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Flow Control of a Solenoid Gas Injector and Its Application on a Natural Gas Engine

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솔레노이드 가스 인젝터의 유량제어와 천연가스엔진에서의 응용

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ABSTRACT

An air-fuel ratio control is essential in reducing hazardous exhaust emissions from a compressed natural gas(CNG) engine, and can be accomplished by accurate control of gas injection flow. In this study, theoretical research was conducted on injection characteristics of a solenoid gas injector, and injection experiments for calibration and analysis were performed. Various factors for gas injection flow such as injection pressure, gas temperature, and supply voltage are studied. A dynamic flow equation of the natural gas was proposed on the basis of flow dynamics theories and results of the injection experiment. The verification of the dynamic flow equation of the solenoid injector was carried out with a large CNG-engine applied to an urban bus. Air-fuel ratio control experiments were conducted in both steady and transient state. Results of injection experiments for the solenoid injector and the CNG-engine was proved the control method proposed herein to be effective.

Key Words : Solenoid Injector, Gas Injection Flow, Dynamic Injection Flow, Natural Gas Engine

1. Introduction

In a spark-ignition CNG-engine, the solenoid injector is responsible for fuel injection control aimed at reducing hazardous exhaust gases, and the injection characteristics of the solenoid injector are a key factor for enhancing air-fuel ratio control performance[1-2]. The control of the injection flow of gaseous fuels like the natural gas can be classified into continuous flow control and the intermittent injection of a necessary amount within a limited space. The solenoid injector is mainly used when controlling a small and precise injection flow in the former both cases. In designing the solenoid injector, essential are analysis of injection flow characteristics of an injection nozzle outlet, the magnetic field strength of solenoids, and an dynamic characteristics of armature, spring-magnetic forces; on the basis of this, solenoid injectors aimed at controlling injection flow are designed, and their control performance can be analyzed through experiments of static and dynamic injection flow characteristics[3-4].

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2. Injection Characteristics

2.1 Gas flow inside the solenoid injector

Assuming that the flow of an ideal gas flow in the solenoid gas injector, the gas flows through a reduced throat that is injected into the injector outlet, as shown in Fig. 1.

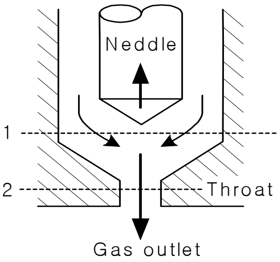

Fig. 1 Gas flow through a throat in injector

The static gas flow at the injector outlet can be shown as in the following equation when expressed as the flow for the real gas[5].

$$\dot{m}_s = C_D \rho_2 A_2 v_2 = C_D \frac{A_2 p_1}{\sqrt{RT_1}} \cdot \Phi \qquad (1)$$

The discharge coefficient(C_D) is the ratio of the actual discharge to the theoretical discharge, and it can be calculated from the experiment. The theoretical gas flow equation can be different to the real gas flow because the former is an ideal value under various restrictive conditions such as the ideal gas flow, an isentropic, and without friction and work.

The pressure ratio influence factor(Φ), on the other hand, is a coefficient that shows the influence of the pressure ratio on the actual discharge. It is expressed as Eq. (2) or Eq. (3), according to the pressure conditions.

$$\Phi = \left[\left(\frac{2k}{k-1}\right)\left(\left(\frac{p_2}{p_1}\right)^{\frac{2}{k}} - \left(\frac{p_2}{p_1}\right)^{\frac{k+1}{k}}\right)\right]^{\frac{1}{2}}$$

, sub-sonic flow (2)

$$\Phi^* = \left[k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}\right]^{\frac{1}{2}}$$

, sonic flow (3)

Using Eq. (2) and Eq. (3), the pressure ratio influence factors of the various gaseous fuels that were studied herein were obtained, as shown in Fig. 2. The gaseous fuels can be considered methane(CH_4), hydrogen(H_2), and propane(C_3H_8) gas.

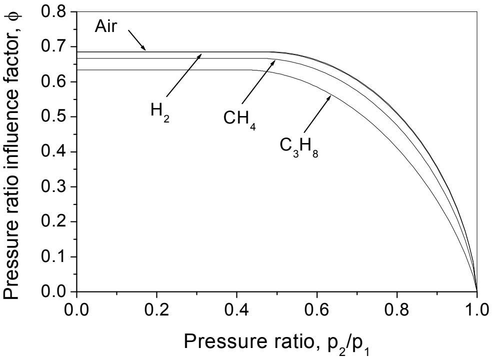

Fig. 2 Relationship of the pressure ratio influence factor and the pressure ratio in a gas flow

In the injection of the gaseous fuels in the solenoid gas injector, the gas injection flow was reduced to about 60-70% because the pressure ratio influence factor was decrease under the sonic flow condition. Above the critical condition(air: 0.528; H_2: 0.527; CH_4: 0.546; C_3H_8: 0.579), the pressure ratio influence factor was not varied but continuous depending on the pressure ratio. The static gas flow under the sonic condition can be written;

$$\dot{m}_{s.sonic} = f(C_D, A_{2,} p_1, T_1) \qquad (4)$$

According to various injection systems, the outlet pressure of the injector can be changed during the CNG-engine is working. However the gas injection flow will not be affected by variation of the outlet pressure if the injection pressure is constant under the sonic flow condition. It is very effective for the precise control of the gas injection flow to be injected with the use of the solenoid gas injector. The injection pressure must be adjusted highly in the CNG-engine within a turbocharger because the outlet pressure of the injector is increased by a compressed air.

2.2 Dynamic injection flow

The gaseous fuels are injected during the high-speed ON/OFF operation of the solenoid injector in the CNG -engine. Therefore, the static gas flow can't be applied to the dynamic gas flow. However, it can be only used the theoretical result that the gas injection flow will not be affected by variation of the outlet pressure (p_2) under the sonic flow condition.

The dynamic injection flow is affected by the dynamic characteristics of a needle and electro-magnetic characteristics of the solenoid[6]. In reality, time delay occurs in the dynamic injection flow until the injector is opened during the initial driving. When the voltage is applied to the solenoid coil according to the driving signal of the injector, the current starts to flow, and time delay occurs until the static current flows through the inductance of the coil. Moreover, because the amateur-needle also has mass, although it is very small, there is resistance due to inertia. Motion of the needle is resisted by a return spring to close the injector outlet. Therefore, the nozzle may not open completely and may become stuck if the driving signal is smaller than the rise time of the needle.

3. Experimental and results

3.1 Bench test and results

The solenoid injector shown in Fig. 3 was used in this test to verify the injection characteristics of the solenoid gas injector and to analyze its flow characteristics. Table 1 shows specifications of the solenoid injector and test conditions. The solenoid injector that was used in the test was a Servojet gas injector, and it was driven by DC12V. The high-pressure gas that was used was the CNG, and its injection pressure can be varied using the pressure regulator. The injector driver was used a Peak & Hold circuit which is an appropriate method to use for driving a low-resistance injector.

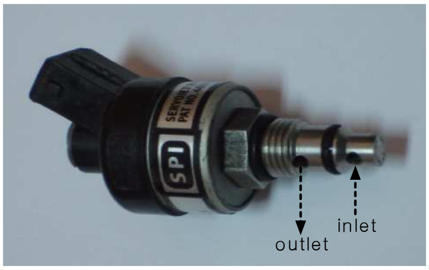

Fig. 3 The solenoid gas injectors for the test

Table 1. Specifications and test conditions.

Items	Type
Solenoid injector	Servojet SPI014
Voltage	DC12V
Coil resistance	2.0Ω
Driver and control	Peak & Hold, 50Hz PWM
Injection Gas	Natural gas
Injection pressure	700kPa
Temperature	20℃

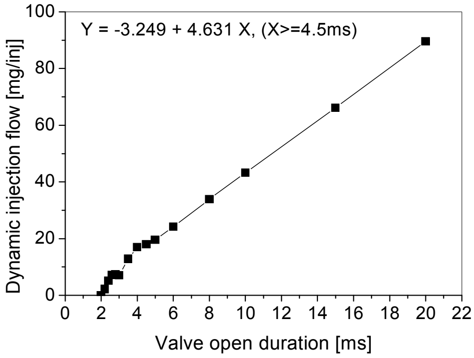

Fig. 4 Dynamic injection flow

Fig. 4 shows the dynamic gas flow at a time depending on the length of time that the solenoid injector was open, under a constant injection pressure of 700kPa. The CNG was not injected for a period of 0 to 2ms because the injector was not opened, and the nonlinear characteristics was observed to be remarkable 2-4.5 ms. More than 4.5 ms after the injector was opened completely, the gas injection flow increased in proportion to the increase in the time that the injector was open. Therefore, in order to precisely control the gas injection flow, it is recommended that the injection duration be maintained at more than 4.5 ms as there would be a stable gas injection flow by then.

3.2. Compensation of the dynamic injection flow for various conditions

In general, various injection conditions are changed when the CNG-engine is working. It is necessary that compensation of the dynamic injection flow for many variables such as the injection pressure, the gas temperature, and supply voltage to the solenoid injector. Influence of the injection conditions must be minimized, and compensation of the gas injection flow for the variables is necessary to precisely control the dynamic injection flow.

In order to correct for many variables, the dynamic injection flow is expressed as Eq. (5) based upon the experimental results on the calibration test and the calculation values.

$$m_{dyn} = m_{cal} \cdot F_p \cdot F_T \cdot F_V \tag{5}$$

The dynamic injection flow, m_{cal} is measured from calibration bench test when the injection conditions are constant same as Table 1. The dynamic injection flow is derived from the test result shown as Fig. 5.

$$m_{cal} = -3.249 + 4.631 \cdot t_{inj} \tag{6}$$

The pressure compensation factor, F_P is value that the various injection pressures divided by the calibration gas pressure.

$$F_p = \frac{p_{inj}}{p_{cal}} \tag{7}$$

Fig. 5 shows the pressure compensation factor for various gas injection pressures. The calibration pressure is 700kPa. The pressure compensation factor is linearly changed from 0.435(P_{cal}=300kPa) to 1.594(P_{cal}= 1100 kPa), and 1.0 at 700kPa.

The temperature compensation factor, F_T for the gas temperature variations is defined as

$$F_T = \frac{\sqrt{T_{cal}}}{\sqrt{T_{inj}}} \tag{8}$$

Fig; 6 shows the temperature compensation factor for various gas temperatures. The calibration temperature is 20°C(=293.15K). The temperature compensation factor is decreased from 1.93805 (T_{cal}=-20°C) to 0.7611(T_{cal}=60°C), and 1.0 at 20°C.

The voltage compensation factor, F_V is derived as Eq. (9) and it is ratio the dynamic injection flow under various supply voltage for the gas injection flow under the constant calibration voltage.

$$F_V = \frac{m_{dyn}(V_{inj})}{m_{dyn}(V_{cal})} = 0.66082 + 0.04547\, V_{inj} - 0.00143\, V_{inj}^2 \tag{9}$$

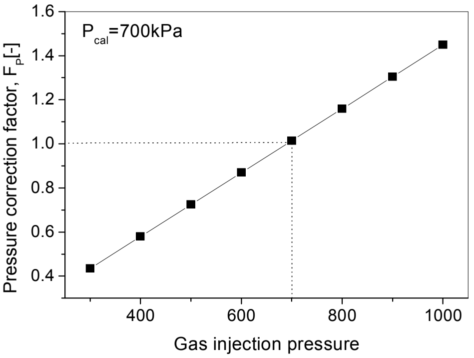

Fig. 5 Pressure compensation factor for the various injection pressures

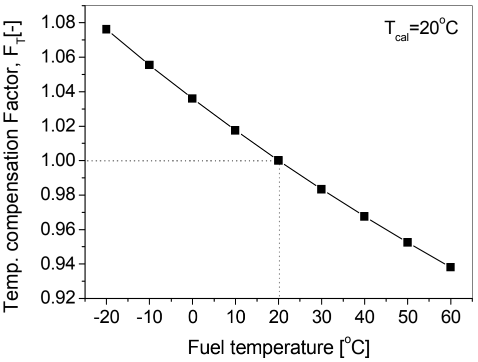

Fig. 6 Temperature compensation factor

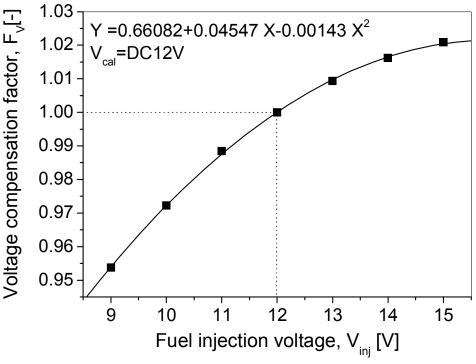

Fig. 7 Voltage compensation factor for variations of the injection voltage

Fig. 7 shows voltage compensation factor as a function of the supply voltage to the solenoid. The supply voltage at the dynamic injection test is DC12V. The voltage compensation factor is experimental valve that each dynamic injection flows are divided by the dynamic injection flow at DC12V.

4. Application test and results

To verify the dynamic injection flow of the solenoid injector that was studied herein, a verification test was performed on an 12,000-cc large commercial CNG-engine, which is applicable to the urban bus, as shown in Table 2 and Fig. 8. The CNG-engine that was used in the test was an inline 6-cylinder engine with a compression ratio of 9.5:1. It was tested within the stoichiometric air-fuel ratio(λ=1.0) range. The solenoid injector that was used in the application test was the Servojet gas injector same as the dynamic injection test. The solenoid injectors are assembled on an injector block and can be used variably. The injected gas from the solenoid injector are mixed with the air in a mixer before the throttle valve for the inlet air control. An air intake system that was used as natural aspiration system without a turbo-charger.

Table 2 Basic Specifications of the CNG-engine

Items	Type
Engine type	Inline, 6-cylinder
Displacement	12,000cc
Compression ratio	9.5 : 1
Solenoid injector	Servojet SPI014
Gaseous fuel	Natural gas
Injection pressure	700 kPa
Mixture formation	SPI before the throttle valve

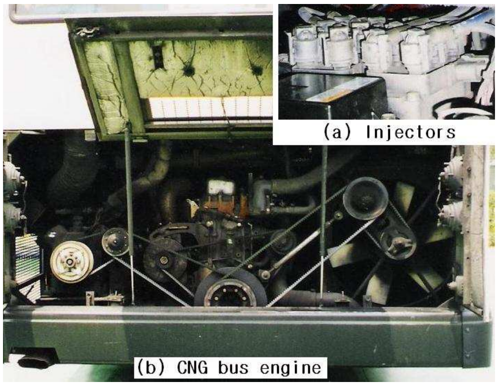

Fig. 8 The CNG-engine for application test

Fig. 9 shows the dynamic injection flow of the CNG-engine depending on the engine speed and manifold absolute pressure(MAP), under a steady-state operation condition(λ=1.0). The injected-gas flow varied from 1.0 to 11.5 g/sec, depending on the engine condition, and the injection gas flow increased according to variations of the engine revolution speeds and the loads(MAP). In this case, the injection pressure(p_1) of the high-pressure gaseous fuel was 700kPa, and the pressure ratio of the solenoid injector was under the sonic flow condition, which was not affected by the injector outlet pressure.

Fig. 10 shows the results of the experiment that was conducted to verify the flow control characteristics of the solenoid injector under constant speed transient conditions(1600 rpm). The throttle angle was changed within the range of 13 to 28 degree, and, accordingly, the manifold pressure was varied from 25 to 90 kPa.

The relative air-fuel ratio(λ) varied from 0.98 to 1.05 at abrupt throttle change, and the control performance within the stable throttle range was 1.0±0.02 at constant throttle angle, which is satisfactory. The increase of the error in the relative air-fuel ratio during the abrupt throttle change was due to the time delay from start of the CNG injection to the air-fuel ratio was detected at the oxygen sensor in the exhaust manifold, and the performance can be enhanced by improving the injection control algorithm.

Fig. 11 shows the dynamic injection flow of the CNG in the solenoid injectors. Test conditions of this result such as TPS, MAP, and engine speed are same as Fig. 10. Errors of the dynamic injection flow at the start of the abrupt throttle change are increased because the natural gas was injected to control the relative A/F ratio during to rapid increase of the inlet airflow. This results show that the estimation method of the dynamic injection flow for the solenoid gas injector was very effective.

5. Conclusion

The following results were obtained from the experiment for the solenoid gas injector by the mathematical and the experimental equations, which is applicable for the injection flow control of high-pressure natural gas using the solenoid injector. From the verification tests that were conducted in line with the study, including the calibration and the analysis bench test for the natural gas and the application test for the CNG-engine:

1. To ensure the precise control for the injection flow of the solenoid injector, the injection pressure ratio must be determined as the sonic flow condition, in which the gas injection flow will not be affected by the outlet pressure condition. Moreover, the injection flow control performance of the solenoid injector will improve because the pressure ratio influence factor becomes constant at the sonic condition.

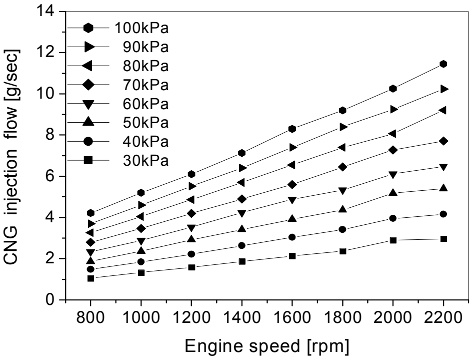

Fig. 9 Dynamic injection flow of the CNG-engine at steady conditions

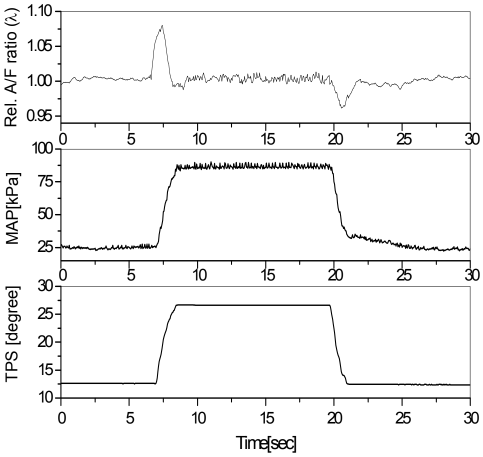

Fig. 10 Air-fuel ratio results at transient conditions

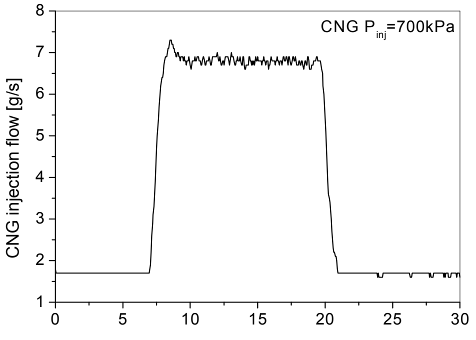

Fig. 11 Dynamic injection flow at transient test under transient conditions(same as Fig. 10)

2. In the calibration bench test that was conducted to determine the injection characteristics of the CNG using the solenoid injector, the nonlinear characteristics were observed to be remarkable when the injector was open for less than 4.5 ms, and the dynamic injection flow was proportional to the injection duration when the injector was open for more than 4.5 ms. Therefore, to ensure the precise control of the injection flow, it is recommended that the injection duration be maintained at more than 4.5 ms.
3. The experimental equation of the dynamic injection flow is proposed from the analysis results of the calibration bench test. Compensation factors for variables such as injection pressure, temperature, and driving voltage are derived from simple calculation and analysis of the experimental result. The calibration injection flow and the compensation factor for the voltage variation are experimental equation. And the pressure compensation factor and the temperature compensation factor are mathematical equations.
4. Verification test for the experimental flow equation of the solenoid gas injector was performed on the CNG-engine. In the measurement of the relative air-fuel ratio under constant speed transient conditions, the flow control characteristics of the solenoid gas injector were found to be satisfactory.

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Nomenclature

A : area
C_D : discharge coefficient
F : factor
k : specific heat ratio
m : mass
p : pressure
R : gas constant
T : temperature
V : voltage
v : velocity
ϕ : pressure ratio influence factor
ρ : density
cal : calibration
inj : injection
s, dyn : static, dynamic condition