An experimental study on advanced injection rate measurement of a marine engine using the Zeuch method

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Received 22 May 2016

Abstract
In this study, an injection rate meter that can be used to measure marine engine nozzle injection rates is developed and the results obtained using this equipment are presented. This main focus is on differences resulting from changing the rack stroke using marine diesel oil. In addition, marine engine injection system design variables are shown to be related to by the shape of the cam profile to nozzle geometry and to the control parameters influencing the injection quantity (fuel rack position) and timing. Changing the load and fuel rack position, we calculated the injection rate by using the Zeuch method, simultaneously measuring the amount of fuel injected from the marine nozzle for 10 minutes. The difference between calculated and measured quantities is less than 1%. Comparison demonstrated the reliability of the developed injection meter. In addition, injection rate characteristics of a marine nozzle under various conditions were investigated. This study shows that it is possible to measure the injection rate and quantity of the complete marine engine using the Zeuch method.

Key words: Zeuch method, Injection rate, Bosch tube method, Marine diesel nozzle, FIE (Fuel Injection Equipment) system

1. Introduction

Direct-injection diesel engines have proved to be an efficient option in heavy-duty applications such as transportation or power generation, where fuel consumption at low speed and high load is a primary concern. However, owing to the natural conditions of high pressure and temperature in the combustion process, diesel engines emit considerable amounts of pollutants, especially nitrogen oxides (NOx) and particulate matter (PM). Other pollutions such as hydrocarbon (HC) and carbon monoxide (CO) are also present in diesel engine exhaust but not at the levels of particulate and NOx. This is why major importance has been given to decreasing emission levels and breaking the widely observed NOx-particle trade-off, i.e., without reducing the efficiency of the engine (Herzog et., Al., 1992, Erlach, H. et., Al., 1995, Needham et., Al., 1990).

Emission standards have led to the development of many new high-pressure injection systems as a means of improving the combustion process in diesel engines. In addition to high injection pressure, the injection rate configuration has also been shown to influence emissions (Bower, G et., Al., 1991). It is now essential to know the rate profile as well as the injection pressure when attempting to optimize engine operation. Therefore, accurate measurement of injection rate shapes using an injection rate meter is an important part of injection system development. When evaluating an injection rate meter, accuracy is the most important consideration.

The importance of fuel injection systems in the operation of marine diesel engines has been recognized since the engines’ early days. The rate at which fuel is introduced into the combustion chamber determines the performance of the engine. Therefore, knowing the spray characteristics (Bosch, W., et., Al., 1996, K.H. Lee et., Al., 2007, Pickett, L et., Al., 2013) of the fuel injection rate (Arcoumanis et, Al., 1993, J. Dernotte., et, Al., 2012, Z. He, et, Al., 2014, M. Marčič, et, Al., 1999, L. Postrioti, et, Al., 2014, P. Tinprabath, et, Al., 2015) is very significant in designing marine diesel engines. Therefore, many fuel injection rate measurement methods have been developed, among which Zeuch’s (Arcoumanis et, Al., 1993, L. Postrioti, et, Al., 2014) and especially Bosch’s (Bower, G et., Al., 1991) are most frequently used today.
In the case of solenoid injectors, injection rates have been measured by changing the injection duration. This system is very simple and uses small injection quantities. However, in the case of 1.4-MW marine engines, the quantity of fuel used in a single stroke is about 6 g. It is not possible to measure the injection rate using Zeuch’s existing system for these cases. In solving this problem, it must be recognized that the system is composed of a motor, cam box (installed cam), and fuel injection pump. The conditions in this system are the same as in engine’s fuel injection pump system.

In this paper, the fuel injection rates in a marine diesel engine are measured using Zeuch’s method while changing the engine load and injection conditions and the resulting injection rates are analyzed and compared.

2. Experimental apparatus and methodology

Figure 1 shows a schematic diagram for measuring the injection rate of marine nozzles. This system is composed of various sections: the supplied fuel and oil system, operating system, motor control, data acquisition system, control system, and injection rate measurement.

Table 1 shows the specification of test apparatus used in this research. Basically, the specification of the number of nozzle holes and diameter were 6 and 0.166mm, respectively. And the plunger type of fuel pump is upper helix type of mechanical type. Table 2 shows the test conditions and used fuel property. The main test parameter in this experiment are fuel rack position (this means the load of engine at the constant engine speed) and chamber pressure at the condition of engine load. We found the compression pressure at the various condition of engine load is different from engine monitoring data. The used fuel in this study was used in ASTM D975. The fuel injection pump (Fig. 2(a)) used in this research is of the upper helix type (Fig. 2(c)) with a barrel and plunger, as shown in Fig. 2. It measures the injection rate with changing fuel rack position (termed the load) and compression pressure on the loads.

The basic concept of a manufactured injection rate measurement system is shown in Fig. 3 along with what is called the Zeuch method. As fuel is injected into an airtight chamber by an experimental nozzle, the pressure inside the airtight chamber increases in proportion to the injection amount. The equation used to calculate injection rate is shown in equation (1):

\[
\frac{dm}{dt} = \rho_f \cdot V \cdot \frac{dp}{dt} = \text{Const} \cdot \frac{dp}{dt}
\]

where \(\rho_f\) is the density of fuel, \(V\) is the volume of the chamber, \(K\) is the bulk modulus of the fuel, and \(p\) is the chamber pressure.

Legend: (1) motor, (2) motor controller, (3) cam box system, (4) fuel injection pump, (5) fuel oil supply system, (6) high-pressure chamber(Volume=0.06m³) for the Zeuch method, (7) fuel nozzle, (8) DAQ system, (9) injector driver, (10) encoder signal, (11) chamber pressure signal, (12) chamber temperature signal, (13) high-pressure pipe pressure signal, (14) displacement signal, (15) venting nozzle.

Fig. 1 Schematic diagram of injection rate and fuel amount measurement system.
Table 1. Specification of test apparatus

| Items           | Specification       | Items          | Specifications |
|-----------------|--------------------|----------------|----------------|
| Engine speed    | 900 min⁻¹          | Nozzle hole diameter | 0.186 mm       |
| CAM speed       | 450 min⁻¹          | Plunger type   | Upper helix type |
| Nozzle hole     | 6                  | Pump           | Mechanical type |

Table 2. Test conditions and used fuel property

| Items                        | Condition | Fuel oil property    | Standard specification oil | ASTM D975 |
|------------------------------|-----------|----------------------|-----------------------------|-----------|
| CAM speed                    | 450 min⁻¹ | Flash point (°C)     | Standard specification oil | 93        |
| Fuel rack position(mm)       | 12, 21, 25 and 31 | Kinematic viscosity (mm²/s) | Max 2.4          |
| Chamber pressure(MPa)        | 5.4, 7.8, 11.5 and 15.5 | Sulfur, ppm | Max 15 |

As the injected fuel amount is \( m_{\text{inj}} \), the integration of equation (1) gives the injected fuel mass. As the bulk modulus coefficient is constant, equation (2) arises:

\[
m_{\text{inj}} \approx \text{Const} \int_{t_0}^{t} \frac{dp}{dt} \, dt
\]

(2)

Therefore, rearranging equation (2), the constant is obtained as follows in equation (3):

\[
\text{Const} = \frac{m_{\text{inj}}}{\int_{t_0}^{t} \frac{dp}{dt} \, dt}
\]

(3)

Using the result of equation (3), the transient injection rate of fuel is calculated by equation (4):

\[
m = \text{const} \times \frac{dp}{dt}
\]

(4)

Selecting the pressure chamber as follows from Fig. 3, the variation equation for net volume (\( \Delta V \)) according to the injected fuel amount is given in equation (5):

\[
\Delta P = K \times \frac{\Delta V}{V}
\]

(5)

We are determined on the volume of constant chamber as followed Table 3. As considered with bulk modulus constant and increasing pressure at the constant chamber, finally the volume of constant chamber was set on the 0.6m³.

Table 3 Pressure increase caused by fuel injection in a constant chamber

| Net volume (\( \Delta V \), 10⁶ m³) | Bulk modulus (used fuel) K (MPa) | Increasing pressure at the chamber volume (V=0.06 m³) (MPa) |
|-----------------------------------|---------------------------------|----------------------------------------------------------|
| 100                               | 1.5 \times 10³                  | 0.025                                                    |
| 500                               | 1.5 \times 10³                  | 0.125                                                    |
| 1000                              | 1.5 \times 10³                  | 0.250                                                    |
| 2000                              | 1.5 \times 10³                  | 0.5                                                      |
| 4000                              | 1.5 \times 10³                  | 1.0                                                      |
| 6000                              | 1.5 \times 10³                  | 1.5                                                      |
| 8000                              | 1.5 \times 10³                  | 2.0                                                      |

The crank angle with time is measured in the operating part of Fig. 1. The result shows that the amount of time per crank angle (CA) does not correspond to 450 min⁻¹ (CAM speed). This result is shown in Fig. 4. In general, the time per
0.2CA at 450 min\(^{-1}\) of CAM speed (based on 1 cycle) is 33.35 \(\mu\)s. From Fig. 4, the local region shows a different time with crank angle. Therefore, equation (1) is modified as follows:

\[
\frac{dm}{d\theta} = \rho f \frac{V}{K} \times \frac{dp}{d\theta}
\]  

where the crank angle \(d\theta\) measured in our system is \(d\theta \neq dt\).

Fig. 2 Schematic diagram of the fuel injection pump and helix plunger (A.K. Kathpal et al., 2007)
In the supplied fuel and oil system, we controlled the pressure of supplied fuel and oil, which were 0.5 MPa and 0.4 MPa, respectively. The motor speed was 450 min\(^{-1}\). The method of injection rate determination in a marine diesel engine is shown in Fig. 5.

The algorithm for measuring the injection rate is shown in Fig. 5(a). The measurement for a marine diesel engine nozzle was accomplished using the following process.

- Initially, the first-stage value was obtained from the displacement of the nozzle using a needle lift sensor (manufactured by micro-epsilon Co. Ltd.), inside pressure of the high-pressure pipe (obtained using an absolute pressure sensor) and chamber temperature.
- Second, after applying the compression pressure while changing the engine load, the injection rate and amounts were measured and calculated with increasing chamber pressure.
Third, the increased pressure (applied by compression pressure and loads) above the reference pressure was vented by an electric injector.

Fourth, the injection rate was measured repeatedly with changing experimental conditions. Finally, we determined the times of the data acquisition.

Fig. 5(b) shows the concept of controlling the injection rate in detail.

Fig. 6 shows the results of injection rate measurement using high pipe pressure, which was applied as displacement of the lift needle used for measuring injection duration and injection timing. Through the injection rate and needle lift curves injection duration was determined. The final curve is shown in a different position because the sac volume retained liquid fuel. We determined the injection duration from the injection rate curve.
Fig. 6 Comparison of injection rate, high pipe pressure, and needle lift displacement results.

3. Results and investigations

3.1 Compression pressure with changing load conditions in a marine diesel engine

Fig. 7 shows the results of compression pressure with changing load conditions in the case of a marine diesel engine. The pressure increased linearly with increasing fuel rack position. This result was obtained while constant chamber pressure was applied with changing loads or fuel rack pump positions.

Fig. 7 Compression pressure with changing load conditions in a marine diesel engine.

3.2 Injection rate with changing fuel rack distance

Fig. 8 shows the injection rate with changing fuel rack distance (i.e., engine load). Our pump barrel was of the upper-helix type. In this case, it was possible to control the injection timing. Operating at full load, the injection timing was retarded more than at low loads. The advantage of the upper-helix type is that the injection timing changes with the load and it is possible to control NOx emissions with varying load.

From the results shown in Fig. 8, the injection rate and injection duration both increased with increasing fuel rack distance and injection timing was retarded.
3.3 Injected amount comparison with real and calculated mass

Fig. 9 shows the injected amount with fuel rack distance. We measured and analyzed the amount of fuel injected by an FIE (Fuel Injection Equipment) system. With increasing rack distance, the FIE system’s total injection rate and injection amount increased linearly. Comparing calculated and measured injection amounts, the error ratio was ±1%.

Fig. 10 shows the injection amount with changing chamber pressure measured while applying compression pressure in a marine engine under a given load. We measured the injection rate and amount with changing chamber pressures. When the chamber pressure was set between 8 MPa and 15 MPa with engine load, the injected amount was compared with the calculated and measured values. The differences in the rate and the amount with changing chamber pressure are about 0.004 g/stroke and 3.7% between 8 MPa and 15 MPa. From this result, the injection rate and amount are affected by the compression pressure. In the Bosch tube method, the pressure of the tube was set to 5 MPa. The peak pressure and compression pressure increased with increasing loads. Compared with applying no compression pressure in a combustion chamber, the injected amount comes with 5% error.
3.4 Injection duration and injection rate with changing loads

Fig. 11 shows the injection duration with changing load and fuel rack distance. The injection duration with increasing fuel rack position is 17 CA, 28 CA, 33 CA and 36 CA. The injection duration with fuel rack position was measured with the methodology shown in Figs. 6 and 7. The injection duration increased linearly until the 25 mm fuel rack position was reached. The slope of injection duration after the 25 mm fuel rack position is different compared with that before the 25 mm position. The friction coefficient of fuel in the case of the 31 mm fuel rack position is not effect on the decreased injection duration. This reason that it is the geometric configuration effect to be related with the effective stroke of the upper helix plunger.

Fig. 12 shows the calculated injection rate with chamber pressures for 9 sets of pumps. The injected amount is affected by the chamber pressure. The figure shows the difference of injection rate with 9 sets of pumps; hence, the fuel rack position for different pump settings is different.
4. Conclusions

In the case of a 1.4-MW marine engine, the quantity of fuel transferred in a single stroke is about 1.4 g. This paper shows that it is now possible to measure the injection rate in this case using the Zeuch system. In solving this problem, we considered that the system is composed of a motor, cam box (installed cam), and fuel injection pump. The condition of this system is the same as in the engine’s fuel injection pump system. This paper investigated how the injection rate and injection time were affected by the fuel cam profile, compression pressure of the cylinder, and fuel injection pump as follows:

[1] The injection rate was measured with changing fuel rack displacement and compression pressure under different engine loads using the Zeuch method. We measured and calculated the injection rate and found that the real and calculated injected amounts using the Zeuch method exhibited an error rate of about ±1%.

[2] It is possible to measure the injection rate for large marine engines using the Zeuch method and to measure the injection timing, injection duration, and injection rate curve profile. These parameters are necessary in simulating and analyzing combustion using CFD with applicable parameters.

[3] From measuring the injection rate and amount with changing chamber pressure, when the chamber pressure was set between 8 MPa and 15 MPa under the imposed engine loads, the injection amount error rate was about 4%.

Acknowledgement

This work was supported by a research fund from Songwon University.

References

Arcoumanis, C. and Baniasad, M., Analysis of Consecutive Fuel Injection Rate Signals Obtained by the Zeuch and Bosch Methods, SAE Technical Paper 930921, (1993).

A.K. Kathpal, Avinsh Kumar Agarwal, Baskran R and Anirudh Gautam, Design and development of double helix fuel injection pump for four stroke V-16 rail traction diesel engine, Proceedings of the ASME Internal Combustion Engine Division 2007 Fall Technical conference, Oct. 14-17, Charleston, South Carolina, USA.

Bosch, W., "The Fuel Rate Indicator: A New Measuring Instrument for Display of the Characteristics of Individual Injection", SAE Technical Paper 660749, (1966).

Bower, G. and Foster, D., A Comparison of the Bosch and Zuech Rate of Injection Meters, SAE Technical Paper 910724, (1991).
Erlach, H., Chmela, F., Cartellieri, W., and Herzog, P., Pressure Modulated Injection and Its Effect on Combustion and Emissions of a HD Diesel Engine, SAE Technical Paper 952059, (1995).
Herzog, P., Bürgler, L., Winklhofer, E., Zelenka, P., NOx Reduction Strategies for DI Diesel Engines, SAE Technical Paper 920470, (1992).
J. Dernotte, C. Hespel, F. Foucher, S. Houillé, and C. Mounaim-Rousselle, Influence of physical fuel properties on the injection rate in a Diesel injector, Fuel, 96 (2012) 153–160.
K. H. Lee and C. H. Lee, Characterization of the flow field and stratification effects of fuel spray in a visualization engine using DPIV and entropy analysis, Exp. Therm. Fluid Sci., 31 (6) (2007) 579–592.
L. Postrioti, G. Buitoni, F. C. Pesce, and C. Ciavavino, Zuech method-based injection rate analysis of a common-rail system operated with advanced injection strategies, Fuel, 128 (2014) 188–198.
M. Marčič, A new method for measuring fuel-injection rate, Flow Meas. Instrum., 10 (1999) 159–165.
Needham, J., May, M., Doyle, D., Faulkner, S., Injection Timing and Rate Control - A Solution for Low Emissions, SAE Technical Paper 900854, (1990).
P. Tinprabath, C. Hespel, S. Chanchaona, and F. Foucher, Influence of biodiesel and diesel fuel blends on the injection rate under cold conditions, Fuel, 144 (2015) 80–89.
Pickett, L., Manin, J., Payri, R., Bardi, M., Transient Rate of Injection Effects on Spray Development, SAE Technical Paper 2013-24-0001, (2013).
Z. He, T. Xuan, Y. Xue, Q. Wang, and L. Zhang, A numerical study of the effects of injection rate shape on combustion and emission of diesel engines, Therm. Sci., 18 (1) (2014) 67–78.

**Nomenclature**

P : chamber pressure, kg/cm²
ρ : density of fuel, kg/m³
K : bulk modulus of fuel
m : injection amount, mg
ΔV : net volume, m³
V : chamber volume, m³

**SUBSCRIPTS**

f : fuel
cy : cycle