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Numerical Analysis of the Effects of Fuel Injection Duration and Spray Angle on the Combustion Process in a Compression Ignition Engine

Fethi BALABAN[1] Serdar HALİS[2*] H. Serdar YÜCESU[3]

[1] *National Defense University, Army NCO Vocational HE School, Balıkesir, Türkiye*
[2] *Pamukkale University, Department of Automotive Engineering, Faculty of Technology, Denizli, Türkiye*
[3] *Gazi University, Department of Automotive Engineering, Faculty of Technology, Ankara, Türkiye*

Keywords

Diesel Engine
CFD
Spray Angle
Injection Duration

Abstract

The changes in injection strategies for diesel engines have a major impact on the performance and pollutant emission characteristics of diesel engines. If injection strategies like injection duration, injection timing, injection pressure and spray angle are properly adjusted, combustion can be improved. The engine performance will increase and emissions will decrease with the combustion improvement. In this work, the influences of injection duration and spray angle on the combustion characteristics of single cylinder, natural aspirated, electronically controlled injection, compression ignition engine were investigated. In the first stage of the work, experiments were executed on a single cylinder CI engine using a Cussons P8160 DC dynamometer. After the experiments, the piston bowl geometry of the engine was modeled and numerical simulation studies were achieved at 7 different injection durations and 7 different spray angles using Converge CFD software. As a result of this study, it was observed that there is a good match between experimental and simulation data of heat release rate (HRR) and in-cylinder pressure. In-cylinder pressure decreased with longer injection duration. The highest max. in-cylinder pressure was roughly 101.0 bar at 4°CA injection duration and the lowest max. in-cylinder pressure was roughly 82.0 bar at 10°CA injection duration. When the HRR data were analyzed, it was seen that as the injection duration increased, the amount of heat released by combustion decreased. When examining the results of the spray angle analysis, it was concluded that there were not very large differences in-cylinder pressure and HRR data, and there was a difference of 1.4 bar between the highest and lowest max. in-cylinder pressure values. In addition, the highest in-cylinder pressure of approximately 86.7 bar was obtained at a spray angle of 77°. It was observed that the CA50 value was obtained at angles closer to the top dead center by increasing the spray angle and decreasing the injection duration. Moreover, the longest combustion durations were realized at 60° spray angle and 10°CA injection duration.

Cite

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Author ID (ORCID Number)	
0000-0002-5072-837X	Fethi BALABAN
0000-0002-6099-7223	Serdar HALİS
0000-0002-7805-6085	H. Serdar YÜCESU

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1. INTRODUCTION

Nowadays, increasing global warming is a significant threat to life on Earth. High energy intensive processes that generate significant carbon dioxide (CO), carbon monoxide (CO_2), hydrocarbon (HC) and carbon black emissions on the earth's surface greatly increase global warming. The internal combustion engine is the main source of these emissions. These emissions consist of the combustion of petroleum-derived fuels such as diesel and petroleum used in internal combustion engines.

In the diesel engine, combustion characteristics are improved to reduce exhaust pollutants and also increase the performance of engine and reduce fuel consumption. Many modification processes have been carried out to improve combustion characteristics. Modifications to the combustion chamber and injection system are the

*Corresponding Author, e-mail: shalis@pau.edu.tr

most important changes. The combustion efficiency of the engine has been increased by improving the movement of air into the combustion chamber through changes in the piston bowl geometry. By using various piston bowl geometries, the turbulent motion of the air entering the combustion chamber can be increased so that the air and fuel mixture in the cylinder is evenly distributed throughout the cylinder (Basshuysen & Schafe, 2004). At the same time, modifications to the injection system in CI engines aim to provide higher atomization of fuel injected inside the cylinder. Through this higher atomization, combustion efficiency is increased by providing a homogenous blend of air and fuel into the piston bowl. Injection system modifications such as injection timing, injection pressure, injection characteristics and spray angle greatly affect combustion in diesel engines. In the literature, many studies have been conducted considering these parameters. Jha et al. (2022) investigated the combustion of diesel-methane fuel pairs at different injection timing in their simulation study. Consequently in this work, they found that the combustion process of diesel was delayed with methane and after the combustion was completed, methane could not participate in the combustion reaction by accumulating in the piston ring gaps, piston crown and near the cylinder liner. Sener (2022) analyzed the influences of the grooved injection method on CI engine pollutant emission and combustion characteristics in a numerical study. Consequently in this work, they concluded that emissions were significantly reduced by using the grooved injection method. Jurić et al. (2019), in their analysis study with different injection methods, concluded that the common rail pressure has less effect on the combustion processes by shifting the injection timing to after TDC and that both single and multiple injection timings are consistent with experimental data. Mohan et al. (2014) researched the influence of injector spray characteristics on pollutant exhaust gases and combustion characteristics in the system using biodiesel. Consequently, they found that a balance between NO_x-soot emission values can be achieved by using a spark plug head injection profile under medium load and medium speed conditions. Huang et al. (2019) researched the effect of pre-injection method on combustion and pollutant exhaust gases of a CI engine using 100% diesel fuel and 30% butane + 70% diesel blend fuel. Consequently in this work, it was found that the in-cylinder pressure enhanced and brake specific fuel consumption (BSFC) reduced with a range of decreasing pre-injection timing and enhancing pre-injection rate. In case of using 100% diesel, the highest maximum in-cylinder pressure was approximately 9.0 MPa at 15% pre-injection rate and 15°CA pre-injection range, and the highest BSFC was roughly 260 g/kWh at 20% injection rate and 45°CA pre-injection interval. They also concluded that soot and NOx emissions increased with decreasing pre-injection range and enhancing pre-injection rate. Yousefi et al. (2018) examined the influences of conventional single injection timing on emissions and combustion in natural gas-diesel double fuel combustion. In this work, they concluded that advancing the single injection timing of diesel engines increased thermal efficiency by approximately 6%, reduced unburnt methane and carbon monoxide emissions by 62% and 61% respectively, and increased NO_x emissions by 74%. Halis et al. (2022) analyzed the influences of lambda and injection timing on RCCI engine combustion. They concluded that the max. cylinder pressure enhanced by bringing forward the timing of the injection. They also concluded that the max. in-cylinder pressure increased and combustion improved by the reduction of the lambda. They obtained the highest in-cylinder pressure and HRR of roughly 45 bar and 213 J/°CA at the start of injection at -50° CA aTDC and at a lambda value of 1.2. Khan et al. (2018) analyzed the influences of different spray angles and piston bowl geometries on pollutant exhaust gases and combustion. They concluded the pressure in the cylinder, the HRR, nitrogen oxide and carbon black emissions increase as the spray angle increases. They also obtained the highest max. pressure in the cylinder and HRR of roughly 70 bar and 80 J/°CA in a toroidal re-entry piston bowl and 165° spray angle. Wei et al. (2014) investigated the effects of different nozzle angles and a new vortex chamber combustion system on combustion and emissions. Consequently, they stated that as the nozzle angle increased, the equivalence ratio and soot emission rose, the amount of NO decreased. Jaichandar et al. (2012) focused on the piston bowl geometry and optimization of injection timing to improve engine performance and pollutant exhaust gases in a CI engine using bio-diesel as fuel. In this work, they finalized that the specific fuel consumption (SFC) and HC, CO and carbon black emissions decreased, but nitrogen oxide emissions increased with the use of toroidal reentrant combustion chamber geometry. It was also found that when a toroidal reentrant piston bowl was used, a decrease in in-cylinder pressure occurred by the retardation of the injection timing due to the ignition delay of about 2°CA. Ranganatha Swamy et al. (2014) analyzed the influences of injection timing, piston bowl geometry and injector nozzle holes on CI engine performance. Consequently in this work, It has been shown that delaying the injection timing increases soot emissions by 20%, while the use of a toroidal piston cup geometry increases brake thermal efficiency and nitrogen oxide emissions and reduces carbon black, carbon monoxide and HC emissions. The injector with 5 nozzle hole numbers provides a more homogeneous air and fuel mixture and reduces soot emissions. In addition, It was found that the use of a 0.2

mm orifice injector increased cylinder pressure and HRR. Mehta and Tamma (1998) investigated the influences of air vortex and injection pressure on combustion characteristics in a CI engine. It is observed that as the swirl ratio increased, the in-cylinder pressure and HRR decreased. They obtained the highest in-cylinder pressure of approximately 70 bar at an air vortex ratio of 2.0 and an injection pressure of 300 bar. They also concluded that the increased injection pressure improved combustion characteristics and allowed combustion to occur in less time. Sener et al. (2020) examined the influences of parameters such as spray angle of fuel, the new version of the swirl combustion chamber, re-entrant piston bowl geometry and injection pressure on engine performance. When the results were analyzed, it was seen that reduced thermal efficiency and increased exhaust emissions by the increase in the spray angle in both the re-entry and basic piston bowl geometry of the engine. They also indicated that pressure inside the cylinder increased and soot emission decreased with increasing injection pressure and the highest in-cylinder pressure was obtained at approximately 11.0 MPa with the use of 150° spray angle and 1000 bar injection pressure in dual swirl piston bowl geometry. Mishra et al. (2023) investigated the influence of hemispherical and toroidal piston bowl geometries on engine performance in a CI engine with HCCI combustion mode. In addition, they used variable spray angles to provide a good mixture of air and fuel in the piston bowl and to reduce fuel density in certain areas of the combustion chamber. Consequently, they concluded that the thermal efficiency increased by 3-5% with the use of toroidal combustion chamber and the combustion processes were improved with modified piston geometry and multi-stage injection strategy. They also defined that the max. in-cylinder pressure increases up to 45° spray angle and decreases up to 70° spray angle. Cengiz and Unverdi (2023) researched the influences of injection timing and injection angle on combustion and exhaust pollutants of a diesel engine using PCCI combustion mode. As a result, they stated that combustion efficiency and average effective pressure increased with decreasing spray inclusion angle; while improvement in NO_x emissions was observed, soot and carbon monoxide emissions decreased. They obtained the highest combustion efficiency of 97.8%, average effective pressure of 3.37 bar, the lowest carbon black emission of 33.5 ppm and the lowest CO emission of 2.2 ppm with staggered spraying into the combustion chamber, 100° spray inclusion angle and -50°CA start of injection. Kumar et al. (2022) investigated the effects of fuel injection pressure and injection timing of Jatropha biodiesel as a pilot fuel on the operation and pollutant exhaust gases of an engine using hydrogen as fuel. Consequently, they found that BSFC increased to 32.15% and nitrogen oxide emissions enhanced by 20.61% at 1500 bar injection pressure and 17°CA bTDC with the use of a biodiesel-hydrogen fuel pair. At 1500 bar injection pressure and 11°CA bTDC, they concluded that unburned HC emissions decreased by 59.12% and soot emissions decreased by 46.18%. They also concluded that the max. in-cylinder pressure and heat dispersion increased with enhancing injection pressure and injection timing. Ge et al. (2022) analyzed the influences of variable multiple injection strategies on the performance and exhaust pollutants of a diesel-biodiesel-ethanol triple mix fuel engine at low idle conditions in their experimental study. They concluded that the diesel-biodiesel-ethanol blend and different main pilot injection timings have a major influence on the CI engine performance and pollutant exhaust gas characteristics. Hao et al. (2022) optimized the injection timing and piston bowl geometry to increase the mixing process of air and fuel in a CI engine and to optimize full load combustion process in their study. They concluded that spray angle has a major effect on the combustion process and mixture of air and fuel, engine power is increased by optimizing the piston bowl geometry. Also, they obtained maximum power as 80 kW at a spray angle of 153°. Using a premixed charge compression ignition (PCCI) combustion mode, Lu et al. (2023) researched the influence of a multiple injection strategy on heavy-duty engine operation and pollutant exhaust gases characteristics. They obtained a very small rise in thermal efficiency of 8.66% with the injection strategy at low speed of the engine and 0.33% at medium engine speeds for single injection with 15° CA bTDC. Pham et al. (2022) researched the effect of spray angle on combustion and polluted exhaust gases in a four-stroke CI engine using natural gas combined with diesel. Consequently, they found that soot emissions were reduced by 17% in dual fuel use and 56% in single diesel use with a spray angle of 150° and the optimal NO_x emission was observed at a spray angle of 145°. They also concluded that the spray angle alone is not sufficient to determine the engine combustion quality.

In this study, a four-stroke diesel engine was operated at a compression rate of 17.5:1, intake air temperature of 300 K and a constant engine speed of 2000 rpm. The effects of fuel injection duration and spray angle on combustion characteristics in a CI engine were analyzed numerically using Converge CFD computer program along with validation of experimental results. Numerical studies investigating the effects of injection parameters such as injection duration and spray angle in a compression ignition engine using diesel fuel are not found in the literature. It is aimed to obtain the best combustion conditions by determining the appropriate injection duration and spray angle in a CI engine using diesel fuel and to overcome this gap in the literature with this numerical research.

2. MATERIAL AND METHOD

2.1. Experimental Set-up

Experiments were achieved by connecting the water-cooled, four-stroke, electronically controlled, direct injection, single cylinder LD510 model Lombardini-Antor CI engine to a Cussons P8160 electric DC dynamometer capable of absorbing 10 kW power at a maximum of 4000 rpm. Technique specifications of the experiment engine obtained from the manufacturer are shown in Table 1.

Table 1. *Characteristics of the experiment engine*

Cylinder number	1
Fuel type	Diesel
Compression rate	17,5:1
Stroke (mm) × cylinder diameter (mm)	90 × 85
Max. torque (Nm)	32,8@1800 rpm
Cylinder volume (cm^3)	510
Max. engine speed (rpm)	3000
Engine power (HP)	12
Crankcase oil volume (lt)	1,75
Fuel tank capacity	5,3
Oil consumption (g/h)	8

The injection system of experiment engine was modified and converted into an electronically controlled common-rail system. Thanks to this system, parameters affecting combustion such as injection pressure, timing, duration and amount can be easily adjusted via electronic controls shown in Figure 1.

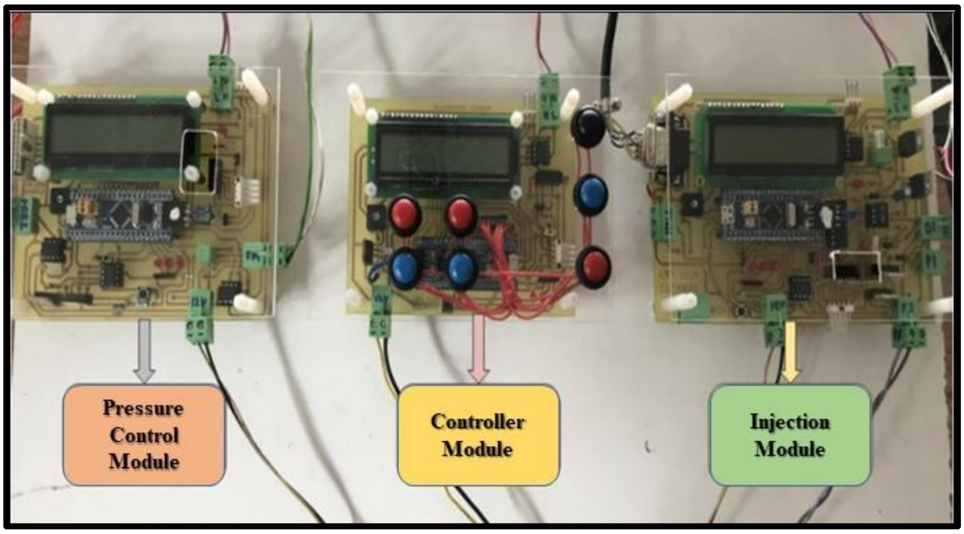

Figure 1. *Fuel injection system*

KISTLER 6056A model cylinder pressure sensor, whose technical specifications are given in Table 2, was used to read the in-cylinder pressure inputs instantaneously during the experiments on the L9Motor. To obtain the most accurate cylinder pressure data, the position of the sensor is very important. For this reason, the in-cylinder pressure sensor was positioned on the cylinder cover near the center of the engine, taking into account the position of the valves and injectors.

Table 2. *KISTLER 6056A sensor technical specifications*

Measurement interval	0 – 250 (bar)
Sensivity	-20 (pC/bar)
Operating temperature	(-20°C) – (+350°C)
Linearity	≤±0.3
Frequency of natural	160 (kHz)

At the same time, the position of the crankshaft is very important for accurate pressure data acquisition. For this reason, OPKON brand 1000 pulse optical incremental encoder was used to determine the position of the crankshaft. Then, National Instruments 6259 USB data transfer card was used to read the data received from the in-cylinder pressure sensor and encoder. In addition, Merriam brand Z50MC2-4F model laminar flow measurement device was used to measure the air consumption of the experiment engine. In general, the schematic of the test rig is shown in Figure 2. In-cylinder pressure, temperature, HRR, SFC, cumulative heat release rate (IHRR) and variable engine efficiency values obtained as a result of the experiments were calculated with a MATLAB code. An average of 50 cycles was obtained with this code for removing cyclic differences and offering a precise method for data collection. The amount of HRR depending on the crank angle is obtained from Eq. 1 by the energy conservation law of thermodynamics (Heywood, 2018).

$$\frac{dQ}{d\theta} = \frac{n_c}{n_c - 1} P \frac{dV}{d\theta} + \frac{1}{n_c - 1} V \frac{dP}{d\theta} + \frac{dQ_{heat}}{d\theta} \tag{1}$$

The heat transfer between the cylinder and the jackets was computed using Eq. 2. In the equation, the heat transfer coefficient was computed using Woshcnie's revised heat transfer model (Heywood, 2018).

$$\frac{dQ_{heat}}{d\theta} = \frac{1}{6n} h_g A\left(T_g - T_w\right) \tag{2}$$

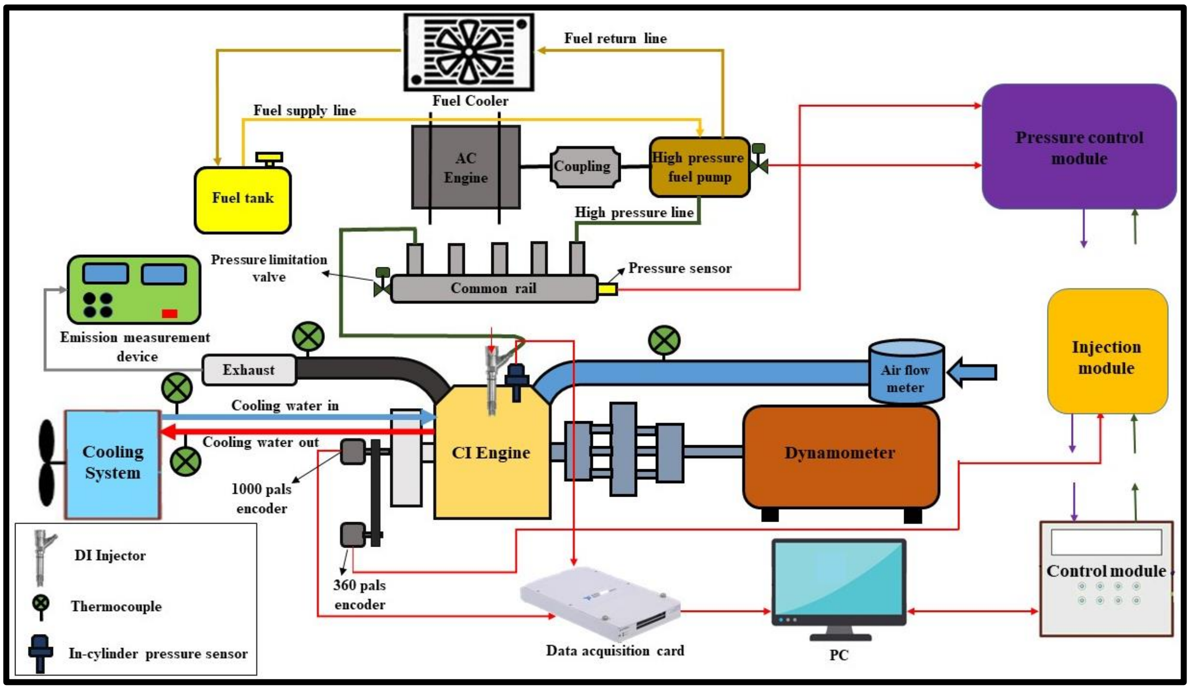

Figure 2. *Schematic of experimental set-up*

2.2. Numerical Model and Validation Study

Converge CFD simulation program was used to analyze the data obtained after the experimental work on a single cylinder CI engine. The piston bowl geometry of the experiment engine was modeled in Solidworks design program. The mesh structure was then applied to the combustion chamber geometry using the auto-mesh determination module. In the simulation, an adaptive mesh refinement (AMR) was applied to sensitive and dense areas of combustion and mobile flow zones. The combustion chamber geometry model and mesh structure of a single cylinder engine are shown in Figure 3.

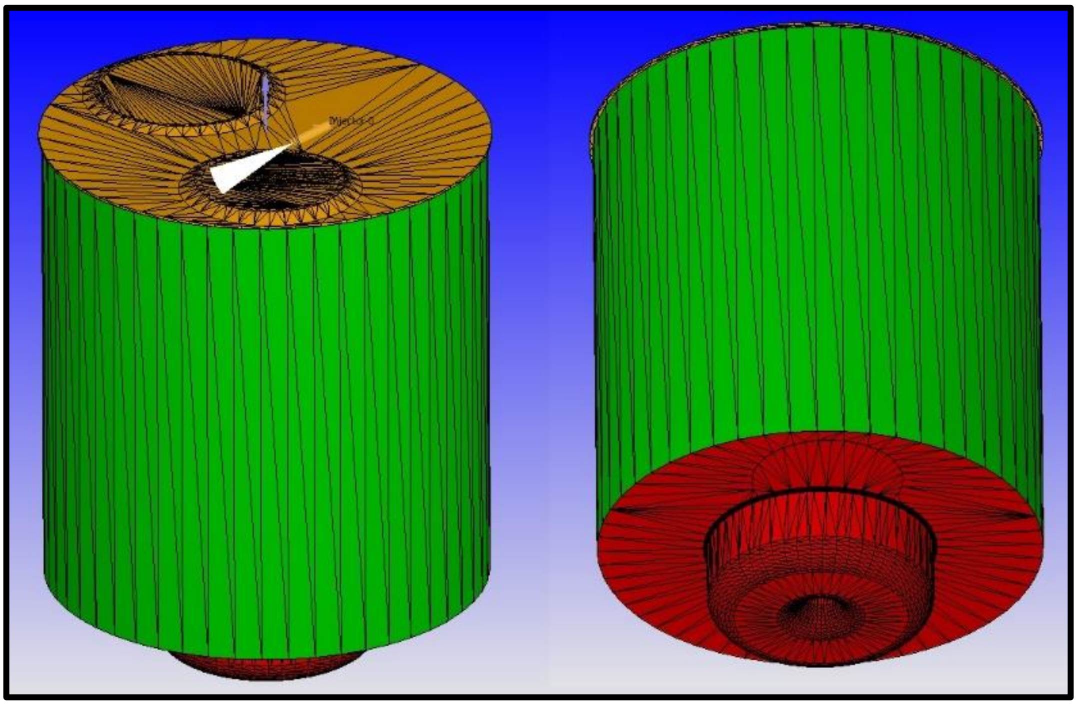

Figure 3. *Piston bowl geometry used in the simulation study*

In the numerical simulation model, the pressure of the injection system was set to 750 bar, injection duration to 8.25°CA, injection timing to 6.5°CA and injection amount to 24 mg/cycle. In addition, the simulation was performed using closed loop assumptions from closing the inlet valve to opening the exhaust valve.

In the simulation study, the Reynolds Averaged Navier-Stokes based Renormalised Group (RNG) k-epsilon turbulence model improved by Yakhot and Orszag (1986) has been used to model the turbulent motion of fuel drops in the combustion chamber. The Kelvin-Helmholtz (KH)/Rayleigh-Taylor (RT) fragmentation model improved by Beale and Reitz (1999) was used to model the fragmentation of fuel spray droplets. In this model, the primary fragmentation of the droplet is predicted using the KH model and the RT model is used to predict the secondary fragmentation. To model the combustion phenomena inside the cylinder, SAGE chemical kinetic solvents as described by Turns (1996) were used. The Naber and Reitz wall impact model developed by Gonzalez et al. (1991) has been used to model the interaction of fuel droplets between the cylinder or cylinder walls. For DSMC computations, the NTC model, on the basis of techniques from gas dynamics, was used to model the collision of fuel droplets (Schmidt & Rutland, 2000). The O'Rourke&Amsden heat transfer model has been used to model the heat transfer to the combustion chamber or cylinder walls (Amsden & Findley, 1997; Converge, 2016).

A validation study was carried out using experimental data and a simulation model. To select the appropriate base grid size, which is one of the most important steps of the validation study, analyses were performed at different base grid sizes. Figure 4 demonstrates the crank angle dependent in-cylinder pressure results obtained from different base grid size analyses. As a result of the numerical simulation study, the optimum base grid size for the simulation model was determined as 5.8 mm. After determining the appropriate base grid size, the numerical simulation model was successfully validated using the initial conditions shown in Table 3. Figure 5 shows the variation of in-cylinder pressure and HRR as a function of crank angle. When the experimental and

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numerical simulation data of the combustion processes of the experiment engine are analyzed, there is a difference of 3°CA in-cylinder pressure, while there is a small difference of 0.5 J/°CA in the HRR.

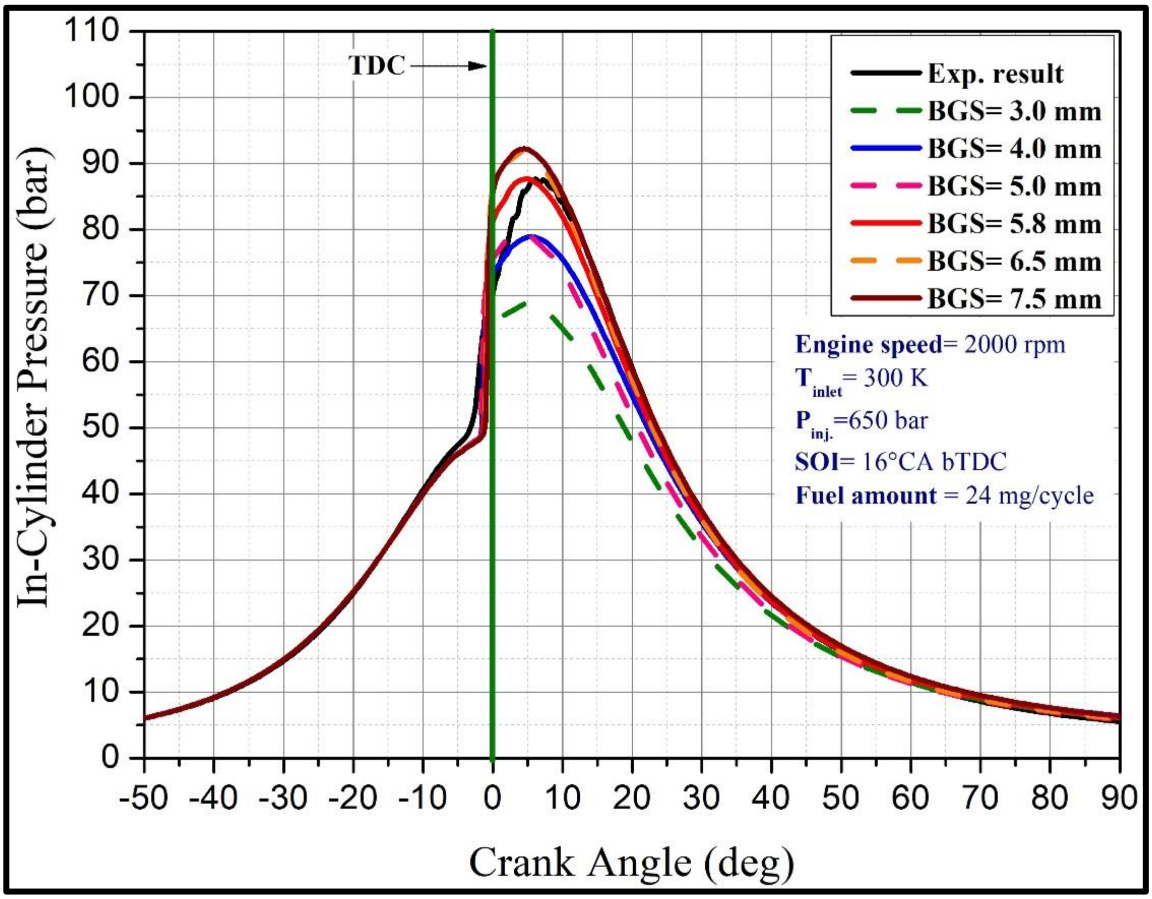

Figure 4. *In-cylinder pressure graphs for variable partition sizes*

Table 3. *Numerical simulation model conditions*

Fuel type	Diesel
Inlet air temp.	300 K
Cylinder Wall temp.	450 K
Engine speed	2000 rpm
Lambda	1.35
Inj. pressure	650 bar
Start of injection (SOI)	-16°CA
Amount of fuel injected	24 mg/cycle
Embedded AMR level	2
Base grid size	5.8 mm
Cell size with AMR	1.45 mm × 1.45 mm × 1.45 mm
Min. time increment	1e-08 s
Max. time increment	1e-04 s

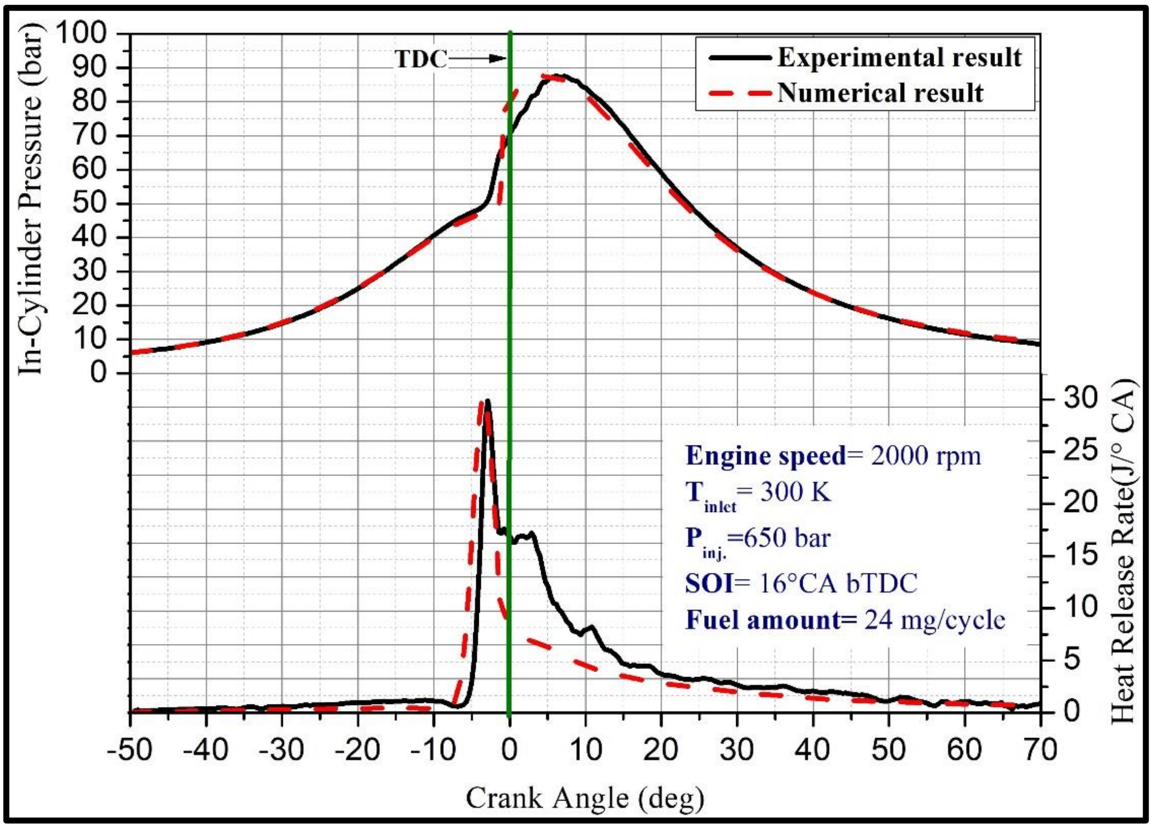

Figure 5. *Results of experimental and numerical simulations*

3. RESULTS AND DISCUSSION

After the validation of the numerical model was successfully performed, the influences of injection duration and spray angle on the process of diesel combustion were investigated through this numerical simulation study.

3.1. Effect of Injection Duration

Analyses were achieved at variable injection durations and the influences on the in-cylinder pressure and HRR of the diesel engine are shown in Figures 6 and 7, separately. To investigate the effect of this parameter, analyses were performed under the conditions of 2000 rpm engine speed, 300 K inlet temperature, 650 bar injection pressure, 24 mg/cycle fuel amount and 16°CA bTDC. Consequently in the analyses, it was observed that the max. in-cylinder pressure increased with decreasing injection pressure. The highest max. in-cylinder pressure was obtained at 4°CA injection duration and the lowest maximum pressure was attained at 10°CA injection duration. The reason for this situation is thought to be that the ignition delay time will also shorten at low injection duration and the pressure and temperature in the cylinder increases due to the abbreviated ignition delay. In an article, Du et al. (2018) stated that with enhancing injection pressure, the injection duration is abbreviated, finer fuel spray droplets are formed and thus efficient combustion is achieved. As with the in-cylinder pressure results, the highest maximum HRR was approximately 42.22 J/°CA at 4°CA injection duration and the lowest maximum HRR was approximately 24.12 J/°CA at 10°CA injection duration.

CA50, defined as the crank angle position at which half of the mixture in the cylinder is completely combusted, is an important parameter that provides information about the combustion characteristics. The CA50 value should be reached just after the top dead center (TDC) to achieve higher thermal efficiency (Gunaydin, 2022; Gupta & Subramanian, 2022; Sanli et al., 2023). Another parameter that provides information about combustion characteristics is the duration of combustion. The crank angle position at which 10% of the mixture combusts (also known as the flame propagation angle) is referred to as CA10 and the crank angle position at which 90% of the mixture combusts is referred to as CA90. Combustion continues for the period between these two crank angle positions. The combustion duration also referred to as the rapid combustion angle, is denoted as CA10-90 (Gurbuz et al., 2013).

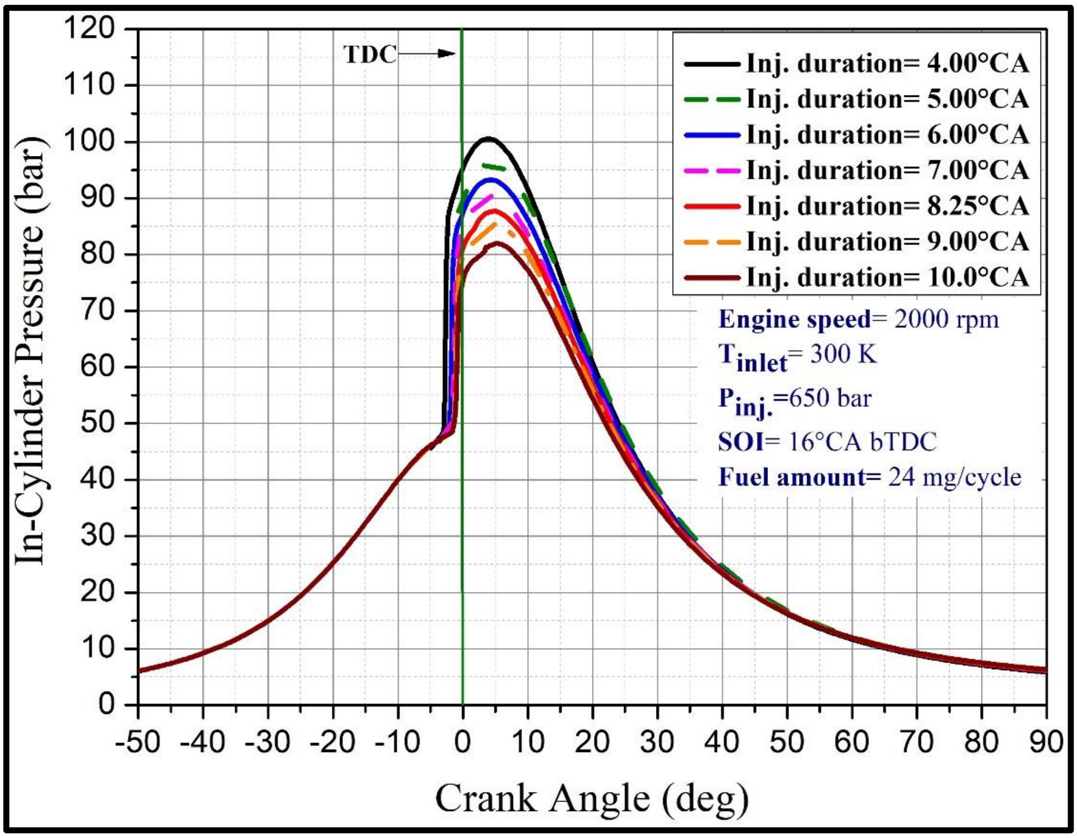

Figure 6. *Variation graph of in-cylinder pressure at variable injection durations*

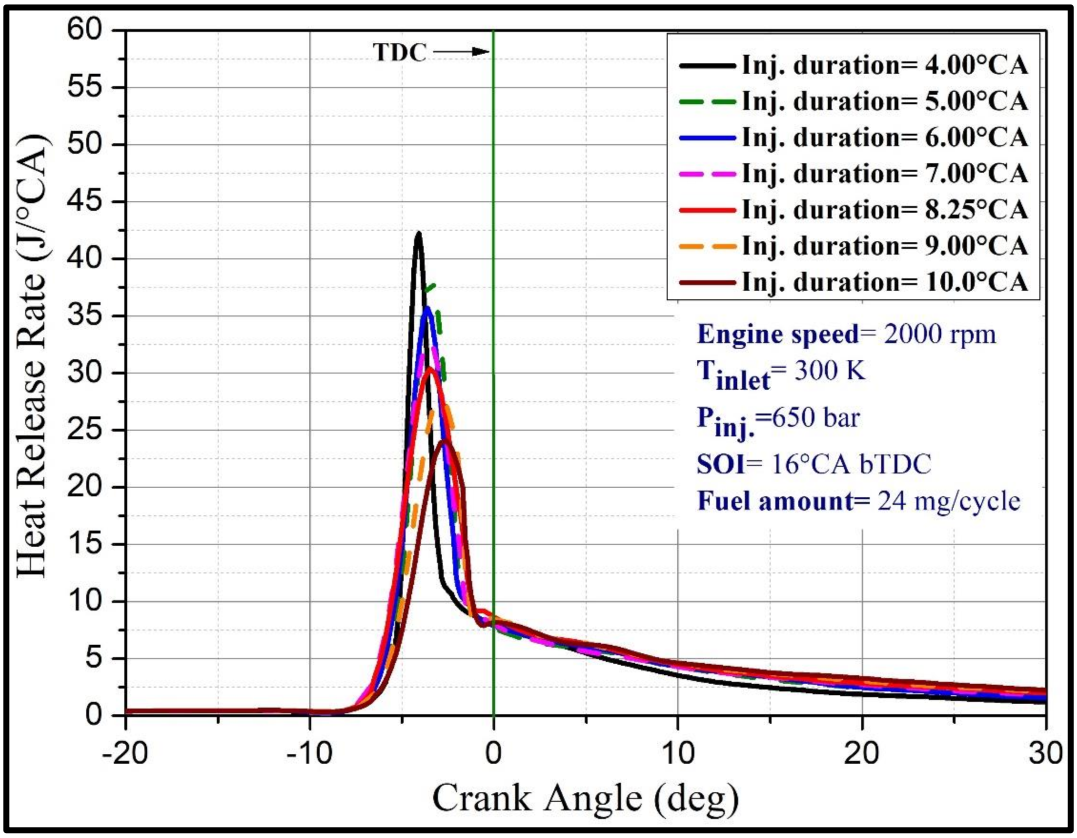

Figure 7. *Variation graph of HRR at variable injection durations*

Figure 8 presents the changes in CA50 and combustion duration depending on the lambda values for different injection durations. It is seen that the CA50 value tends to decline with the rise in lambda value due to the decreasing amount of diesel fuel in the mixture. Similarly, it can be stated that combustion takes place in a shorter time with increasing lambda value. Because more time is required to complete the combustion of the overall mixture at lower lambda values. The longest combustion of the fuel mixture occurred at 10°CA injection duration. As the injection duration increases, it is seen that the crank angle at which the CA50 value is obtained moves away from the top dead center and the combustion continues longer. This is thought to be due to the better atomization behavior of the fuel at lower injection durations.

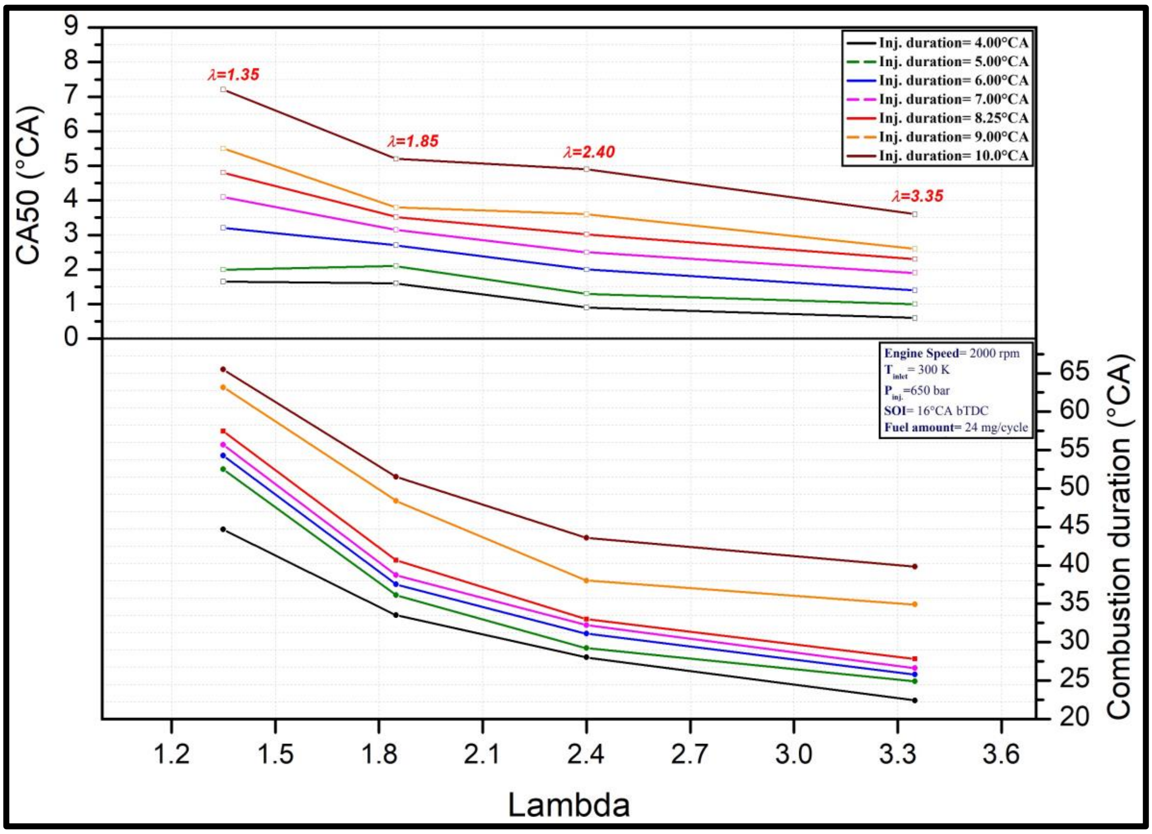

Figure 8. *Variation of CA50 and combustion duration for different injection durations*

3.2. Effect of Spray Angle

In this passage of the work, the influence of fuel spray angle (injector position) on combustion characteristics was investigated. The analysis was carried out by considering the change in-cylinder pressure and HRR according to the crankshaft angle.

The results attained as a result of the examination are shown in Figure 9 and Figure 10. The study made use of the same simulated initial conditions as were used in the injection duration analysis. Consequently, in the numerical simulation study, it is observed that the changes in the spray angle do not cause excessive changes in the in-cylinder pressure. The reason for this is thought to be that the spray angle alone cannot be effective. In a study, Shu et al. (2019) stated that spray angle alone cannot be effective on diesel combustion and that the combustion chamber geometry should be optimized together with the spray angle. When the pressure values inside the cylinder were also analyzed, a difference of approximately 1.2 bar was observed between the 77° spray angle with the highest max. in-cylinder pressure and the 60° spray angle with the lowest max. end of in-cylinder pressure. Regarding the HRR, the highest maximum HRR was approximately 30.3 J/°CA at 70° spray angle and the lowest maximum HRR was approximately 27.5 J/°CA at 60° and 62° spray angles.

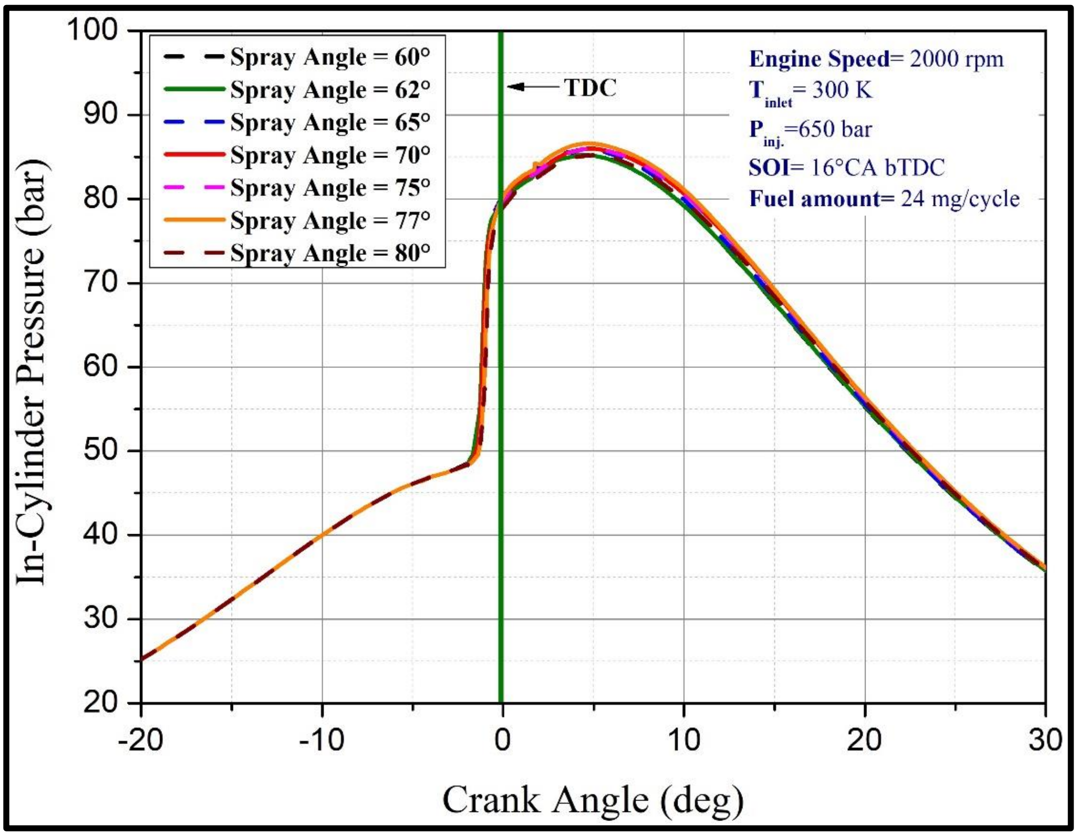

Figure 9. *Variation graph of in-cylinder pressure at variable spray angles*

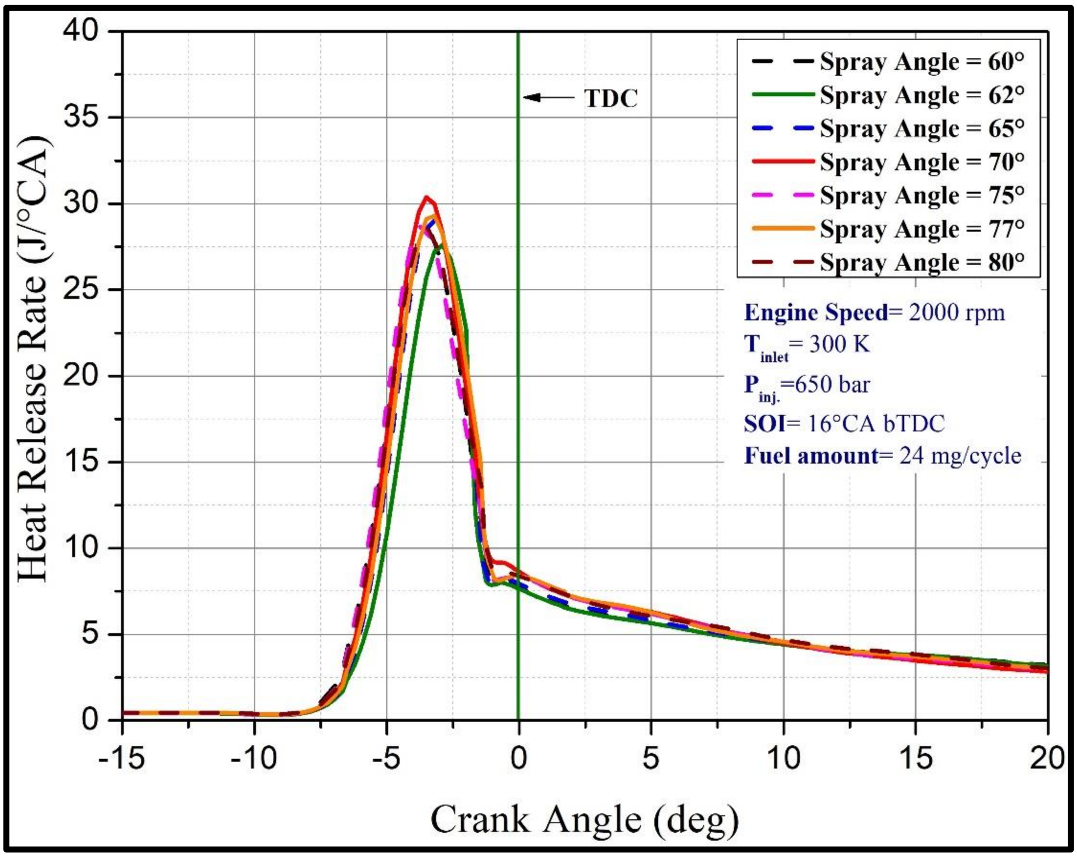

Figure 10. *Variation graph of HRR at variable spray angles*

Figure 11 illustrates how the lambda values for various spray angles affect the CA50 and combustion duration. Although changing the spray angle concerning the injector position did not have much effect on the in-cylinder pressure, it considerably affected the CA50 and combustion duration. It can be said that the CA50 value trends downward with the increase in lambda value. As a result of the mixture's decreased diesel fuel content, it can be observed that the combustion duration shortens as the lambda value increases. The lower the lambda value, the more time is required to complete the combustion of the total mixture. It is thought that by increasing the spray angle except for the 80° spray angle, a more homogeneous mixture is formed in the cylinder and the combustion process is completed in shorter periods. The longest combustion of the fuel mixture occurred at 60° spray angle. It is seen that as the spray angle increases, the crank angle at which the CA50 value is obtained gets closer to TDC. It is thought that this may be due to the better atomization behavior of the fuel as the spray angle is increased.

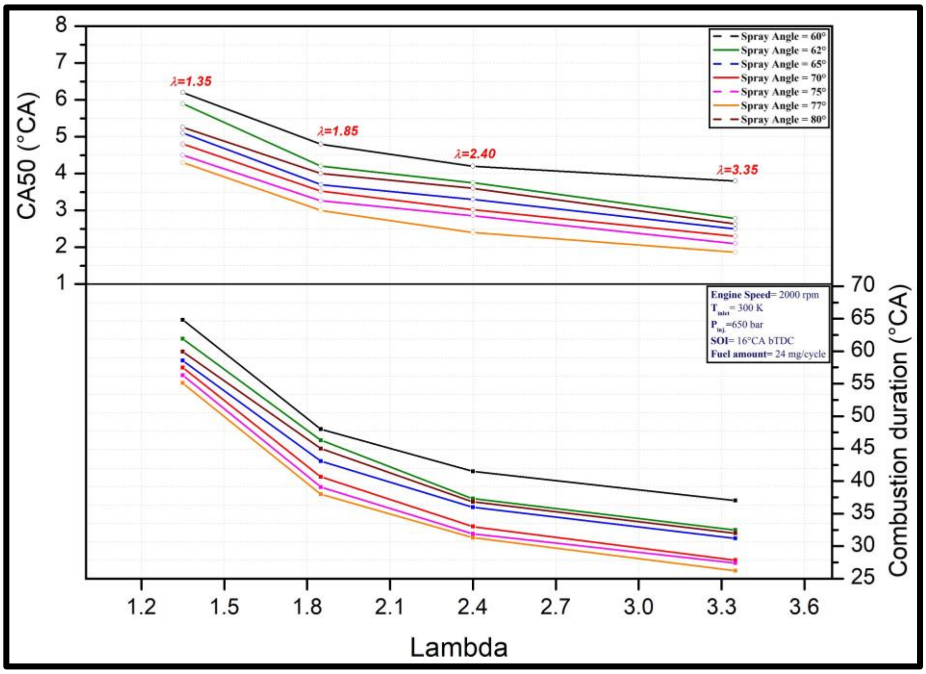

Figure 11. *Variation of CA50 and combustion duration for different spray angles*

4. CONCLUSION

In this work, the influences of injection duration and spray angle on diesel combustion were researched using experimental values validated using Converge CFD program in a single cylinder CI engine. When the data attained from the numerical simulation and the experimental data are compared, it can be said that the validation of study has been achieved successfully. The following results were obtained from the numerical study:

- ✓ The in-cylinder pressure and HRR values decreased with the raise in injection duration and the highest max. in-cylinder pressure was obtained at 4°CA injection duration. The lowest in-cylinder pressure was attained at 10°CA injection duration. Likewise, when the change in HRR is analyzed, the highest maximum HRR of 42.22 J/°CA at 4°CA injection duration and the lowest maximum HRR value of 24.12 J/°CA at 10°CA injection duration were obtained.

- ✓ It was also found that the change in spray angle did not affect the in-cylinder pressure much. A pressure difference of 1.2 bar was observed between the 77° spray angle, where the highest max. in-cylinder pressure was obtained, and the 60° and 62° spray angles, where the lowest max. in-cylinder pressure was obtained. In the study, it was attained that the max. HRR was approximately 30.3 J/°CA at the highest spray angle of 70°.

- ✓ It was observed that the CA50 value was obtained at angles closer to the top dead center by increasing the spray angle and decreasing the injection duration. In addition, the longest combustion durations were realized at 60° spray angle and 10°CA injection duration.

How other different injection parameters affect the combustion process can also be investigated. Considering this numerical study, comparative studies can be carried out using methods such as Response Surface Method.

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AUTHOR CONTRIBUTIONS

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

Abbreviations

A	Area
AMR	Adaptive mesh refinement
BGS	Base grid size
BSFC	Fren özgül yakıt tüketimi
CA	Crank angle
CI	Compression ignition
CFD	Computitional fluid dynamics
CO	Carbonmonoxide
CO_2	Carbondioxide
DSMC	Direct simulation monte carlo
HC	Hydrocarbon
HCCI	Homogenous charged compression ignition
HRR	Heat release rate
h_g	Gas heat transfer coefficient
IHRR	Cumulative heat release
KH	Kelvin Helmholtz
NO_x	Nitrogen oxide
NTC	Negative temperature coefficient
P	Pressure
PCCI	Premixed controlled compression ignition
Q	Heat
RCCI	Reactivity controlled CIcombustion
RNG	Renormalization group
RT	Rayleigh-Taylor
SI	Spark ignition
SFC	Specific fuel consumption
SOI	Start of injection
TDC	Top dead center
T_g	Gas temperature
T_w	Cylinder wall temperature
V	Volume
θ	Crank angle

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