by the ΔP of 3.0, 3.5, 4.0, 4.5, and 5.0 bar as expressed in equation (9) to (13), respectively. Since the actual DP is generally adjusted to be constant entire engine's operation by a fuel pressure regulator, thus, the characteristic correlation programmed in the fuel consumption monitoring system is not necessary to be involved by the ΔP as the variable parameter. In this study, the ΔP of the fuel system in the tested vehicle was initially set from a manufacturer to be constant at 3.0 bar, thus, equation (9) was chosen to be programmed onto the microcontroller of the system. The correlations presented here are used to calculate the fuel injection rate of one fuel injector. Multiplying with numbers of fuel injector is important to be considered.

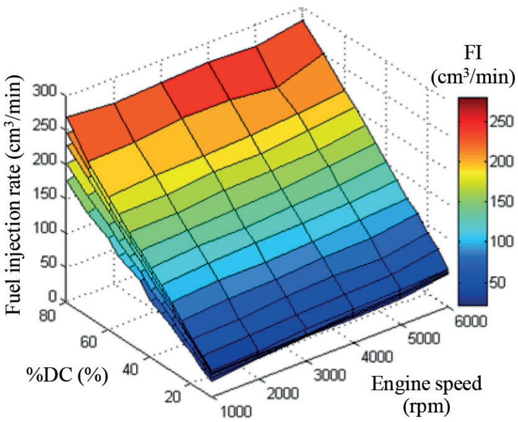

Fig. 9 Relationship of the characteristics of fuel injector and the fuel injection rate

$$FI = -8.580 + 2.212(\%DC) + 0.006(N) \quad (9)$$

$$FI = -8.832 + 2.612(\%DC) + 0.005(N) \quad (10)$$

$$FI = -5.534 + 2.886(\%DC) + 0.005(N) \quad (11)$$

$$FI = -3.778 + 3.013(\%DC) + 0.004(N) \quad (12)$$

$$FI = -2.251 + 3.202(\%DC) + 0.004(N) \quad (13)$$

3.2 On-road test results and data verification

From the on-road test, the fuel consumption monitoring system designed and fabricated in this study was successfully operated. All measured data were correctly displayed and recorded. Reliability of the system's operation was verified by comparing the fuel volume along the test route of 38 km obtained from three different measurements, i.e., (i) the actual fuel volume (FV_{act}), (ii) the fuel volume obtained from the system by measuring the fuel injector's control signal and calculating the characteristic correlation (FV), and (iii) the fuel volume obtained from the system without consideration on the characteristic correlation (FV_{ideal}) as shown in **Fig. 10.**

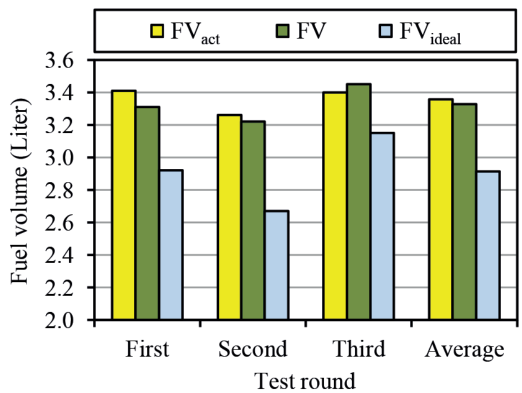

Fig. 10 The fuel volumes from the on-road tests

It was found that the actual fuel volumes (FV_{act}) from three-round tests were 3.41, 3.26, and 3.40 liter and they were averaged to be 3.36 liter. The fuel volumes obtained from the system considering the characteristic correlation (FV) were 3.31, 3.22, and 3.45 liter and averaged to be 3.33 liter. Discrepancies of the FV deviating from the FV_{act} were

2.93%, 1.23%, and 1.47% and averaged to be 1.88%. This can be proved that the fuel consumption monitoring system designed and fabricated in this study has acceptable reliability with high accuracy. In addition, the fuel volumes obtained from the system without consideration on the characteristic correlation (FV_{ideal}) were 2.92, 2.67, and 3.15 liter and averaged to be 2.91 liter. Discrepancies of the FV_{ideal} deviating from the FV_{act} were 14.37%, 18.10%, and 7.35% and averaged to be 13.27%. This verification is the evidence to support that the fuel consumption monitoring system measuring the fuel injector's control signal with considering the characteristic correlation provides significantly higher accuracy of the data than the system that the characteristics of the fuel injector are not considered.

3.3 Impacts

Academic impact is that the relationships between the characteristics of the fuel injector and the fuel injection rate are obtained. These can be used to enhance accuracy of the data obtained from the fuel consumption monitoring system. Social impact is that drivers can instantly change their driving behaviors to save fuel. Subsequently, total amount of the fuel used in the nationwide transportation section will be reduced.

4. Conclusions

The characteristics of a fuel injector affecting on the fuel injection rate have been investigated in this study. The characteristic correlations have been consequently established for programming in the fuel consumption monitoring system hat has been designed and fabricated in this study to enhance accuracy and reliability. Conclusions are listed as follows.

- The engine speed is a factor that causes the actual fuel injection rate to be more than the rate corresponding to the pattern of the fuel injector's control signal.
- The percentage of fuel injector's duty cycle (%DC) is a factor that causes the actual fuel injection rate to be less than the rate corresponding to the pattern of the fuel injector's control signal.
- The accuracy of the fabricated system is acceptable with the average discrepancy of 1.88%.

5. Acknowledgement

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