Automotive Experiences
Vol. 5 No. 3 (2022) pp. 507-527
p-ISSN: 2615-6202 e-ISSN: 2615-6636

Research Paper

Combustion and Emission Characteristics of CNG-Diesel Dual Fuel Engine with Variation of Air Fuel Ratio

Dori Yuvenda[1,2], **Bambang Sudarmanta**[3], **Jamaludin**[3], **Oki Muraza**[4], **Randi Purnama Putra**[1,2], **Remon Lapisa**[1,2], **Krismadinata**[1,5], **Rahadian Zainul**[1,6], **Asnil**[1,5], **Muji Setiyo**[7,8], **Sri Rizki Putri Primandari**[1,2]

[1]Centre For Energy and Power Electronics Research (CEPER), Universitas Negeri Padang, 25131, Indonesia
[2]Department of Mechanical Engineering, Universitas Negeri Padang, 25131, Indonesia
[3]Department of Mechanical Engineering, Institut Teknologi Sepuluh Nopember, 60111, Indonesia
[4]Department of Chemical Engineering, King Fahd University of Petroleum & Minerals, 31261, Saudi Arabia
[5]Department Electrical Engineering, Universitas Negeri Padang, 25131, Indonesia
[6]Department Chemical, Universitas Negeri Padang, 25131, Indonesia
[7]Department of Automotive Engineering, Universitas Muhammadiyah Magelang, 56126, Indonesia
[8]Center of Energy for Society and Industry (CESI), Universitas Muhammadiyah Magelang, Indonesia

doriyuvenda@ft.unp.ac.id

https://doi.org/10.31603/ae.7807

Check for updates

Published by Automotive Laboratory of Universitas Muhammadiyah Magelang collaboration with Association of Indonesian Vocational Educators (AIVE)

Article Info
Submitted: 05/09/2022
Revised: 03/12/2022
Accepted: 05/12/2022
Online first: 18/12/2022

Abstract

Compressed natural gas (CNG) is a popular alternative fuel because of its more environmentally friendly properties than fossil fuels , including applications in diesel engines. However, supplying too much compressed natural gas fuel causes poor engine performance and emissions due to a decrease in the air-fuel ratio on the dual-fuel engine. The addition of air using electric superchargers was done to return the air-fuel ratio to ideal conditions. Lambda value (λ) was variation under low load (1.52 to 2.71), medium load (1.18 to 2.17), and high load (0.94 to 2.17) on a CNG-diesel dual fuel engine. The addition of pure air in each load can increase combustion stability in certain lambda, which was indicated by an increase in thermal efficiency, heat release rate, and a decrease in ignition delay, combustion duration, hydrocarbon, and carbon monoxide emissions.

Keywords: CNG, Engine performance; Emission; Air fuel ratio; Thermal efficiency

1. Introduction

Anxiety about global warming gets special attention in every country, especially Indonesia. One of the biggest sources of increasing world temperature was exhaust gas from an internal combustion engine [1]. Also, it has impact on the greenhouse effect, emissions were also harmful to human health [2], and the environment [3], especially nitrogen oxide (NO_x), hydrocarbon (HC), carbon monoxide (CO), and sulfur oxide (SO_x) gases [4]. Thus, strict regulation was needed on exhaust gases produced by an internal combustion engine.

The diesel engine was one of the internal combustion engine (ICE) that produce very high nitrogen oxide (NO_x) and particulate matter (PM) emissions [5]–[10]. Various efforts have been made by automotive researchers to reduce NOx and PM emissions on diesel engines, such as exhaust gas recirculation (EGR) [11], [12], direct water injection [13] and dual fuel systems [14]–[18]. Currently, dual fuel system technology in a diesel engine was more developed, because it was more effective in reducing NO_x and particulate matter emissions, while also reducing fossil fuel consumption by substituting alternative fuels. An alternative fuel that was widely used in dual fuel systems was natural gas [19], [20]. The reason for utilizing natural gas was its availability which was quite large, especially in Indonesia [21]–[23].

One of the natural gases that can be applied to a diesel dual fuel (DDF) engine was compressed natural gas (CNG) [24]–[29]. The reason was CNG has an octane number and self-ignition temperature was high [6], [30], therefore it can withstand cylinder temperature and pressures were high in the combustion chamber [16], [18]. The advantage of using CNG as the main fuel in a CI engine with dual fuel systems was that it can reduce NO_x and PM emissions significantly [16], [18], [31]–[33].

However, the use of CNG on DDF engines has caused a reduction in the performance of the engine, especially thermal efficiency, and a significant increase in emissions of HC and CO [18], [29], [33], [34]. This was due to the fuel mixture that was too rich in CNG-DDF engine when compared to a standard diesel engine. The CNG as the main fuel injected through the inlet can reduce the amount of combustion air so that it will reduce the air fuel ratio (AFR) and volumetric efficiency significantly. Ehsan et al. [35] described that the inclusion of CNG through the inlet causes a decrease in AFR, and then affects the decrease in engine power and thermal efficiency. Cheenkachorn et al. [36], said that after CNG was supplied to the engine that operated with dual fuel, CNG replaced some of the pure air entering and caused a reduction in volumetric efficiency. Imran et al. [37] explained that the value of volumetric efficiency on a DDF engine was lower than standard diesel because some of the incoming air has been substituted by CNG. Tarabet et al. [38] also explained that DDF engine has a higher equivalent ratio compared to a diesel engine. This was influenced by CNG which was supplied at the suction stroke and then mixed with air to replace some of the incoming air. Kalsi et al. [39] concluded in their study that the flow rate of air decreases with increasing substitution of CNG fuel because the CNG fuel replaces the amount of air available.

The problem that occurred in the dual-fuel diesel engine described above, was also encountered by the author in previous work. This research was conducted to determine the characterization of the performance of the DDF engine through variations in the pressure of CNG injection [24]. Then this study was continued by Kurniawan et al. [40] and Silva et al. [41], by optimizing the injection timing of CNG and pilot. The results of the study also found that there was a reduction in engine performance, especially in thermal efficiency and AFR when compared to a standard diesel engine.

Based on the research described above it can be concluded that the combustion air on a CNG-DDF engine was significantly reduced because some of the air was substituted by CNG that enters through the air inlet. As it was known that combustion air was needed for the combustion process in the combustion chamber [6], and when the amount of air entering the cylinder become reduced, then the mixture of CNG-diesel with oxygen was less and allows the production of less ignition sources, thereby reducing the combustion performance. Also, a decrease in the airflow rate causes the air-fuel mixture to be richer and allows incomplete combustion, so that much fuel does not burn. Non-combustible fuel will produce HC emissions and also the tendency to form higher CO emissions on CNG-DDF engines [18], [42], [43].

Overcoming this problem, some researchers added combustion air to CNG-diesel dual fuel CI engines, such as; Hassan et al. [44] comparing the characteristics of engine performances and emissions in the gasification-DDF engine, between adding combustion air using an air compressor with natural aspirated. The results obtained were increased thermal efficiency and then a decrease in brake-specific energy consumption (BSEC) and CO emission, but the emission of NOx slightly increased with the addition of combustion air. Abdelaal et al. [45] added pure oxygen to the cylinder of a natural gas-DDF engine. The results show that there was an increase in the pressure of the cylinder and a decrease in ignition delay. Too, with HC, CO, and smoke emissions there was a significant decrease, but the heat release rate (HRR) was still low and bad NOx emission. Nataraja et al. [46] analyzed the effect of using a turbocharger on engine performances of a DDF engine with RBOME biodiesel and producer gas fuels. They were concluding that the use of turbochargers can increase thermal efficiency, cylinder pressure, and HRR. A decrease in ignition delay better characterizes the burning performance. Emissions of CO, HC, and smoke have a low value, however, emissions of NOx increase due to engine temperature increases. Nayak and Swain [47], analyzed the effect of adding a turbocharger on the emissions of a DDF engine. The results show that using a turbocharger can decrease the CO, HC, and smoke emissions in all engine loads. However, the emission of NOx had increased due to the increase in engine temperature.

Based on the efforts made by researchers on a CNG-DDF engine, it was concluded that the addition of combustion air could improve engine performance, combustion processes, and reduce emissions. The addition of combustion air can use an air compressor, pure oxygen, turbocharger, or supercharger, where the aim was to increase the air-fuel ratio value of the engine itself. The addition of combustion air intensifies the amount of oxygen entering the cylinder and allows more oxygen to be mixed with fuel, especially CNG fuel, thus that more fuel burns and produces greater combustion. Likewise, forcing air into the cylinder can increase volumetric efficiency, thus the engine pressure and temperature rise. These will affect the speed of flame development in the combustion chamber [35]. Both of these parameters will affect the speed of flame that develops in the combustion chamber [45].

However, the combustion air requirements at each engine condition vary according to the amount of fuel in the cylinder. The amount of fuel consumed by the engine was affected by the load engine and its speed. Thus, it is necessary to optimize the addition of combustion air according to the engine load, to obtain a mixture of stoichiometric fuel and air. Previous research was not carried out optimization according to the needs of the engine so as to allow for excessive additions and consequently the mixture of fuel became poor. The poor mixture of fuel and air also affects the decrease in performance and increased exhaust emissions.

Therefore, this research was carried out on a compression ignition engine, a four-stroke single cylinder, which has been modified into a CNG-DDF engine. This research has been carried out with the addition of combustion air using an electrically controlled electric supercharger, in order to achieve ideal A/F values (stoichiometry) at each engine load so that there is an increase in the combustion process and a decrease in emissions of HC and CO on a CNG-DDF engine. The purpose of this research was to optimize the combustion air requirements in each engine load, so that the performance, combustion process, and emissions were better. The performance parameters analyzed include power, torque, brake mean effective pressure (BMEP) and specific fuel consumption (SFC), and CNG substitution, while combustion characteristics such as cylinder pressure, HRR, ignition delay (ID), and combustion duration (CD). Then, emissions of CO, HC, and PM were also analyzed in this study.

2. Method

2.1. *Test Engine*

Tests were carried out on conventional diesel engine, a four-stroke single cylinder, and then modified into a CNG-DDF engine using an electric supercharger at intake manifold. The test engine specifications used are shown in **Table 1** as follows [48].

Table 1. Specification of CNG-DDF engine

Item	Specification	
Type	DI 800 CNG-diesel dual fuel engine	
Model	Single cylinder, four stroke	
Bore x Stroke	82 mm x 78 mm	
Displacement	411 cc	
Maximum power	5.9 HP (4.4 KW) /2000 rpm	
Continuous power	4.8 HP (3.6 KW)/1500 rpm	
Compression Ratio	18:1	
Cooling system	Hopper	
Lube capacity	1.8 liter	
Pilot injection timing	13° BTDC	
CNG injection timing	80° ATDC	
CNG injection duration	70° CA	
Valve timing	Opening	Closing
Intake	30° BTDC	50° ABDC
Exhaust	55° BBDC	35° ATDC

2.2. Fuels

The fuels used in the test engine were diesel and CNG fuels. The properties of the two fuels can be seen in **Table 2** [49]. The CNG fuel with a working pressure of 2 bar is injected near the port at the intake manifold, based on previous research [50]. The CNG timing injection of 80° ATDC at the suction step [51] and the CNG duration injection of 70° CA [52] was kept constant from the optimal value of previous studies, without injection settings. Diesel fuel was injected directly into the combustion chamber with a fuel pump pressure of 21.57 MPa and timing of diesel pilot injection of 13° BTDC.

2.3. Instrumentation and Data Acquisition

The measuring instrument used in this test is a measuring cup function to determine the volume of diesel fuel. The gas flow meter functions to measure the mass flow rate of CNG fuel to the cylinder. The airflow meter functions to measure the mass flow rate of pure air to the cylinder. The gas analyzer functions to measure the level of exhaust emissions from dual fuel engines such as CO and HC emissions. Smoke opacity tester functions to measure the emission levels of particulate matter (PM) emissions. Digital current meter functions to get the value of the current and voltage generated from the loading engine.

Pressure transducer sensor functions to determine the combustion pressure, combustion temperature, and HRR on a CNG-DDF engine. The encoder sensor is used to determine the crank angle (CA). TMR combustion analyzer functions as data acquisition to process input data from the pressure transducer and encoder sensor to determine the value of the cylinder pressure, combustion temperature, HRR, etc. The specifications of the measuring instrument is presented in **Table 3**.

2.4. Analysis of Uncertainty

In reducing errors in measurement it is necessary to analyze the uncertainty. Measurement error is caused by several factors such as human error, environmental conditions, the condition of the measuring instrument, and data collection methods [53]. Thus the analysis of uncertainty is required by using Eq. (1) [54], [55]:

$$\bar{X} = \frac{\sum X_m}{n} \quad (1)$$

Table 2. Properties of fuels

Fuel Properties	Diesel	CNG
Low heating value (MJ/kg)	42.8	48.6
Cetane number	52.5	-
Octane number	-	130
Auto-ignition temperature (°C)	316	650
A/F_{stoic} (kg/kg)	14.69	17.2
Carbon content (%)	87	75

Table 3. The specifications of the measuring instrument

Divice	Type	Property	Sensibility
Burette Meter	Class A, DIN ISO 385 standard	1-25 ml	± 0.05 ml
Pressure Transducer Sensor	IEPE sensors	0-200 bar	± 1%
Manometer & Flow Meter Different Pressure	Manometer	0-999.900 CFM	± 0.3% FSO
Data Acquisition	TMR 150	8 channel, ± 10V s/d ± 200mV	-
Encoder Sensor	S65 Series	50 ppr – 23040 ppr	-
Gas Analyzer	Stargas 898	CO: 0-15 %vol	± 0.001
		CO_2: 0-20 % vol	± 0.01
		HC: 0-30,000 ppm vol	± 1
		O_2: 0-25.00 % vol	± 0.01
		NO_x: 0-5,000 ppm vol	± 1
		Lambda: 0.5-2	± 0.001
Smoke Opacity Meter	NEOMOTECH CGO-600	0-100 %	± 0.01

Where, $\bar{X}$ is the average value of the measurement, n is the number of repetitions of measurements, and X_m is the measurement result. The standard deviation (SD) uses the following Eq. (2):

$$SD = \sqrt{\frac{\sum_{m=1}^{n}(X_m - \bar{X})^2}{(n-1)}} \tag{2}$$

Then the measurement the analysis of uncertainty (U) can be calculated using the Eq. (3):

$$U = \frac{SD}{\sqrt{n}} \tag{3}$$

The results of the measurement the analysis of uncertainty are shown in **Table 4**.

2.5. *Parameters and Procedures of Test*

Tests were carried out with the experimental method on a CNG-DDF engine as shown in the test scheme in **Figure 1**. Before data collection, the engine was heated for ± 30 minutes. The engine speed was set constant during testing, which was 1500 rpm. The test is done by varying the lambda value (λ) obtained from the calculation of the ratio between the A/F_{actual} with the A/F_{stoic}. Technically in the field, a variation of this research was carried out by forcibly adding air using an electric supercharger attached to the intake manifold. Where the supercharger rotation can be varied by using the electric current flowing to the electric motor as the driver of the supercharger. Then from the intake air setting, it is then converted to a lambda value as one of the parameters in determining the quality of the fuel and air mixture.

The engine load is calculated from the maximum engine power capacity of 5.9 HP (4.4 kW) as shown in **Table 1**. In determining the engine load, it is calculated as follows Eq. (4)-(6). Each load is carried out variations on the parameter lambda value (λ), as shown in **Table 5**. The engine load uses a lamp with an increase of 500 watts. The current and voltage values obtained from the digital multimeter are used to calculate the performance of engines such as power, BMEP, torque, SFC, and volumetric efficiency.

The variations made are by varying the lambda value (λ) shown in **Table 5** with the equation used as follows Eq. (7) [30]:

$$\lambda = \frac{A/F_{actual}}{A/F_{stoic}} \tag{7}$$

The mass flow rate of fuel in a diesel dual-fuel engine at each engine load is described in **Error! Reference source not found.**. Then along with variations in lambda values at different engine loads, combustion performance data retrieval is also performed using a combustion analyzer, and emissions of CO, HC, and PM using a gas analyzer and smoke tester.

Table 4. The analysis of uncertainty

Device	Uncertainty (U)
Burette Meters	± 0.509902
Pressure Transducer Sensor	± 0.106066
Manometer & Flow Meters Different Pressure	± 0.003741
Gas Analyzer	CO : ± 0.000447
	CO_2 : ± 0.333333
	HC : ± 0.374166
	O_2 : ± 0.050990
	NO_x : ± 0.005831
Smoke Opacity Meter	± 0.037417

$$Low\ load = \frac{Lamp\ load}{Maximum\ power\ engine} x\ 100\% = \frac{1000\ Watt}{4400\ Watt} x100\% = 22.72\% \tag{4}$$

$$Medium\ load = \frac{Lamp\ load}{Maximum\ power\ engine} x\ 100\% = \frac{2500\ Watt}{4400\ Watt} x100\% = 56.81\% \tag{5}$$

$$High\ load = \frac{Lamp\ load}{Maximum\ power\ engine} x\ 100\% = \frac{4000\ Watt}{4400\ Watt} x100\% = 90.90\% \tag{6}$$

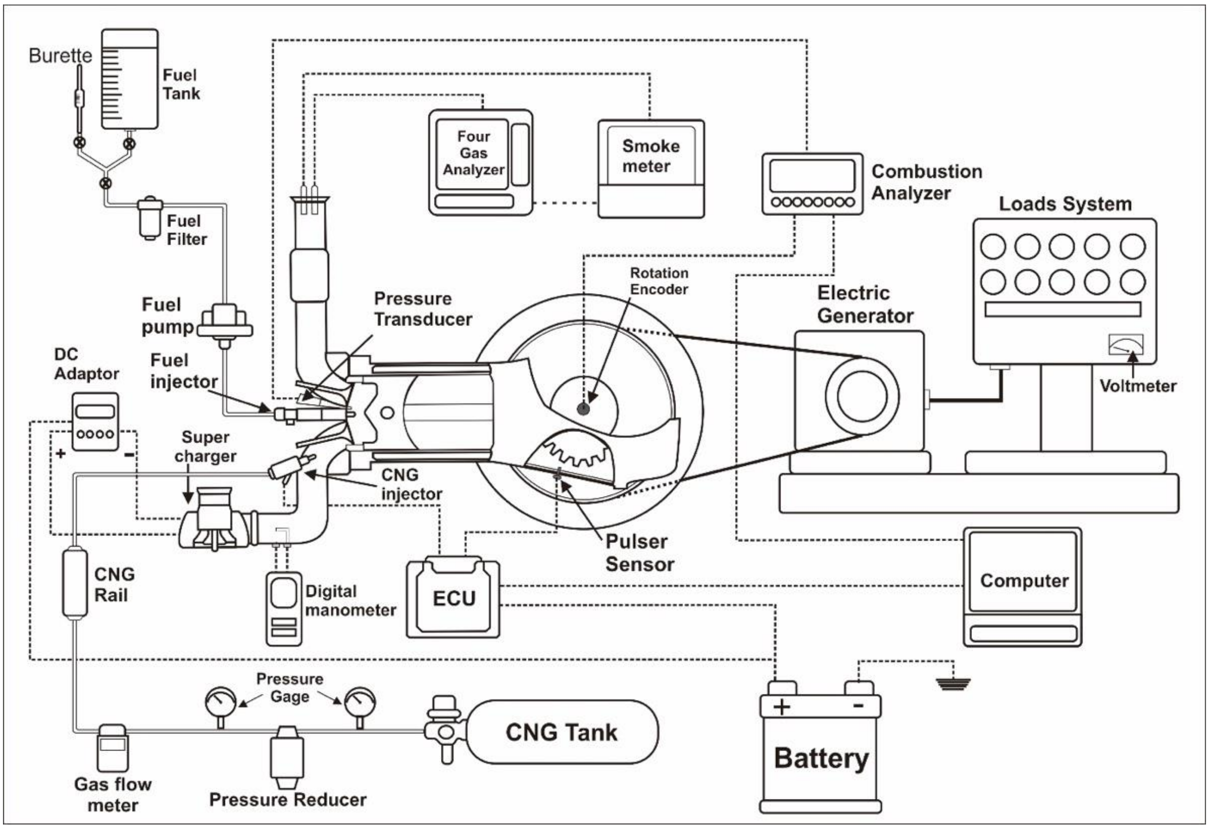

Figure 1. Experimental setup on CNG-DDF engine

3. Results and Discussion

The engine that uses dual fuels has a lower air-fuel ratio (AFR) compared to a single-fuel engine [35]. The AFR was too low, illustrating that a dual-fuel engine has a mixture that was too rich. A mixture that was too rich affects the combustion process which causes a reduce in performance and an increase in emissions of HC and CO [18]. Thus the optimum value of lambda (λ) was needed by adding combustion air to each engine load. Lambda value (λ) was calculated from Eq. (7). Then, for obtain the actual air-fuel ratio value was obtained by Eq. (8):

$$A/F_{actual} = \frac{\dot{m}_{air}}{\dot{m}_{dual\ fuel}} \quad (8)$$

Where, the value of air-fuel ratio stoichiometry of dual-fuel and the equivalent ratio can be calculated using Eq. (9) [56] and Eq. (10) [30].

$$A/F_{stoic} = \frac{[\alpha\left(x_d + \frac{y_d}{4}\right) + \beta\left(x_g + \frac{y_g}{4}\right)\ MW_{air}}{\alpha(x_d MW_C + y_d MW_H) + \beta(x_g MW_C + y_g MW_H)} \quad (9)$$

$$\Phi = \frac{A/F_{stoic}}{A/F_{actual}} \quad (10)$$

Finally, the CNG substitution is how much diesel fuel is replaced by CNG fuel. The equation used to calculate CNG substitution is presented by Eq. (11):

$$CNG\ substitution = \frac{\dot{m}_{diesel\ fuel}}{\dot{m}_{CNG\ fuel} + \dot{m}_{diesel\ fuel}} x\ 100\% \quad (11)$$

3.1. *Engine Performances*

The effects of lambda on power, torque, and brake mean effective pressure (BMEP) under different engine loads was shown in **Figure 2**. The higher value of lambda was followed by an increase in power, torque, and BMEP. However, each engine load has an optimal lambda value. In low load, the optimal lambda value of 1.98 with the maximum power of 0.977 kW, a torque of 4.646 N.m, and BMEP of 1.936 kg/cm². In medium load, the optimal lambda value of 1.99 with maximum power of 2.281 kW, torque of 9.713 N.m, and BMEP of 3.936 kg/cm². In high load, the optimal lambda value of 1.69 with the maximum power of 3.036 kW, torque of 14.427 N.m and BMEP of 6.013 kg/cm².

This shows that supplying more air to the cylinder, can increase the amount of oxygen in the cylinder and then allow the mixture of the two fuels, especially CNG with oxygen. The amount of mixture of fuel and oxygen that allows more fuel

Table 5. Variation of research parameters

Engine load (%)	Lambda variation	Mass flow rate of fuel on dual fuel (kg/s)
Low load	1.52	0.0001413
	1.56	0.0001383
	1.71	0.0001349
	1.98	0.0001320
	2.51	0.0001295
	2.71	0.0001252
Medium load	1.18	0.0001727
	1.21	0.0001696
	1.32	0.0001648
	1.56	0.0001600
	1.99	0.0001574
	2.17	0.0001514
High load	0.94	0.0002039
	0.99	0.0001943
	1.07	0.0001937
	1.29	0.0001855
	1.69	0.0001785
	1.86	0.0001709

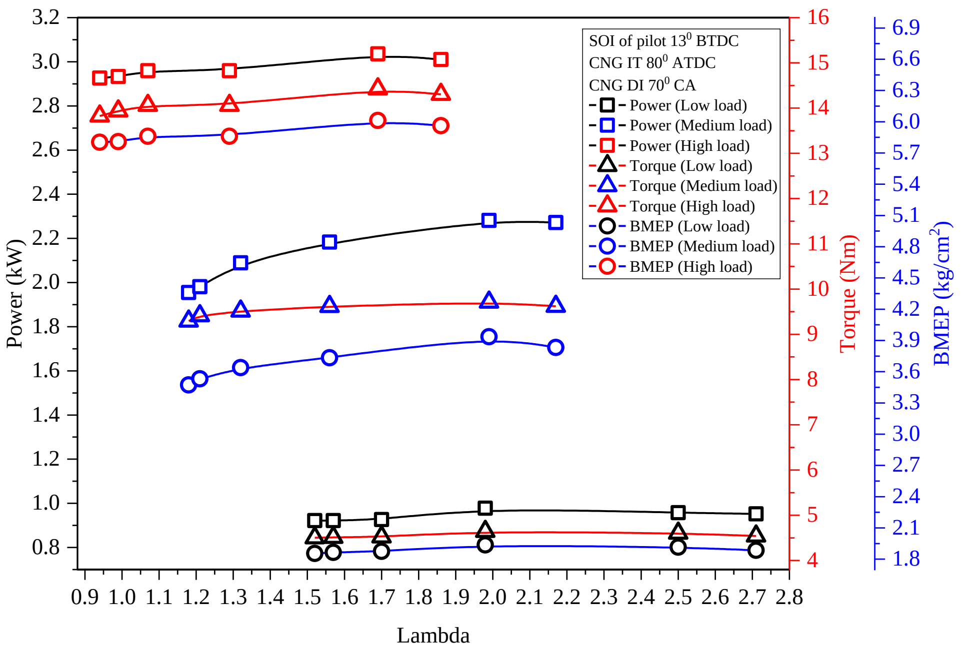

Figure 2. The influence of lambda on the power, torque, and BMEP under different loads

to burn especially from burning CNG, thus that it produces a larger explosion and then affects the increase in engine power. An increase in torque and BMEP follows increased engine power because both were functions of power. However, when adding too much air causes a decrease in power, torque, and BMEP and this condition occurs in all engine loads. This was because the mixture of air and fuel was too poor, and this allows the stability of combustion to be worse, thus that combustion was not perfect and consequently a decrease in engine power.

Figure 3 explains the effect of lambda values on thermal efficiency, SFC_{dual}, SFC_{diesel}, and CNG substitution under different engine loads. The increase in lambda value resulted in an increase in

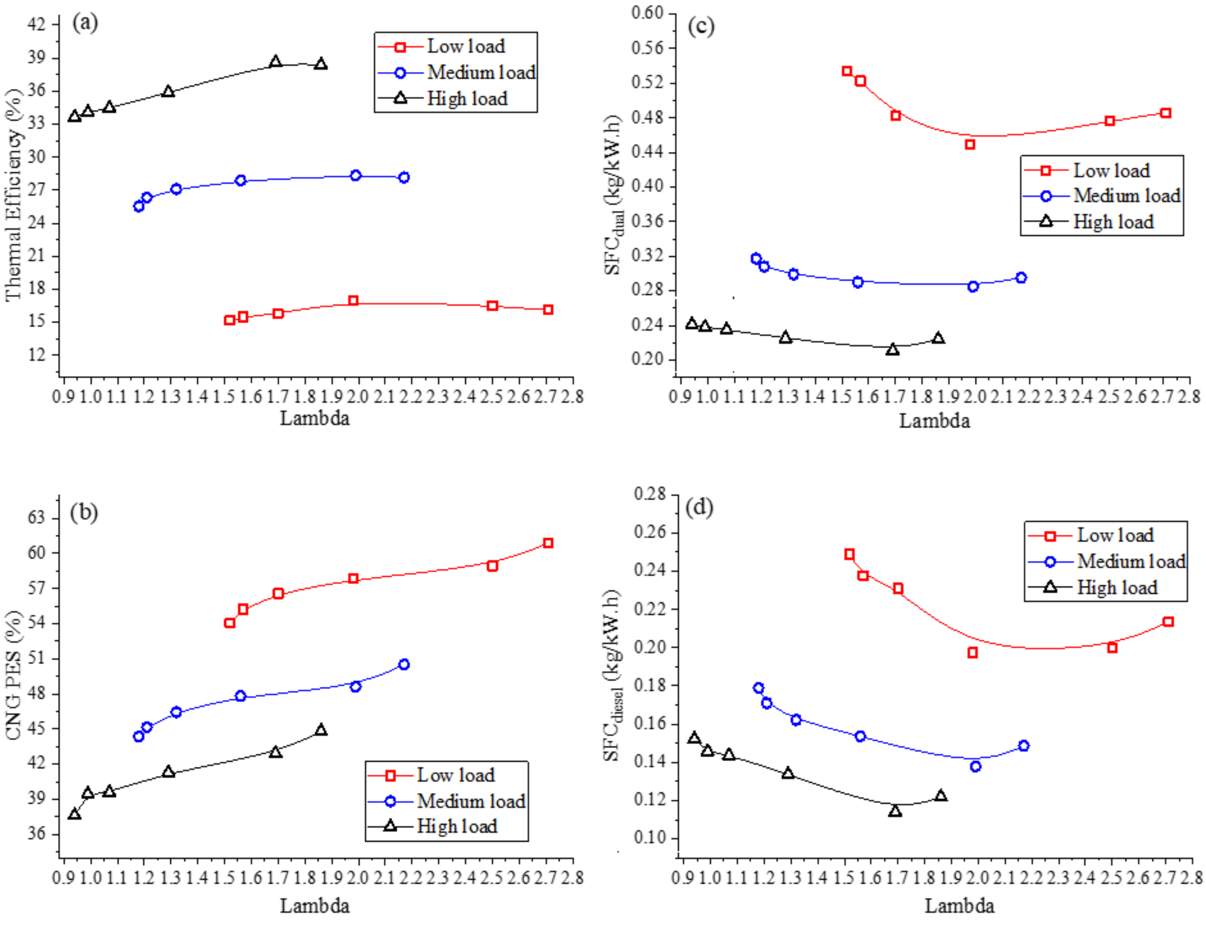

Figure 3. The influence of lambda on (a) the thermal efficiency, (b) The CNG Substitution, (c) SFC dual, (d) SFC diesel under different loads

thermal efficiency, dual SFC, SFC diesel and CNG substitution on a CNG-DDF engine. However, each engine load has a certain value as well as power, torque, and BMEP. In low load the optimal lambda value was obtained at 1.98 with the maximum thermal efficiency of 16.95%, a minimum SFC_{dual} value of 0.449 kg/kW.h and minimum SFC_{diesel} of 0.1973 kg/kW.h. However, the maximum percentage energy substitution of CNG was 60.89% with lambda value of 2.71. In medium load optimal lambda value was obtained at 1.99 with the maximum thermal efficiency of 28.34%, a minimum SFC_{dual} value of 0.285 kg/kW.h and minimum SFC_{diesel} of 0.1379 kg/kW.h. However, the maximum percentage energy substitution of CNG was 50.51% at lambda 2.17. In high load the optimal lambda value was obtained at 1.69 with the maximum thermal efficiency of 38.60%, a minimum SFC_{dual} value of 0.211 kg/kW.h and minimum SFC_{diesel} of 0.114 kg/kW.h. However, the maximum percentage energy substitution of CNG was 44.81% with lambda value of 1.86.

The value of lambda raised has a positive impact on thermal efficiency, CNG, SFC dual and SFC diesel substitutions at each engine load. As explained earlier, that the addition of combustion air can increase oxygen from the environment into the cylinder so that the proportion of oxygen mixes with the fuel (diesel-CNG) is more and the combustion reaction is more stable, resulting in an increase in performance. Thus the engine was more effective in consuming pilot fuel, so it has a good impact on increasing thermal efficiency and CNG substitution and decreasing SFC on a CNG-DDF engine, this phenomenon was also seen in previous studies [57], [58]. However, adding too much combustion air, the mixture of air and fuel was too thin and allows smaller combustion due to misfire that has formed.

Figure 4 shows the effect of lambda on volumetric efficiency under different engine loads on a CNG-DDF engine. Increasing the lambda value results in intensification in the value of volumetric efficiency at all engine loads. In low load with a lambda value of 2.71, it produces the maximum volumetric efficiency of 91.38%. In medium load with a lambda value of 2.17, it produces the maximum volumetric efficiency of 88.42%. In high load with a lambda value of 1.86, it produces the maximum volumetric efficiency of 85.46%. This proves that increasing the amount of pure air using an electric supercharger can lead to volumetric efficiency. With the increase in the quantity of pure air entering the cylinder resulting in an increase in the value of lambda in a CNG-DDF engine, this phenomenon has also been shown in previous studies [38]. Increased volumetric efficiency has a positive impact on engine performance, this is characterized by an intensification in temperature and pressure of combustion on a CNG-DDF engine. **Figure 4** also shows that increasing engine loads results in reduced volumetric efficiency. This is due to the increase in the quantity of diesel fuel cause controlled by the centrifugal governor so that the quantity of pure air entering the cylinder also goes down. Thus the volumetric efficiency is low, this phenomenon has also been shown in previous studies [37].

Figure 5 shows the effect of lambda on excess air under different loads on a CNG-DDF engine. The value of excess air increases by increasing the lambda value at all engine loads. This is due to the addition of the proportion of pure air that enters the cylinder thereby increasing the value of the excess air. **Figure 5** also shows that the value of excess air decreases with increasing engine loads, this phenomenon is also seen in previous studies [38], [59]. This is because the amount of diesel fuel adds a lot to offset the engine load controlled by the centrifugal governor, so the lambda value decreases, thus the excess air in the cylinder becomes less, this is also explained by Tarabet et al. [38].

3.2. The Combustion Characteristics

3.2.1. The Cylinder Pressure and HRR

Figure 6 displays the effect of lambda on cylinder pressure and HRR under low load. The optimal lambda value was obtained at 1.98 by producing cylinder pressure of 45.67 bar and HRR of 55.07 kJ/m³/°CA. This phenomenon was also shown in previous studies [57], [59]. The addition of air supply from the outside, allows an increase in volumetric efficiency, thus as to produce a high temperature of combustion and influence the increase in cylinder pressure. This increase has a positive effect on HRR value, this can be seen in **Figure 6**, where the increase in heat rate follows the trend of cylinder pressure.

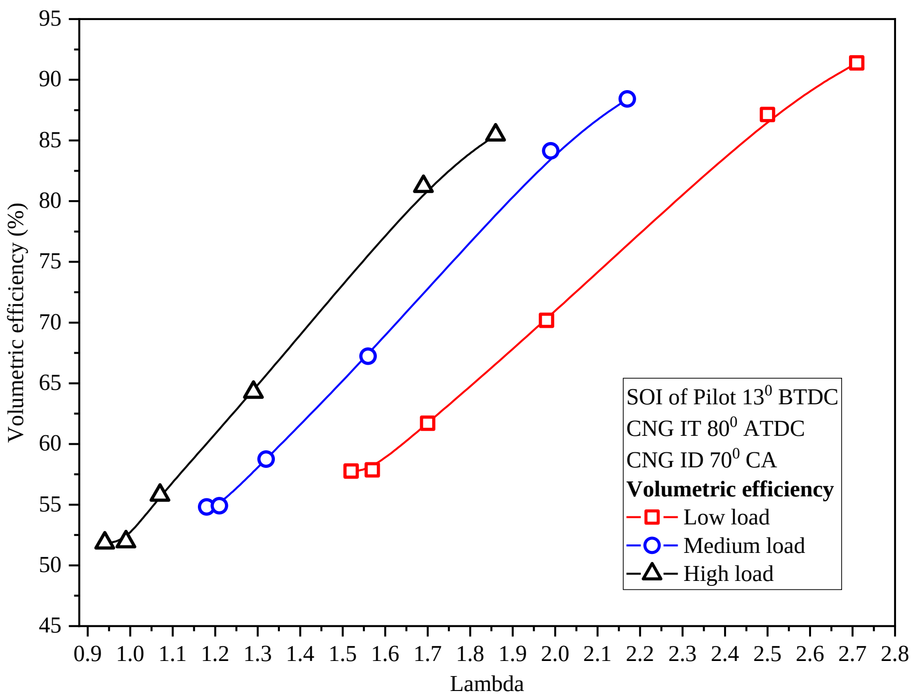

Figure 4. The influence of lambda on the volumetric efficiency under different loads

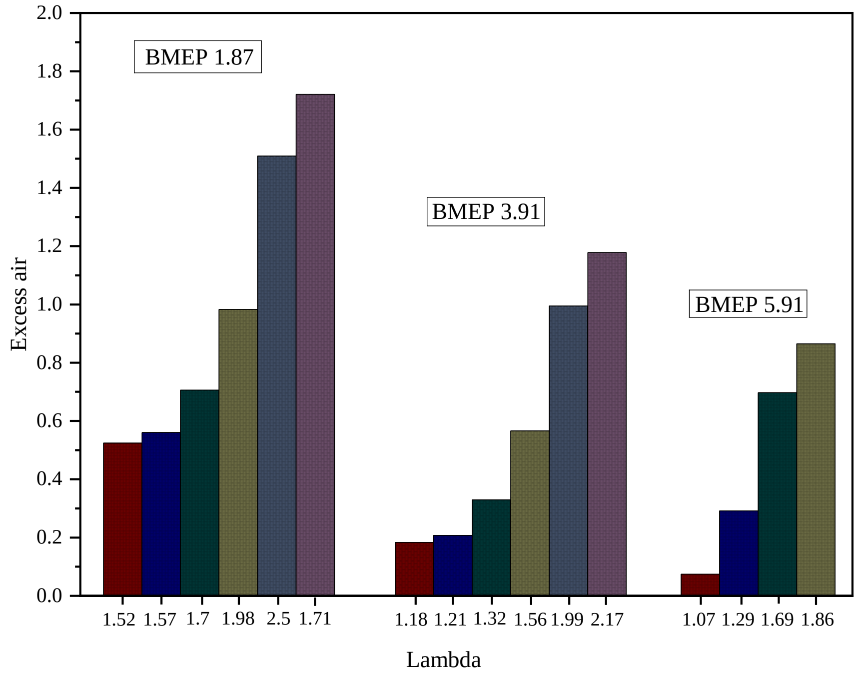

Figure 5. The influence of lambda on the excess air under different loads

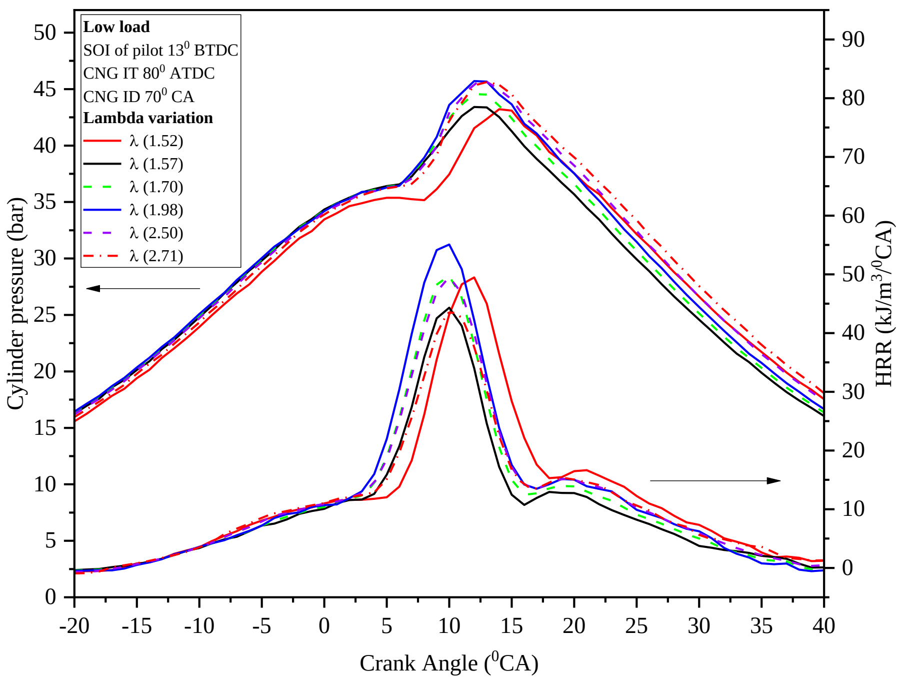

Figure 6. The influence of lambda on the cylinder pressure and heat release rate under low load

Besides that, the addition of combustion air to the cylinder can reduce the specific heat capacity value of charge (air-CNG mixture) and have an effect on increasing the pressure and temperature at the end of the compression step. This results in an increase in cylinder pressure and HRR. However, with the addition of too much combustion air, cylinder pressure tends to decrease followed by the HRR. This was because the air and fuel mixture was poor, thus that there was a misfire from the combustion process because of the excess air, allowing a decrease in the temperature of the cylinder and then having an impact on the decrease in cylinder pressure and HRR.

Figure 7 shows the effect of lambda on cylinder pressure and HRR at medium load. In **Figure 7** it can be seen that the trend of increasing cylinder pressure and HRR were the same as a low load. However, the cylinder pressure and HRR values were higher than the low load. It was caused by an intensified temperature of combustion because the additional load requires more fuel to maintain engine working conditions at constant rotation and results in maximum combustion with cylinder pressure of 54.83 bar and HRR of 84.72 kJ/m3/°CA at optimal lambda value of 1.99. This proves that increasing the combustion air supply, allows more oxygen to enter the cylinder, thus increasing the oxygen partial pressure. This increase will affect the increase in temperature and cylinder pressure during the compression step. An increase in temperature and cylinder pressure will facilitate the evaporation of pilot fuel and interact with oxygen faster, and allow faster reaction rates so that the uncontrolled combustion from diesel fuel was greater. This increase has a large impact on the diffusion combustion of CNG fuel, and then it will produce a higher heat release rate, this was also explained by Sarkar et al. [57]; Zheng et al. [59]. However, when the pure air were too much, the mixture of air and fuel becomes poorer, and the excess air causes incomplete combustion so that the temperature of combustion and pressure cylinder decrease.

Figure 8 displays the effect of lambda on cylinder pressure and HRR under high load. The consequence of adding engine load was to increase diesel fuel in the combustion chamber. Adding too much fuel produces a rich mixture, thus affecting the combustion performance of the CNG-DDF engine. Efforts to add combustion air can reduce the rich mixture so that more oxygen fills in the cylinder chamber and then makes the fuel and air mixture more ideal. In **Figure 8** it can be seen that forcing the air environment into the cylinder it can affect the increase in the cylinder pressure and HRR. The optimal lambda value of 1.69 by producing a cylinder pressure of 63.40 bar and an HRR of 109.11 kJ/m³/°CA, this phenomenon is also shown in previous studies [57], [59]. As also explained in **Figure 6** and **Figure 7**, the addition of oxygen can increase the partial pressure in the cylinder so that it can increase the temperature and pressure of the cylinder during the compression step. Coupled with high load where the temperature and combustion pressure were very high. With the addition of combustion air and then mixing with a large amount of fuel in that situation, it was possible to produce premixed, and diffusion combustions were very large from both fuels, especially CNG. Thus more energy was generated, which was indicated by an intensification of in-cylinder pressure and HRR. **Figure 8** also shows that with a lambda of 1.99 there was a decrease in cylinder pressure and heat release rate, due to too much external air supply so that the mixture of air and fuel returns to poor and combustion becomes incomplete.

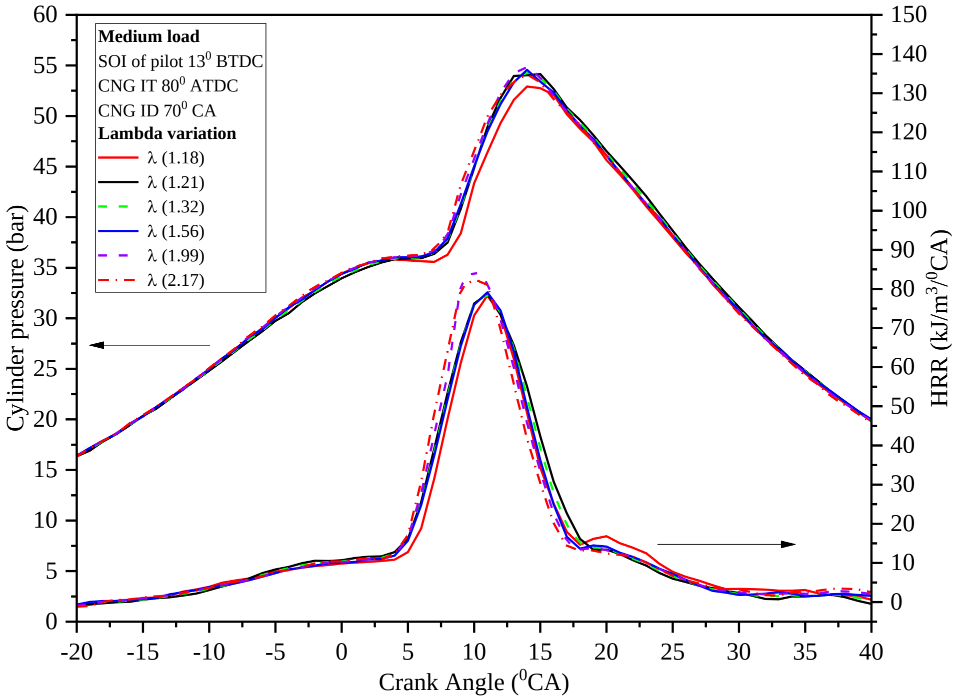

Figure 7. The influence of lambda on the cylinder pressure and heat release rate under medium load

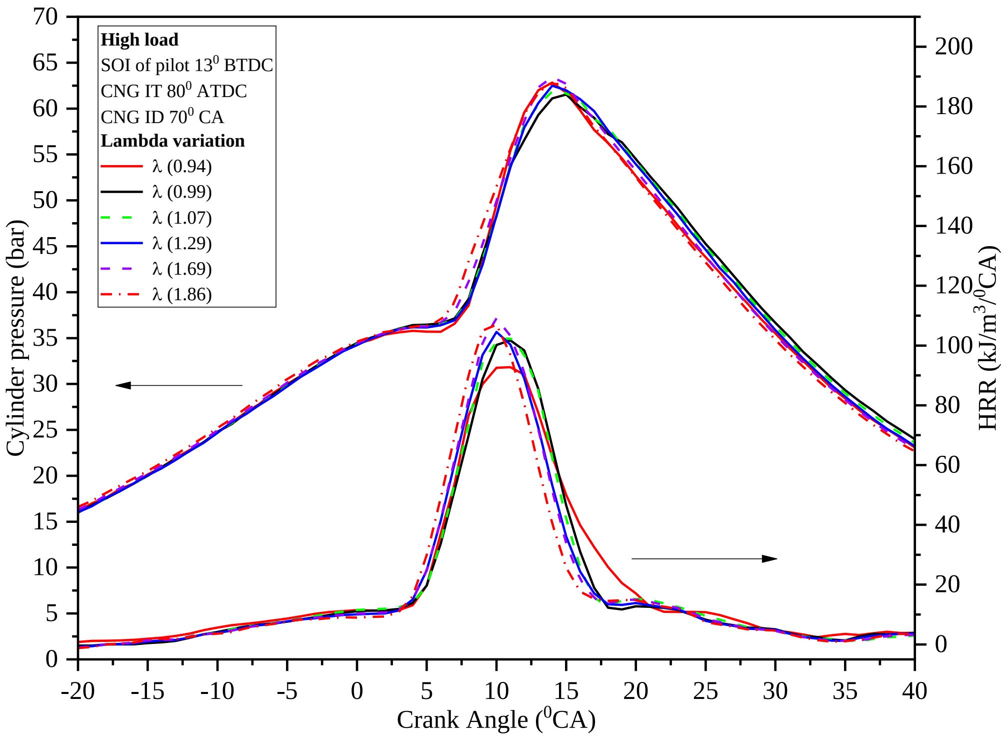

Figure 8. The influence of lambda on the cylinder pressure and heat release rate under high load

3.2.2. The Temperature of Combustion

Figure 9 shows the temperature of combustion of the crank angle function with lambda variations under low load. The temperature of combustion seems to increase along with increasing the lambda value. The maximum combustion temperature is 1049 K with a lambda value of 1.98 under low load. This is due to the maximum combustion so as to produce high temperatures, this is indicated by an increase in combustion pressure and HRR, this is also explained by Tomita et al. [60]; Zheng et al. [59]. However, the lambda value is too high resulting in a decrease in the temperature of combustion under low load. This is due to a mixture of air and fuel that is too poor so combustion becomes incomplete and results in poor combustion quality. Thereby reducing the combustion pressure so that it has an impact on the reduction in the temperature of combustion. Zheng et al. [59] explained that the decrease in temperature was caused by a decrease in the amount of charge in the cylinder. This is related to the lambda being too high causing a decrease in the amount of charge from the fuel so that the mixture becomes too poor.

Figure 10 shows the temperature of combustion of the crank angle function with lambda variations under medium load. The temperature of combustion value is higher under medium load compared to low load. This increase was caused by the increase in the quantity of diesel fuel by the governor to offset the engine load so that the combustion of premixed diesel fuel was greater. Then the intensity and speed of the combustion rate produced by combustion diffusion are faster. Thus the amount of CNG and diesel fuels that are burned more so that the temperature of combustion increases.

The temperature of combustion also appears to increase with increasing lambda values such as at low load. The highest temperature of combustion is 1771 K with a lambda value of 1.99 under medium load. The increase in the temperature of combustion is due to an increase in combustion quality indicated by an increase in combustion pressure. This tendency is also explained by Tomita et al. [60] in their research by adding a supercharger to a dual-fuel engine. However, lambda values that are too high occur in the temperature of combustion decreases, this is affected by a decrease in combustion quality because the fuel-air mixture is too poor and does not mix homogeneously.

Figure 11 shows the temperature of combustion of the crank angle function with lambda variations under high load. The temperature of combustion value is higher under high load compared to loads of medium and low. Thus the combustion of premixed from pilot fuel is greater and results in a faster combustion intensity and rate of combustion. This condition will cause the quantity of CNG and diesel fuel to burn more, thereby increasing the temperature of combustion. The combustion temperature is also seen to increase with increasing lambda values as in medium and low loads. The maximum combustion temperature is 2167 K with a lambda value of 1.69 under high load. This proves that by increasing the quantity of pure air supply to the cylinder, the amount of fuel (CNG-diesel) and oxygen are mixed more so that it produces maximum combustion and has an effect on rising

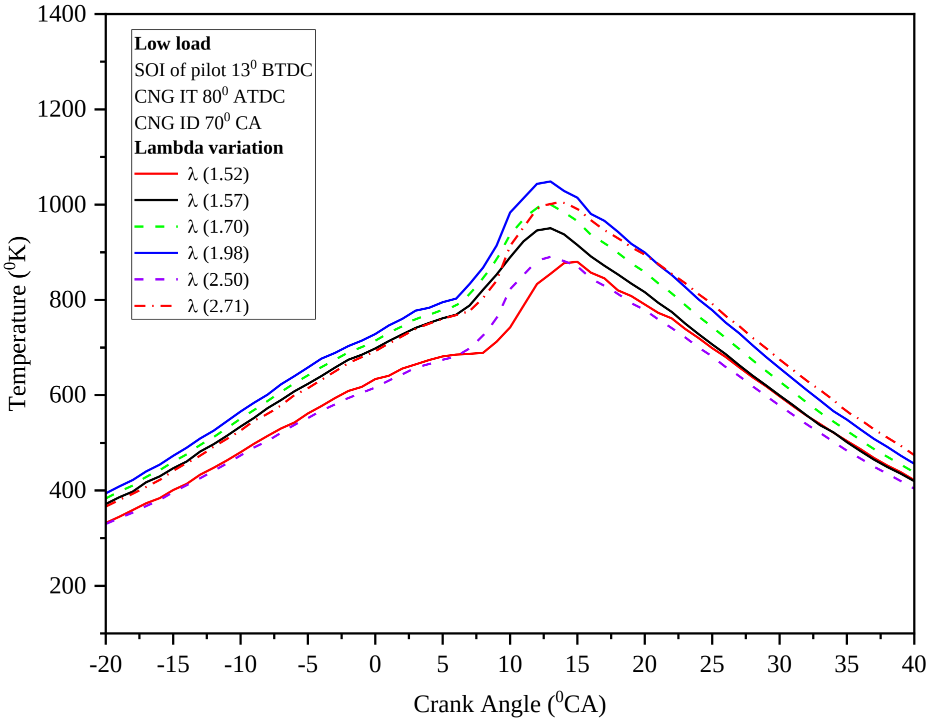

Figure 9. The influence of lambda on the temperature of combustion under low load

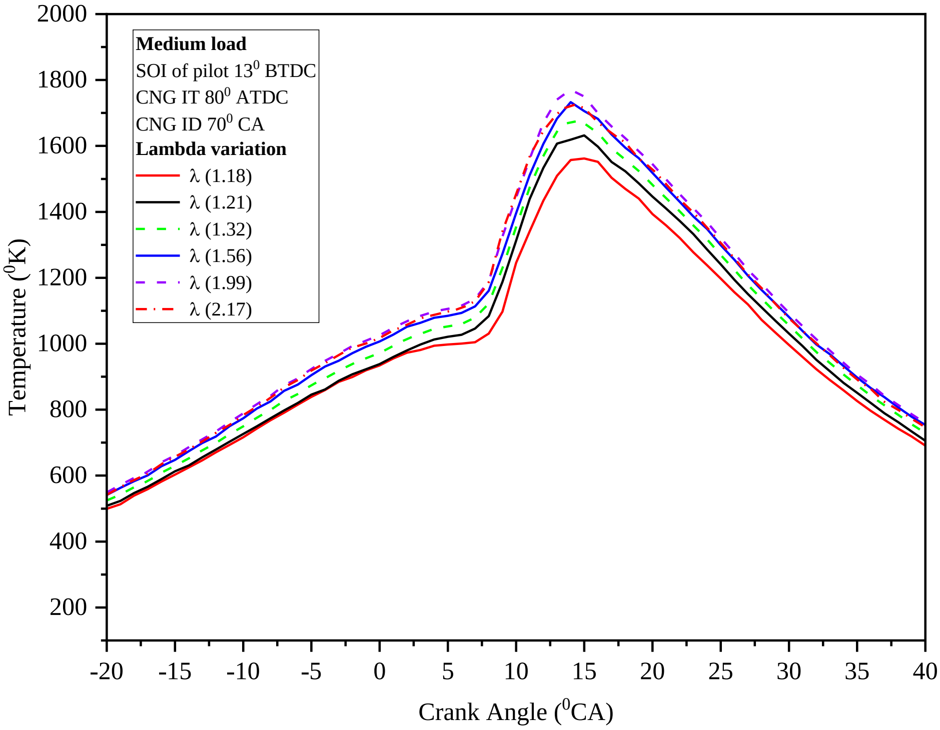

Figure 10. The influence of lambda on the temperature of combustion under medium load

combustion temperatures, this phenomenon was also shown in previous studies [60]. Then also, increasing the quantity of pure air entering the cylinder can increase the volumetric efficiency value and affect the quality of combustion as shown in **Figure 4**. However, if the lambda value is too high causing a decrease in temperature, this is due to a decrease in the amount of charge in the cylinder as explained by Zheng et al. [59].

3.2.3. *The Ignition Delay (ID) and Combustion Duration*

Figure 12 shows the effect of lambda on the ignition delay and the combustion duration under different loads. Ignition delay is influenced by temperature of combustion, this is also descrided by Sarkar et al. [57]. An increase in lambda value causes a decrease in ID and the combustion duration at all loads. The minimum ignition delay value of 12° CA and minimum combustion duration of 20° CA occurs in high load conditions with a lambda value of 1.69. This phenomenon is also shown in the research of Sarkar et al. [57] that ignition delay and combustion duration increase when the equivalent value of the ratio increases in all engine loads, this means that when the lambda value decreases, ID and duration of combustion also increase are longer.

Besides that, the addition of combustion air causes an increase in volumetric efficiency, because more air was supplied to the cylinder chamber and causes the temperature and cylinder pressure to rise. The increase in temperature and cylinder pressure accelerates the chemical delay process in the ignition delay period so that it accelerates the initial combustion in the combustion chamber. Then also, the rise in temperature and cylinder pressure also accelerates the rate of combustion so that the time needed to burn fuel is less and thus will shorten the duration of combustion. However, if too much air was added, the mixture of fuel and air becomes poor, resulting in incomplete combustion, which affects the ID and combustion duration. J. B. Heywood [6] and S. R. Turn [30] explain that if the equivalent ratio value is below 1, then the air-fuel ratio (AFR) includes a poor or excess air mixture. From the variation of the lambda (λ) value that was carried out, it was found that the lambda value was below the value of 2 which indicates that too much air is supplied to the cylinder.

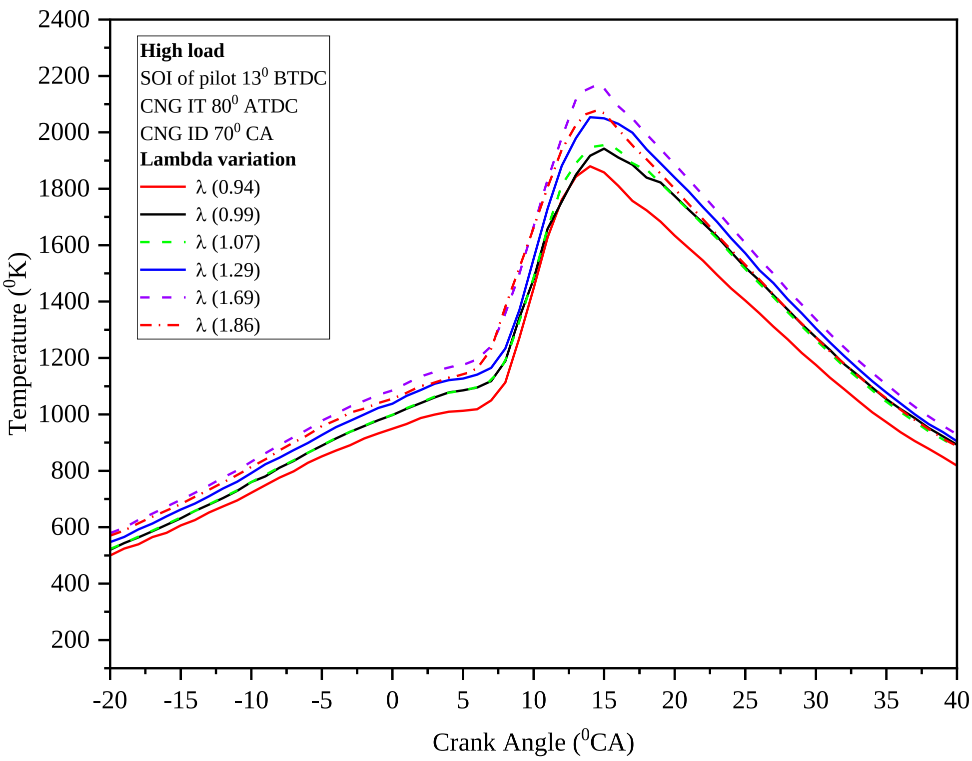

Figure 11. The influence of lambda on the temperature of combustion under high load

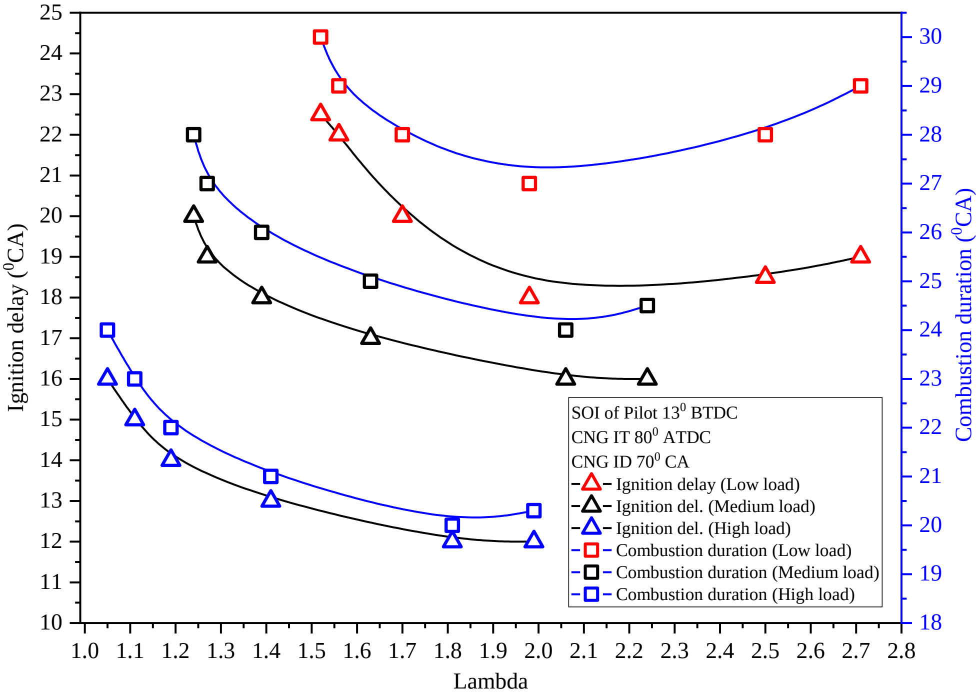

Figure 12. The influence of lambda on the ID and combustion duration under different loads

3.3. Emissions

3.3.1. Carbon Monoxide (CO) Emissions

In CNG-DDF engine has high CO emission values compared to a standard diesel engine. This increase was dominated by CNG fuels that were not completely burned, as has been explained by previous studies[61], [62]. **Figure 13** shows the influence of lambda on CO emissions with different engine load variations. With the value of lambda raised, it can reduce CO emission, and this case occurs at all different loads, this phenomenon was also shown by Sarkar et al. [46] in their research. The minimum CO emission value of 0.1641 g/kW.h with optimal lambda value of 1.69 under high load. More added air causes AFR to be poor, and more supplied oxygen so CO formation can be reduced, especially low load. Then also affected by a significant increase in temperature by raising the value of lambda so that CO emissions emit easily oxidize, as described by Sarkar et al. [57]. Where in the medium and high loads the temperature of combustion is above 1500 K so that it will make it easier for CO molecules to form CO_2 with the chemical reaction $CO + \left(\frac{1}{2}\right) O_2 \rightarrow CO_2$ [57], and if the lambda value is high, the availability of O_2 reacts more with CO molecules. This will reduce CO emissions with more air.

In high loads, it can be seen the effect of adding combustion air to the reduction of CO emission, even though at this load there was an increase in the supply of diesel fuel. Increasing the supply of diesel fuel can be balanced with the addition of pure air, and the AFR was still above stoichiometry so that CO emission produced can still be reduced. Then also at high load the temperature and pressure combustion increase, due to the increase in volumetric efficiency, as a result, the air supply was very much, so the temperature of the mixture of air and fuel becomes higher and allows the CNG fuel to be easily oxidized with oxygen.

3.3.2. Hydrocarbon (HC) Emissions

Figure 14 shows the effect of lambda on HC emissions under different loads. Previous research [61], explained that HC emissions produced on a CNG-DDF engine were 80% of CNG fuel that was not burned, especially under low load. With the use of dual fuels it produces a richer mixture of air and fuel, so that part of the already formed fire was easily extinguished, especially low load. This was caused by cooling the cylinder walls due to CNG temperatures that were too low which accumulate a lot in the area.

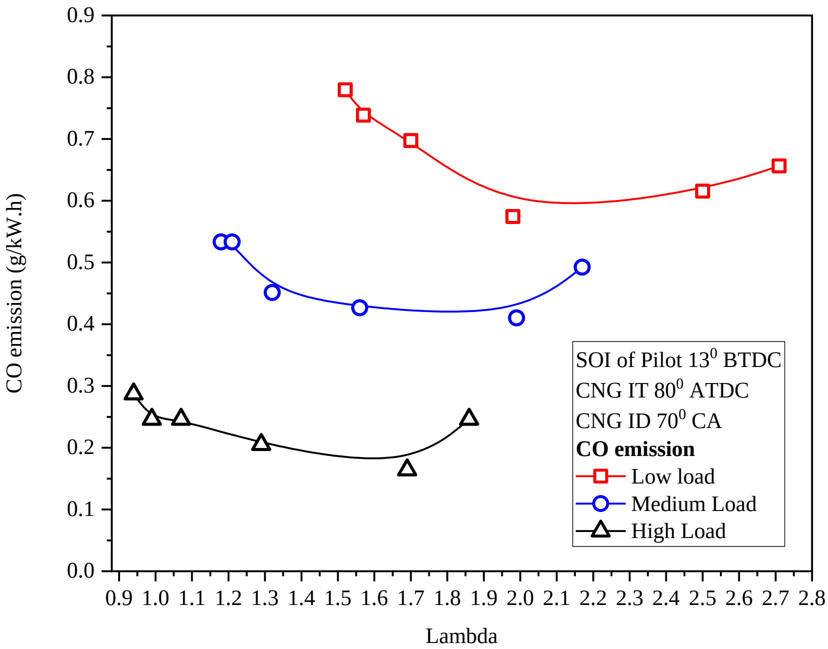

Figure 13. The influence of lambda on the CO emission under different loads

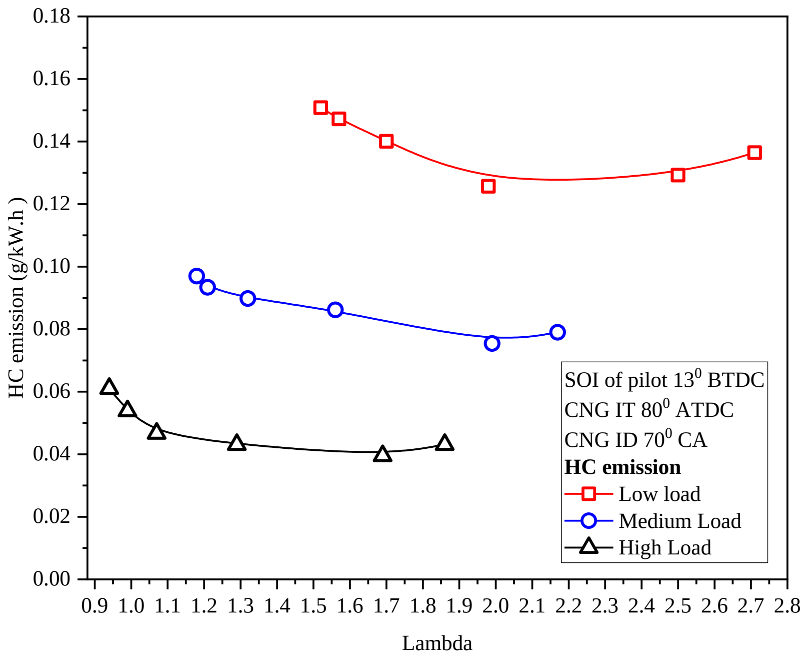

Figure 14. The influence of lambda on the HC emission under different loads

3.3.3. Particulate matter (PM) emission

In CNG-DDF engine has lower PM emission than a standard diesel engine, as described in previous studies [16]–[18], [44]. However, if the engine load was increased, particulate matter emission will increase. The reason was that the amount of diesel fuel was added automatically by the centrifugal governor to compensate for the engine load, and allows the formation of more dominant PM emission.

Figure 15 shows the effect of lambda on PM emissions under different loads. Different engine loads have the same trend, where PM emissions decrease with an increasing value of lambda. The lowest PM emission was obtained under a low load of 0.0024 g/kW.h with the optimal lambda value of 1.98. This shows that the addition of pure air can compensate for the addition of diesel fuel so that more diesel fuel mixes with air and allows it to burn more perfectly.

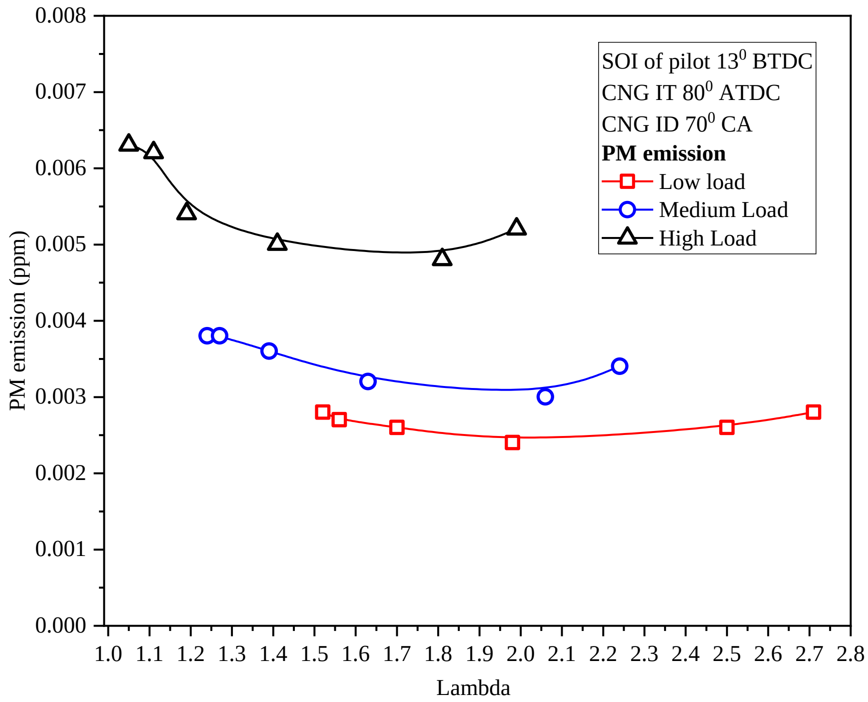

Figure 15. The influence of lambda on the PM emission under different loads

4. Conclusion

The effect of air-fuel ratio on performance, combustion performance. and emissions on a CNG-DDF engine has been tested experimentally so the conclusions can be drawn as follows:

a. Addition of combustion air on a CNG-DDF engine was needed to improve engine performance and reduce emissions on the engine. Each engine load has the optimum lambda value so that the ideal air-fuel ratio was obtained, resulting in better combustion.
b. In low load, the optimum lambda value of 1.98 with better performances and lower emissions, where maximum engine power of 0.977 kW, minimum SFC of 0.449 kg/kW.h, thermal efficiency of 16.95%, and the minimum value for HC emission of 0.1256 g/kW.h, CO emission of 0.5743 g/kW.h, and PM emission of 0.0024 g/kW.h. Performances and emissions improvements were indicated by an increase in cylinder pressure of 5.29% and HRR of 25.10% with a decrease in the ID of 18.18% and combustion duration of 6.89%.
c. In medium load, the optimum lambda value of 1.99 with better engine performances and lower emissions, where maximum engine power of 2.281 kW, minimum SFC of 0.285 kg/kW.h, thermal efficiency is 28.34%, and the minimum value for HC emission of 0.0754 g/kW.h, CO emission of 0.4102 g/kW.h, and PM emission of 0.0030 g/kW.h. Performances and emissions improvements were indicated by an increase in cylinder pressure of 1.48% and HRR of 15.39% with a decrease in the ID of 15.78% and combustion duration of 11.11%.
d. In high load, the optimum lambda value of 1.69 with better engine performance and lower emissions, where maximum engine power of 3.036 kW, minimum SFC of 0.211 kg/kW.h, thermal efficiency of 38.60%, and the minimum value for HC emission of 0.0395 g/kW.h, CO emission of 0.1641 g/kW.h, and PM emission of 0.0048 g/kW.h. Performances and emissions improvements were indicated by an increase in cylinder pressure of 3.76% and HRR of 8.93% with a decrease in the ID of 20% and combustion duration of 13.04%.
e. The volumetric efficiency and air excess values increase by increasing the lambda value in the CNG-DDF engine at all engine loads so as to improve engine performance and reduce emissions.

This research contributes to improving performance and reducing emissions in internal combustion engines using dual fuels, especially CNG and diesel fuels through the addition of combustion air using a forced air system.

Acknowledgements

The authors would like to thank the Ministry of Education, Culture, Research and Technology of the Republic of Indonesia and the Institute for Research and Community Services, Universitas Negeri Padang, Indonesia, which has funded this research with a grant number: 1753/UN35.13/LT/2022. This research is also supported by the Center of Energy for Society and Industry (CESI), Universitas Muhammadiyah Magelang, Indonesia

Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study, The authors took responsibility for data analysis, interpretation and discussion of results and The authors read and approved the final manuscript.

Funding

This research was funded by Kementerian Pendidikan, Kebudayaan, Riset dan Teknologi Republik Indonesia and Universitas Negeri Padang.

Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

References

[1] T. Kivevele, T. Raja, V. Pirouzfar, B. Waluyo, and M. Setiyo, "LPG-Fueled Vehicles: An Overview of Technology and Market Trend," *Automotive Experiences*, vol. 3, no. 1, pp. 6–19, 2020, doi: 10.31603/ae.v3i1.3334.

[2] H. Li, S. You, H. Zhang, W. Zheng, and L. Zou, "Analysis of the impacts of heating emissions on the environment and human health in North China," *Journal of cleaner production*, vol. 207, pp. 728–742, 2019.

[3] W. Austin, G. Heutel, and D. Kreisman, "School bus emissions, student health and academic performance," *Economics of Education Review*, vol. 70, pp. 109–126, 2019.

[4] I. Veza *et al.*, "Strategies to achieve controlled auto-ignition (CAI) combustion: A review," *Mechanical Engineering for Society and Industry*, vol. 3, no. 1, pp. 22–34, 2023.

[5] M. Mofijur, M. Rasul, N. M. S. Hassan, and M. N. Uddin, "Investigation of exhaust emissions from a stationary diesel engine fuelled with biodiesel," *Energy Procedia*, vol. 160, pp. 791–797, 2019.

[6] J. B. Heywood, "Combustion engine fundamentals," *1ª Edição. Estados Unidos*, 1988.

[7] S. Ozer, M. Akçay, B. Doğan, D. Erol, and M. Setiyo, "The Effects of Canola Oil/Diesel Fuel/Ethanol/N-Butanol/Butyl Di Glycol Fuel Mixtures on Combustion, Exhaust Gas Emissions and Exergy Analysis," *Automotive Experiences*, vol. 5, no. 3, pp. 268–287, 2022.

[8] A. Sule, Z. A. Latiff, M. A. Abbas, I. Veza, and A. C. Opia, "Recent Advances in Diesel-Biodiesel Blended with Nano-Additive as Fuel in Diesel Engines: A Detailed Review," *Automotive Experiences*, vol. 5, no. 2, pp. 182–216, 2022, doi: 10.31603/ae.6352.

[9] A. Bhikuning, "The simulation of performance and emissions from rapeseed and soybean methyl ester in different injection pressures," *Automotive Experiences*, vol. 4, no. 3, pp. 112–118, 2021.

[10] R. Rosid, B. Sudarmanta, L. Atmaja, and S. Özer, "An Experimental Study of the Addition of Air Mass Flow Rate Using a 30% Emulsion-Fueled Diesel Engine at High Load," *Automotive Experiences*, vol. 3, no. 2, 2020.

[11] M. Setiyo, D. Yuvenda, and O. D. Samuel, "The Concise Latest Report on the Advantages and Disadvantages of Pure Biodiesel (B100) on Engine Performance: Literature Review and Bibliometric Analysis," *Indonesian Journal of Science and Technology*, vol. 6, no. 3, pp. 469–490, 2021, doi: 10.17509/ijost.v6i3.38430.

[12] S. Saravanan, "Effect of exhaust gas recirculation (EGR) on performance and emissions of a constant speed DI diesel engine fueled with pentanol/diesel blends," *Fuel*, vol. 160, pp. 217–226, 2015.

[13] S. Zhu *et al.*, "A review of water injection applied on the internal combustion engine," *Energy conversion and management*, vol. 184, pp. 139–158, 2019.

[14] W. Zhang, S. Chang, W. Wu, L. Dong, Z. Chen, and G. Chen, "A diesel/natural gas dual fuel mechanism constructed to reveal

combustion and emission characteristics," *Energy*, vol. 179, pp. 59–75, 2019.

[15] M. Feroskhan, S. Ismail, M. G. Reddy, and A. S. Teja, "Effects of charge preheating on the performance of a biogas-diesel dual fuel CI engine," *Engineering Science and Technology, an International Journal*, vol. 21, no. 3, pp. 330–337, 2018.

[16] K. Nithyanandan, Y. Lin, R. Donahue, X. Meng, J. Zhang, and F. L. Chia-fon, "Characterization of soot from diesel-CNG dual-fuel combustion in a CI engine," *Fuel*, vol. 184, pp. 145–152, 2016.

[17] N. N. Mustafi, R. R. Raine, and S. Verhelst, "Combustion and emissions characteristics of a dual fuel engine operated on alternative gaseous fuels," *Fuel*, vol. 109, pp. 669–678, 2013.

[18] R. G. Papagiannakis and D. T. Hountalas, "Combustion and exhaust emission characteristics of a dual fuel compression ignition engine operated with pilot diesel fuel and natural gas," *Energy conversion and management*, vol. 45, no. 18–19, pp. 2971–2987, 2004.

[19] R. M. Susanto and M. Setiyo, "Natural Gas Vehicle (NGV) : Status Teknologi dan Peluang Status Teknologi dan Peluang Pengembangannya," *Automotive Experiences*, vol. 1, no. 01, pp. 1–6, 2018, doi: https://doi.org/10.31603/ae.v1i01.2000.

[20] M. Y. E. Selim, "Sensitivity of dual fuel engine combustion and knocking limits to gaseous fuel composition," *Energy Conversion and Management*, vol. 45, no. 3, pp. 411–425, 2004.

[21] W. W. Purwanto, Y. Muharam, Y. W. Pratama, D. Hartono, H. Soedirman, and R. Anindhito, "Status and outlook of natural gas industry development in Indonesia," *Journal of Natural Gas Science and Engineering*, vol. 29, pp. 55–65, 2016, doi: 10.1016/j.jngse.2015.12.053.

[22] M. Setiyo, "Alternative fuels for transportation sector in Indonesia," *Mechanical Engineering for Society and Industry*, vol. 2, no. 1, pp. 1–6, 2022, doi: 10.31603/mesi.6850.

[23] S. Munahar, M. Setiyo, M. M. Saudi, A. Ahmad, and D. Yuvenda, "Modelling Fuel Cut Off Controller on CNG Engines Using Fuzzy Logic: A Prototype," *International Journal on Advanced Science, Engineering and Information Technology*, vol. 12, no. 5, pp. 1857–1865, 2022, doi: 10.18517/ijaseit.12.5.16849.

[24] B. Sudarmanta, A. Setiyawan, A. B. K. Putra, D. Yuvenda, and J. D. Silva, "Optimization of pilot diesel injection timing on load variation dual fuel diesel-CNG engine on combustions and emissions characteristics," *Int Rev. Mech Eng*, vol. 13, 2019.

[25] N. S. Octaviani and M. B. Zaman, "The implementation of CNG as an alternative fuel on marine diesel engine," *International Journal of Mechanical Engineering and Technology*, vol. 9, no. 13, pp. 24–33, 2018.

[26] M. Y. E. Selim, "Pressure–time characteristics in diesel engine fueled with natural gas," *Renewable energy*, vol. 22, no. 4, pp. 473–489, 2001.

[27] B. Yang and K. Zeng, "Effects of natural gas injection timing and split pilot fuel injection strategy on the combustion performance and emissions in a dual-fuel engine fueled with diesel and natural gas," *Energy conversion and management*, vol. 168, pp. 162–169, 2018.

[28] M. Xu, W. Cheng, H. Zhang, T. An, and S. Zhang, "Effect of diesel pre-injection timing on combustion and emission characteristics of compression ignited natural gas engine," *Energy Conversion and Management*, vol. 117, pp. 86–94, 2016, doi: 10.1016/j.enconman.2016.02.054.

[29] R. G. Papagiannakis, D. T. Hountalas, and C. D. Rakopoulos, "Theoretical study of the effects of pilot fuel quantity and its injection timing on the performance and emissions of a dual fuel diesel engine," *Energy Conversion and Management*, vol. 48, no. 11, pp. 2951–2961, 2007.

[30] S. R. Turns, *An introduction to combustion: concepts and applications*, 3rd Editio. New York: McGraw-Hill Co, 2012.

[31] B. B. Sahoo, N. Sahoo, and U. K. Saha, "Effect of engine parameters and type of gaseous fuel on the performance of dual-fuel gas diesel engines—A critical review," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 6–7, pp. 1151–1184, 2009.

[32] B. Yang, L. Ning, W. Chen, B. Wang, K. Zeng, and W. Dong, "Parametric investigation the particle number and mass distributions characteristics in a diesel/natural gas dual-fuel engine," *Applied Thermal Engineering*, vol. 127, pp. 402–408, 2017.

[33] S. Verma, L. M. Das, S. S. Bhatti, and S. C. Kaushik, "A comparative exergetic performance and emission analysis of pilot diesel dual-fuel engine with biogas, CNG and hydrogen as main fuels," *Energy Conversion and Management*, vol. 151, pp. 764–777, 2017.

[34] R. G. Papagiannakis, C. D. Rakopoulos, D. T. Hountalas, and D. C. Rakopoulos, "Emission characteristics of high speed, dual fuel, compression ignition engine operating in a wide range of natural gas/diesel fuel proportions," *Fuel*, vol. 89, no. 7, pp. 1397–1406, 2010.

[35] M. Ehsan and S. Bhuiyan, "Dual fuel performance of a small diesel engine for applications with less frequent load variations," *International Journal of Mechanical and Mechatronics Engineering*, vol. 9, no. 10, pp. 30–39, 2009.

[36] K. Cheenkachorn, C. Poompipatpong, and C. G. Ho, "Performance and emissions of a heavy-duty diesel engine fuelled with diesel and LNG (liquid natural gas)," *Energy*, vol. 53, pp. 52–57, 2013.

[37] S. Imran, D. R. Emberson, A. Diez, D. S. Wen, R. J. Crookes, and T. Korakianitis, "Natural gas fueled compression ignition engine performance and emissions maps with diesel and RME pilot fuels," *Applied Energy*, vol. 124, pp. 354–365, 2014.

[38] L. Tarabet, K. Loubar, M. S. Lounici, K. Khiari, T. Belmrabet, and M. Tazerout, "Experimental investigation of DI diesel engine operating with eucalyptus biodiesel/natural gas under dual fuel mode," *Fuel*, vol. 133, pp. 129–138, 2014.

[39] S. S. Kalsi and K. A. Subramanian, "Experimental investigations of effects of EGR on performance and emissions characteristics of CNG fueled reactivity controlled compression ignition (RCCI) engine," *Energy Conversion and Management*, vol. 130, pp. 91–105, 2016.

[40] M. A. Kurniawan, D. Yuvenda, and B. Sudarmanta, "The Effects CNG Injection Timing on Engine Performance and Emissions of A Diesel Dual Fuel Engine," *IPTEK The Journal for Technology and Science*, vol. 30, no. 2, pp. 64–67, 2019.

[41] J. da Silva, D. Yuvenda, and B. Sudarmanta, "Effects of Pilot Injection Timing on The Engine Performance of A Diesel Dual Fuel Engine," *IPTEK The Journal of Engineering*, vol. 5, no. 2, 2019.

[42] J. Vávra, I. Bortel, M. Takáts, and M. Diviš, "Emissions and performance of diesel–natural gas dual-fuel engine operated with stoichiometric mixture," *Fuel*, vol. 208, pp. 722–733, 2017.

[43] M. M. Abdelaal and A. H. Hegab, "Combustion and emission characteristics of a natural gas-fueled diesel engine with EGR," *Energy conversion and management*, vol. 64, pp. 301–312, 2012.

[44] M. F. Mohd Nor, S. Hassan, Z. ZA, and M. MA, "Performance and Emission Characteristics of Supercharged Biomass Producer Gas-Diesel Dual Fuel Engine," *Journal of Applied Sciences*, 2010.

[45] M. M. Abdelaal, B. A. Rabee, and A. H. Hegab, "Effect of adding oxygen to the intake air on a dual-fuel engine performance, emissions, and knock tendency," *Energy*, vol. 61, pp. 612–620, 2013.

[46] S. V Khandal, N. R. Banapurmath, V. S. Yaliwal, G. Manavendra, and P. M. Akshay, "Effect of turbo charging on the performance of dual fuel (DF) engine operated on rice bran oil methyl ester (RBOME) and coconut shell derived producer gas induction," *J Pet Environ Biotechnol*, vol. 6, no. 216, p. 2, 2015.

[47] C. Nayak and R. Swain, "Effect of turbocharger on the emission of a dual fuel diesel engine using producer gas and blends of karanja oil methyl ester," *Br J Renew Energy*, vol. 1, pp. 46–51, 2016.

[48] D. Yuvenda, B. Sudarmanta, A. Wahjudi, and O. Muraza, "Improved combustion performances and lowered emissions of CNG-diesel dual fuel engine under low load by optimizing CNG injection parameters," *Fuel*, vol. 269, no. November 2019, p. 117202, 2020, doi: 10.1016/j.fuel.2020.117202.

[49] B. Yang, L. Wang, L. Ning, and K. Zeng, "Effects of pilot injection timing on the combustion noise and particle emissions of a diesel/natural gas dual-fuel engine at low load," *Applied Thermal Engineering*, vol. 102, pp. 822–828, 2016.

[50] D. Yuvenda, B. Sudarmanta, R. P. Putra, M. Martias, and E. Alwi, "Pengaruh Tekanan Injeksi Gas Terhadap Konsumsi Bahan Bakar dan Efisiensi Termal pada Mesin Diesel Dual Fuel," *INVOTEK: Jurnal Inovasi Vokasional dan Teknologi*, vol. 19, no. 1, pp. 35–42, 2019.

[51] D. Y. Exoryanto, "Studi Eksperimen Unjuk Kerja Mesin Diesel Menggunakan Sistem Dual Fuel Solar-Gas CNG Dengan Variasi Tekanan Injection Gas Dan Derajat Waktu Injection." Institut Teknologi Sepuluh Nopember, 2016.

[52] Z. Wisnu and B. Sudarmanta, "Studi Eksperimen Pengaruh Variasi Start Of Injection Dan Durasi Pemasukan Bahan Bakar Compressed Natural Gas Terhadap Performa Mesin Diesel Sistem Dual Fuel," *Institut Teknologi Sepuluh Nopember*, 2015.

[53] J. You, Z. Liu, Z. Wang, D. Wang, and Y. Xu, "Impact of natural gas injection strategies on combustion and emissions of a dual fuel natural gas engine ignited with diesel at low loads," *Fuel*, vol. 260, p. 116414, 2020.

[54] M. S. Acar and O. Arslan, "Exergo-economic Evaluation of a new drying system Boosted by Ranque-Hilsch vortex tube," *Applied Thermal Engineering*, vol. 124, pp. 1–16, 2017.

[55] M. Ş. Acar, O. Erbaş, and O. Arslan, "The performance of vapor compression cooling system aided Ranque-Hilsch vortex tube," 2019.

[56] J. Stewart, A. Clarke, and R. Chen, "An experimental study of the dual-fuel performance of a small compression ignition diesel engine operating with three gaseous fuels," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 221, no. 8, pp. 943–956, 2007.

[57] A. Sarkar and U. K. Saha, "Role of global fuel-air equivalence ratio and preheating on the behaviour of a biogas driven dual fuel diesel engine," *Fuel*, vol. 232, pp. 743–754, 2018.

[58] J. Cho, S. Park, and S. Song, "The effects of the air-fuel ratio on a stationary diesel engine under dual-fuel conditions and multi-objective optimization," *Energy*, vol. 187, p. 115884, 2019.

[59] J. Zheng, J. Wang, Z. Zhao, D. Wang, and Z. Huang, "Effect of equivalence ratio on combustion and emissions of a dual-fuel natural gas engine ignited with diesel," *Applied Thermal Engineering*, vol. 146, pp. 738–751, 2019.

[60] E. Tomita, Y. Harada, N. Kawahara, and A. Sakane, "Effect of EGR on combustion and exhaust emissions in supercharged dual-fuel natural gas engine ignited with diesel fuel," *SAE Technical Papers*, 2009.

[61] B. Yang, C. Xi, X. Wei, K. Zeng, and M.-C. Lai, "Parametric investigation of natural gas port injection and diesel pilot injection on the combustion and emissions of a turbocharged common rail dual-fuel engine at low load," *Applied Energy*, vol. 143, pp. 130–137, 2015.

[62] J. Liu, F. Yang, H. Wang, M. Ouyang, and S. Hao, "Effects of pilot fuel quantity on the emissions characteristics of a CNG/diesel dual fuel engine with optimized pilot injection timing," *Applied Energy*, vol. 110, no. x, pp. 201–206, 2013, doi: 10.1016/j.apenergy.2013.03.024.