International Conference on Applied Energy 2019
Aug12-15, 2019, Västerås, Sweden
Paper ID: 873

A SIMULATION AND EXPERIMENTAL STUDY OF OPERATING CHARACTERISTICS OF A GASEOUS FUEL INJECTION SYSTEM USING A SOLENOID INJECTOR COMBINED WITH AN ELECTRIC PRESSURE REGULATOR

Nguyen Ba Hung[1], Ocktaeck Lim [1*]

1 School of Mechanical Engineering, University of Ulsan, Ulsan 44610, Republic of Korea

* Corresponding Author, email: otlim@ulsan.ac.kr

ABSTRACT

A simulation and experimental study is conducted on a natural gas fuel injection system. The injection system includes a rail tube, a solenoid gas injector and an electric pressure regulator (EPR). The purpose of this study is to examine the operating characteristics of the injection system such as EPR control voltage, EPR plunger displacement, gas pressure in the rail tube, and injection flow rate. Mathematical models are established to describe the operation of solenoid gas injector and EPR. Besides, a control model is built to examine the response as well as injection pressure controlled by EPR. These models are solved in Matlab-Simulink.

Effects of EPR design parameters such as spring stiffness and plunger mass on the operating characteristics of the gaseous fuel injection system are investigated. The simulation results show that the operating performance of the gaseous fuel injection system can be improved if EPR spring stiffness and plunger mass are suitably chosen. In addition, the electric pressure regulator can be successfully controlled to maintain a stable output pressure providing to the solenoid injector. The simulation results are validated with experimental results for the controlled gas pressure.

Keywords: Solenoid injector, injection system, pressure regulator, plunger mass, spring stiffness

NONMENCLATURE

Abbreviations	
EPR	electric pressure regulator
CNG	compressed nature gas
Symbols	
m_{pr}	plunger mass of the EPR
k_r	spring stiffness of the EPR
F_{er}	electromagnetic force of the EPR
F_{sr}	spring force of the EPR
F_{dr}	damping force of the EPR
F_p	gas force acting on the EPR plunger
F_{gr}	gravitational force of the EPR plunger

1. INTRODUCTION

Unlike a normal pressure regulator with a mechanical mechanism, an electric pressure regulator (EPR) is an energy conversion device using a solenoid valve that is continuously controlled to ensure the stable and precise output pressure for a fuel injection system. The combination of the EPR with a fuel injection system using gaseous fuels such as hydrogen and compressed natural gas (CNG) is considered a good solution to further improve engine performance and reduce exhaust emissions due to the benefits of these gaseous fuels [1], [2], [3], [4], [5]. Besides EPR, a solenoid injector is also a key component of the gaseous fuel injection system, which directly affects the fuel amount providing to the intake manifold. A study of a gaseous fuel injection system using a combination of solenoid injector and EPR was not mentioned in the previous studies.

The purpose of this study is to examine the operating characteristics of a CNG fuel injection system integrated with an EPR and a solenoid gas injector. Mathematical models are established to describe the operation of both the EPR and the solenoid gas injector. In order to provide information for this study, the effects of EPR structural parameters such as plunger mass and spring stiffness on the operating characteristics of the gaseous fuel injection system are investigated. A control model for EPR is also built. Besides, an experimental study is conducted on the gas injection system to examine gas pressure in the rail tube under the effects of set gas pressure when injection process is applied.

2. SIMULATION STUDY

2.1 General model of CNG injection system

A general model of the CNG injection system is described in Fig. 1, in which it includes an EPR, a rail tube and a solenoid gas injector.

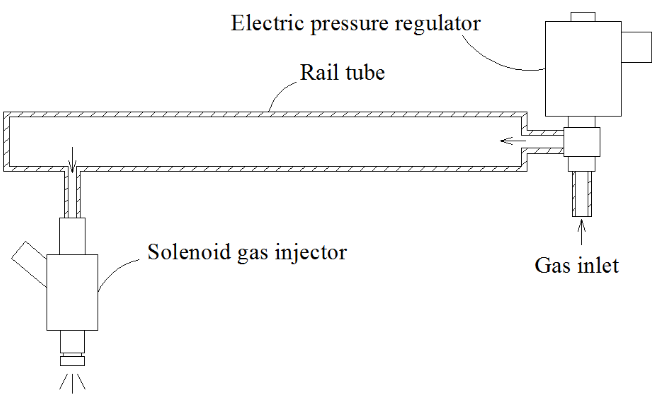
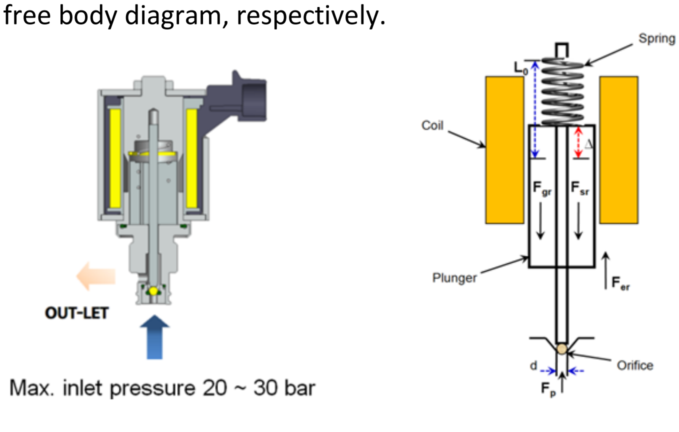


Fig. 1 General model of CNG injection system

2.2 EPR model

Figures 2a and 2b shows the model of EPR and its free body diagram, respectively.



(a) (b)

Fig. 2 Model (a) and free body diagram (b) of the EPR

The plunger motion of the EPR is based on Newton's second law:

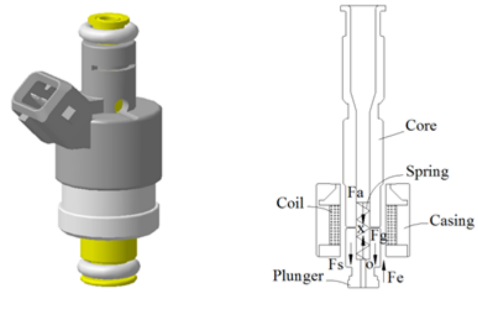
$$\sum F = m_{pr} \frac{d^2 x_{pr}}{dt^2} \quad (1)$$

$$F_{er} - F_{sr} - F_{dr} + F_p - F_{gr} = m_{pr} \frac{d^2 x_{pr}}{dt^2} \quad (2)$$

$$F_{er} - k_r (x + \Delta) - b_r \frac{dx_{pr}}{dt} + P_{in} S_o - m_{pr} g = m_{pr} \frac{d^2 x_{pr}}{dt^2}$$
(3)

2.3 Solenoid gas injector model

A solenoid-type natural gas injector along with its free body diagram is shown in Fig. 3



(a) (b)

Fig. 3 Model (a) and free body diagram (b) of the solenoid gas injector

The plunger motion of the solenoid gas injector is based on Newton's second law:

$$\sum F = ma = m\frac{dv}{dt} = m\frac{d^2 x}{dt^2} \quad (4)$$

$$F_e - F_s - F_d - F_a - F_g = m\frac{d^2 x}{dt^2} \quad (5)$$

$$\frac{d^2 x}{dt^2} = \frac{1}{m}\left[F_e - k(x + l_0) - b\frac{dx}{dt} - F_a - mg\right] \quad (6)$$

where, m is the mass of the plunger, F_e is the electromagnetic force, F_s is the spring force, F_d is the damping force, F_a is the gas force, F_g is the gravitational force.

2.4 Control model

A control model for EPR using PID controller is described in Fig. 4.

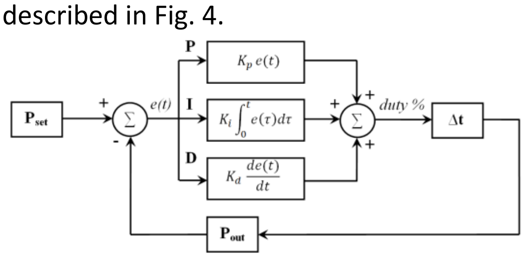


Fig. 4 Control model of the EPR

2.5 Simulation results

2.5.1 *Effects of EPR plunger mass*

The effects of EPR plunger mass on the operating characteristics of the injection system are shown in Figs 5 and 6, in which m_{pr} is varied at 31 g and 51 g.

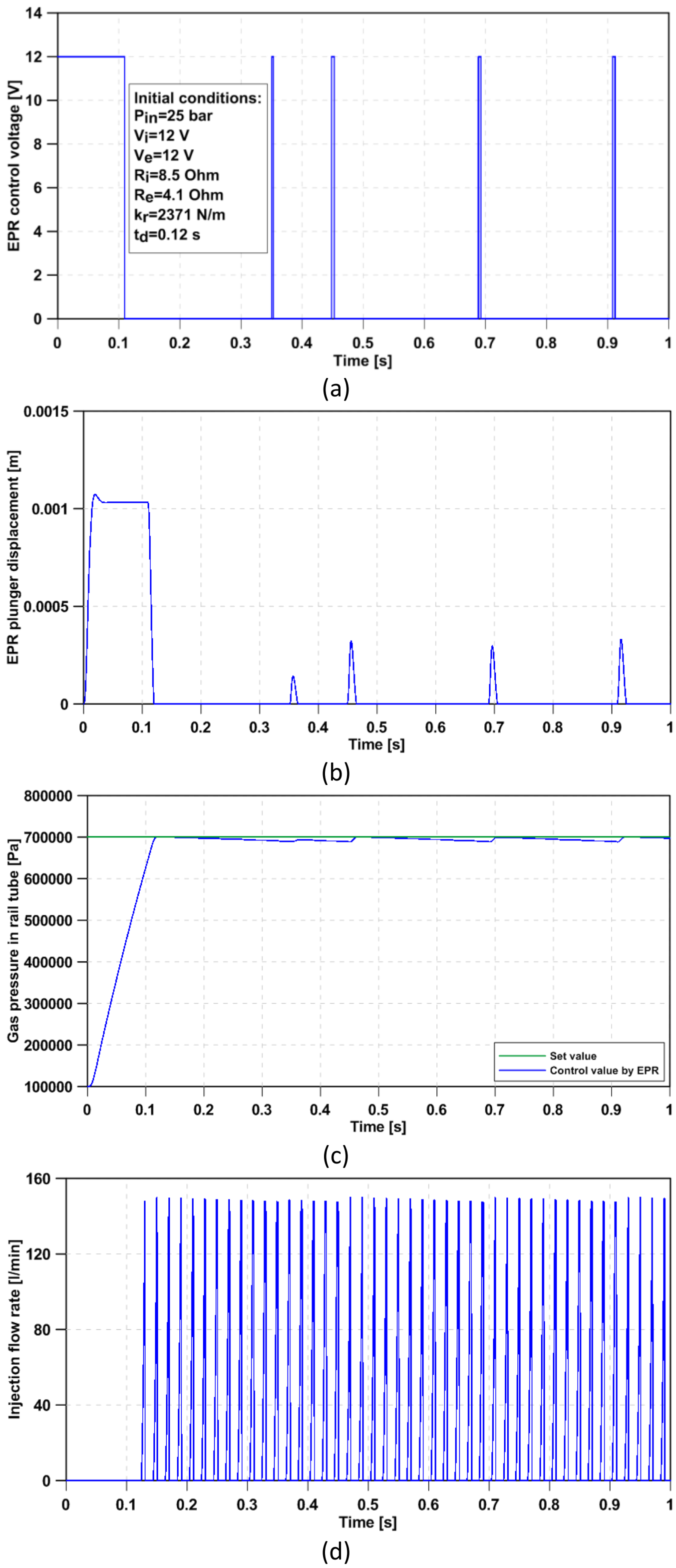


Fig. 5 Operating characteristics of the injection system at m_{pr}=31 g, k_r=2371 N/m

As shown in Figs. 5a and 5b, EPR plunger is control by voltage pulse to open and close it. The objective is to remain a set value of gas pressure in the rail tube during injection process, as shown in Figs. 5c and 5d.

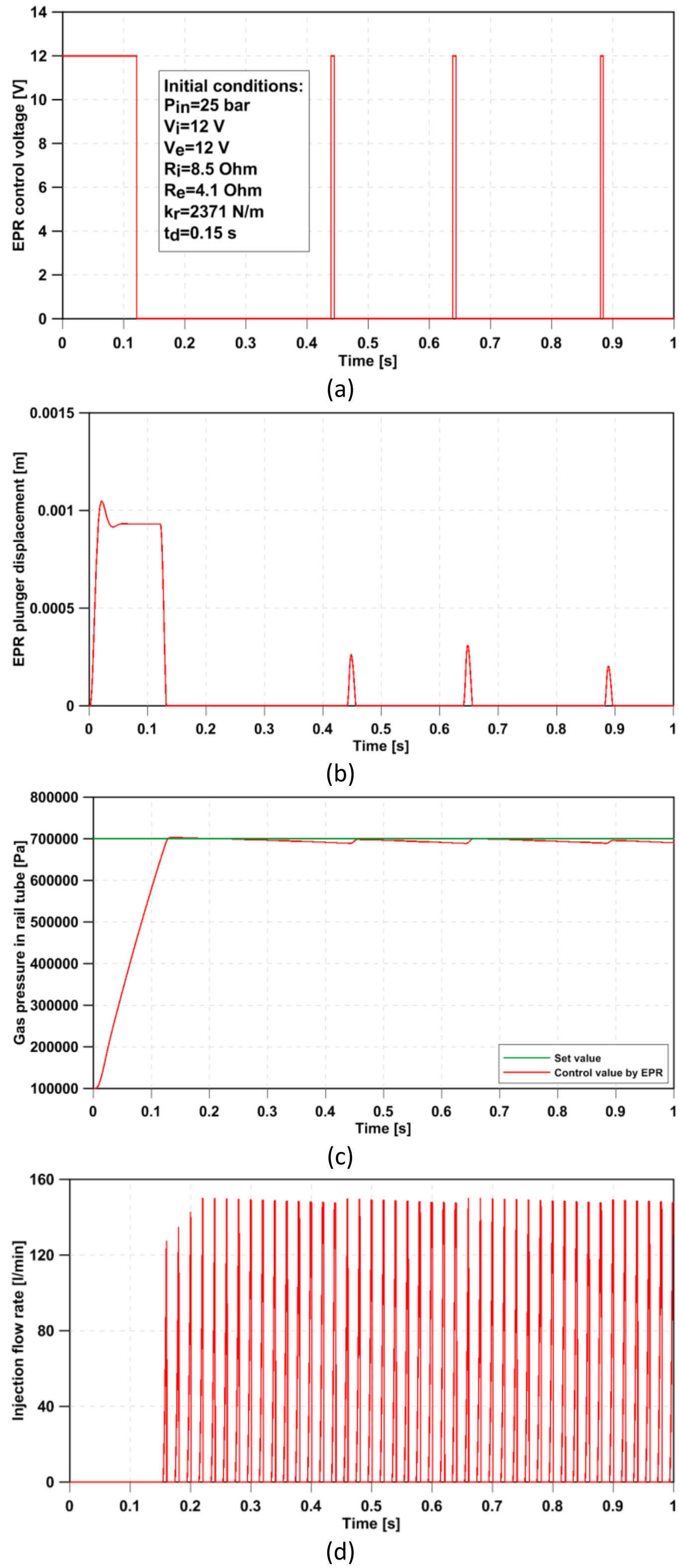
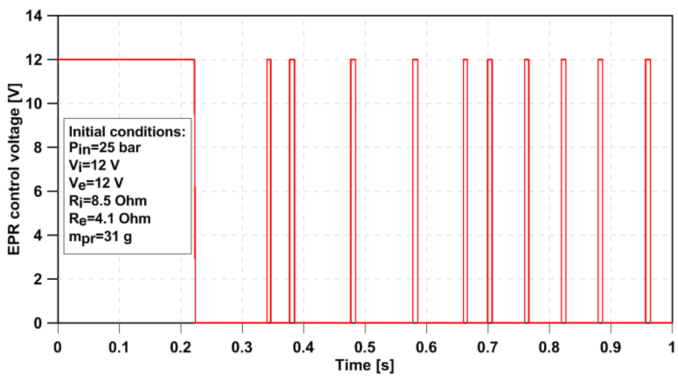


Fig. 6 Operating characteristics of the injection system at m_{pr}=51 g, k_r=2371 N/m

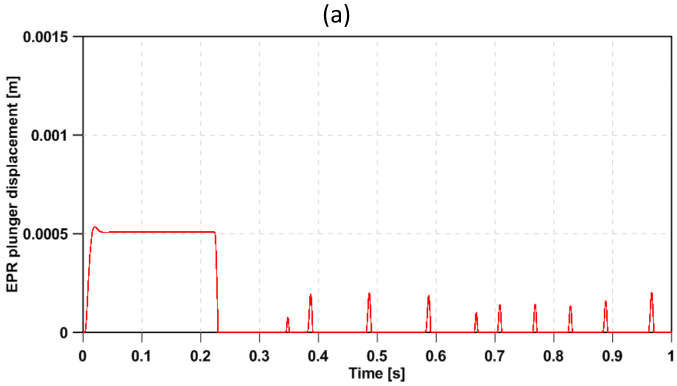
It can be found that when the EPR plunger mass is increased to 51 g, shown in Fig. 6, the gas pressure in the rail tube is slower increased to the set value due to the effect of inertial force acting on the EPR plunger. As the result, the injection flow rate is not stable.

2.5.2 Effects of EPR spring stiffness

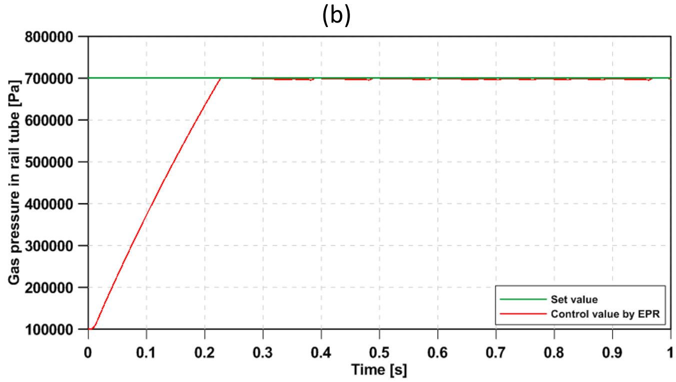
Figs. 5 and 7 show the effects of EPR spring stiffness on the operating characteristics of the injection system, in which k_r is varied at 2371 N/m and 2471 N/m.



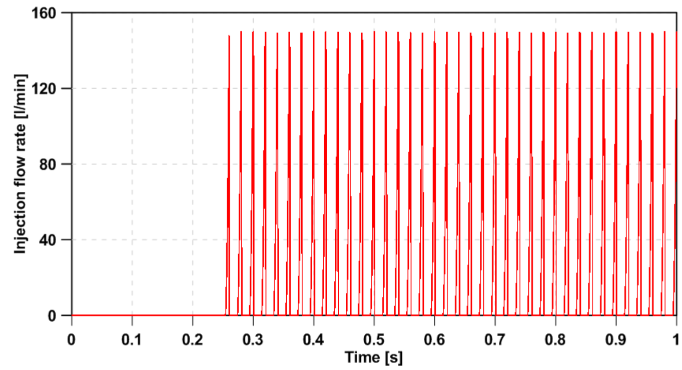
(a)



(b)



(c)



(d)

Fig. 7 Operating characteristics of the injection system at m_{pr}=31 g, k_r=2471 N/m

It can be seen that the voltage pulse providing to the EPR is increased when the EPR spring stiffness is increased from 2371 N/m and 2471 N/m. In particular, when the EPR spring stiffness is increased to 2471 N/m, the gas pressure in the rail tube is more stable than that of k_r=2371 N/m. As the result, the injection flow rate is also more stable than that of k_r=2371 N/m.

3. EXPERIMENTAL STUDY

3.1 Experimental setup

An experimental system is established for the gas injection system, as shown in Fig. 8, which includes rail tube, gas line, EPR, gas injector, pressure sensor, pressure indicator, data acquisition (DAQ) device, electronic control unit (ECU), direct current (DC) power, and computer.

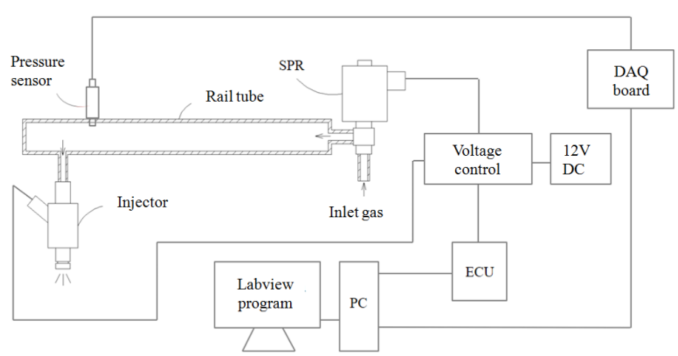


Fig. 8 Experimental system

3.2 Experimental results

Fig. 9 shows simulation and experimental results for the gas pressure in the rail tube that is controlled to follow a set value P_{set}=300 kPa.

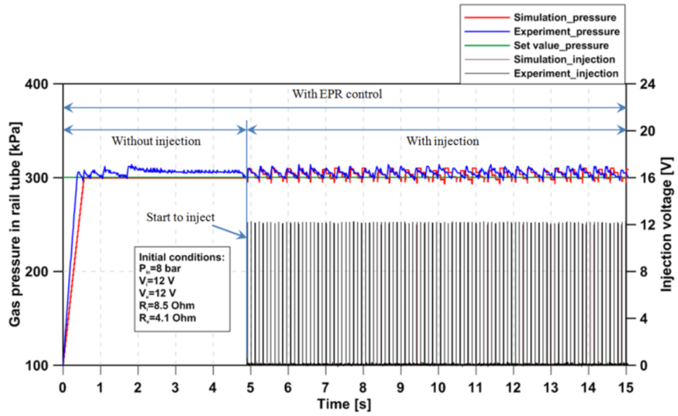


Fig. 9 Controlled gas pressure in the rail tube at set gas pressure P_{set}=300 kPa

When the injection is activated, both simulation and experimental results for the gas pressure shows more fluctuations as compared with their values at the previous period (without injection).

It can be seen that, even though the simulation and experimental gas pressures are fluctuated in the injection period, their values still close to the set value.

4. CONCLUSION

A gaseous fuel injection system integrated with a solenoid injector and an EPR was modeled and simulated using mathematical and control models. The effects of key parameters including EPR plunger mass and spring stiffness on the operating characteristics of the injection system, such as EPR control voltage, EPR plunger displacement, gas pressure in the rail tube, and injection flow rate, were investigated. Besides, an experimental study was conducted on the gaseous fuel injection system.

This study showed that the increase of EPR plunger mass was not good for the control of gas pressure in the rail tube as well as the injection flow rate. In particular, this study found that the increase of EPR spring stiffness is a good way to increase the stability of gas pressure in the rail tube and injection flow rate. Both simulation and experimental results showed that the gas pressure in rail tube was successfully controlled to maintain a certain set value.

ACKNOWLEDGEMENT

This work was supported by Upbringing Business with Innovative Urban Public Institutions by the Ministry of Trade, Industry and Energy(MOTIE, Korea)[Project Name: Establishment of Battery/Ess-Based Energy Industry Innovation Ecosystem].

REFERENCE

[1] Navarro E, Leo TJ, Corral R. CO2 emissions from a spark ignition engine operating on natural gas–hydrogen blends (HCNG). Applied Energy 2013;101:112-120.

[2] Liu C, Wang Z, Song H, Qi Y, Li Y, Li F, Zhang W, He X. Experimental and numerical investigation on H2/CO formation and their effects on combustion characteristics in a natural gas SI engine. Energy 2018;143:597-605.

[3] Liu J, Dumitrescu CE. Flame development analysis in a diesel optical engine converted to spark ignition natural gas operation. Applied Energy 2018;230:1205-1217.

[4] Lim C, Kim D, Song C, Kim J, Han J, Cha JS. Performance and emission characteristics of a vehicle fueled with enriched biogas and natural gases. Applied Energy 2015;139:17-29.

[5] Hung N.B, Lim O.T. A simulation and experimental study on the operating characteristics of a solenoid gas injector. Advances in Mechanical Engineering 2019;11:1-14.

