VOL. 16, NO. 24, DECEMBER 2021 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

A COMPARATIVE STUDY OF THE MEASUREMENT OF THE FUEL INJECTION RATE OF A DIESEL PIEZO INJECTOR WITH A SCALE AND A POSITIVE DISPLACEMENT FLOW METER

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ABSTRACT

The fuel injection rate of a diesel piezo injector was measured using a scale and a positive displacement flow meter (PDFM). The measurement results of the injected fuel quantity were compared in each case. The piezo injector was driven by a microcontroller. The piezo injector driver is designed to charge and discharge current to the piezo injector. The control signal was generated by a microcontroller. The fuel injection durations used in this study were 0.5, 1.0 and 2.0 ms. the common rail pressure was controlled under the three conditions of 30, 100, and 150 MPa. The injected fuel mass per injection was calculated from the total injected fuel mass when the fuel injection was repeated 500 times. The lower the rail pressure, the greater the variation in the injected fuel mass. Variations in the injected fuel quantity per injection with the injection duration were reduced with longer fuel injection durations. In all injection conditions, the accuracy of the scale was higher than that of the PDFM.

Keywords: fuel injection rate, piezo injector, diesel engine, scale, positive displacement flow meter (PDFM).

INTRODUCTION

The injected fuel mass per injection has a considerable influence on the performance of the engine. Accurate control of the injected fuel mass is crucial for proper air-fuel ratio control. For a gasoline engine, the air-fuel ratio must be accurately held at the theoretical equivalence ratio such that a three-way converter can simultaneously remove the harmful exhaust gases HC, CO and NOx [1]. In diesel engines, fuel injection control is directly related to control of the engine load.

As electronic control approaches are introduced as part of engine control schemes, the injected fuel mass is determined by the injector solenoid activating time [2-5]. Reducing the variation of the injection rate for the given rail pressure and solenoid activation time is the most important factor when evaluating the injector performance. There are static and dynamic methods for measuring the fuel injection rates of injectors. The static method involves the measurement of the injected fuel mass when the fuel is continuously injected for a certain time when the nozzle needle of the injector is continuously lifted. The activation time of the injector solenoid is at least 30 seconds to measure the injected fuel mass under static conditions. For a mechanical type of injector without a solenoid, after removing the spring holding the nozzle needle in the injector, the injected fuel mass is measured. The static fuel injection quantity is used to calculate the required injected fuel mass under the engine maximum power condition.

On the other hand, the dynamic measurement method is used to inject fuel by intermittently activating the injector solenoid for a given injection duration. Fuel injection measurements under dynamic conditions can be considered as the injector being operated under actual engine conditions. During dynamic measurements, the injector solenoid is repeatedly activated for a given rail pressure and injection duration to collect the injected fuel. The injected fuel mass per injection is determined by dividing its mass by the number of injections. Generally, the fuel injection duration should be approximately 1.0 ms. In addition, there are about 500~1000 injections. To evaluate the linearity of the injected fuel mass with the solenoid activation time, the dynamic flow range (DFR) is determined by a dynamic method [6, 7].

A method to measure the time-resolved injection rate when the injector injects fuel in a single injection has also been devised. The time-resolved fuel injection rate is mainly used as input data for CFD simulations of engine performance capabilities. This type of approach is mainly used to measure the time-resolved fuel injection rate of diesel injectors and GDI injectors. The Bosch method [8] and the Zeuch method [9] are the most commonly used methods for measuring the time-resolved fuel injection rate. Postrioti *et al.* [11] studied the time-resolved injection rate of a port fuel injection (PFI) injector. Another study was carried out to find the cumulative fuel injection mass with the running time of a vehicle by driving the injector similarly to actual vehicle driving conditions [12].

Various methods for evaluating injector performance outcomes have been introduced, as outlined above. Among them, the most commonly used method for evaluating injector performances by automobile companies is the dynamic method, during which the collected fuel mass from several thousand injections at a given rail pressure and fuel injection duration is divided by the number of injections to obtain the injected fuel mass per injection. The total injected fuel mass from repeated injections was measured with a scale in this study. To the best of the author's knowledge, few studies have reported the application of a PDFM to measure the injected fuel masses from injectors. In this study, the injected fuel mass from a piezo injector passing through a PDFM and was collected in a mass cylinder installed on the scale. The accuracy of the PDFM was evaluated by comparing the data from the scale under various injection conditions.

EXPERIMENT

A schematic diagram of the experimental setup is shown in Figure-1. The experimental setup consists of a high-pressure fuel pump, a low-pressure fuel pump, a common rail, a piezo injector driver, an injector, a rail pressure controller, a scale, a volumetric flow meter (PDFM), a heat exchanger and a fuel filter. The high-pressure fuel pump is driven with a 7.5 kW AC motor. An inverter is used to control the AC motor speed.

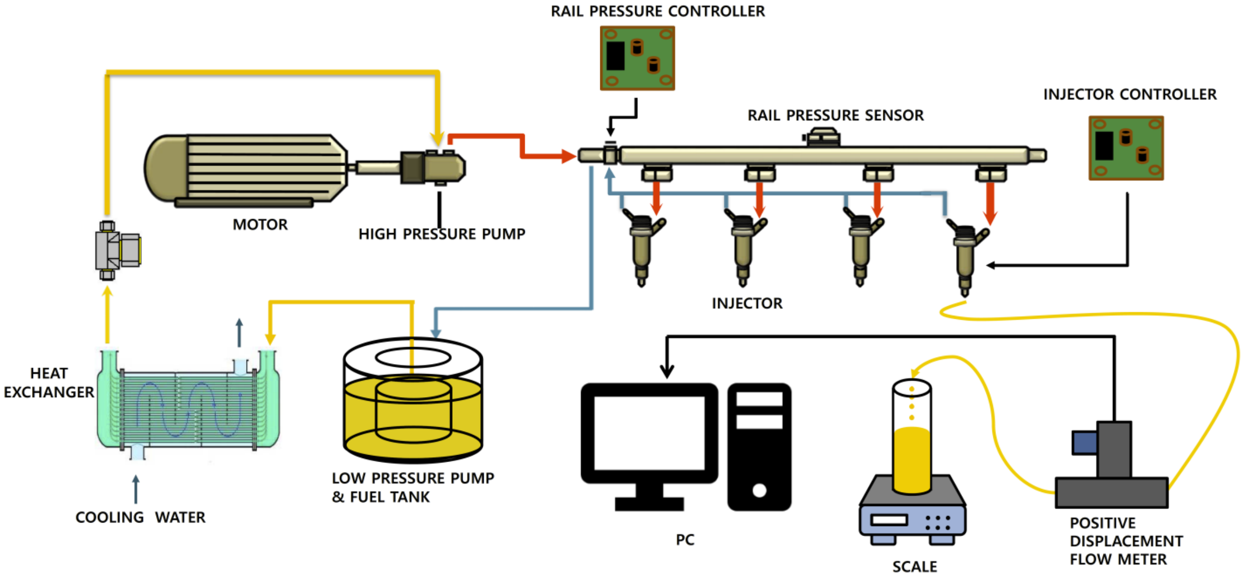

Figure-1. Schematic diagram of the experimental setup.

The process of supplying high-pressure fuel to the common rail can be summarized as follows. When the low-pressure fuel pump in the fuel tank delivers 0.4 MPa of fuel, it is supplied to the high-pressure fuel pump through the heat exchanger and the fuel filter. The high-pressure fuel pump pressurizes the fuel and transfers it to the common rail. The common rail pressure is controlled by the PWM control signal generated by the rail controller. The PWM control signal is output from the CCP pin of the microcontroller, a PIC-16F917 in this case. The fuel tank temperature was measured using a K-type thermocouple. Fuel temperature control is possible by controlling the amount of cooling water supplied to the heat exchanger. During the experiment, the fuel temperature was kept nearly constant at 27 ° C.

Piezo injector drivers were studied by Lee and Lee [13]. Figure-2 shows a conceptual diagram of the piezo injector drive circuit used in this study. The piezo injector driving process consists of the three steps of charging, maintaining and discharging. Charging can occur by setting MOSFET 1 to on and MOSFET 2 to off. In the charge step, driving voltage of 140 V is applied to the injector, causing the piezo element stack in the injector to expand. The fuel injection starts after a certain time delay with expansion of the piezo element stack. In the maintain step, both MOSFET 1 and MOSFET 2 remain in the off state. The fuel injection is maintained during the maintain step. In the discharge step, MOSFET 1 and MOSFET 2 are set to on and off, respectively. The charge current in the piezo element stack is discharged. In the discharge step, the expanded piezo element stack returns to its original size and the fuel injection is cut off. Charge and discharge control signals are generated from the two CCP terminals of the PIC16F917 microcontroller.

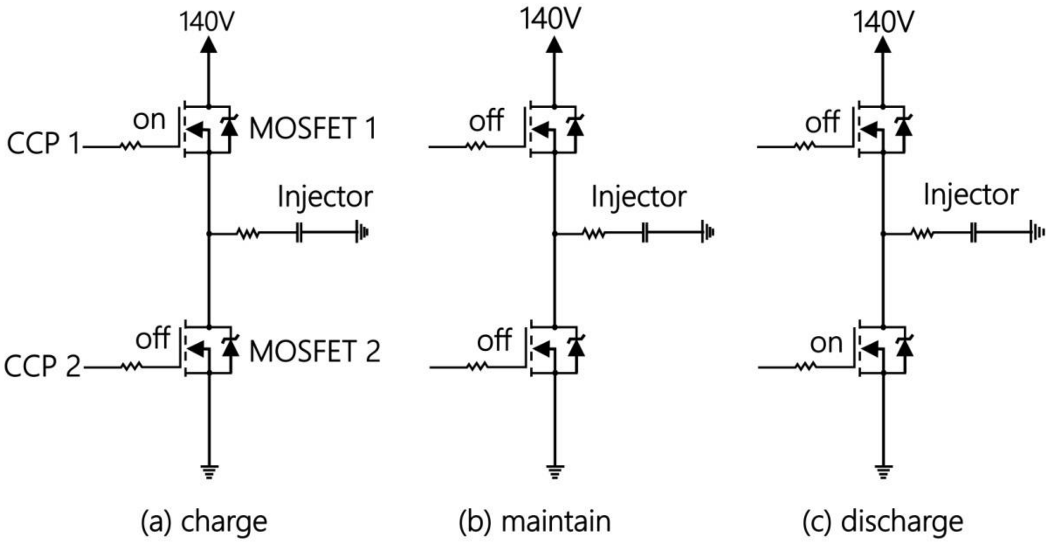

Figure-2. A MOSFET 1 and MOSFET 2 on-off conditions in the piezo injector driving circuit for the (a) charge (b) maintain and (c) discharge conditions [13].

The process of measuring the injected fuel mass per injection from a piezo injector can be summarized as follows. After the number of revolutions of the AC motor is set, the high-pressure fuel pump is rotated. Next, the rail pressure controller knob was adjusted until the target rail pressure is reached. When the target rail pressure is reached, the fuel injection is repeated by the piezo injector driver. The fuel injection was repeated 500 times for a given rail pressure and injection duration. The injected fuel from the piezo-injector passes through the PDFM, and the fuel is collected in a mass cylinder on a scale. The measurements of the 500 times fuel injection set are repeated 30 times for each fuel rail pressure and injection duration. In addition, they were repeated upon a change of the charge pattern. The total fuel mass in the mass cylinder was measured with a scale, and its mass was divided by 500 to obtain the injected fuel mass per injection. In the PDFM, the number of revolutions of the micro oval gear was recorded using a counter module in a DAQ board. The uncertainty analysis was performed using the experimental data obtained from the 500 times fuel injection set with 30 repeated measurements. The PDFM used in this study was a Bio-Tech micro oval gear flow meter. The accuracy of the PDFM is ±1%. The accuracy of the scale used here is ±0.01g.

RESULTS AND DISCUSSIONS

Figures 3-5 show the measurement results of the injector driving voltage, injector driving current, charge control signal, and discharge control signal measured with a digital oscilloscope when the piezo injector was driven as shown in Figure-2. In Figures 3-5, the injector fuel injection durations are 0.5 ms, 1.0 ms, and 2.0 ms, respectively. The driving voltage and current were increased nearly vertically in sync with the charge control signal. During the charge step, the injector driving current dropped immediately after a steep rise of the current. On the other hand, the driving voltage of 140 V was mostly maintained continuously after the charge control signal. During the synchronization step with the rise of the discharge control signal, the driving voltage dropped to 0 V and the current dropped rapidly to a negative value. The charge and discharge peak current is nearly 20 A. The duration of the charge and discharge control signals are 400 μs and 560 μs, respectively. The fuel injection duration based on the control signal is from the beginning of the charge to the beginning of the discharge. The actual fuel injection duration differs from the injection duration based on the control signal. That is, the actual fuel injection starts upon a certain delay after the charge control signal rises. The actual fuel injection stops upon a certain delay after the start of the discharge control signal [14].

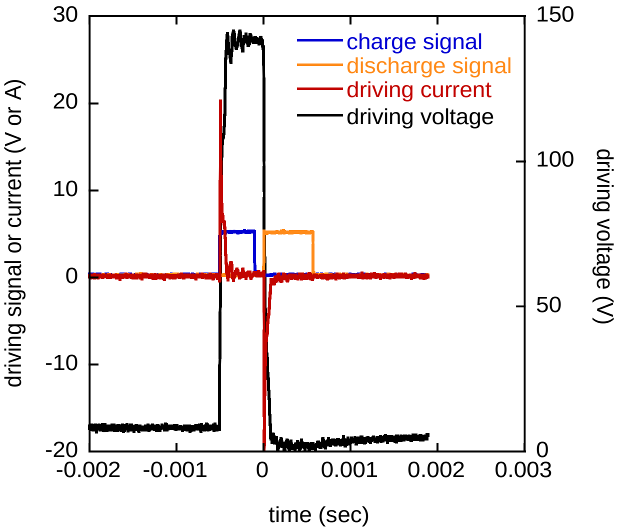

Figure-3. Measurement results of injector driving control signals with a fuel injection duration of 0.5 ms.

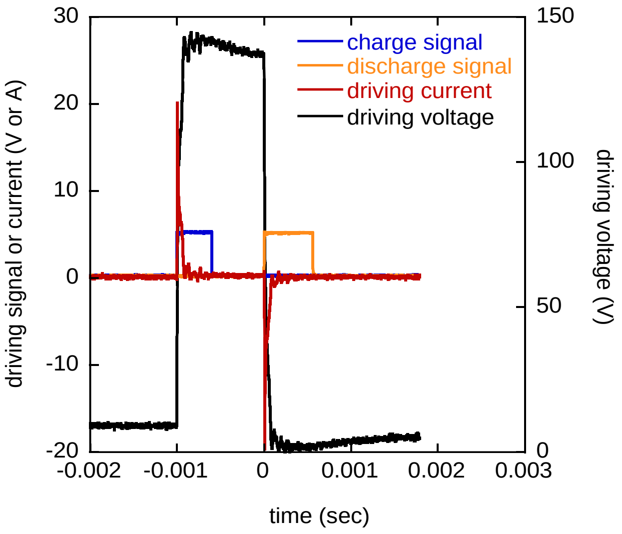

Figure-4. Measurement results of injector driving control signals with a fuel injection duration of 1.0 ms.

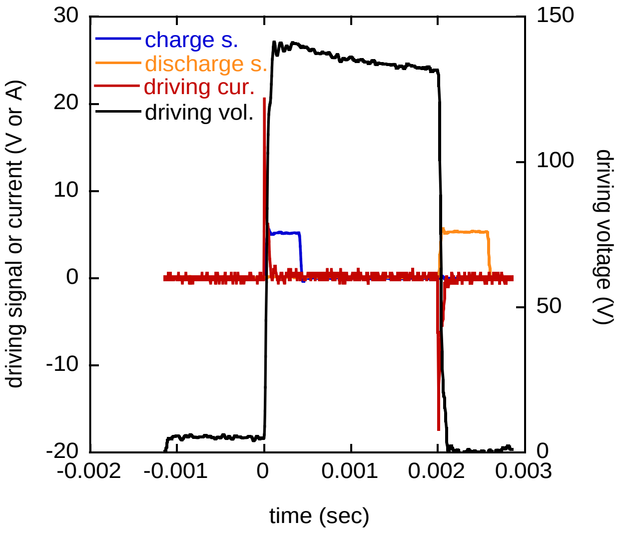

Figure-5. Measurement results of injector driving control signals with a fuel injection duration of 2.0 ms.

Figure-6 shows the results after counting the number of revolutions of the micro oval gear of the PDFM when the 500 times fuel injection set were repeated 30 times (measurement number) for various rail pressures and injection durations. The fuel injection durations are 0.5, 1.0 and 2.0 ms. the rail pressure was maintained at the three conditions of 30, 100 and 150 MPa. At the rail pressure of 30 MPa with fuel injection duration of 0.5 ms, the fuel injection was unstable and thus the experiment was not performed. The counted numbers of pulses generated by the PDFM were 24 at 30 MPa/1.0 ms and 3100 at 150 MPa/2.0 ms, respectively. It was found that the number of counts accumulated during the 500 times fuel injection set with the PDFM fluctuates slightly.

Figure-7 shows the measurement results of the total injected fuel mass with the 500 times fuel injection set. The measurement conditions are identical to those in Figure-6. The total injected fuel mass ranged from 2.4 g at 30 MPa/1.0 ms to 68.5 g at 150 MPa/2.0 ms. The total injected fuel mass from the 500 times fuel injection set according to the experiment number on the x-axis show mostly constant values. Compared to the PDFM pulse number in Figure-6, the total injected fuel mass in Figure-7 shows almost no fluctuation.

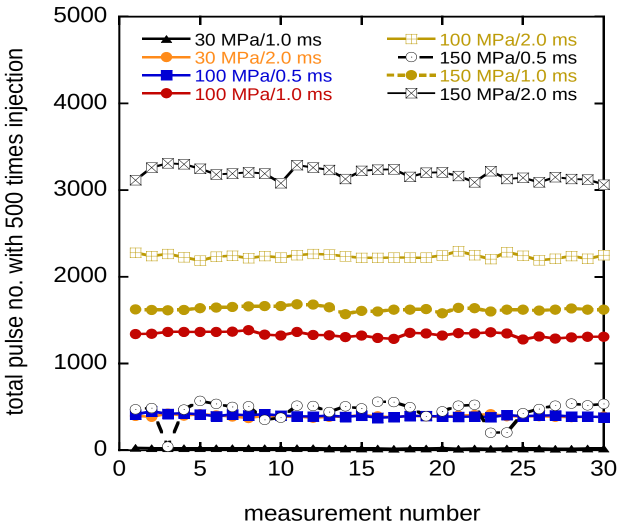

Figure-6. Total calculated number of pulses of the PDFM upon 500 trials of fuel injection for various experimental conditions.

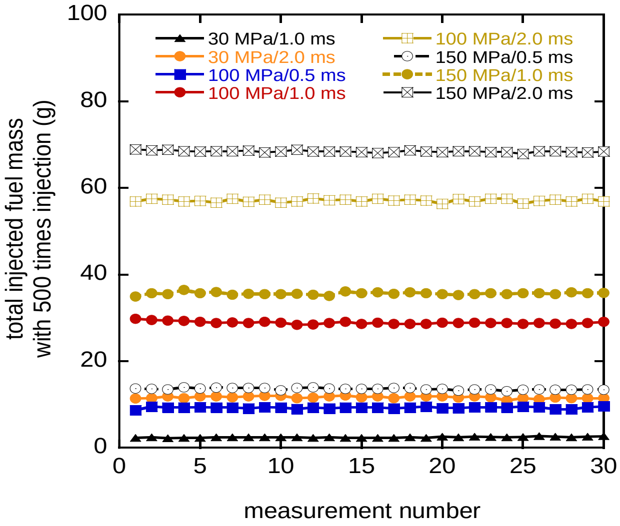

Figure-7. Total injected fuel mass measured with the scale upon 500 trials of fuel injection for various experimental conditions.

Figures 8-10 show the results of uncertainty analyses for the 30 repetitive measurements of the 500 times fuel injection set shown in Figures 6-7. In Figures 8-10, the fuel injection durations are 0.5, 1.0, and 2.0 ms, respectively. A normal distribution was used as an error function in the uncertainty analyses. The deviation percentage from the average value was calculated from the experimental data measured by both the PDFM and the scale. The deviation percentage at the 95% confidence level was obtained. Overall, the deviation percentages with the scale were much smaller than those from by the PDFM. The lower the rail pressure is, the greater the deviation percentage becomes for both the scale and the PDFM. The deviation percentage with the scale was 0.1% under all measurement conditions. For all experimental conditions, the PDFM-based deviation percentage ranges from 0.1% at both 100 MPa and 150 MPa up to 0.9% at 30 MPa. The fuel injection becomes unstable at lower rail pressures. The unstable fuel injection at lower rail pressure levels is related to the fuel injection mechanism of the piezo injector. That is, when the piezo element stack in the piezo injector expands, high rail pressure acts to lift the nozzle needle upward instantly. However, at lower rail pressures, the lift force is not sufficiently large. Thus, the needle may be lifted unstably at lower rail pressures. The longer the fuel injection duration becomes, the smaller the deviation percentage in both the PDFM and scale measurements.

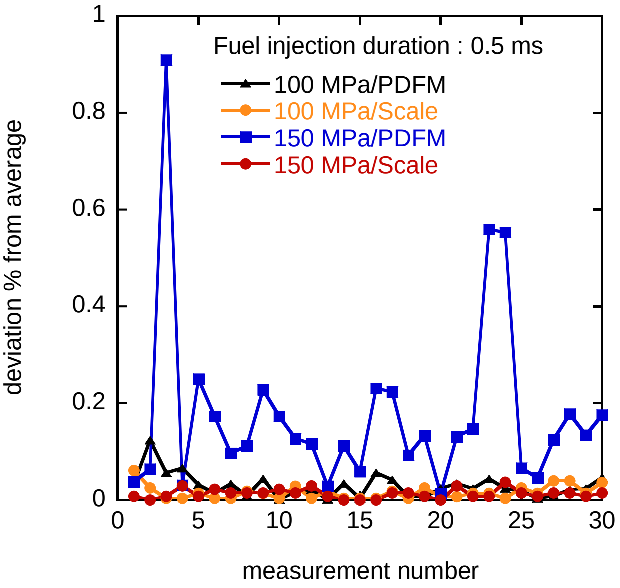

Figure-8. Deviation percentages from the average value measured with the scale and the PDFM at a fuel injection duration of 0.5 ms.

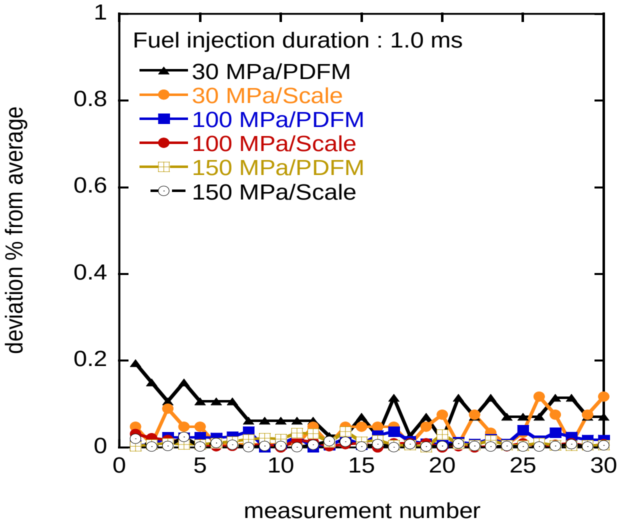

Figure-9. Deviation percentages from the average value measured with the scale and the PDFM at a fuel injection duration of 1.0 ms.

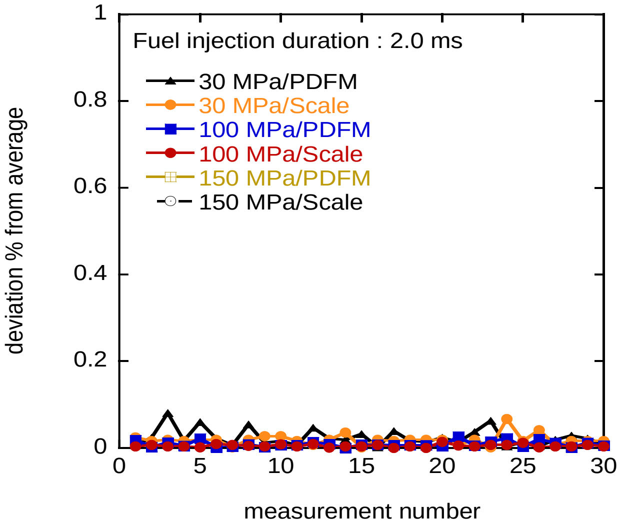

Figure-10. Deviation percentages from the average value measured with the scale and the PDFM at a fuel injection duration of 2.0 ms.

CONCLUSIONS

The injected fuel mass from a diesel piezo injector was measured using a scale and a positive displacement flow meter (PDFM). The results from the PDFM were evaluated in comparisons with those from the scale. An experiment involving the 500 times fuel injection set was repeated 30 times for each experimental condition. This experimental data was then used for an uncertainty analysis. The following results were obtained.

a) The deviation percentage from the average injected fuel mass with the scale was lower than 0.1% at the 95% confidence level in all experimental conditions. The deviation percentage with the PDFM ranged from

0.1% to 0.9% at the 95% confidence level according to the experimental condition.

b) The lower the rail pressure is at all injection conditions, the greater the deviation percentage becomes with both the scale and the PDFM.

c) The longer the fuel injection duration for all rail pressure conditions, the smaller the deviation percentage becomes with the both scale and the PDFM.

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