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Study on Natural Gas/Diesel Dual-fuel Engine Energy Ratio: Effect of Natural Gas Injection Parameters

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Abstract. Natural gas has been a promising demand for several years in Indonesia as a fuel for a diesel engine by converted into a natural gas/diesel dual-fuel engine. However, determining the energy ratio of the diesel and natural gas fuel is important due to the engine performance and emissions which affect the engine safety operation. This study presents the method to determine the natural gas and diesel fuel energy ratio on intake port natural gas injection mode through experiment. A direct injection diesel engine is converted to a natural gas/diesel dual-fuel engine by injecting natural gas into the intake port. The diesel injection parameters are unmodified for the experiment; besides the natural gas injection variations are studied to determine the energy ratio. Moreover, the engine is tested for low to high load conditions. However, natural gas injection duration, pressure, and injection timing variation affect the fuel energy ratio and indicated thermal efficiency (ITE). At low load, the optimum fuel energy ratio and ITE are achieved at a long injection duration (10 ms) and with advanced injection timing. Moreover, at high load, the optimum fuel energy ratio and ITE is achieved at high natural gas injection duration (12 ms), high injection pressure (3 bar), and advancing the injection timing.

1. Introduction

The abundant natural gas resource in Indonesia is projected to market interest over years [1]. Natural gas is mostly used for factories and power plants; it is slightly used for others such as transportation. However, natural gas is applicable to use for transportation internal combustion engines. Besides, it is less popular in Indonesia, especially for land-based transportation. Meanwhile, marine transportation keeps in progress for optimizing the natural gas as ship fuel to reduce the contribution to greenhouse gas (GHG) emissions [2,3].

Most of the ships are powered by a diesel engine which is mainly fueled by diesel fuel. A diesel engine is suitable for a heavy-duty industry that needs a high power output with high efficiency. Combining diesel with natural gas fuel (dual-fuel) is an improvement to keep the diesel engine running with nearly equivalent performance and lower GHG emissions [4]. Natural gas/diesel dual-fuel engines can be used to utilize natural gas. In dual-fuel mode, natural gas fuel dominates the energy fraction of the combustion process more than diesel fuel [5]. The low energy fraction of diesel fuel is the ignition source for the natural gas able to ignite in a compressed ignition engine.

Natural gas can be utilized in the diesel engine in dual-fuel engine mode by being injected into the intake port at low pressure [6]. However, the energy ratio of natural gas fuel should be determined due to the effects on the engine performance and emissions as reported in several studies [7–10]. The proper energy ratio of natural gas and diesel fuel enhances the combustion process and emissions [11]. Moreover, engine load conditions may vary the fuel energy ratio of natural gas/diesel to result in high combustion efficiency [12–14]. In contrast, it may affect knock at high loads or deteriorate the combustion quality which leads to safe operation and uncontrolled emissions, respectively [11,15].

For that reason, determining the energy ratio of the natural gas and diesel fuel is important due to the engine performance and emission. However, most of the research identifies the effect of natural gas/diesel fuel energy ratio on engine performance and emissions [10,14,16]. Nevertheless, it does less explain the method to determine the energy ratio of natural gas/diesel dual-fuel engine, especially for a manual controlled diesel engine or without an electronic control unit (ECU) to control the fuel injection. This study presents the method to determine the natural gas/diesel fuel energy ratio using natural gas injection into the intake port and direct injection of diesel by experiment. Several methods are observed to regulate the fuel energy ratio of natural gas/diesel, such as varying natural gas injection timing, pressure, and duration. All the variations are identified in low and high load conditions. The method's effects on the performance are briefly discussed; meanwhile, the effects on emissions are discussed in another study.

2. Methodology

In this section, the methodology for determining the natural gas/diesel fuel energy ratio is described. There are several sub-sections that are discussed, such as experimental setup, fuel properties, and injection strategies. The strategy of natural gas injection in detail is discussed as the focus of studying the energy ratio of natural gas/diesel fuel.

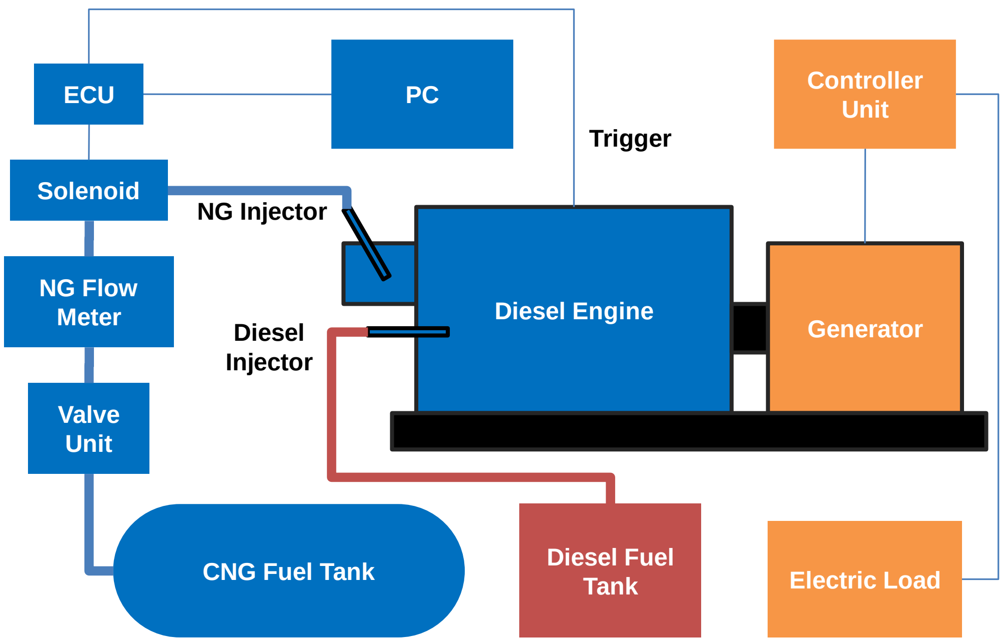

Figure 1. Experimental setup.

2.1. Experimental Setup

In this section, the experimental setup is briefly explained; a detailed explanation is reported in another study [17]. The experimental study used a dedicated diesel engine that is fueled by diesel. The engine is converted to a dual-fuel (natural gas and diesel) engine by injecting natural gas into the intake port and is controlled by the ECU. The engine specification detail is shown in another work [18].

Moreover, diesel fuel is injected directly into the combustion chamber. Moreover, the engine is used an electric load unit by an electric heater and is controlled by a controller unit. The illustration of experimental setup is depicted in Figure 1.

2.2. Fuel Properties
The experiment on the natural gas/diesel dual-fuel engine used compressed natural gas (CNG) and diesel fuels. Furthermore, the CNG fuel pressure is regulated to low pressure by a regulator. The fuel properties details are shown in Table 1.

2.3. Injection Strategies
The focus of this experiment is natural gas fuel injection rather than diesel fuel. Besides, the diesel fuel injection strategies are also described sufficiently as follows. The diesel injection in this experiment is unmodified from the original setting from the manufacturer. Meanwhile, the fuel mass injection is regulated by the manual handle attached to the engine which adjusts the flow rates of natural gas fuel substitution. However, the natural gas substitution is using the percentage of energy substitution (PES) calculation which is described in another study [17]. In brief, the PES is the natural gas fuel energy percentage compared to the total fuel energy.

Thus, the engine is fully operated in diesel fuel mode at first to the engine speed and load target. After that, the natural gas is injected at the target mass flow rates and leads to an increase in the engine speed. In that condition, the diesel fuel mass injection is decreased until the engine speed decreases to the normal target. The injection factors that affect the natural gas flow are regulated (e.g., pressure, timing, and duration). The natural gas injection parameters for the experiment are detailed in Table 2.

Table 1. Fuel properties.

	Natural Gas	Diesel
Density at 15°C (kg/m^3)	0.656	820
Cetane Number	-	53
Octane Number	120	-
LHV (MJ/kg)	50	43.2

Table 2. Natural gas injection parameters.

	Duration (ms)	Pressure (bar)	Timing (°CA BTDC)
Low Load (1 kW)	9	-	100
	10	-	130
	11	-	160
High Load (4 kW)	11	2	100
	12	3	130
	13	4	160

3. Result and Discussion
The experiment was conducted to analyze the proper method for determining the natural gas/diesel fuel energy ratio in manual diesel engines. However, there are some results on the engine performance in every natural gas injection parameter in low and high loads conditions, 1 kW (25%) and 4 kW (100%), respectively. The effect of natural gas injection parameters on the PES and ITE is described. The effect on PES determines the injection parameters that affect the PES; meanwhile, the effect on ITE determines the effectiveness of the combustion inside the chamber.

3.1. Effect of Injection Strategies on Low Load

Figure 2 depicts the effect of natural gas injection parameters applied in low load conditions. There are two parameters are used in this case, injection duration and injection timings at the same injection pressure (3 bar). The injection pressure is avoided by vary due to the rich fuel mixture condition which leads to power loss, very low ITE, and deteriorated emissions. Thus, the injection pressure remained to be low enough.

Figure 2 shows that by prolonging the injection, the duration increases the PES (10 ms) and slightly lowers the PES at the very long injection duration (11 ms). However, in this case, the injection timing is controlled at 160ºCA BTDC. The injection duration of natural gas affects the natural gas mass flow to the combustion chamber. The longer injection duration increases the natural gas mass and energy. Besides, the data shows that there are other factors that affect the natural gas mass trapped in the combustion chamber due to non-linear curves made. It is possibly due to the part of natural gas fuel being trapped in the intake port as described by Felayati et al. [19]. Thus, the PES slightly decreased at a very long injection duration.

In this case, a long injection duration (10 ms) leads to an increase in the ITE and the longest injection duration deteriorates the ITE. It indicates that sufficient natural gas trapped in the combustion chamber with a long injection duration may increase the combustion quality [20]. However, the longer injection duration may prevent the air from entering the combustion chamber thus rich natural gas/air mixture occurs thus decreasing the ITE.

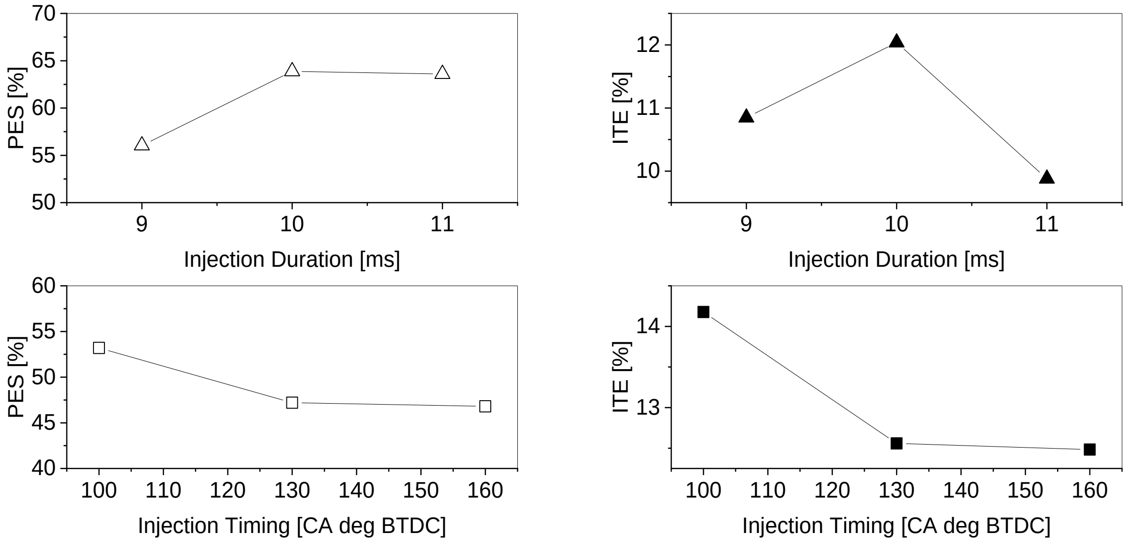

Figure 2. Effect of injection timing and duration on PES and ITE at low load.

Moreover, the injection timing also affects the PES of natural gas. Figure 2 also shows the effect of natural gas injection timing on the PES with a controlled injection duration of 8 ms. It shows that advancing the injection timing of natural gas (160ºCA BTDC) lowers the PES. However, advancing the injection timing of natural gas may cause the natural gas trapped in the cylinder when the intake valve opens (IVO) to be more sufficient for combustion.

Besides, in this case, most of the injection timings are at intake valve close (IVC), and only at 160ºCA BTDC is slightly at IVO. Thus, most of the natural gas entered into the chamber is in the next cycle. It means that advancing the injection timing of natural gas prolongs the natural gas/air mixture duration in the intake port [21]. The well-mixed natural gas/air leads to lower mixture stratification thus decreasing the combustion quality [19]. As a result, the ITE decreases as advancing the natural gas injection timing.

However, in this experiment results (Figure 2) clearly indicate that the natural gas injection duration and timing can be used as a method to determine the diesel and natural gas fuel energy ratio at low load conditions. As stated earlier, the injection pressure of natural gas is avoided use as the method to vary the fuel's energy ratio for some reasons mentioned. Thus, only natural gas injection duration and timing are able to vary in this case to determine the natural gas and diesel fuel energy ratio.

3.2. Effect of Injection Strategies on High Load

Figure 3 shows the natural gas injection parameter's effect on the PES and ITE with high load conditions (4 kW). In this case, the effects of injection duration, injection timing, and injection pressure are identified. However, the injection duration is regulated at 1800 rpm and 3 bar for the engine speed and injection pressure, respectively. Meanwhile, the injection pressure variations are set at 12 ms, 2000 rpm, and 4 lpm for the injection duration, engine speed, and natural gas flow rate, respectively. Both injection duration and injection pressure parameters are regulated at 160°CA BTDC for the injection timing. Moreover, the injection timing parameters are set at 2000 rpm, 12 ms, and 3 bar for the engine speed, injection duration, and injection pressure, respectively.

Figure 3 depicts that at high load conditions, a longer injection duration increases the PES. A longer duration of the injection means a higher concentration of the natural gas in the intake port [8]. Thus, it is reasonable that the PES increases as the injection duration increases. However, the ITE increases in a linear pattern as the injection duration increases. Besides, a longer injection duration at 13 ms lowers the ITE. It indicates that very high PES deteriorates the combustion in the cylinder thus lowering the ITE.

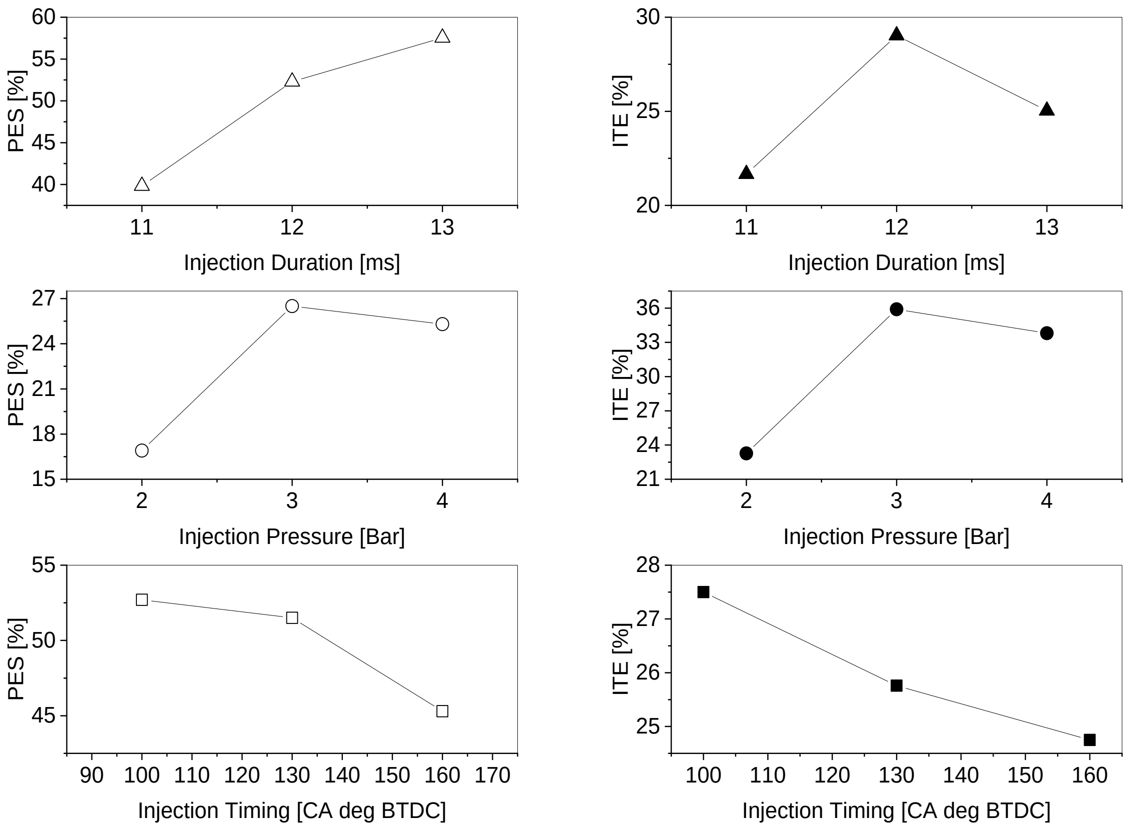

Figure 3. Effect of injection timing, pressure, and duration on PES and ITE at high load.

Furthermore, injection pressure variation affected the PES and ITE in the same pattern (Figure 3). The PES and ITE increase with the higher injection pressure but slightly decrease at the higher injection pressure (4 bar). It also shows that the injection pressure variations less affect the PES at a high value. It indicates that high injection pressure tends to vary the kinetic energy besides the natural gas mass trapped in the cylinder [21]. It leads to an increase in the combustion characteristics as increases the injection pressure (3 bar) then decreases in the high injection pressure (4 bar) as the ITE lowers.

Figure 3 also shows that in high load conditions, advancing the injection timing also lowers the PES and ITE in low load condition cases. As discussed in low load condition cases, the injection timings are conducted when IVC thus the natural gas fraction is trapped in the intake port and flows to the combustion chamber when IVO is in the afterward cycle. Advancing the injection timing means the longer time natural gas has to enter the combustion chamber. Thus, the natural gas/air mixed more homogeneously with advancing injection timing [19]. It caused the natural gas concentration to lower with advancing the injection timing. However, advancing the injection timing lowers the stratification of the natural gas/air mixture. Thus, it caused the ITE to be lower than advancing the injection timing due to lower combustion characteristics.

However, the results (Figure 3) indicate that natural gas injection duration, pressure, and timing can be used for determining the diesel and natural gas fuel energy ratios at high load conditions. Compared to the low load condition, the natural gas injection pressure is able to vary in high load conditions. Thus, the engine load condition should be considered in order to determine the fuel energy ratio of natural gas and diesel.

4. Conclusion

The method for determining the fuel energy ratio on natural gas/diesel dual-fuel engines is studied at low and high load conditions by an experiment using natural gas injection strategies. There are several conclusions can be mentioned from the experiment:

a. At low load conditions, the fuel energy ratio can be determined with natural gas injection timing and duration variation. The long natural gas injection duration (10 ms) achieved higher PES and ITE. Moreover, advancing natural gas injection timing increases the PES and ITE.
b. At high load conditions, natural gas injection pressure, duration, and timing variation are able to regulate the fuel energy ratio. The optimum PES with high ITE is achieved at a long injection duration (12 ms). High natural gas injection pressure (3 bar) leads to higher PES and ITE. Moreover, advancing natural gas injection timing leads to an increase in the PES and ITE.

However, this research is a brief study about the method of determining the natural gas injection variation effect on the diesel/natural fuel energy ratio. A parametric study is suggested that combines all of the natural gas injection strategies to achieve high performance and lower exhaust emissions.

5. References

[1] Felayati F M, Semin, Cahyono B, Prayogi U and Winarno A 2022 Future perspective of the ship alternative fuels in Indonesia *IOP Conf. Ser. Earth Environ. Sci.* **972** 012024
[2] Ariani B, Ariana I M and Fathallah M A 2019 Effect of natural gas injection timing on combustion performance & methane slip emission of diesel – NG dual fuel engine: An experimental study *AIP Conf. Proc.* **2187** 020003
[3] Pan P, Sun Y, Yuan C, Yan X and Tang X 2021 Research progress on ship power systems integrated with new energy sources: A review *Renew. Sustain. Energy Rev.* **144** 111048
[4] Karim G A 2015 *Dual-fuel diesel engines* (CRC Press)
[5] Felayati F M, Semin, Zaman M B and Gusti A P 2019 Consideration of Split Injection Strategy for Marine Diesel Engine Combustion Process *AIP Conference Proceedings* vol 030021
[6] Kakaee A-H, Rahnama P and Paykani A 2015 Influence of Fuel Composition on Combustion and Emissions Characteristics of Natural Gas/Diesel RCCI Engine *J. Nat. Gas Sci. Eng.* **25** 58–65

[7] Huang H, Lv D, Zhu J, Zhu Z, Chen Y, Pan Y and Pan M 2019 Development of A New Reduced Diesel/Natural Gas Mechanism for Dual-Fuel Engine Combustion and Emission Prediction *Fuel* **236** 30–42
[8] Zaman M B, Rahmatullah D T, Semin and Felayati F M 2019 Effect of natural gas injection pulse width to diesel dual fuel performance *AIP Conference Proceedings* vol 2187 (American Institute of Physics Inc.) p 020023
[9] Zhang Y, Fu J, Shu J, Xie M, Zhou F, Liu J and Zeng D 2019 A Numerical Investigation of The Effect of Natural Gas Substitution Ratio (NGSR) on The In-Cylinder Chemical Reaction and Emissions formation Process in Natural Gas (NG)-Diesel Dual Fuel Engine *J. Taiwan Inst. Chem. Eng.* **105** 85–95
[10] Liu J, Guo Q, Guo J and Wang F 2021 Optimization of a diesel/natural gas dual fuel engine under different diesel substitution ratios *Fuel* **305**
[11] Wang Z, Fu X, Wang D, Xu Y, Du G and You J 2021 A multilevel study on the influence of natural gas substitution rate on combustion mode and cyclic variation in a diesel/natural gas dual fuel engine *Fuel* **294**
[12] Felayati F M, Semin, Cahyono B and Bakar R A 2021 Numerical investigation of dual-fuel engine improvements using split injection natural gas coupled with diesel injection timings at low load condition *Int. J. Eng. Appl.* **9** 31–8
[13] Ariani B, Ariana I M and Fathallah A Z 2020 Experimental Investigation on Natural Gas Injection to Minimize Abnormal Combustion and Methane Slip in the Diesel - Natural Gas Dual Fuel Engine at Low Load *Int. Rev. Mech. Eng.* **14** 599–606
[14] Wang Z, Du G, Wang D, Xu Y and Shao M 2018 Combustion Process Decoupling of A Diesel/Natural Gas Dual-Fuel Engine at Low Loads *Fuel* **232** 550–61
[15] García Valladolid P, Tunestål P, Monsalve-Serrano J, García A and Hyvönen J 2017 Impact of Diesel Pilot Distribution on The Ignition Process of A Dual Fuel Medium Speed Marine Engine *Energy Convers. Manag.* **149** 192–205
[16] Wang Z, Fu X, Wang D, Xu Y, Du G and You J 2021 A multilevel study on the influence of natural gas substitution rate on combustion mode and cyclic variation in a diesel/natural gas dual fuel engine *Fuel* **294** 120499
[17] Felayati F M, Semin, Cahyono B, Bakar R A and Birouk M 2021 Performance and emissions of natural gas/diesel dual-fuel engine at low load conditions: Effect of natural gas split injection strategy *Fuel* **300** 121012
[18] Felayati F M, Semin, Cahyono B and Bakar R A 2019 Investigation of the effect of natural gas injection timing on dual-fuel engine emissions using split injection strategies *Int. Rev. Mech. Eng.* **13** 645–54
[19] Felayati F M, Semin and Cahyono B 2021 Methane Emissions Evaluation on Natural Gas/Diesel Dual-Fuel Engine during Scavenging Process *IOP Conference Series: Earth and Environmental Science* vol 698 (IOP Publishing Ltd) p 012036
[20] Song E, Liu Z, Yang L, Yao C, Sun J and Dong Q 2017 Effects of Nozzle Structure on The Gas Mixture Uniformity of Marine Gas Engine *Ocean Eng.* **142** 507–20
[21] Baratta M, Misul D and Xu J 2021 Development and application of a method for characterizing mixture formation in a port-injection natural gas engine *Energy Convers. Manag.* **227** 113595