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Effect of Injection Pressure, Injection Duration, and Injection Frequency on Direct Injector's Mass Flow Rate for Compressed Natural Gas Fuel

Mohamad Hafizul Rahman Alias[1], *Mohd Fadzil* Abdul Rahim[1,2,*], *Muhamad Haziq* Mohd Ismail Rodzi[1], and *Rosli* Abu Bakar[1]

[1]Faculty of Mechanical Engineering, Universiti Malaysia Pahang, Pahang, Malaysia.
[2]Innovative Manufacturing and Mechatronics and Sports (IMAMS) Laboratory, Faculty of Manufacturing Engineering, Universiti Malaysia Pahang, Pahang, Malaysia.

Abstract. A conventional gasoline direct injector is converted for gaseous fuel application. The conversion alters the injector characteristic which further affect the mixture formation and combustion processes. The purpose of this study is to investigate the effects of injection pressure (case 1), injection duration (case 2), and injection frequency (case 3) on the injector's mass flow rate. An injector was independently tested by using an injector test bench. In Case 1, the injection pressure was tested from 20 bar to 60 bar at 24 ms of injection duration for 1000 injection counts. In Case 2, the injection duration was set from 2 to 24 ms at a constant 50 bar injection pressure for different engine speed. Whereas in Case 3, the averaged mass flow rate are plotted at different injection frequency. Theoretical calculations were carried out to compare the experimental and theoretical result. The experiment results shown that the injection pressure affected the injector mass flow rate linearly. At short injection duration, the mass flow rate inconsistent and highly fluctuated. At higher injection frequency, the mass flow rate is becoming higher. The theoretical results able to predict the mass flow rate trend but were unable to spot the fluctuating effects.

1 Introduction

For many years, researchers and manufacturers have been working hard to comply with the ever-demanding stringent emissions regulations set by every country around the world. Compress natural gas (CNG) has already regarded as one of the most recognise fuel for Gasoline and Diesel replacement. Compared to conventional fuel, the fuel cost of CNG is 20 to 40% lower which is the major advantage.[1] CNG also most sought after for the sake of its massive reserves and its distinctive cleaner combustion.[2] CNG has a higher thermal efficiency and higher knock resistance[3], [4] as a result of its high octane number (RON = 110–130).[5], [6] The ratio between carbon and hydrogen in CNG fuel can produce higher

* Corresponding author: mfadzil@ump.edu.my

compression rate while emits less CO_2 compare to conventional fuels.[5], [6] Basically, natural gas engines can be conducted at lean burn under stoichiometric circumstances.[7] Port-injected engines generally known to work in stoichiometric mixture of air-fuel ratio (AFR) complementary to its mode combustion of homogeneous-charge.[8] Installing the turbocharger is one of the many ways to better refining the commercial grade and emission waste of rotary engine. [9] Diesel engine is a more utilised platform for CNG engine conversion.[10] A comparison study between direct injected gasoline, port injected gasoline and carburetted gasoline have been conducted.[11] Crucial information obtained from the results that the maximum power of CNG-DI is only 5% lower than gasoline port injection.

Direct Injection (DI) system gives the engine a boost in its volumetric capability[2],[8] which allows an increase in total power hence reduce the needed for throttling control[6], to such a degree the pumping revolution deficiency and heat transfer losses can be cut down which promote low fuel consumption. [7] It is concluded that CNG-DI engine has the best capability to revamp fuel flow and ignition process that stimulate a more comprehensive engine performance and lessen the fuel usage[11] as well as emissions.[5], [8] As the DI system enhancing the injection strategy and carry out the stratified allocation of fuel, it can accurately manage the framework of fuel injection, such as injection timing and the angle of injection.[9] Per contra, the DI is required to introduce a very high pressure to the fuel injection operation which is a complex task to solve because of the leaking issue of CNG happen around the nozzle area.[2] The challenge for CNG is as there is neither dedicated CNG direct injector nor commercialise direct injector for gaseous fuel. Hence, we resorted to the conversion of the conventional direct injector. The changes of fuel properties from liquid to gases affect the injector characteristic benchmarked by the manufacturer. It is the reason why the injector characterisation is greatly desired by researchers. Most of the engine that converted into the bi-fuel system is initially were multiport injection (MPI) oriented, where the engines are known to be unable to produce high thermal capacity.[11]

Based on the literature review, from the previous studies on the direct fuel injector, Direct injection has been identified as the most relevant option to improve natural gas engine performance. However, previous injection characterization studies were mainly focused on conventional fuel application on diesel and gasoline. Hardly any study of direct fuel injector characterisation for natural gas can be found. Therefore, it is very crucial to investigate the injection characteristics of CNG direct injection as it affects the overall engine performance. This study was conducted to specifically investigate the effect of injection pressure, injection duration, and injection frequency on direct injector's mass flow rate using CNG as the fuel. Finally, this study is hoped to bring a better understanding of the cause-effect relationship among injector parameters.

2 Experimental setup and data collection

2.1 Case study

The experimental approach was used to investigate the effect of converting liquid injector into a gaseous injector. This study is a continuation of the previous analysis presented in [12] where theoretical modelling had been presented. As the type of fuel running into the injector has been changed, it was assumed that the overall operating system of the injector would be affected. Table 1 shows the summary of each case study.

Table 1. Case study summarisation.

	Controlled parameter	Fixed parameter	Significant of each case
Case 1	Injection pressure: 20 - 60 bar.	Injection duration: 24 ms, Injection counts: 1000. Injection frequency: 1000 RPM.	To determine the effect of injection pressure on the injector mass flow rate.
Case 2	Injection duration: 2 - 24 ms.	Injection pressure: 50 bar, Injection counts: 1000, Injection frequency: 2000 - 5000 RPM.	To determine the effect of injection load on the injector mass flow rate.
Case 3	Injection frequency: 2000 - 5000 RPM.	Injection pressure: 50 bar, Injection counts: 1000, Injection duration: 2 - 24 ms.	To determine the effect of injection frequency on injector mass flow rate.

2.2 Injector specification

Table 2. General BOSCH model HDEV 1.2 injector specification. [13]

Attributes	Values
Mechanical specifications	
Allowable maximum pressure (bar)	200
Volume flow rate (gasoline fuel/cm3/min) at 100 bar	30
Weight (g)	78
Length (mm)	85
Electrical specifications	
Resistance (Ohm)	0.9 @ 1.5
Voltage (Volt)	90 V
Allowable peak current (Amp)	20 A
Operating Condition (Gasoline fuel)	
Fuel Input	Axial (top feed)
Operating Temperatures (^{o}C)	30-120
Permissible Fuel Temperatures (^{o}C)	<80

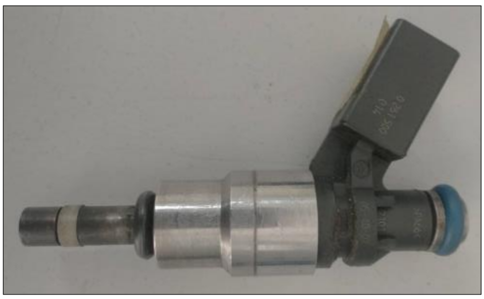

Fig. 1. BOSCH model HDEV 1.2 Injector physical appearance.

Figure 1 shows the physical appearance of the injector used in this experiment. This injector made by BOSCH with model name HDEV 1.2. The injector typically used in GDI engine. The specification of the injector is listed in Table 2 above. The injector used in this experiment is a single-hole type model. It improves the atomization of fuel as the fuel is forced into the combustion chamber to turn into fine mist.

3 Testing layout

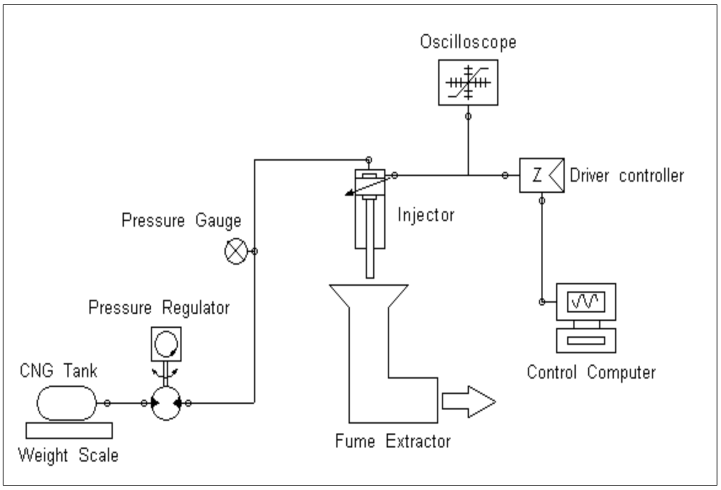

Fig. 2. Schematic diagram of the experimental setup.

A schematic diagram of the experimental setup is presented in Figure 2. The CNG storage tank is used to supply fuel to the injector. A weighing scale is used to measure the instantaneous mass of the CNG tank. The determination of injector mass flow rate is based on the change of CNG tank mass. The CNG pressure was regulated by a pressure regulator and oversees by a pressure gauge. The PWM driver and Arduino UNO microprocessor act as an ECU to control the duration and frequency of injector. The computer was used to modify the input parameters of experimentation and send the signal to the driver and controller. Oscilloscope acted as a tool to observe and record the signal voltage produced by the injector as it operated.

4 Results and discussions

4.1 Case 1: effect of injection pressure

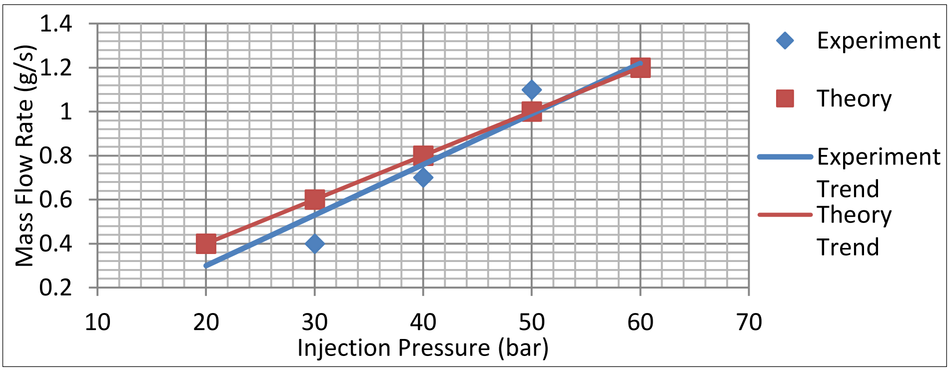

Fig. 3. Comparison of injection pressure with mass flow rate.

Figure 3 show the effect of injection pressure with mass flow rate results summary. Based on the graph, the mass flow rate is linearly increased as the injection pressure increased. For injection pressure 30 bar, 40 bar, and 50 bar the increasing mass flow rate is in between 35

% to 40 %. The increment of the mass flow rate is not linear as expected by theoretical calculation as a result between 20 bar and 30 bar shows no increment. Between 50 bar and 60 bar, the increment is only 10 %. It is noticeable that the mass flow rate will increase linearly with increased injection pressure. The increased injection pressure has provided a larger mass delivery to the injector. It has enabled the a higher amount of mass flowing through the nozzle. As a summary, higher injection pressure will increase the mass flow rate.

4.2 Case 2: effect of injection duration

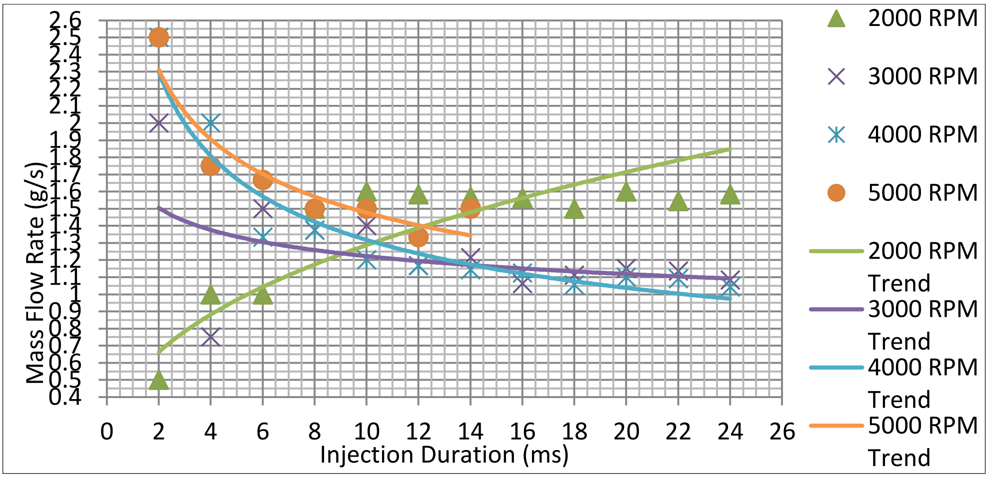

Fig. 4. Comparison of mass flow rate on different injection duration.

Figure 4 presents a comparison of the mass flow rate graph based on different injection duration at different engine speed (RPM). The mass flow rate patterns show a higher fluctuation at low injection duration lower than 10 ms at all engine speed. After 10 ms, the mass flow rate plot gradually becomes constant. However, at the engine speed of 2000 RPM the mass flow rates showing an increasing trend. The maximum mass flow rate recorded was 2.5 g/s at 5000 RPM and the minimum mass flow rate recorded was 0.5 g/s at 2000 RPM. Theoretically, the mass flow rate is constant at a specific engine speed or frequency. The real reasons for this fluctuation especially at short injection duration are due to the inconsistent effective opening time of the injector nozzle.

4.3 Case 3: Effect of injection frequency

Figure 5 presents the measured average mass flow rate at different injection frequency. The measured average mass flow rate shows a polynomial trend where the minimum average mass flow rate is obtain at the injection frequency of 25 Hz. Theoretically, the average mass flow rate will increase linearly with increased of injection frequency since the injection duration is fixed. The reason of this nonlinearity is due to highly fluctuated data at low injection frequency of 2000 RPM and 3000 PRM.

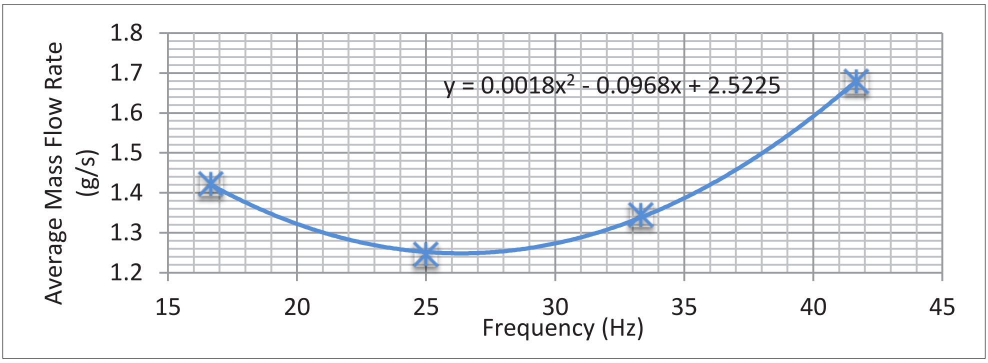

Fig. 5. The measured average mass flow rate at different injection frequency.

5 Conclusion

Experimental work has been carried out to describe the injection characteristics of CNG fuel on a single-hole direct injector. Injection pressure linearly affected the mass flow rate of injector. The degree of mass flow rate fluctuation is higher at short injection duration compared to long injection duration. The fluctuation also affected the mass flow rate at lower frequency. The theoretical calculation of the injector unable to predict the fluctuating trend. Further study on how to eliminate or reduce the fluctuating effect need to be done to ensure optimum injector performance.

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