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An Investigation of the Effect of Fuel Supply Parameters on Combustion Process of the Heavy-Duty Dual-Fuel Diesel Ignited Gas Engine

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Abstract: Modern research in the area of internal combustion engines is focused on researching and investigating the technologies that will improve fuel efficiency and decrease emissions. Application of dual-fuel engines is considered as a potential solution to these problems. In the dual-fuel engine, a natural gas-air mixture is ignited by a small amount of the diesel fuel directly injected into a combustion chamber. Pilot fuel injection parameters can strongly effect the combustion process. The aim of this paper is to investigate the effect of such fuel-supply parameters as pilot fuel mass, pilot fuel injection pressure, pilot fuel injection timing and excess air ratio on the combustion process. Investigation is based on the data obtained during bench tests conducted with the use of measurement equipment. The dependences of engine characteristics from the fuel supply parameters under review were obtained based on the results of the experimental study. Optimal values for every investigated fuel-supply parameter were chosen based on the obtained results. Over the course of the investigation, the coefficient for heat release rate according to the Vibe equation was calculated for each operating point.

Keywords: dual-fuel engine; pilot fuel mass; diesel ignited gas engine; pilot fuel injection pressure; start of injection; excess air ratio; combustion; heat release

1. Introduction

According to the more stringent emission legislation and increasing of oil fuel prices, modern research of internal combustion engines is focused on investigation of technologies that will improve fuel efficiency and ecological safety, while retaining efficiency of the combustion process at a high level. Application of the dual-fuel engine, in which a small amount of diesel fuel is used to ignite a natural gas-air mixture, is considered as one of the solutions to the mentioned problems. In such an engine, gaseous fuel is injected through the port gas supply system, while diesel fuel is directly injected into the combustion chamber.

In this article, an investigation on the effect of fuel-supply parameters such as pilot fuel mass, pilot fuel injection pressure, pilot fuel injection timing and excess air ratio on the combustion process of the dual-fuel engine was carried out and is the basis of the obtained results.

The review of published research results was focused on the problem mentioned. Investigation of the combustion process of the dual-fuel engine was carried out by "NAMI" [1,2]. The effect of the pilot fuel mass on reduced brake specific fuel consumption of diesel fuel at different values of torque and excess air ratios was investigated [1]. Pilot fuel mass is a very important parameter when operating in dual-fuel mode, since it provides stable ignition of gaseous fuel-air mixture and affects the emission of harmful substances. At a given operating point (1200 rpm, 8 bar of brake mean effective pressure—BMEP), the pilot fuel mass was defined as a combination of total diesel and gaseous fuel mass injected per cycle. According to the results, the optimal value of the pilot fuel mass was determined to be from 6 to 11 mg per cycle (5–10% of the total mass of diesel and gaseous fuel injected).

The investigation of the effect of the diesel pilot fuel mass on parameters of the combustion process was conducted in [3]. According to the obtained results, an increase in the pilot fuel mass results in a decrease of ignition delay of the gaseous fuel-air mixture and an increase in the mixture part that is ignited by the pilot fuel flame. According to the results, it is found that the increase of the pilot fuel mass leads to higher values of the peak cylinder pressure.

Authors, in [4], conducted an investigation on the effect of pilot fuel quantity and injection pressure on the combustion process and harmful emissions. It is found that an increase in the pilot fuel mass from 2 to 10 mg/cycle leads to a decrease in NO_x emissions by three times, when the pilot fuel injection timing is 12° before top dead center (BTDC).

Authors, in [5], conducted an investigation of the effect of the pilot fuel mass on the combustion process in the dual-fuel engine. The authors concluded that applying a bigger mass of the pilot fuel enhances the engine power. An increase in the pilot fuel mass provides better flame propagation throughout the combustion chamber. Following the investigation, the larger the pilot fuel mass, the shorter the ignition delay of the fuel-air mixture is.

In the paper [6], the effect of the pilot fuel mass of a dual-fuel engine working on gas-diesel mode on the combustion process and emissions was experimentally defined. It was investigated that an increase in the pilot fuel mass leads to a decrease in combustion delay and an increase in the amount of NO_x emissions.

It was experimentally defined in the paper [7] that an increase in the pilot fuel mass directly injected into a cylinder resulted in a better combustion process and increased NO_x emissions. The strongest effect of the pilot fuel mass on the combustion process can be seen at low-load and low-speed conditions, where the amount of gaseous fuel can barely provide stable ignition gaseous fuel-air mixture and combustion only occurs in the close vicinity of the diesel fuel flame front. Conversely, at high-load conditions, the gaseous fuel amount is enough to sustain stable mixture combustion and the mass of the pilot fuel does not have a strong effect in this case.

The authors in the paper [8], conducted a numerical investigation of the effect of the pilot fuel mass on the combustion process at part-load conditions. The authors figured out that, at part-load conditions, the air-fuel mixture is very lean and combustion proceeds very slowly. It was discovered that the flame front structure largely depends on the operating conditions of engine. The authors concluded that an increased amount of diesel fuel can provide stable ignition of a lean gaseous fuel-air mixture and fast propagation of its flame front.

Pilot fuel injection pressure plays an important role in the development of the gas-diesel engine combustion process. An increase in pressure in the fuel rail results in a decrease in hydrocarbons and CO emissions, reflecting the improvement of the combustion process and more efficient combustion of the gaseous fuel-air mixture. For the same reason, a significant increase in NO_x emissions is observed, which could be a reason to limit usage of high diesel fuel injection pressure with regard to the gas-diesel engine.

An investigation of the effect of pilot fuel injection pressure on the combustion process and emissions of the engine working on a blend of biodiesel and natural gas was conducted in [9]. It is noteworthy that the properties of biodiesel fuel is similar to the ones of conventional diesel fuel. According to the results obtained, under the dual-fuel operation mode, an increase in pilot fuel injection pressure from 30 to 150 MPa leads to an increase in NO_x brake specific emissions by 12.9 times.

In the paper [7], the authors conducted an investigation of the effect of diesel pilot fuel injection pressure on the combustion process and emissions of the gas-diesel engine. It was defined that an increase in pilot fuel injection pressure results in better diesel fuel propagation throughout the combustion chamber, an increase in the heat release rate, maximum cylinder pressure and NO_x emissions.

Pilot fuel injection timing is a very important factor that affects gas-diesel engine combustion process efficiency. It was investigated how pilot fuel injection timings affect such combustion parameters like cylinder pressure, ignition delay and cylinder temperature [5]. To sum up, the authors consider that, to avoid a negative impact on the combustion process and engine in general, pilot fuel injection timings need to be individually determined for each operating point.

In the paper [10], an investigation of the effect of the pilot fuel supply parameters on emissions at low-load conditions was conducted. According to the obtained results, advancing the pilot fuel injection timing results in an increase in the maximum cylinder pressure and heat release rate. Advancing the pilot fuel injection timing results in an increase in NO_x emissions.

In order to achieve low NO_x brake specific emissions and high fuel efficiency in a dual-fuel gas-diesel engine, the author of [11] analyzed different pilot fuel injection timings in a single-cylinder diesel engine. At full-load conditions and a speed of 1700 rpm, the optimal pilot fuel injection timing is in a range between 25° and 40° BTDC. Operating at these timings allows decreasing NO_x brake specific emissions by 3.9–7 times due to longer diesel fuel ignition delay and combustion at a lower heat release rate.

In the paper [12], the authors investigated the effect of pilot fuel injection timing on the combustion process and emissions in a dual-fuel engine. It was defined that the use of more advanced pilot fuel injection timings allows obtaining combustion that is more complete. Higher heat release rates during combustion of a premixed air-fuel mixture leads to an increase in combustion temperature.

In the article [13], it was experimentally defined that applying more advanced pilot fuel injection timings within the range of the timings of a conventional diesel engine results in an increase in the maximum cylinder pressure, efficiency and NO_x emissions throughout the range of speed and load conditions. Moreover, applying more advanced pilot fuel injection timings results in a decrease in unburned CH_4 at low-load and low-speed conditions.

An investigation of the effect of the pilot fuel injection timing on indicated pressure in a cylinder was conducted in [14]. According to the experimentally obtained results, when advancing the pilot fuel injection timing, cylinder pressure increases.

The author in [15] investigated the effect of the pilot fuel injection timing on the combustion process in a gas-diesel engine. It was experimentally defined that when advancing the pilot fuel injection timing from 10° to 30° BTDC, the maximum cylinder pressure increases, which in turn, leads to an increase in combustion process efficiency and torque.

The author in the paper [9], defined that the advanced pilot fuel injection timings lead to an increase in the maximum cylinder pressure, combustion process efficiency and NO_x emissions. Furthermore, the author investigated that the more advanced pilot fuel injection timings allow more complete combustion to be obtained, in low-load and medium-load conditions.

In the paper [16], it was defined that the advanced pilot fuel injection timings lead to an increase in the maximum cylinder pressure. In addition, the author investigated that the advanced pilot fuel injection timings result in an increase in NO_x emissions.

In the paper [17], an experimental investigation of the effect of the pilot fuel injection timing on the combustion process and emissions was conducted. According to the results, it was defined that when advancing the pilot fuel injection timing from 11° to 25° BTDC, the maximum cylinder pressure increases. The subsequent advancement of the pilot fuel injection timing from 25° BTDC results in a decrease in the maximum cylinder pressure. It was also found that, when the pilot fuel injection timing is within the range of 20° to 25° BTDC, minimum air-fuel mixture ignition delay takes place. Thus, according to the author's opinion, the optimal pilot fuel injection timing is in the range of 20° to 30° BTDC.

The researchers of "NAMI" conducted an investigation in order to define the optimal value of excess air ratio (λ) that, on one hand, provides complete and effective combustion of gaseous fuel, and on the other hand, provides stable ignition of the minimum mass of diesel pilot fuel. It was defined that the highest engine efficiency along with the minimum total brake specific fuel consumption of both fuels, in gas-diesel operating mode, is achieved when the excess air ratio is within the range of 1.3 to 1.45.

In the paper [18], an experimental investigation of the effect of excess air ratio on the combustion parameters and NO_x emissions in a dual-fuel engine was conducted. It was defined that the highest combustion efficiency is achieved when the excess air ratio is within the range of 1.40 to 1.55. However, operating at a mixture with such an excess air ratio results in an increase in NO_x emissions in comparison with NO_x emissions when operating at mixtures with higher values of excess air ratio.

The effect of advanced injection timing on the performance of natural gas (NG) used as primary fuel in dual-fuel combustion was examined in [19]. It was defined that the advanced timing system incurs a penalty on fuel consumption for a given operating condition (2400 rpm and 3000 rpm at low-load). The poor performance of gas engines at low load levels is due to the effect of gas residuals and low cylinder temperature.

The author in the paper [20] compared the effect of diesel pilot fuel injection timing on the combustion noise (maximum pressure rise rate during combustion) and ignition delay of a dual-fuel engine. It was defined that with the presence of gaseous fuel in the fuel mixture, any advance in pilot fuel injection results in a longer ignition delay period and an increase in pressure rise rate.

The author, in [21], investigated the effect of pilot fuel/gas ratio on combustion process parameters and knock characteristics of a dual-fuel engine. Dual-fuel operation shows longer ignition delay as measured by the author. The degree of knock in this phase depends on the ratio of the alternative fuel (NG) to the pilot fuel and on the load and speed of operation. The increase in speed increases the ignition delay when running on pure diesel fuel, hence the quantity of premixed pilot fuel that takes part in combustion increases. Increasing the pilot fuel and reducing primary fuel reduces the knocking phenomena in dual-fuel engines.

This research is aimed at investigating the effect of fuel-supply parameters such as diesel pilot fuel mass, pilot fuel injection pressure, pilot fuel injection timing and excess air ratio on the combustion process of a dual-fuel, gas-diesel engine. The presented overview of the studies dedicated to this problem, demonstrates that a lot of attention is paid to this problem nowadays, and shows that it is relevant for further, more detailed investigations of the development of the combustion process in dual-fuel engines.

2. Materials and Methods

The object of the investigation into the effect of fuel-supply parameters is an in-line six-cylinder heavy-duty diesel engine with a total displacement of 11.96 L. The engine was converted for operation with natural gas with the use of a small diesel fuel amount, called pilot fuel, as an ignition source. The main parameters of the engine under research are listed in Table 1. The main properties of the fuels used during the experimental investigations are cited in Table 2.

Table 1. Main characteristics of the engine under investigation.

Name of Parameter	Value
Engine type	Dual-fuel diesel-ignited natural gas engine equipped with the two-stage turbocharging system and two intercoolers
Geometrical compression ratio	16.5
Net power, kW	515
Rated speed, rpm	1900 ± 25
Maximum torque, Nm	2350
Speed of maximum torque, rpm	1100–1400
Minimum idle speed, rpm	600 ± 50
Maximum idle speed, rpm	2150
Specific fuel consumption according to full-load curve, g/kWh	
minimum at a speed of 1100–1600 rpm	185
at the gross power	210

Table 2. Properties of the used fuels.

Property	Value
Diesel Fuel	
Cetane number	54.7
Kinematic viscosity at 20 °C (mm^2/s)	4.5
Density at 15 °C (kg/m^3)	833
Flash point (°C)	71
Natural Gas	
Density in 1 atm, at 300 K (kg/m^3)	0.754
Stoichiometric air to fuel ratio (vol %)	9.936
Volumetric heating value (MJ/m^3)	32.970
Boiling point (°C, at 1 atm)	−126
Mass lower heating value (MJ/kg)	43.726

The experimental investigations were conducted with the use of the ZÖLLNER-KIEL test bench, equipped with the hydraulic brake machine. Air mass flow was measured with the use of the AVL FLOWSONIX AIR 150 ultrasonic flow meter that measures in the range of 0 to 2880 kg/h and has an accuracy of ±1%. Fuel mass flow was measured with the use of the AVL 733 flow meter. Yokogava Rotamass RCCS30-M01D4SH was used to measure gaseous fuel mass flow. To define excess air ratio on the engine under investigation, an Innovate Motorsports LC-1 O_2 Lambda sensor was mounted. It enables the determination the value of excess air ratio by means of detecting the composition of exhaust gases. A schematic diagram of experimental equipment is provided in Figure 1.

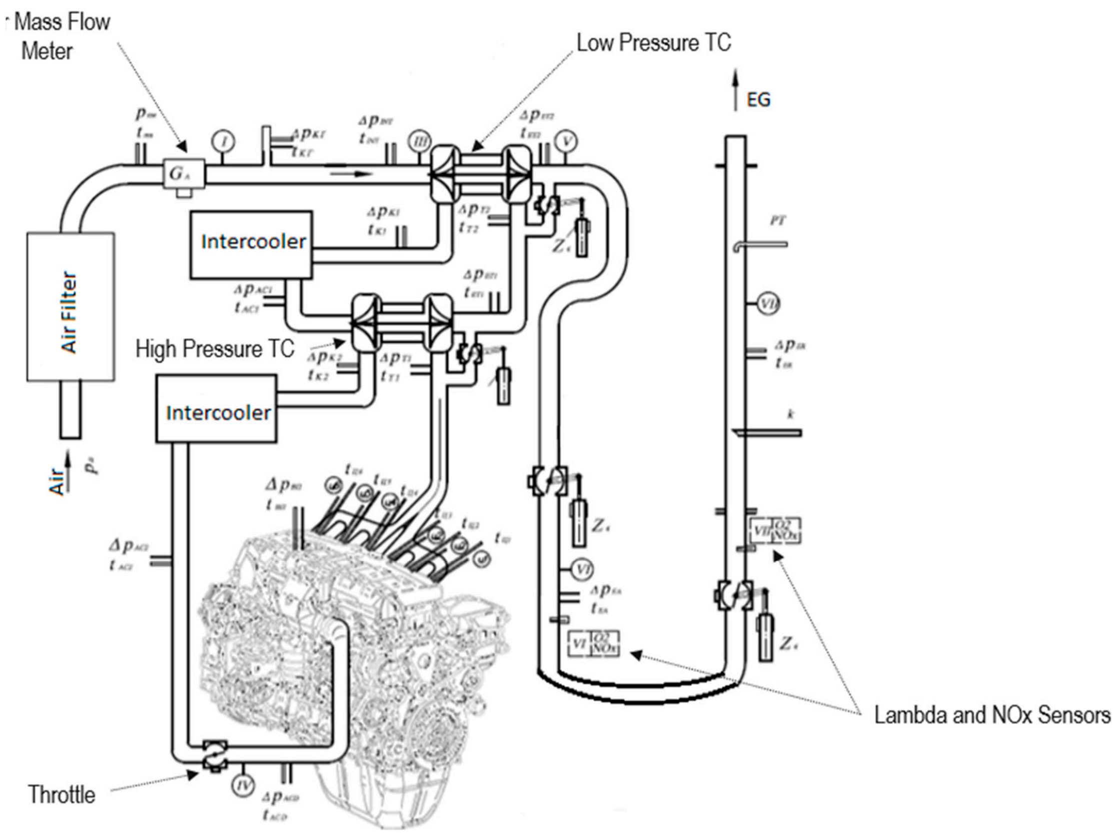

Figure 1. Schematic diagram of experimental equipment.

An AVL Indiset was used to evaluate cylinder pressure and an AVL Indicom was used to analyze the measurement results obtained. The further processing of the results was conducted with the use of the BURN utility of AVL BOOST software (Version 2019, Manufacturer AVL GmbH, Graz, Austria).

In order to work in a dual-fuel mode, the port gas supply system was installed on the engine. Gaseous fuel are supplied to the engine through channels in an intake manifold with the use of low-pressure fuel injectors. Diesel fuel is supplied through a conventional fuel-supply system. In addition, the engine is equipped with a throttle and two electronic control units, one of them is responsible for diesel fuel supply and the other is responsible for gaseous fuel supply and throttle control.

The testing procedure included experimental investigations that enabled estimation of the effect of such fuel-supply parameters as diesel pilot fuel mass, pilot fuel injection pressure, pilot fuel injection timing and excess air ratio, at speeds of 1000, 1400 and 1800 rpm and at specified torque values of 300, 600 and 1200 Nm. The most representative results are included in this paper due to the large amount of the results obtained. The experimental conditions of the operating points, reviewed below, are listed in Table 3.

Table 3. Experimental conditions. BTDC, before top dead center; CA, crank angle; NG, natural gas.

Test Number	n (rpm)	Specified Brake Torque (Nm)	BMEP (bar)	Pilot Fuel Mass (mg per Cycle)	Pilot Fuel Injection Timing (°CA BTDC)	Pilot Fuel Injection Pressure (bar)	Excess Air Ratio	Pilot Fuel Mass Fraction	NG Mass Fraction
1	1400	600	5.94	5	10	600	1.4	0.1195	0.8805
			6.49	10				0.3278	0.6722
			7	15				0.2256	0.7744
			7.8	20				0.2784	0.7216
			8.2	25				0.3217	0.6783
2	1000	600	6	7	17	300–1300	1.4	0.0936	0.9064
3	1000	600	6	8	0–20	600	1.4	0.1063	0.8937
4	1400	600	5.5	8	9	600	1.2–1.6	0.1111	0.8889

3. Results and Discussion

The most representative results, according to the measurements obtained for each of the parameters, are given below. Specified values of the other parameters, that were constant during the testing, are also given in Table 3.

3.1. Effect of Pilot Fuel Mass

Following the experimental investigation of this fuel-supply parameter, the results, obtained at a speed of 1400 rpm and at a specified brake torque of 600 Nm, are presented. When conducting the tests, excess air ratio was kept at a value of 1.4, pilot fuel injection timing was kept at a value of 10° BTDC, and pilot fuel injection pressure was kept at a value of 600 bar. Diesel fuel pilot mass was changed from 5 to 25 mg per cycle.

Engine parameters, depending on pilot fuel mass, are given in Figure 2. As can be seen in Figure 2, an increase in pilot fuel mass resulted in an increase in brake power and torque. This is because, when increasing pilot fuel mass, a larger amount of fuel burns over each cycle, more heat is released and combustion process efficiency increases. This explains the decrease in total brake specific fuel consumption of both fuels, when the pilot fuel mass was increased. Gaseous fuel mass flow rate changed insignificantly during the tests.

As can be seen from Figure 2, an increase in pilot fuel mass resulted in an increase in air mass flow. This is because a constant value of excess air ratio was provided using throttle opening angle. It can be seen that an increase in pilot fuel mass resulted in an increase in NO_x brake specific emissions since the temperature in a cylinder increased in direct proportion to pilot fuel mass and the main mechanism of NO_x emissions formation is thermal.

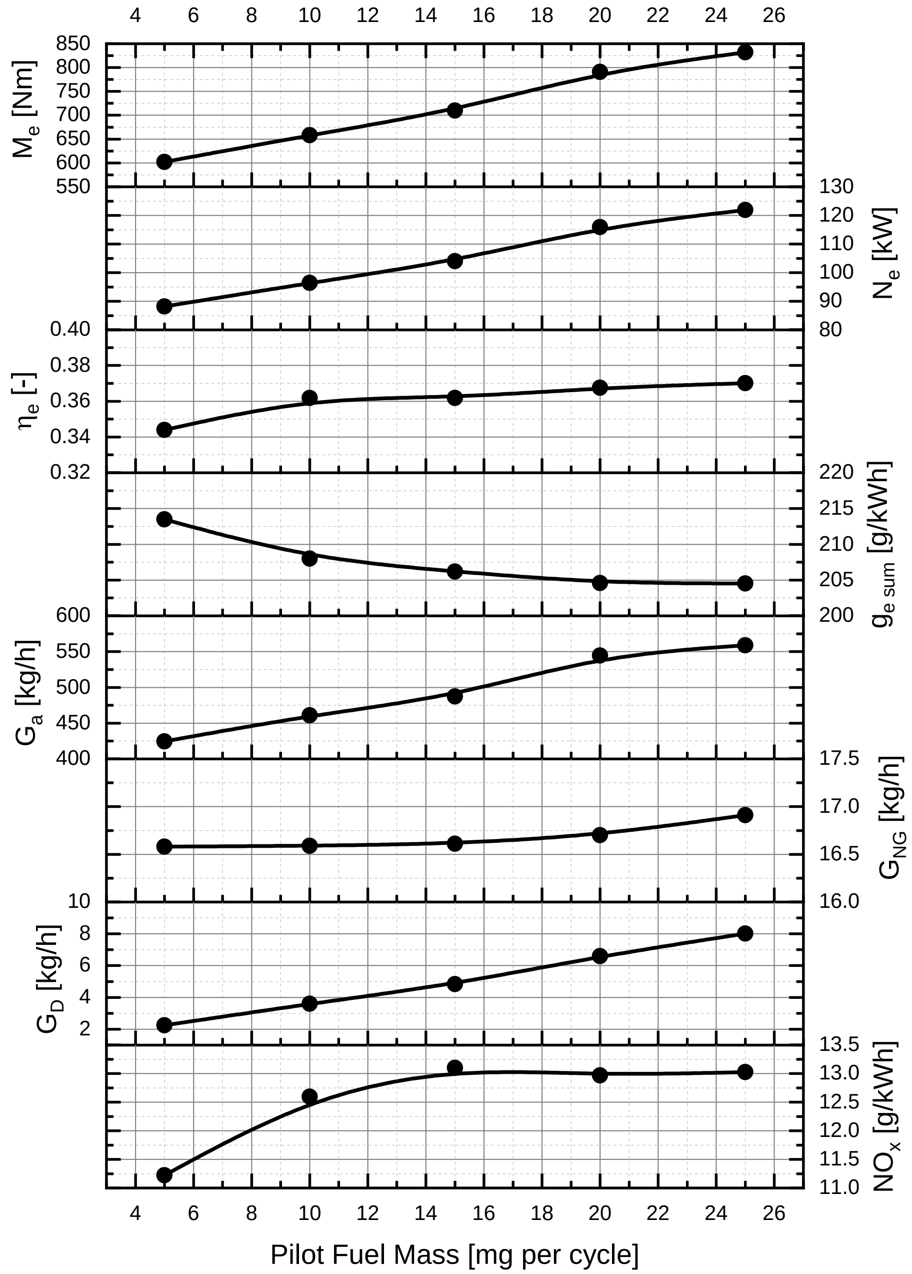

Figure 2. Engine parameters versus pilot fuel mass (n = 1400 rpm). M_e, brake torque; N_e, brake power; η_e, brake efficiency; $g_{e\ sum}$, total brake specific fuel consumption of both fuels; G_a, air mass flow; G_{NG}, Natural gas mass flow; G_d, diesel fuel mass flow; NO_x, nitrogen oxides brake specific emissions.

Cylinder pressure curves, depending on diesel pilot fuel mass, are given in Figure 3. It can be seen from the figure that, when pilot fuel mass was increased, cylinder pressure increased from 65 up to 99 bar. Increasing pilot fuel mass from 5 to 25 mg per cycle led to the pressure rise rate increasing by 6.5 times.

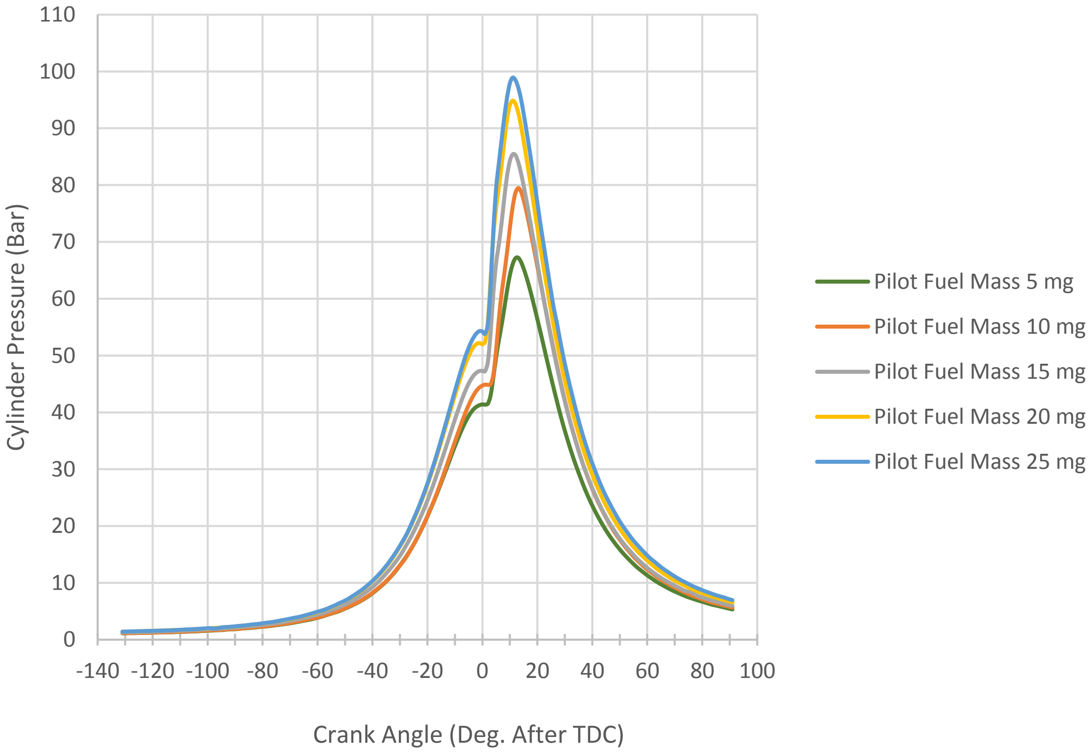

Figure 3. Cylinder pressure versus crank angle (Start of pilot fuel injection (SOI) = 10° BTDC). TDC, top dead center.

Heat release rate curves, depending on pilot fuel mass, are given in Figure 4. As can be seen from the graph, an increasing pilot fuel mass resulted in increasing heat release rate. This is because a higher amount of diesel fuel, when injected into a cylinder and mixed with gaseous fuel-air mixture, provides a higher amount of ignition centers. Combustion develops more rapidly and combustion temperature increases, thus improving combustion process efficiency, as can be seen from Figure 2.

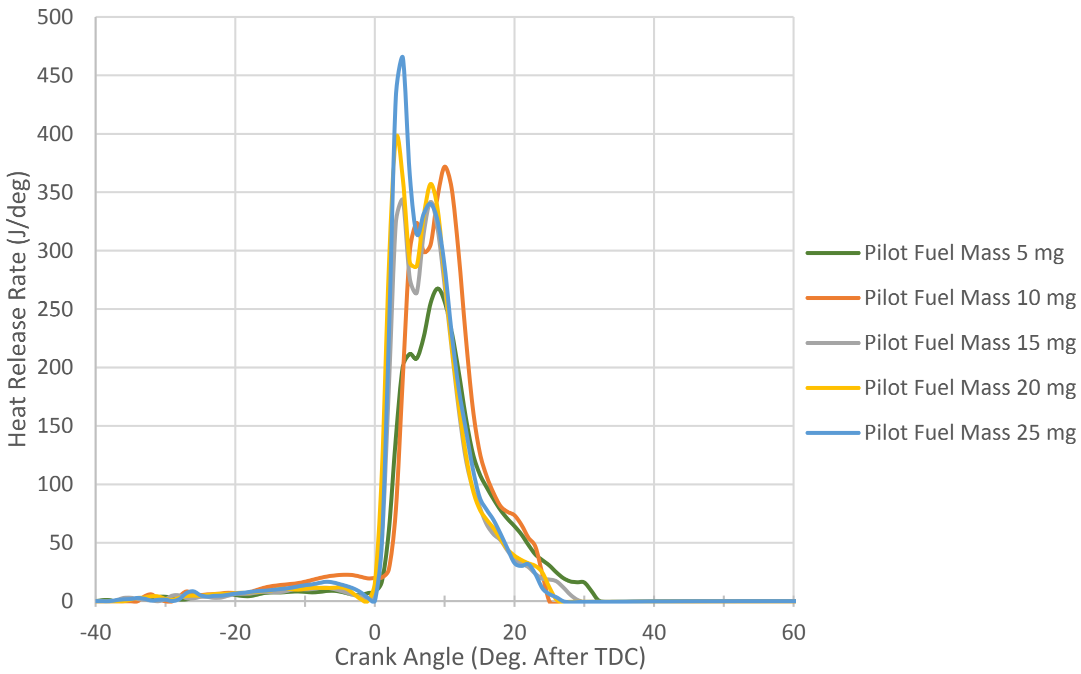

Figure 4. Heat release rate versus crank angle (SOI = 10° BTDC).

In addition, a higher amount of diesel fuel ignition centers ignites a higher amount of gaseous fuel-air mixture throughout the combustion chamber, and that is why an increase in pilot fuel mass from 5 to 25 mg per cycle resulted in a 50% increase in the heat release rate of premixed gaseous fuel-air mixture. When the pilot fuel mass was increased from 5 up to 25 mg per cycle, combustion duration decreased by 8° crank angle (CA) and ignition delay decreased by 18%.

According to the results of the experimental investigation, the coefficient for calculation of relative heat release, according to the Vibe formula, was defined as follows:

$$x_i = 1 - exp\left[-6.908\left(\frac{\tau_i}{\tau_{com}}\right)^{m+1}\right] \quad (1)$$

where τ_i is the current combustion angle, i.e., $\tau_i \in [0,\ \tau_{com}]$; τ_{com} is the combustion duration; m is the Vibe coefficient.

The obtained value of Vibe formula coefficients is given in Table 4.

Table 4. Vibe coefficient *m* and combustion parameters.

Pilot Fuel Mass (mg)	Vibe *m*	Start of Combustion (°ATDC)	Combustion Duration (°CA)
5	1.2	1	30
10	1.3	1	28
15	1.4	−1	28
20	1.3	−1	26
25	1.28	−1	22

As can be seen from Table 4, the maximum value of the Vibe coefficient was achieved when the value of pilot fuel mass was 15 mg per cycle.

According to the experimental investigation results, the optimal value of pilot fuel mass is 15 mg per cycle. With this value, short ignition delay of the gaseous fuel-air mixture, rapid combustion and high combustion efficiency are achieved.

3.2. *Effect of Pilot Fuel Injection Pressure*

Following the results of the experimental investigation of this fuel-supply parameter, the results, obtained at a speed of 1000 rpm and a specified torque of 600 Nm, are presented. Over the course of the investigation, excess air ratio was kept at a value of 1.4, pilot fuel injection timing was kept at a value of 17° BTDC, pilot fuel injection pressure was changed from 300 to 1300 bar. Pilot fuel mass was kept at a value of 7 mg per cycle.

Engine parameters, depending on pilot fuel injection pressure, are given in Figure 5. As can be seen from Figure 5, when pilot fuel injection pressure was increased from 300 up to 900 bar, engine power and torque did not change their values significantly, but when the pilot fuel pressure was further increased up to 1300 bar, a decrease in torque by 2.5% and a decrease in power by 6% occurred.

When pilot fuel injection pressure was changed from 300 to 900 bar, combustion process efficiency did not change significantly, but when the pilot fuel injection pressure was further increased up to 1300 bar, combustion process efficiency decreased by 1%.

When pilot fuel injection pressure was increased from 300 to 1300 bar, total brake specific fuel consumption of both fuels, air mass flow and mass flow of both fuels did not change significantly.

As can be seen from Figure 5, an increase in pilot fuel injection pressure from 300 to 1300 bar resulted in an increase of NO_x brake specific emissions by 61% since combustion temperature increased due to an increase in heat release rate.

Cylinder pressure curves, depending on pilot fuel injection pressure, are given in Figure 6. In the figure, it can be seen that an increase in pilot fuel injection pressure from 300 to 1300 bar resulted in an increase in maximum cylinder pressure by 27% and its peak value moved by 5° CA closer to top dead center (TDC). As can also be seen in Figure 6, an increase in pilot fuel injection pressure from 300 up to 1300 bar resulted in an increase in cylinder pressure rise rate by 2.1 times.

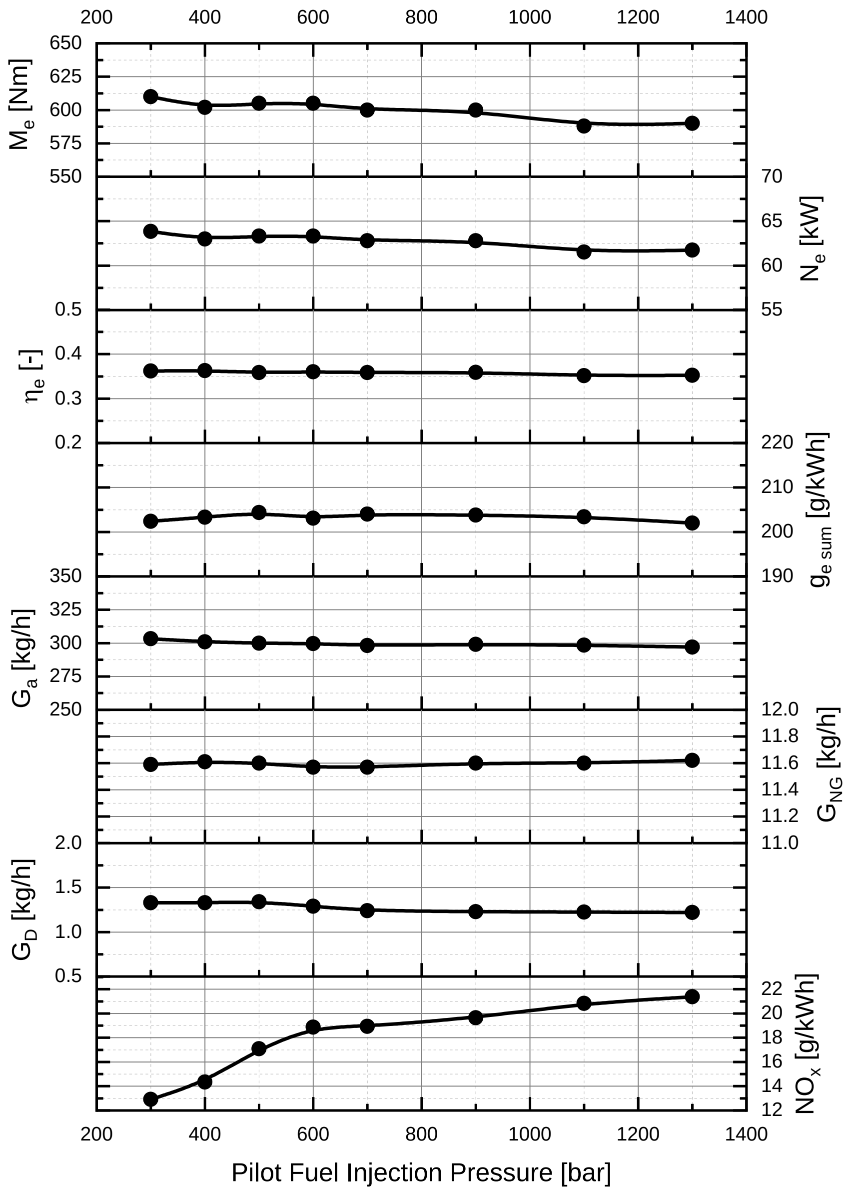

Figure 5. Engine parameters versus pilot fuel injection pressure (n = 1000 rpm).

Heat release rate curves, depending on pilot fuel injection pressure, are presented in Figure 7. As can be seen from the figure, when pilot fuel injection pressure was increased from 300 up to 1300 bar, heat release rate increased by 65.5%. This is because applying an injection of pilot fuel under higher pressure results in a smaller size of pilot fuel droplets injected and more uniform ignition center distribution throughout larger combustion chamber volumes. This means that a larger amount of pilot fuel ignition centers more uniformly distributed throughout the combustion chamber, provides a more stable flame front and more rapid and complete gaseous fuel-air mixture combustion. Therefore, combustion develops more intensively with higher temperatures in the combustion chamber, which facilitated an increase in NO_x brake specific emissions by 61%, when pilot fuel injection pressure was increased.

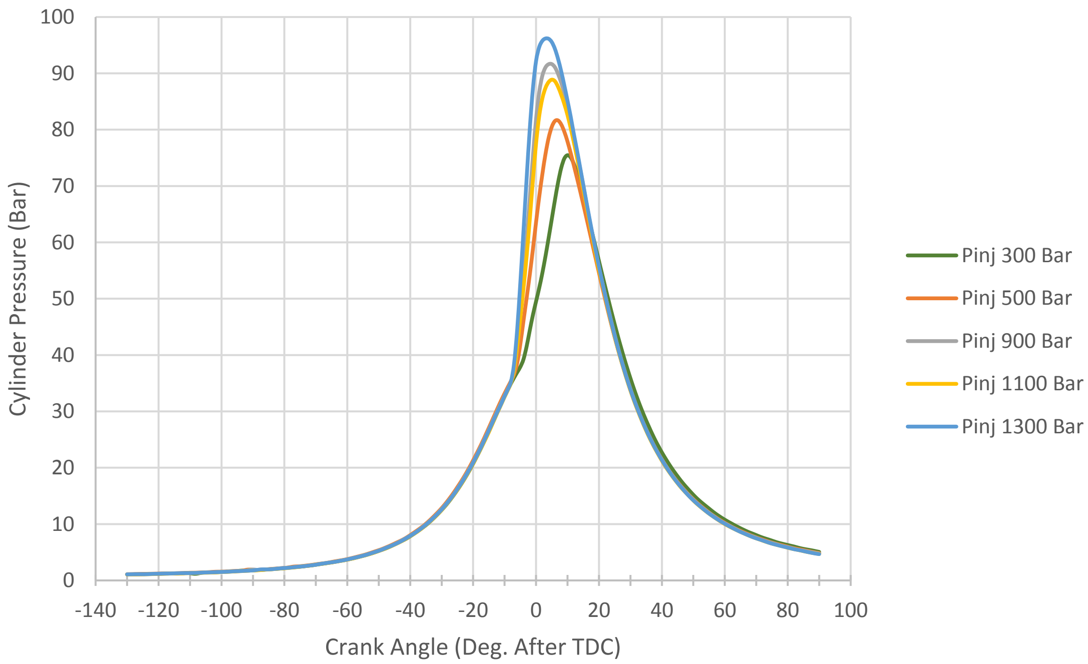

Figure 6. Cylinder pressure versus crank angle (SOI = 17° BTDC). P_{inj}, pilot fuel injection pressure.

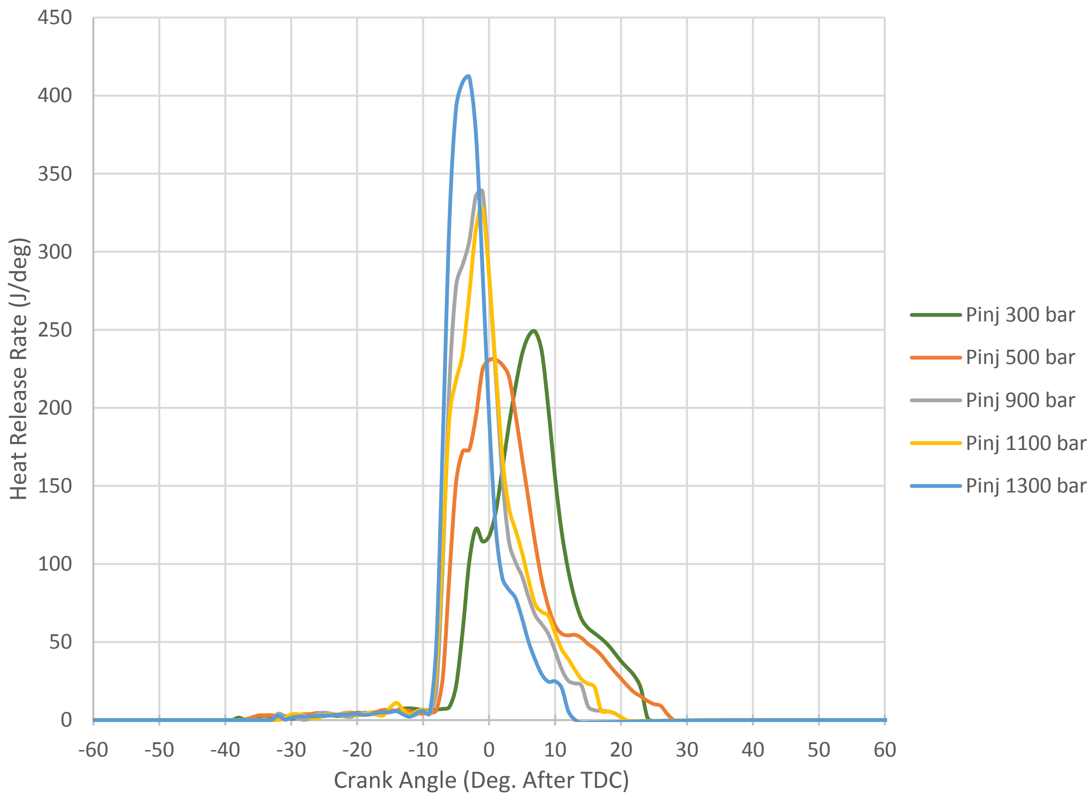

Figure 7. Heat release rate versus crank angle (SOI = 17° BTDC).

The pilot fuel ignition delay was reduced by 35% and the peak value of heat release rate shifted closer to TDC, while pilot fuel injection pressure was increased. Moreover, when pilot fuel injection pressure was higher than 900 bar, the peak value of heat release rate was achieved before TDC. This could be a reason for a decrease in combustion process efficiency since an amount of heat released before TDC can impede piston movement towards TDC. An increase in pilot fuel injection pressure from 300 up to 1300 bar resulted in a decrease in combustion duration by 14.2° CA since combustion develops more intensively.

According to the results of the experimental investigation, the Vibe coefficient for the heat release calculation was defined and is presented in Table 5. It can be seen from Table 5 that the Vibe coefficient was unaffected by changing pilot fuel injection pressure from 300 up to 1300 bar.

Table 5. Vibe coefficient *m* and combustion parameters.

P_{inj} (bar)	Vibe *m*	Start of Combustion (°ATDC)	Combustion Duration (°CA)
300	1.35	−5	33
500	1.35	−8.5	33
900	1.35	−9	25.5
1100	1.35	−9.2	25.1
1300	1.35	−9.3	18.8

Based on the results of the investigation into the effect of the given parameter on the combustion process, the optimal value of pilot fuel injection pressure is 600 bar. Injecting under such a pressure provides high combustion efficiency, uniform diesel fuel ignition center propagation throughout the gaseous fuel-air mixture, stable and intensive combustion and short ignition delay.

3.3. Effect of Pilot Fuel Injection Timing

Following the investigation of the parameter, the results, obtained at a speed of 1000 rpm and a specified torque of 600 Nm, are presented below. Over the course of the investigation, excess air ratio was kept at a value of 1.4, pilot fuel injection pressure was kept at a value of 600 bar, pilot fuel mass was kept at a value of 8 mg per cycle, while pilot fuel injection timing was changed from 0° up to 20° BTDC.

Engine parameters, depending on pilot fuel injection timing, are given in Figure 8. As can be seen in the figure, when pilot fuel injection timing was equal to 10° BTDC, maximum combustion efficiency, torque and power were achieved. This is because, when applying injection timing more advanced or more retarded than 10° BTDC, pilot fuel ignition delay increases and combustion takes place in a larger volume of the combustion chamber. When pilot fuel injection timing was 10° BTDC, minimal total brake specific fuel consumption of both fuels was achieved. This is because combustion efficiency is maximal at this point. Over the course of the experimental investigation, both fuels and air mass flow did not change significantly. When applying more advanced pilot fuel injection timings, there was an increase in NO_x brake specific emissions by 2.6 times. This can be related to higher combustion temperatures, when advancing pilot fuel injection timing.

Cylinder pressure curves, depending on pilot fuel injection timing, are presented in Figure 9. As can be seen in the figure, advancing pilot fuel injection timing from 0° up to 20° BTDC resulted in an increase in maximum cylinder pressure by 2.15 times and its peak value shifted towards TDC. When changing pilot fuel injection timing from 0° up to 20° BTDC, pressure rise rate increased by 2.12 times.

Heat release rate curves, depending on pilot fuel injection timing, are presented in Figure 10. As can be seen from the figure, when pilot fuel injection timing was advanced, heat release rate increased by 2.6 times. This is because, when applying more advanced injection timings, ignition delay increases and there is more time available for diesel fuel evaporation and mixture formation. As a result, diesel fuel ignition centers propagate more uniformly and a more stable flame front develops throughout the gaseous fuel-air mixture volume.

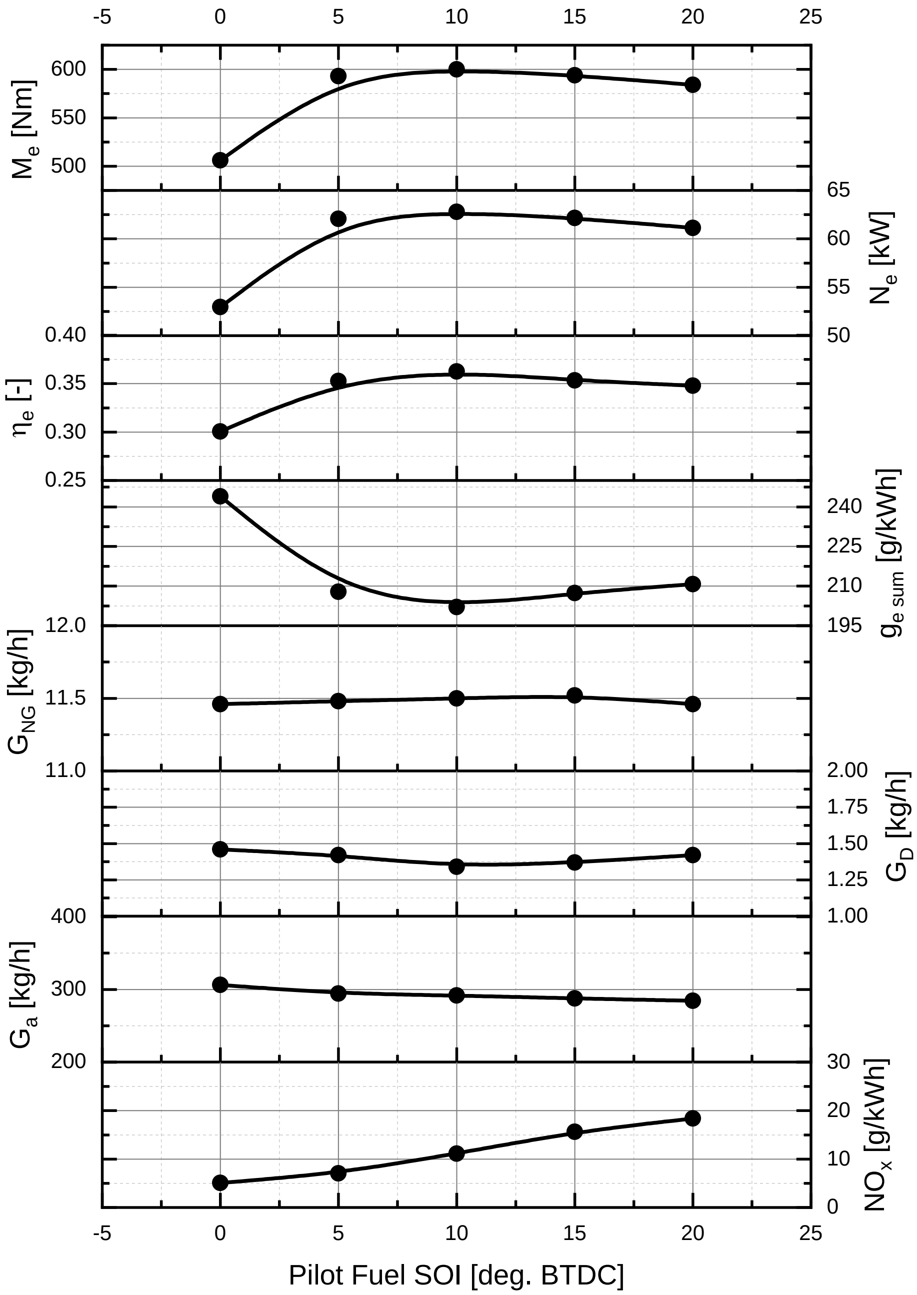

Figure 8. Engine parameters versus pilot fuel start of injection (n = 1000 rpm).

As a result of more advanced pilot fuel injection timings, the start of combustion also shifted to be more advanced relative to TDC. This means that fuel charge is retained under higher pressure and temperature, high temperatures improve oxidation reactions, thus providing more intensive and complete combustion of most of the gaseous fuel-air mixture with a higher temperature and shorter ignition delay. This explains the increase of NO_x brake specific emissions by 2.6 times, when pilot fuel injection timing was advanced. Combustion duration decreased by 2.25 times, when pilot fuel injection timing was advanced from 0° to 20° BTDC. This is related to increased combustion process intensity. When using retarded pilot fuel injection timing, diesel fuel ignition delay increased and combustion occurred under a pressure and temperature that was insufficient for stable gaseous fuel-air mixture flame front propagation which resulted in incomplete combustion.

According to the investigation results, minimal ignition delay was achieved, when pilot fuel injection timing was 10° BTDC.

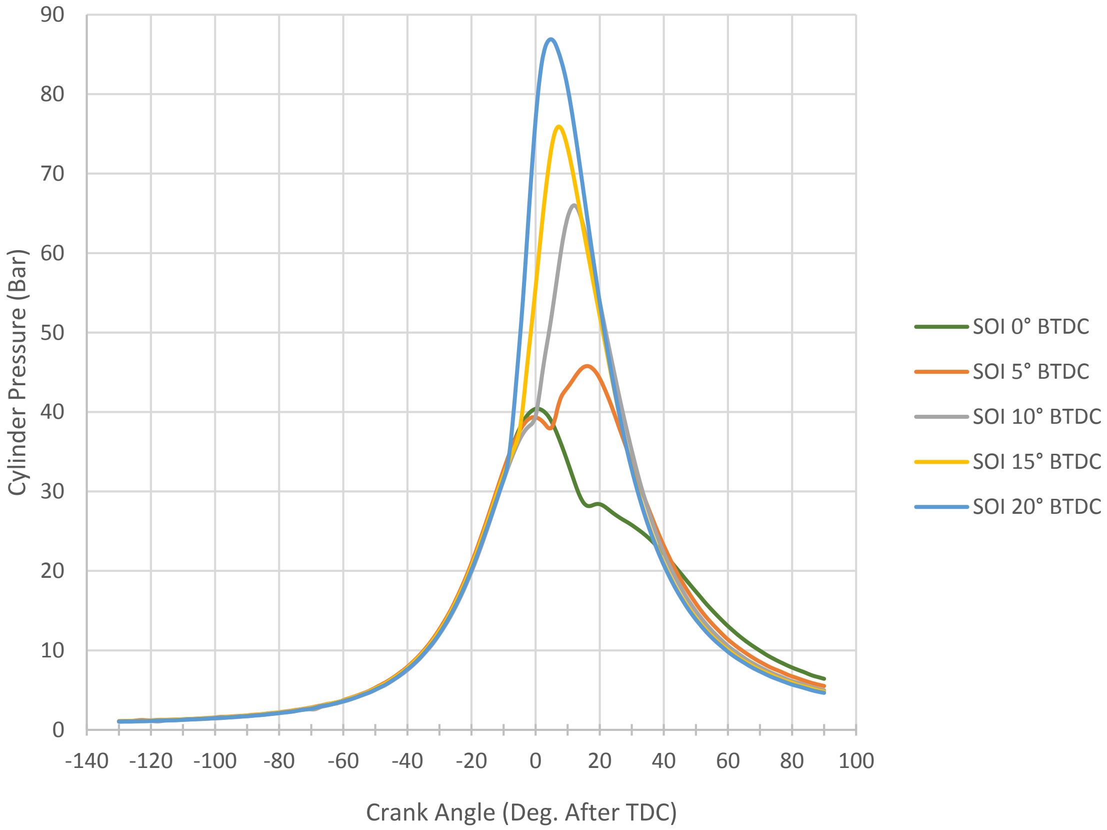

Figure 9. Cylinder pressure versus crank angle.

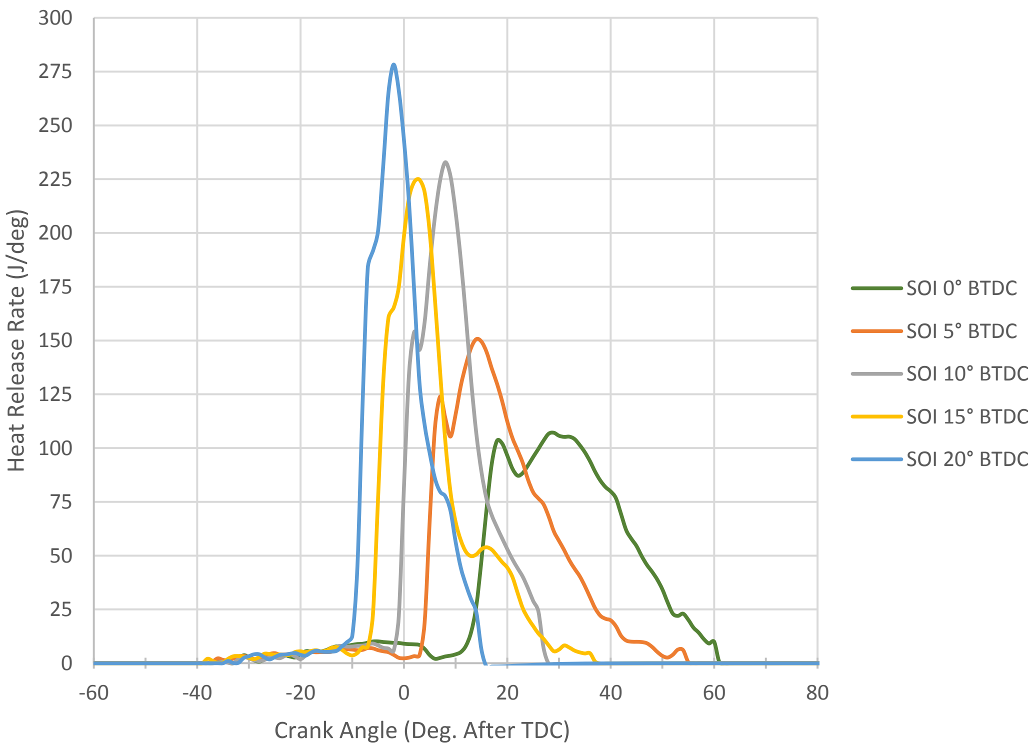

Figure 10. Heat release rate versus crank angle.

The Vibe coefficient for heat release calculation was defined during the investigation results analysis. It is provided in Table 6.

Table 6. Vibe coefficient *m* and combustion parameters.

SOI (°BTDC)	Vibe *m*	Start of Combustion (°ATDC)	Combustion Duration (°CA)
0	1.2	7	70
5	1.21	1	50
10	1.45	−4	36
15	1.46	−9	35
20	1.48	−12	31

As can be seen from Table 6, when pilot fuel injection timing was advanced from 0° up to 20° BTDC, the Vibe coefficient increased and had a maximal value of 1.48.

According to the investigation of the effect of pilot fuel injection timing on the combustion process, optimal pilot fuel injection timing is 10° BTDC. When using this injection timing, maximum combustion efficiency, minimal total brake specific fuel consumption of both of the fuels and minimal ignition delay were obtained. In addition, an acceptable amount of NO_x brake specific emissions and a sufficient amount of time for gaseous fuel-air mixture formation and stable combustion were provided.

3.4. Effect of Excess Air Ratio

Following the investigation of this parameter, the results, obtained at a speed of 1400 rpm and a specified torque of 600 Nm, are presented below. Over the course of the investigation, pilot fuel injection timing was kept at a value of 9° BTDC, pilot fuel injection pressure was kept at a value of 600 bar, pilot fuel mass was kept at a value of 8 mg per cycle, while excess air ratio was changed from 1.2 up to 1.6.

Engine parameters, depending on excess air ratio, are given in Figure 11. As can be seen in the figure, the maximum value of such combustion process parameters as combustion efficiency, torque and power was obtained, when the excess air ratio was equal to 1.4. In addition, when the excess air ratio was equal to 1.4, minimal total brake specific fuel consumption of both fuels was achieved, which was connected to combustion efficiency.

When increasing excess air ratio, a decrease in the brake engine parameters was observed. This is related to the unstable gaseous fuel-air mixture combustion development in the presence of excess air. Moreover, when an excess air ratio of lower than 1.4 was applied, the brake engine parameters decreased as well. This could be related to the lower boost pressure for lower excess air ratios because the pressure was adjusted with the change of throttle opening angle. That is why, as can be seen in Figure 10, air mass flow increased by 1.36 times, when the excess air ratio was increased. Mass flow rate of both fuels did not change significantly within the range of excess air ratios from 1.2 up to 1.6. An increase in the excess air ratio from 1.2 up to 1.6 resulted in a decrease of NO_x brake specific emissions by 1.71 times since combustion occurs with a smaller amount of fuel compared to the amount of air. Thus, the combustion process is less intensive and has lower cylinder temperatures.

Cylinder pressure curves, depending on excess air ratio, are presented in Figure 12. As can be seen from the figure, when the excess air ratio was increased, there was no direct effect on the cylinder pressure. Thus, maximum cylinder pressure was obtained, at an excess air ratio of 1.4–1.5. When the excess air ratio was decreased, cylinder pressure rise rate increased by 75%.

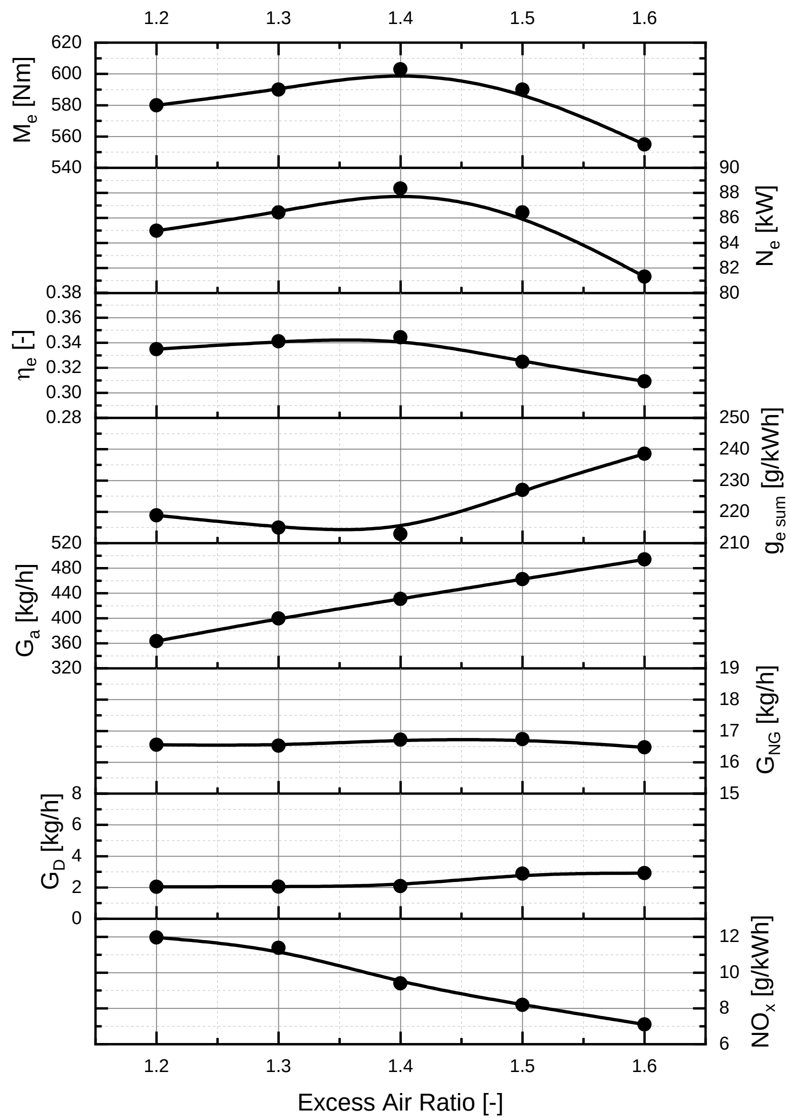

Figure 11. Engine parameters versus excess air ratio (n = 1400 rpm).

Heat release rate curves, depending on excess air ratio, are presented in Figure 13. According to Figure 13, an air-fuel mixture with lower values of excess air ratio burns more intensively and in the presence of higher temperatures, which has a positive effect on gaseous fuel-air mixture ignition. It can be seen from the figure that heat release rate increased and the gaseous fuel-air mixture ignition delay decreased, when the excess air ratio was decreased.

Combustion of the gaseous fuel-air mixture with higher values of excess air ratio begins later in a larger volume of the combustion chamber in the presence of temperatures that are not high enough to provide effective flame front propagation. A decrease in excess air ratio resulted in a decrease in combustion duration by 16° CA and in an increase in pilot fuel ignition delay by 29%. This is because the boost pressure is higher, when applying a higher excess air ratio and that is why the diesel fuel evaporation process and mixture formation occurs faster in the presence of higher pressures and temperatures.

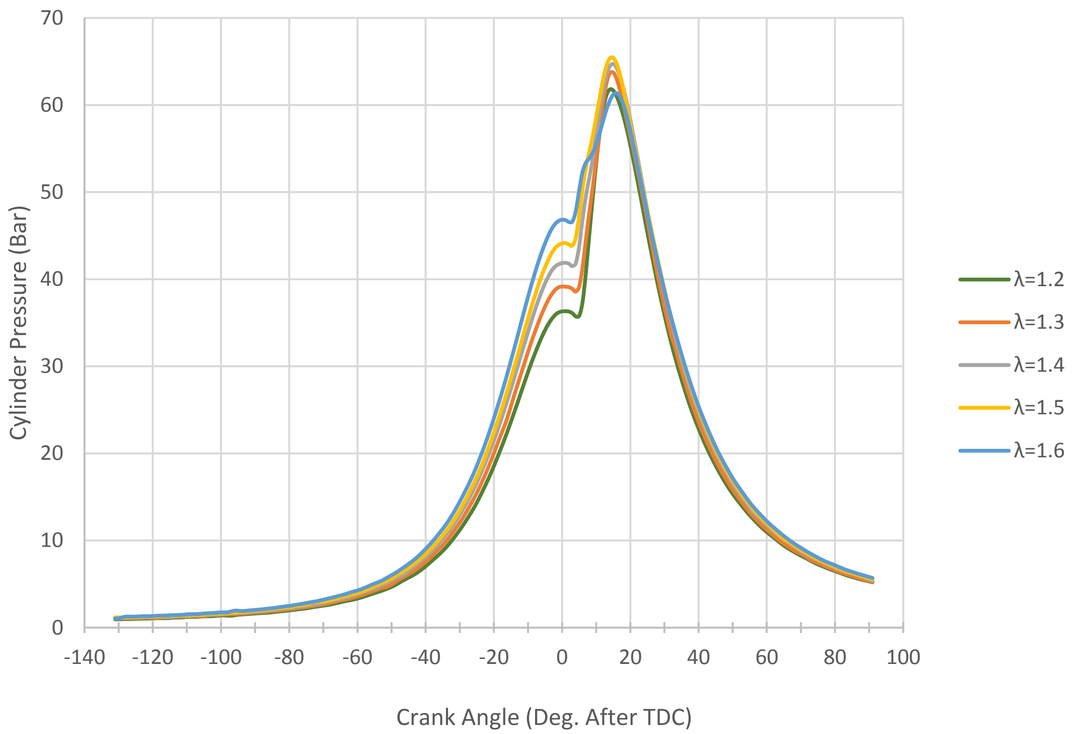

Figure 12. Cylinder pressure versus crank angle (SOI = 9° BTDC).

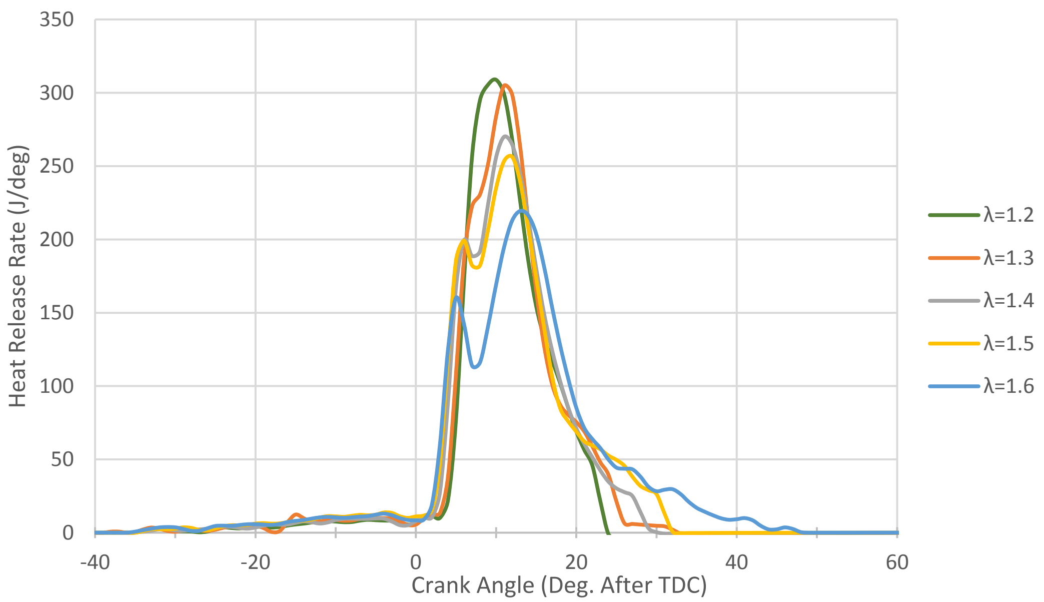

Figure 13. Heat release rate versus crank angle (SOI = 9° BTDC). λ, excess air ratio.

According to the conducted experimental investigation, the Vibe coefficient for heat release calculation was defined. The Vibe coefficient is presented in Table 7.

As can be seen in Table 7, the maximum Vibe coefficient was 1.53 and was obtained when the excess air ratio was 1.4. This confirms the results presented in Figure 11.

According to the results of investigation into the effect of excess air ratio on the combustion process and emissions, the optimal excess air ratio is 1.4. When applying this value of excess air ratio, maximum combustion efficiency, torque and power were obtained. The use of an excess air ratio of 1.4 resulted in acceptable NO_x brake specific emissions and provided a high gaseous fuel-air mixture heat release rate with short ignition delay.

Table 7. Vibe coefficient *m* and combustion parameters.

λ (-)	Vibe *m*	Start of Combustion (°ATDC)	Combustion Duration (°CA)
1.2	1.35	2.5	26
1.3	1.52	1	30
1.4	1.53	−0.5	34
1.5	1.42	−0.8	36
1.6	1.35	−0.9	42

The analysis of the results, obtained over the course of the experimental investigation into the effect of fuel-supply parameters on the combustion process, shows that the obtained results are correlated with those obtained by other researchers in investigations related to the same problem. It means that results obtained in this paper are valid and relevant and can be used in further investigations related to this problem.

It should be noted that, over the course of this investigation, advanced and very significant data, related to the analysis of the combustion process in dual-fuel gas-diesel engines, was obtained and presented.

4. Conclusions

Following the experimental investigation, the analysis of the effect of fuel-supply parameters on the combustion process of gas-diesel engines with a two-stage turbocharging system was conducted. Over the course of the investigation, it was defined that an increase in diesel pilot fuel mass from 5 up to 25 mg per cycle leads to an increase in heat release rate by 50%. Combustion develops more intensively and combustion temperature increases, thus increasing combustion process efficiency. An increase in pilot fuel mass results in an increase of heat release rate during the combustion of a premixed gaseous fuel-air mixture. An increase in pilot fuel mass from 5 up to 25 mg per cycle results in a decrease of combustion duration by 8° CA and in a decrease of pilot fuel ignition delay by 18%.

An increase in pilot fuel injection pressure from 300 up to 1300 bar results in an increase of heat release rate by 65.5%. Combustion occurs more intensively together with higher temperatures in the combustion chamber. This explains the increase of NO_x brake specific emissions by 61%, when increasing pilot fuel injection pressure from 300 up to 1300 bar. Additionally, when increasing pilot fuel injection pressure, diesel fuel ignition delay decreases by 35% and the maximum cylinder pressure peak shifts closer to TDC. An increase in pilot fuel injection pressure from 300 up to 1300 bar reduces combustion duration by 14.2° CA because combustion occurs with higher heat release rates.

When advancing pilot fuel injection timing from 0° up to 20° BTDC, the heat release rate increases by 2.6 times. This is because, when advancing pilot fuel injection timing, diesel fuel ignition delay increases and more time is available for diesel fuel evaporation and mixture formation. This results in more uniform diesel fuel ignition center propagation and provides more stable diffusion of the combustion flame front throughout the gaseous fuel-air mixture. This means that the fuel charge is retained under higher pressure and temperature, thus providing a higher heat release rate and complete combustion of most of the gaseous fuel-air mixture with its reduced ignition delay together with the presence of higher temperatures.

When advancing pilot fuel injection timing from 0° up to 20° BTDC, combustion duration decreases by 2.25 times. Minimal diesel fuel ignition delay is provided at the pilot fuel injection timing value of 10° BTDC.

When decreasing the excess air ratio from 1.6 down to 1.2, heat release rate increases by 29%. This is because an air-fuel mixture with less excess air burns more intensively and has a higher temperature, thus improving air-fuel mixture ignition.

When applying higher values of excess air ratio, combustion of gaseous fuel-air mixture occurs later and under lower pressure together with a temperature that is not high enough to provide stable flame front propagation. When reducing excess air ratio, combustion duration decreases by 16° CA while diesel fuel ignition delay increases by 29%.

According to the analysis of the obtained results, values providing optimal dual-fuel gas-diesel engine combustion process indicators, were defined for each of the parameters under investigation.

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Abbreviations

TDC	Top dead center
BTDC	Before top dead center;
BMEP	Brake mean effective pressure
M_e	Brake torque
N_e	Brake power
η_e	Brake efficiency
$g_{e\ sum}$	Total brake specific fuel consumption of both fuels
G_A	Air mass flow
G_{NG}	Natural gas mass flow
G_D	Diesel fuel mass flow
NO_x	Nitrogen oxides brake specific emissions
x_i	Heat release according to the Vibe formula
τ_i	Current combustion angle
τ_{com}	Combustion duration
m	Vibe coefficient
°CA	Crank angle degree
SOI	Start of pilot fuel injection
P_{inj}	Pilot fuel injection pressure
λ	Excess air ratio

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