Effects of Fuel Injection Pressure to Fuel Consumption and Exhaust Gas Emissions of SI Engine

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Abstract. The present study investigated the effects of fuel injection pressure to fuel consumption and exhaust gas emissions for the Spark Ignition (SI) engine. A series of experiments were carried out in 4-cylinders gasoline engine with capacity of 1500 cc. The default fuel injection pressure was 2.8 kg/cm². In this study, the fuel injection pressures were varied from 1.4 to 4.2 kg/cm². The engine speeds were retained on 800, 2000, and 3000 rpm. Fuel consumption was evaluated by using a burette under static condition and a gas analyser was used to measure exhaust gas emission. As a result, fuel injection pressure affects significantly to the fuel consumption and exhaust gas emission. The lowest fuel consumption and gas (CO and HC) emissions were reached when the injection pressure was 2 kg/cm² for all engine speeds. When the injection pressure indicated above and below the default engine specification, a higher fuel consumption and gas emission occurred. Therefore, a better control of the fuel injection system needs to be considered during the engine operation to reduce fuel consumption and exhaust gas emission.

1. Introduction
Since Indonesia agreed to the COP 21 (Conference of Parties) agreement in 2015, regarding the climate change and greenhouse gas effects, some strategic programs were set to reduce carbon emission until 29% by 2030. One of the important issues is the improvement of the automotive sectors, contributed significantly for Indonesia oil demand during last decades and 30% of energy emissions (lower than 42% of power generation emission). Here, about 90% of transportation emissions comes from road transportation whereas land transportation contributes around 12% of total national CO₂ emissions and almost 90% of urban air pollution (CO, HC, NOx, SOx, PM, O₃) [1-2]. Consequently, the development of automotive sectors especially on the class of internal combustion engine should notice the reduction of greenhouse gas emissions, by considering the engine fuel economy and emission from combustion process. Hence, the recent technologies that are contributed to yield highly efficient combustion during
the engine operation, are engineered to meet such demands, for instance precise fuel consumption control, application of Exhaust Gas Recirculation (EGR), and emission control [3-6].

The inefficient fuel consumption and the uncontrollable exhaust gas emissions become the common problems of automotive engines. Those phenomena become an intricate challenge for the automotive producer during the recent years to develop solutions to increase fuel consumption efficiency and reduce gas emission residue into the surroundings. Among several parameters, fuel injection pressure plays a significant role related to fuel supply and combustion quality. For Compressed Ignition (CI) engine, many works proved that injection pressure contributed significantly in fuel spray and droplet size, impacted to the mixture quality during combustion process [4,5,7,8]. Celikten [7] also conducted that injection pressure affected the performance and exhaust emission of diesel engine. More recent, Budiman et al. [8] also investigated that injection pressure and timing to the gas opacity, equipped by several statistics approaches. However, those works were mainly concerned on the analysis of Compressed Ignition (CI) engine. In recent years, there are lack studies which investigate the gasoline engine, especially for combustion improvement. Even though, the Indonesian car population is still dominated by gasoline-engine car, especially wagon-type car [9].

Considering those reasons, the study on the basic phenomena of injection pressure still attract the previous scholars. They underlined that fuel injection has important features for Spark Ignition (SI) engine which has closely related to engine efficiency and emissions [6,10-12]. Moreover, if it is neglected, an inappropriate injection strategy leads to an abnormal combustion, as stated recently by Pischinger et al. [13]. Meanwhile, either due to economic reasons or life-style people sometimes prefer to maintain their old car. Consequently, the decrease of engine performance and combustion quality should be anticipated. A good understanding on the fuel injection pressure is very important to optimize the engine performance and prevent the excessive emissions. This study was aimed to investigate the effects of fuel injection pressure to the fuel consumption and exhaust gas emissions of SI Engine. Results of this study can be further used as the engineering consideration to arrange the gasoline engine maintenance, especially for passenger car.

2. Research Methodology
This experiment was conducted at the Automotive Laboratory of Yogyakarta State University. Here, a 4-cylinder Spark Ignition (SI) engine with capacity of 1500 cc was coupled by an Eddy current dynamometer and installed at a dedicated engine test bed. The engine used was TIMOR (KIA Sephia) Engine produced in 1994. Fuel was supplied through a multi-point injection method, controlled by an ECU. In the present work, “Pertamax” (gasoline produced by Pertamina—the Indonesia’s state oil company) was used in the experiments. Table 1 and 2 present the important features of engine and fuel specifications, respectively.

| Parameter         | Characteristics          | Parameter         | Characteristics          |
|-------------------|--------------------------|-------------------|--------------------------|
| Engine            | 1500 cc, 16 V GL (88 Hp) | Cylinder Bore     | 78 mm.                   |
| Power             | 88 hp/5000 rpm.          | Piston Stroke     | 78.4 mm                  |
| Maximum speed     | 180 km/h                 | Compression ratio | 9.3                      |
| Fuel tank volume  | 50 litre                 | Number of valves per cylinder | 4                       |
| Engine displacement | 1498 cm³               | Fuel Type         | Petrol (Gasoline)        |
| Torque            | 135 Nm/4000 rpm.         | Number of Gears   | 5 (manual transmission)  |
| Fuel System       | Multi-point injection    | Position of cylinders / number | Inline / 4 cylinders     |
Table 2. Pertamax fuel specifications

| No | Properties                              | Unit | Limit | Test Methods |
|----|-----------------------------------------|------|-------|--------------|
| 1  | Research Octane Number                  | RON  | 92.0  | D 2699       |
| 2  | Oxidation Stability                      | Minutes | 480   | D 525        |
| 3  | Sulphur content                          | % m/m | 0.05  | D 2622/D 4294 |
| 4  | Lead content (Pb)                        | gr/liter | 0.013 | D 3237       |
| 5  | Phosphorus content                       | mg/l  | -     | D 3231       |
| 6  | Metal content (Mn, Fe, etc.)             | mg/l  | -     | D 3831       |
| 7  | Silicon content                          | mg/kg | -     | D 4200       |
| 8  | Oxygen content                           | % m/m | 2.7   | D 4815       |
| 9  | Olefin content                           | % v/v | -     | D 3139       |
| 10 | Aromatic content                         | % v/v | 50.0  | D 3139       |
| 11 | Benzene content                          | % v/v | 5.0   | D 4420       |
| 12 | Distillation:                            |       |       | D 86         |
| 13 | 10% evaporation volume                   | °C    | -     | 70           |
|    | 50% evaporation volume                   | °C    | 77    | 110          |
|    | 90% evaporation volume                   | °C    | 130   | 180          |
|    | Final boiling point                      | °C    | -     | 215          |
|    | Residue                                 | % v/v | -     | 2.0          |
| 14 | Unwashed Gum                             | mg/100 ml | - 70 | D 381       |
| 15 | Washed Gum                               | mg/100 ml | - 5 | D 381       |
| 16 | Steam Pressure                           | kPa   | 45    | 60           |
| 17 | Specific Gravity (at 15 °C)              | kg/m³ | 715   | 770          |
| 18 | Copper strip corrosion merit              |        | 1st Class 1 | D 310  |
| 19 | Doctor test                              |        | Negative |  |
| 20 | Mercaptan sulfur                         | % mass | - | 0.002 | D 3227 |
| 21 | Visual appearance                        |        | Clear and bright | |
| 22 | Color                                    |        | Blue   |   |
| 23 | Dye content                              | gr/1001 | - | 0.13 |   |

According to its specification, the engine has a default injection pressure at 2.8 kg/cm². To study the effects of injection pressure to fuel consumption and exhaust gas emission, we investigated those variables in various injection pressures of 1.4 to 4.2 kg/cm². The engine speeds used in this work were 800, 2000, and 3000 rpm. Figure 1 shows a schematic diagram of the experimental apparatus.
Figure 2 shows documentation of experimental activities. Here, fuel consumption was measured by connecting a burette to the engine fuel pump. The engine was operated during a particular period and the fuel consumption could be observed. For the sake of high-quality experimental result, this method was repeated at least 3 times for each variation of engine speed and fuel injection pressure. Meanwhile, the exhaust gas emission was measured by using Stargas 898 Gas Analyzer which showed levels of CO\textsubscript{2}, O\textsubscript{2}, and emissions of CO, HC. The equivalence ratio (lambda-“λ”), an indicator of air-fuel mixture, was also identified by the device.

3. Results and Discussion

3.1. Influence of injection pressure to fuel consumption and air-fuel mixture

Figure 3 (a) shows that fuel economy went up as engine speed increased. In low fuel injection pressure, engine required more fuel supply for combustion process. For all engine speeds, in low injection pressures (below 2.0 kg/cm\textsuperscript{2}) engine needed more fuel supply compared to medium injection pressures (2.0 to 3.6 kg/cm\textsuperscript{2}). Similar to the low pressure condition, the fuel consumptions at very high injection pressure (4.2 kg/cm\textsuperscript{2}) also achieved a relatively high fuel consumption for each engine speed.

![Figure 3](image)

(a) Figure 3. Effects of fuel injection pressure to (a) fuel consumption (b) air-fuel equivalence ratio.

The measurements from the gas analyzer were able to show the air-fuel mixture quality, addressed as the “λ”, a ratio between stochiometric AFR (air to fuel ratio) to actual AFR. This symbol is also known as air-fuel equivalence ratio. Figure 3 (b) shows that when injection pressure decreased, λ tended to increase. As engine speed increased, injection pressure also increased. Specifically, in medium and high engine speeds (2000 rpm and 3000 rpm), the low injection pressure contributed to form rich-fuel mixture...
but a lean-fuel mixture was influenced by a high injection pressure. It can be referred that injection pressure contributed as the important factor to the engine fuel consumption and air-fuel mixture.

3.2. Influence of injection pressure to exhaust gas emission

As a product of a combustion reaction, the exhaust gas emission should be controlled to prevent the environmental harmful and cleaner combustion process. Here, the emission was analyzed on the basis of the change of fuel injection pressure, as presented in Figure 4 (a) and (b). The presence of CO\textsubscript{2} was analyzed to indicate the combustion quality, whether included as the complete combustion or no. Figure 4 (a) indicates that as the engine speed increases, the CO\textsubscript{2} formed became higher. It means that a better quality of combustion process was obtained. The highest CO\textsubscript{2} formed at the injection pressure of 2.8 kg/cm\textsuperscript{2}, which was the engine default injection pressure. However, the lower levels were obtained at the point of both lower and upper than the default injection pressure. Therefore, it can be stated that the combustion process aside of 2.8 kg/cm\textsuperscript{2} were less optimum where the same phenomena existed for all engine speeds (800 to 3000 rpm).

![Figure 4](image)

(a) (b)

**Figure 4.** Effects of fuel injection pressure to (a) CO\textsubscript{2} emission (b) CO emission.

Figure 4 (b) depicts that CO emission increased significantly as fuel injection pressure and engine speed increased at the condition of larger than 2 kg/cm\textsuperscript{2} or above the engine default injection pressure. This diagram reveals that combustion process above 2 kg/cm\textsuperscript{2} is an incomplete combustion, indicated by the higher content of CO (carbon-monoxide). When fuel is injected in high injection pressure, the fuel droplets became smaller [14] and then lossed their energy to bind with oxygen. Thus, a heterogeneous mixture occurred and caused incomplete combustion. Also, the carbon in fuel was partially oxidized (not fully oxidized to be carbon dioxide), thus formed a CO [6].

![Figure 5](image)

(c) (d)

**Figure 5.** Effects of fuel injection pressure to (a) HC emission (b) O\textsubscript{2} excess.
The effects of fuel injection pressure to Hydrocarbon (HC) emission and O\textsubscript{2} excess are presented by Figure 5 (a) and (b). A quite high HC emission were found at the lowest injection pressure of 800 and 2000 rpm, whilst the lowest injection pressure shows a low HC emission at 3000 rpm, as shown in Figure XX (a). At the lower and higher injection pressures than 2 kg/cm\textsuperscript{2}, the HC emission tended to be higher. Moreover, since fuel was supplied in the low injection pressure, a large fuel droplet size was performed and inhibited the fuel evaporation process. Therefore, Hydrogen (H) contained in the fuel did not maximally bound with oxygen, then produce high HC emissions. Besides, at low injection pressure (less than 2.8 kg/cm\textsuperscript{2}) the O\textsubscript{2} content, as the excess air product, is still relatively high, shown in Figure 5 (b). In this condition, a large fuel droplet size was obtained and fuel did not perfectly bind with oxydator (or oxygen). Hence, the volume of O\textsubscript{2} content in reaction product was still high. Meanwhile, the O\textsubscript{2} content was relatively similar for high injection pressure (more than 2.8 kg/cm\textsuperscript{2}), both for 2000 and 3000 rpm.

4. Conclusion
The experiments to investigate effects of injection pressure to fuel consumption and exhaust gas emission were obtained. As a result, we found that fuel injection pressure was contributed significantly to fuel consumption, both in low and high engine speed. When the injection pressure was set under or over the standard condition (original specification), a higher fuel consumption was obtained. Fuel injection pressure also affects the quality of combustion process and emission quality, especially the amount of CO, CO Cor, and HC emissions. In practical side, it is suggested to operate the engine in the range of 2.0 to 2.8 kg/cm\textsuperscript{2} (about the engine’s standard injection pressure) to obtain relatively low fuel consumption and low emission (CO).

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