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Effect of engine speeds and duty cycle percentages of fuel injection on actual fuel injection rate

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Abstract

This research has been conducted to study the effect of engine speeds and effect of duty cycle of fuel injection on actual fuel injection rate. The 600 cc/min, 2011 Mitsubishi Triton fuel injector was used to be considered and a function generator was used to create a signal to control the fuel injector. After that, the weight of fuel injected in a specified time was measured by digital balance. Then, it was converted to fuel injection rate at the engine speed of 1,000 2,000 3,000 4,000, and 5,000 rpm, at the percentage of the duty cycle equaled to 10.5, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, and 80 of total time period between adjacent injection. The pressure differences between the fuel pressure and the ambient pressure of 3.5, 4.0, 4.5, and 5.0 bar were studied. The results from experiment showed that, the fuel injection rate increased when the engine speed and percentage of duty cycle increased. However, the fuel injection rate had discrepancy from the ideal rate that significantly depended on the engine speed and percentage of the duty cycle.

Keywords: Fuel injection rate, Injector duty cycle, Injector characteristic, Fuel consumption, Fuel injector pulse signal

1. Introduction

In recent year, a fuel consumption meter is widely used in the passenger cars whether that was installed from manufacturers [1] or that was attached later as the additional accessories [2], to show the fuel consumption rate of engine depended on the driving behavior including an encouraging to saving the fossil fuel [3]. The most of fuel consumption meter was designed to measure the amount of fuel that passenger car actually used by measuring the fuel consumption of the engine compared with the distance that the car ran. The amount of fuel was measured by filling up the fuel to fuel tank at the reference point. After the test was completed, the fuel was filled back to the reference point of the fuel tank to measure amount of the used fuel. In the other way of measuring, the fuel consumption was determined from the pulse width of fuel injector signal that was controlled by an electronic control unit (ECU) [4]. It could be the single, double, and triple injector pulse characteristic [5] relating to the year that each passenger car was produced. As in the present, the fuel injector of passenger car is an electronic injector. It needs to get the pulse signal from the ECU for controlling the timing of the injection. And it relates to the pulse width or the duty cycle of the pulse signal. For measuring the fuel consumption of the engine, it was found by measured the width of the injector pulse signal (IPS), and converted to the fuel injection rate [6]. Then, it was send to the meter that was installed at the location where was easy to be seen. The driver noticed the driving behavior that related to the fuel consumption in the real time. Therefore, this method could significantly affect the measurement of fuel consumption rate.

However, this method still had some discrepancy because it was not considered the characteristic of fuel injector [7] that directly affected the fuel injection rate. This included the effect of the inertia from a needle of injector and the effect of pressure difference (ΔP) between the fuel pressure and the ambient pressure that was induced to cavitation effect on the passage inside the injector [8]. Then, this causes an obstruction to the fuel flow. From the recent research of fuel injection rate at the air intake pressure of 3, 5, 7, and 9 MPa and fuel pressure was 160 MPa found that, the fuel injection rate was 49 g/min constantly at full needle lift condition during the certain period of time at every pressure. This result showed the effect of cavitation which was taken place inside the fuel injector. Moreover, it was found that, the momentum flux of fuel injection depended on the pressure difference. This shows that the cavitation phenomenon did not affect to the fuel injection rate. As the factors mentioned above, they affected to fuel injection rate and depended on working condition of the engine, however, it can be controlled. In the addition, there is a factor affecting to precision of fuel metering that the phenomenon cannot be controlled, such as, the temperature of fuel injector. It induced fuel injection rate because the density of the fuel strongly depends on the temperature. If the fuel has high temperature, the density of the fuel decreases. And it affects the fuel volume measurement from injector pulse signal to be higher than the actual fuel injection rate. In the other way, for the low temperature fuel, it induced density of fuel to be

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high. This affected the actual fuel injection rate to be low [9]. Moreover, there is the geometry of injector that induced the cavitation to the fuel injector at the nozzle tip when the needle lift equals to 0.1 mm [10]. This phenomenon affected the jet backup length of fuel injection, such as, an increasing in angle of fuel injection. Conversely, the jet breakup length and droplet size of fuel were decreased. And the last factor that affected the characteristics of the fuel injector was the fuel properties. As each type of the fuel has different properties that affected the precision of fuel metering, especially for the case that the fuel injection rate was determined from the pulse signal. Therefore, when the high accuracy in fuel injection measurement is needed, the characteristic of injector must be also considered.

From the requirement of the high precision and real time fuel injection rate measurement from the injector signal and the consideration of the characteristic of the fuel injector, these became the significance of this study. The objective of this study is to experimentally investigate the effects of engine speeds and duty cycle percentages of fuel injection on actual fuel injection rate. Advantage obtained from this study was expected to be the valuable data for further developing on the fuel consumption meter measuring from the fuel injection signal.

2. Experiment setup and procedure

2.1 Experimental setup

The effects of engine speeds and duty cycle percentages were considered in this study because these parameters have a significant effect on the fuel injection rate of the fuel injector. The engine speed was varied from 1,000 to 2,000 3,000 4,000, and 5,000 rpm and the duty cycle percentage of injector pulse signal (%DC) equaled to 10.5, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 70, and 80. The pressure difference between the fuel pressure and the ambient pressure (ΔP) were 3.5, 4.0, 4.5, and 5.0 bar, which are widely used in the general vehicles [11]. The gasoline octane 91 at controlling ambient temperature was used in the testing. The diagram of the experimental setup is shown in Figure 1. (1) The electronic fuel pump was used to produce the pressure to the fuel. The fuel pump was taken from the 2,400-cc gasoline engine installed in the 2011 Mitsubishi Triton. It was installed to (2) the new custom-made stainless steel fuel tank with capacity of 20 liter. After that, Fuel hose was connected from the fuel pump to (3) the fuel filter to separate the adulterate thing from the fuel that can damage to the fuel injector and the engine. Then, the fuel flows to (4) the fuel line, which was specially constructed from aluminum alloy. The value of ΔP could be directly adjusted by (5) the fuel pressure regulator. For this study, the FLEX fuel pressure regulator was used. It could be set the fuel pressure between the 3.5 and 8 bar [10]. (6) The gasoline injector was used in this study. The fuel injector would be opened when it got the pulse signal that was created from (7) the function generator (DDS, model SG1003). It can produce the output pulse signal with frequency between 0.1 Hz to 3.0 MHz, with frequency accuracy of $\pm 5\times10^{-6}$ Hz, and amplitude accuracy of ±10% (1 kHz, 20 $V_{p\text{-}p}$). After that, the fuel was injected to the (8) catch Tank corresponding to the value of %DC. For generating of the injection pulse signal, it could be determined the signal frequency (f) corresponding to a certain engine speed. Such as a 4-stroke engine, the injection pulse signal frequency could be found from the engine speed as in Eq. (1). And the time period (T) between adjacent injections, which was defined as 100%DC, could be determined from Eq. (2). For adjusting the value of %DC of the fuel injection pulse signal, it could be set directly from the function generator that can be set between 10 and 90% of each injector pulse signal period [12]. After that, the fuel was injected to the catch tank that was located on (9) the electronic balance. Then, the weight of fuel injected in a specified time was weighed. The balance had the maximum capacity of 3,200 g with precision of 0.01 g. Finally, the fuel injection volume could be converted by using the density of the gasoline octane 91 at 25 ^{o}C that is equal to 733.2 kg/m^3.

$$f = \frac{RPM}{2\times60} \tag{1}$$

$$T = \frac{2\times60}{RPM} \tag{2}$$

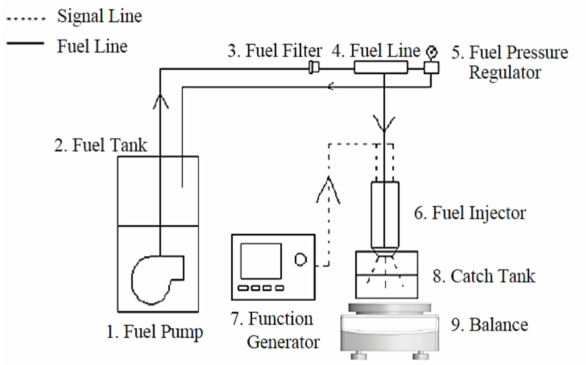

Figure 1 Experimental setup

2.2 Experimental procedure

The experimental procedures started by filled the fuel to the fuel tank. Then, the fuel pump was opened and the ΔP of 3.5 bar was set by adjusting the fuel pressure regulator. After that, the injection pulse signal frequency simulating the engine speed between 1,000, 2,000, 3,000, 4,000, and 5,000 rpm could be adjusted at the function generator between 8.33, 16.67, 25.00, 33.33 and 41.67 Hz, respectively. After that, the %DC was set, and the fuel injection would inject the fuel in one minute. Then, the injected fuel in the catch tank was weighed. All above procedure was repeatedly conducted until all values of the %DC, frequency or engine speed, and ΔP that were initially set in this study, were completely investigated. After the testing is complete, the results obtained from experiment were further analyzed and concluded as in the next section.

3. Results and discussions

The results obtained from the study on effects of engine speed and duty cycle percentages of fuel injection on actual fuel injection rate are shown in Figure 2. Results and discussions are as follow.

3.1 Effect of engine speeds on actual fuel injection rate

The results as in Figure 2 show that when the engine speed increased, the fuel injection rate increased in every ΔP. From the experiment found that the fuel injection rate was the minimum at the 1,000 rpm and the trend of fuel injection rate increased until the maximum fuel injection rate was obtained at 5,000 rpm.

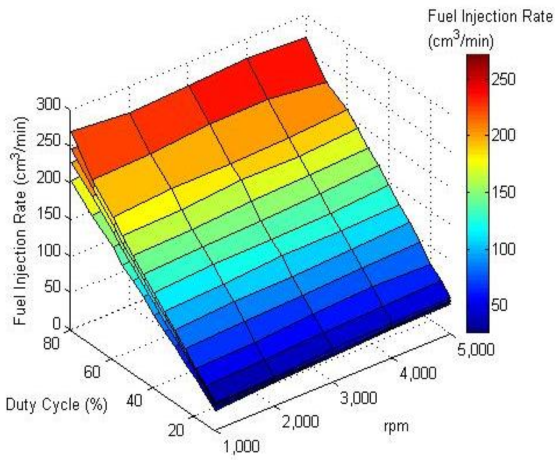

Figure 2 The relationship of fuel injection rate, engine speed and duty cycle percentage

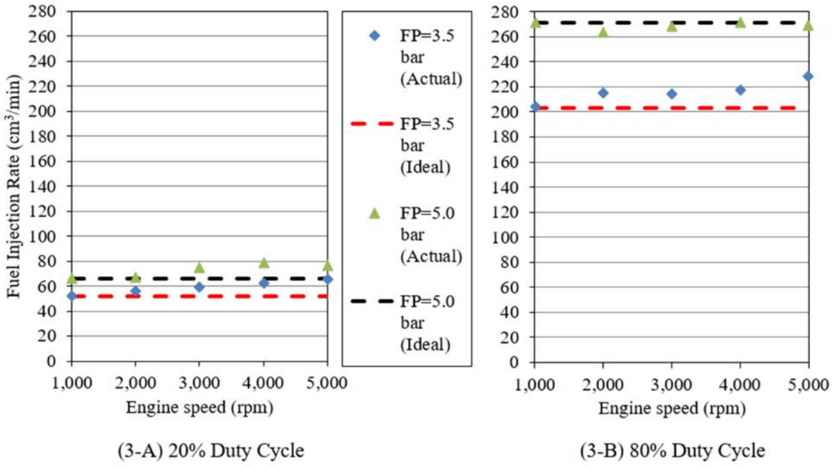

Figure 3 The relationship of fuel injection rate and engine speed

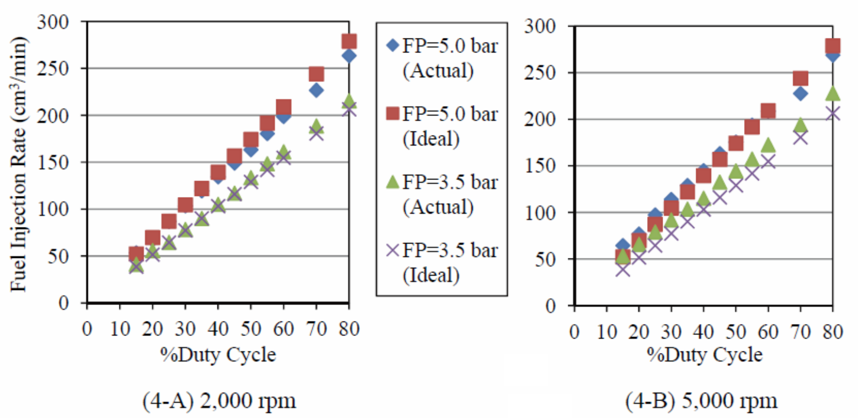

Figure 4 The relationship of fuel injection rate and duty cycle percentage

However, in theory, the fuel injection rate must be constant through every engine speed at a certain %DC and ΔP as shown with the ideal line in Figure 3. This ideal line of the fuel injection rate was referred to the actual fuel injection rate experimentally obtained at 1,000 rpm, which was the lowest engine speed in this study. However, from the actual fuel injection rate, it had the discrepancy compared with the ideal fuel injection rate. It was found that the discrepancy of the actual fuel injection rate increased as an increase in the engine speed for every %DC. On the other hand, it was found that the discrepancy inversely depended on the ΔP. It was found that the highest discrepancy was obtained at the relative low ΔP. Results could be classified into a group of low %DC and high %DC. Each group had two sub-groups of the low ΔP and the high ΔP.

3.1.1 At 20%DC or low %DC

(1) At ΔP = 3.5 bar (Low ΔP), it was found that the maximum discrepancy between the actual and ideal fuel

injection rate equaled to 13.402 cm^3/min. This was obtained at the engine speed equaled to 5,000 rpm, and the minimum discrepancy equaled to 3.682 cm^3/min as investigated at 2,000 rpm, as shown in Figure 3-A.

(2) At ΔP = 5.0 bar (High ΔP), it was found that the maximum discrepancy between the actual and ideal fuel injection rate equaled to 12.530 cm^3/min. This was obtained at the engine speed of 4,000 rpm, and the minimum discrepancy equaled to 1.318 cm^3/min as investigated at 2,000 rpm, as shown in Figure 3-A.

3.1.2 At 80%DC or high %DC

(1) At ΔP = 3.5 bar (Low ΔP), it was found that the maximum discrepancy between the actual and ideal fuel injection rate equaled to 24.604 cm^3/min. This was obtained at the engine speed of 5,000 rpm, and the minimum of discrepancy equaled to 10.129 cm^3/min as investigated at 3,000 rpm, as shown in Figure 3-B

(2) At ΔP = 5.0 bar (High ΔP), it was found that the maximum discrepancy between the actual and ideal fuel injection rate equaled to 7.683 cm^3/min. This was obtained at the engine speed of 2,000 rpm, and the minimum of discrepancy equaled to 0.255 cm^3/min as investigated at 4,000 rpm, as shown in Figure 3-B

The analysis of the discrepancy caused by the engine speeds at 20%DC and 80%DC found that the maximum discrepancy was obtained at 5,000 rpm and the ΔP of 3.5 bar. The result of fuel injection discrepancy, which is caused by the engine speed, shows that the discrepancy occurred as a result from the delay factor or inertia effect during the closing of injector's needle. Since, after the ECU opens the signal circuit to close the injector, the spring and the needle has a small time-delay before it completely travel to close the injector's tip. This causes the actual fuel injection rate to be higher than the ideal one. When the engine operates at higher engine speed, the fuel injector must turn on and off with higher frequency. This causes accumulative discrepancy to increase and it will be the maximum at the highest engine speed. Moreover, the inertia of the injector's spring is also one of dynamic factors of the fuel injector [9].

3.2 Effect of duty cycle percentages on actual fuel injection

The results as in Figure 2 show that when the %DC increased, the fuel injection rate increased in every ΔP. From the experiment found that the fuel injection rate was the minimum at 10.5%DC and the trend of fuel injection rate increased until the maximum fuel injection rate was obtained at 80%DC. However, in theory, the fuel injection rate must increase proportionally to an increase in the %DC at a certain engine speed and ΔP as shown with the ideal line in Figure 4. For example, at the 40%DC, the fuel injection rate should be the twice of the fuel injection rate at the 20%DC at the same engine speed and ΔP. This ideal line of the fuel injection rate was referred to the actual fuel injection rate experimentally obtained at 10.5%DC, which was the lowest %DC in this study. The ideal line was extended following the injector's operation principle that the actual fuel injection rate must be directly proportional to the %DC at a certain engine speed and ΔP. It was found that the discrepancy of the actual fuel injection rate increased as an increase in the %DC for every engine speed. On the other hand, it was found that the discrepancy inversely depended on the ΔP. It was found that the highest discrepancy was obtained at the relative low ΔP. Results could be classified into a group of low engine speed and high engine speed. Each group had two sub-groups of the low ΔP and the high ΔP.

3.2.1 At 2,000 rpm or low engine speed

(1) At ΔP = 3.5 bar (Low ΔP) it was found that the maximum discrepancy between the actual and ideal fuel injection rate equaled to 8.967 cm^3/min. It was obtained at the 80%DC, and the minimum discrepancy equaled to 0.089 cm^3/min as investigated at the 25%DC, as shown in Figure 4-A.

(2) At ΔP = 5.0 bar (High ΔP) it was found that the maximum discrepancy between the actual and ideal fuel injection rate equaled to 17.276 cm^3/min. It was obtained at the 70%DC, and the minimum discrepancy equaled to 0.107 cm^3/min as investigated at the 25%DC, as shown in Figure 4-A.

3.2.2 At 5,000 rpm or high engine speed

(1) At ΔP = 3.5 bar (Low ΔP) it was found that the maximum discrepancy between the actual and ideal fuel injection rate equaled to 21.597 cm^3/min. It was obtained at the 80%DC, and the minimum discrepancy equaled to 11.944 cm^3/min as investigated at the 40%DC, as shown in Figure 4-B.

(2) At ΔP = 5.0 bar (High ΔP) it was found that the maximum discrepancy between the actual and ideal fuel injection rate equaled to 16.376 cm^3/min. It was obtained at the 70%DC, and the minimum discrepancy equaled to 0.452 cm^3/min as investigated at the 60%DC, as shown in Figure 4-B

From the effect of the %DC on the discrepancy of the actual fuel injection rate, it was found that the maximum discrepancy was obtained at the 80%DC at high engine speed, which equaled to 5,000 rpm as in this study, and at the ΔP equaled to 3.5 bars. It could be summarized from the experimental results that the effect of %DC induced the fuel injection rate to be not directly proportional to an increase in the %DC at a certain engine speed and the ΔP. This is because the cavitation effect, which is produced inside the fuel injector during the injector's operation. Since the bubbles obstruct to the flow of fuel in the injector, this causes discrepancy in actual fuel injection rate to be higher. The maximum discrepancy is obtained at the maximum %DC or at 80%DC because the fuel injector lifts the injector's needle for the longest time; therefore, the effect due to the cavitation phenomenon is the strongest at the highest %DC. Moreover, the strongest effect was also obtained at the highest engine speed, at 5,000 rpm in this study because the cavitation is more induced to be occurred at the nozzle tip while the needle is moving more frequently.

4. Conclusions

The results obtained from the study showed that when the engine speeds and %DC increased, the actual fuel injection rate increased in every ΔP. Moreover, it was found that the discrepancy of the actual fuel injection increased as an increase in the engine speed and the %DC at a certain %DC and engine speed, respectively. On the other hand, the discrepancy inversely depended on the ΔP. The result obtained in this study showed that if the fuel injection rate was measured and converted from the injector signal, the effects of engine speeds (RPM) and duty cycle percentage (%DC) of injector pulse signal must be strongly considered to reduce an error of measurement. This problem can be improved by producing the table of discrepancy compensation that was created from the experimental data, or establishing the equation of fuel injector characteristic for individual fuel injector type. Then, the table or equation was programmed as a part of the controller in the fuel consumption meter. These methods will obviously increase the precision and the credibility of the measurement.

5. Acknowledgements

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