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Research Paper

Evaluation of the Effects of Diesel Fuel Injection Timing in a High-Speed RCCI Engine at Low to High Load Conditions

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Abstract: This numerical research mainly aimed to investigate the impacts of diesel fuel direct injection timing on the combustion characteristics, emission formation, and performance in a high-speed diesel-gasoline Reactivity Controlled Compression Ignition (RCCI) engine under low, medium, and high load operating conditions. The numerical achievements indicated that by late diesel injection timing (32 Crank Angle (CA) Before Top Dead Center (BTDC)), regions with a higher temperature and equivalence ratio were formed in the combustion chamber and caused a simultaneous increase in both Nitrogen Oxides (NOx) and soot emissions. On the contrary, early Diesel Injection Timing (DIT) under low load conditions concurrently reduced NOx and soot due to appropriate air-fuel ratio, more homogeneous air-fuel mixture formation as a result of longer Ignition Delay (ID) period, and the absence of high-temperature regions inside the combustion chamber. Also, when DIT was postponed under high load conditions, the combustion process became unstable and noise emission, as well as detonation tendency (sudden auto-ignition), were dramatically increased due to a considerable increase in in-cylinder maximum temperature and pressure rise rate. Furthermore, under low load conditions, because of low flame temperature and its incompetent propagation in the engine cylinder, a substantial amount of unburnt mixture (gasoline) was formed and accumulated at the center of the combustion chamber.

keywords: Diesel-gasoline combustion simulation, High-speed diesel engine, RCCI, Diesel injection timing, Emission, Thermal efficiency.

1. Introduction

Due to the type of combustion mechanism and the thermochemical specifications of consumed fuels, Compression Ignition (CI) diesel engines highly suffer from substantial levels of exhaust gas emissions, e.g., NOx and soot, which raises many environmental concerns. In the past years, extensive effort has been made by research centers around the world to decrease the level of output harmful NOx and soot pollutants simultaneously by enhancing the thermal efficiency of Direct Injection (DI) diesel engines (Wu et al. 2017; Wamanker, Satapathy, Murugan 2015; Torregrosa et al. 2017; Zhou et al. 2019; Mobasheri, Seddiq, and Peng 2018; Jafari, Seddiq, and Mirsalim 2020). To achieve low emission and high performance in CI engines, different strategies have been applied such as changing DIT. DIT is a critical characteristic that affects engine performance and the amount of cylinder-out pollutants since the compression ignition combustion is a mixing controlled process, and as a result, the quality of the direct fuel injection process determines the amount of emission formation and fuel economy (Tess, Lee, and Reitz 2011). Therefore, the influence of DIT has been studied by many researchers in various types of diesel engines for both on-road and stationary applications.

In 2017, in a numerical study conducted by using the CONVERGE Computational Fluid

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Dynamic (CFD) code, the impacts of DIT on the combustion process and emission formation were investigated in a high-speed DI diesel engine (Puri Ing, Soni Ing, and Deshpande 2017). The numerical achievements of their simulations showed that by advancing DIT to 19 CA BTDC, the in-cylinder maximum pressure was increased by nearly 7.15%. Moreover, by retarding DIT to 8 CA BTDC, the maximum combustion pressure was decreased by about 4% compared to baseline engine operating conditions. Their results revealed that fuel injection at 19 CA BTDC increased both NOx and soot emissions by 27% and 2.75%, respectively compared to baseline operating mode. Also, diesel injection at 8 CA BTDC resulted in a simultaneous decrement in both NOx and soot by 14.8% and 6.9%, respectively. In other research, Damodharan et al. (2018) examined the effects of three DITs, i.e., 21, 23, and 25 CA BTDC, on the characteristics of the combustion process, performance, and emission formation in a DI diesel engine at 1500 RPM. They noted that by postponing DIT from 25 to 21 CA BTDC, the combustion phase approached near Top Dead Center (TDC) point and for all Exhaust Gas Recirculation (EGR) rates, the maximum combustion pressure, and the Heat Release Rate Peak Point (HRRPP) were decreased. Regarding emission formation, their achievements showed that diesel injection at 21 CA BTDC decreased the amount of NOx by nearly 52.4%. In addition, researchers observed that by spraying diesel at 25 CA BTDC, both NOx and soot were simultaneously reduced by 38% and 46% respectively.

On the other hand, since the RCCI combustion strategy used two fuels with different reactivity (cetane number), it reduced the regions with high equivalence ratio and temperature inside the engine cylinder of the conventional combustion process, and as a result, both harmful emissions such as NOx and soot were considerably decreased (Kokjohn et al. 2011). In this regard, many studies have been conducted to investigate the effects of high reactivity fuel injection timing in RCCI engines. For instance, Wei et al. (2016) evaluated the impacts of DIT in a methanol-diesel reactivity controlled combustion engine. They reported that by retarding DIT, the ID period became more extended and the combustion duration was initially prolonged but then became slightly shorter. The maximum in-cylinder temperature was decreased by postponing DIT. Regarding the formation of pollutants, postponing DIT significantly reduced NOx. However, due to a notable decrement in the in-cylinder temperature, soot was vastly increased.

Zou et al. (2016) performed multidimensional computations on the impacts of DIT in a heavy-duty RCCI engine. Their numerical achievements indicated that retarding single-stage injection timing under low load conditions resulted in early combustion timing. Also, for the split injection strategy of diesel fuel under high load conditions, the combustion timing occurred earlier by postponing the injection timing of the first pulse. They showed that the combustion phase was more sensitive to single-stage injection timing for when gasoline and butanol were used as low-reactivity fuel compared to ethanol and methanol fuels. Finally, they reported that advanced combustion phasing as a result of retarded single-stage DIT decreased soot but dramatically increased NOx level. In other research, it was reported that by advancing DIT, maximum combustion pressure, thermal efficiency, and NOx level were increased under all load-speed operating conditions in a heavy-duty natural gas-diesel RCCI engine (Yousefi, Guo, and Birouk 2019). Moreover, the amount of unburnt CH_4 was decreased at low load-speed operating conditions.

Over the past several years, extensive research has been conducted to improve the performance and reduce the pollution of DI diesel engines so that, despite the strict rules, these types of internal combustion engines can be used for different applications. Due to the importance of this issue and in continuation of previous studies, the researchers of this work decided to examine the impacts of DIT on the combustion characteristics, emission formation, and performance in a high-speed RCCI engine under low to high load (Indicated Mean Effective Pressure (IMEP) of 4, 6, and 9 bar) operating conditions using the CONVERGE CFD code. Also, in this study, the rates of the formation and oxidation of hydroxyl radicals were used as a tool to qualitatively investigate the influence of flame propagation and development processes in the combustion chamber on NOx and soot emissions, as well as engine thermal efficiency.

2. Computational grid and numerical models

This numerical research was conducted using the CONVERGE CFD code, and its tools were used to create a computational grid (Richards, Senecal, and Pomraning 2016). Because of the symmetric shape of the combustion chamber and the use of a seven-hole injector for each engine cylinder, all calculations were conducted on 51.42-degree segments. The initial grid size was set to 0.6 mm, and the cell size of regions with high velocity and temperature gradients were decreased to 0.15 mm by applying the adaptive mesh refinement method with a scale of 2 to improve the accuracy of computations during diesel injection, combustion, flame propagation process, and emission formation. Thus, velocity and temperature criteria for cells were set to 2 m/s and 2.5 K, respectively. Moreover, two-level fixed embedding was applied for such regions as spray cone area, cylinder head, cylinder wall, and piston bowl. Figure 1 shows the computational grid at 360 CA.

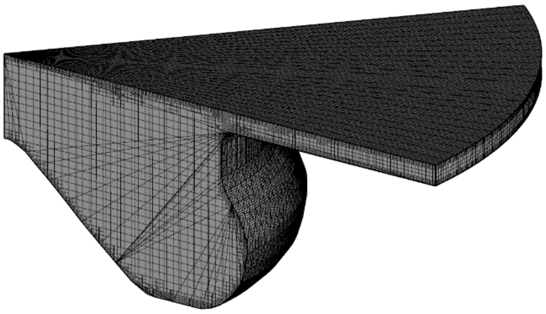

Figure 1. The computational grid at the TDC point

All calculations in this research were started from Intake Valve Closing (IVC) and ended at Exhaust Valve Opening (EVO). The initial time step for computations was set to 25 µs and also, based on the software recommendation, the time step for injection, combustion, and emission formation processes was set to 10 ns. Table 1 reports the initial boundary conditions.

Table 1. Initial boundary conditions (Dempsey 2013)

Swirl ratio @ IVC (-)	1.5
Piston bowl surface temperature @ IVC (K)	525
Cylinder head temperature @ IVC (K)	500
Cylinder wall temperature @ IVC (K)	400

Regarding the diesel-gasoline combustion simulation, the SAGE model was applied in this research coupled with a detailed chemical kinetic mechanism that consists of 80 species and 349 reactions (Senecal et al. 2003; Wang et al. 2014). Moreover, this mechanism was used to simulate the rates of formation and oxidation of emissions, such as NOx and soot, as well as OH radicals inside the combustion chamber. To accelerate the rates of calculations, the multi-zone chemistry model was coupled with the SAGE combustion model (Babajimopoulos et al. 2005). This method considers the cells with identical thermochemical specifications as a single region, which significantly reduces total computations. Also, the physical specifications of Tetradecane ($C_{14}H_{30}$) were used here for high reactivity direct injection fuel (diesel), and the chemical properties of heptane and iso-octane were considered for diesel and gasoline, respectively (Richards, Senecal, and Pomraning 2016). Table 2 shows the CFD models applied for modeling the closed cycle (IVC to EVO event) of the high-speed diesel-gasoline RCCI engine used for this research.

Table 2. The CFD models used for closed-cycle engine simulation

Spray breakup	KH-RT model (Reitz and Bracco 1986; Reitz 1987)
Spray droplets collision	NTC model (Schmidt and Rutland 2000)
Evaporation	Frossling model (Amsden, O'Rourke and Butler 1989)
Spray/wall interaction	Rebound/slide (Naber and Reitz 1988)
Wall heat transfer	Han and Reitz's (1997) model
Turbulence	RNG K-epsilon model (Yakhot et al. 1992)

3. Model verification

A four-cylinder high-speed RCCI engine made by General Motors Company was used for all calculations of the current numerical study (Dempsey, Walker, and Reitz 2013). Table 3 shows the engine and fuel injection system specifications (Dempsey, Walker, and Reitz 2013). In this research, model validations were conducted under three different IMEPs, i.e., low (4 bar), medium (6 bar), and high (9 bar) load operating conditions, at an engine speed of 1900 Revolution per Minute (RPM). All numerical results achieved from validations are compared to Dempsey et al.'s (2013) experimental research work. A full description of the three engine operating conditions are presented in Table 4.

Table 3. The engine and fuel injection system specifications (Dempsey, Walker, and Reitz 2013)

Type of aspiration	Turbocharged
Cylinder bore (mm)	82
Cylinder stroke (mm)	90.4
Connecting rod length (mm)	145.4
Compression ratio (-)	17.4
Engine displacement (Liter)	1.9
IVC (CA BTDC)	132
EVO (CA BTDC)	-112
Type of fuel injection system	Common rail direct injection
Number of nozzle holes	7
Nozzle holes diameter (mm)	0.141
Spray cone angle (degree)	148
Injection pressure (MPa)	50

Table 4. The engine operating conditions (Dempsey, Walker, and Reitz 2013)

Engine load	Low	Medium	High
IMEP (bar)	4	6	9
Intake air pressure (bar)	1.0	1.3	1.65
Intake air temperature (K)	346	327	313
EGR rate (%)	-	-	48
Total fuel per cycle (mg)	10	14	21
Gasoline premixed ratio (%)	70.5	85.2	94

Figure 2 compares the numerical and experimental results of in-cylinder mean pressure and Heat Release Rate (HRR) for different engine operating conditions. Also, the combustion characteristics, such as maximum in-cylinder pressure and combustion phasing of the current study and experimental study by Dempsey et al.'s (2013) study under low to high load operating mode are compared in Table 5.

According to the results presented in Figure 2 and Table 5, a good and reasonable agreement was reached between the numerical and experimental achievements. There are, nevertheless, some disagreements regarding combustion initiation and duration, pressure rise rate, maximum in-cylinder pressure, and HRRPP. This incompatibility can be related to the use of segment mesh instead of a complete computational grid, the exact temperature of the mixture at the beginning of the calculations, or the precise duration of the injection.

Table 6 compares experimental and numerical achievements for engine-out emissions under low to high load conditions. According to this table, the cylinder-out pollutants are modeled with acceptable accuracy compared to experimental results. Thus, it can be concluded that the CFD models selected for the present numerical study were compatible with the experimental conditions.

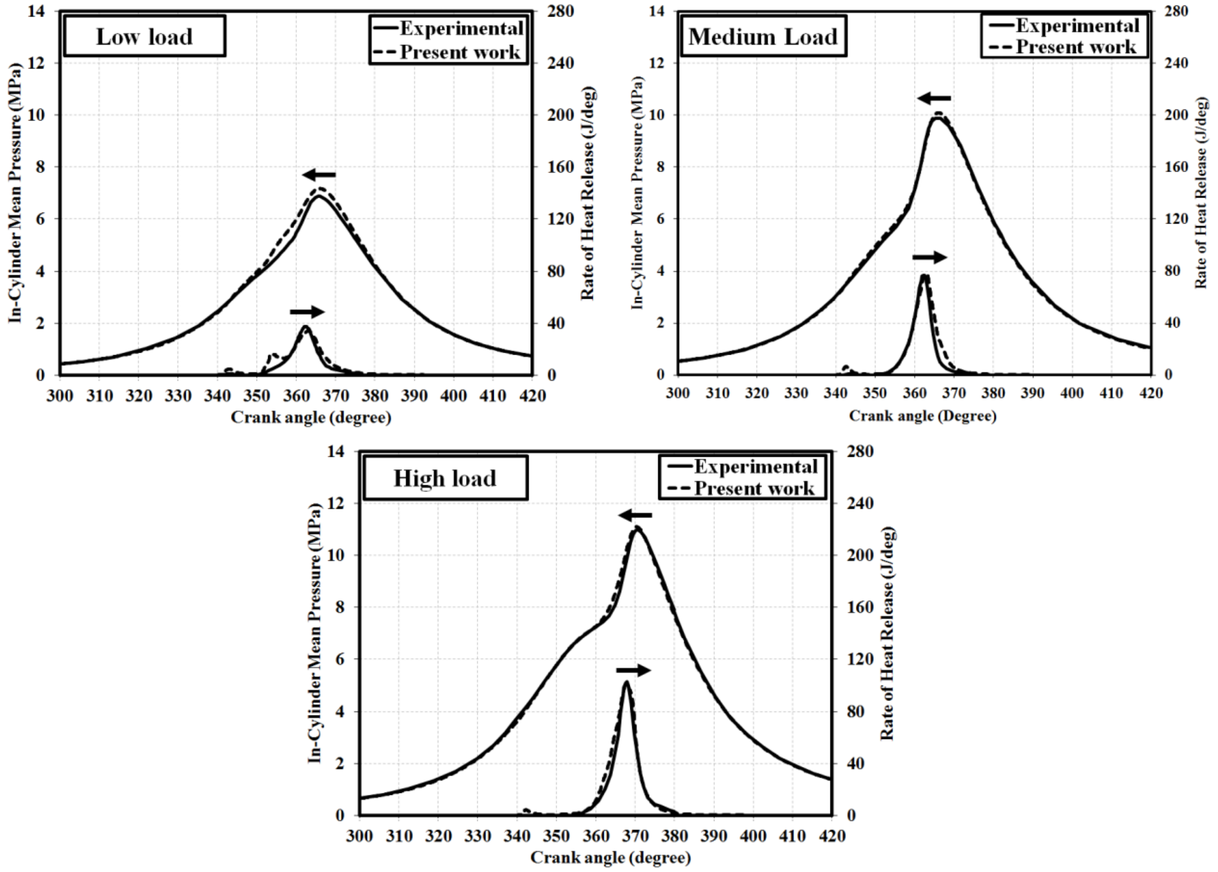

Figure 2. The comparison of the numerical and experimental in-cylinder mean pressure and HRR results (Dempsey, Walker, and Reitz 2013)

Table 5. The comparison of the numerical and experimental results of the combustion characteristics (Dempsey, Walker, and Reitz 2013)

Operating conditions		Maximum in-cylinder pressure (MPa)	Combustion phasing (CA BTDC)
Low load	Experimental Numerical (relative error)	6.87 7.17 (4.5%)	-2.5 -2.1 (16%)
Medium load		10.08 9.88 (2%)	-2.5 -2.4 (4%)
High load		11.10 10.09 (1.8%)	-8 -7.3 (8.75%)

Table 5. The comparison of the numerical and experimental results of the combustion characteristics (Dempsey, Walker, and Reitz 2013)

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Table 6. Experimental and numerical engine-out emissions (Dempsey, Walker, and Reitz 2013)

Operating conditions		NOx	soot
Low load	Experimental Numerical (g/kg. fuel)	0.88 1.11	0.007 0.009
Medium load		1.11 0.99	0.09 0.17
High load		1.66 1.84	0.23 0.32

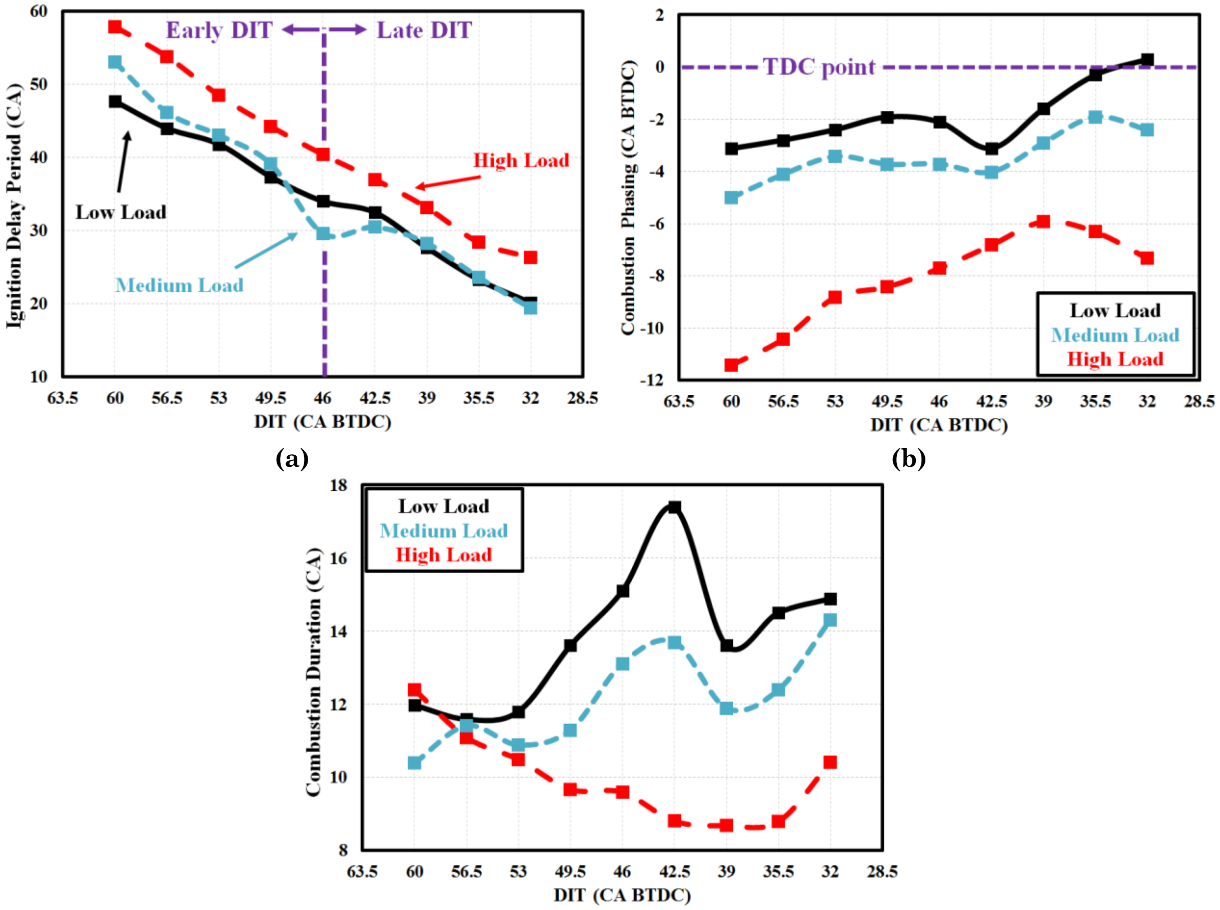
4. Numerical achievements and analysis

This section presents the numerical results obtained from varying the timing of single-stage injection of diesel fuel under different operating conditions. Based on the two engine operating variables, including injection timing of diesel fuel and operating load, 27 simulations were performed in this research. For diesel fuel spray, nine timings were considered, varying from 60 to 32 CA BTDC with 3.5 CA steps under three operating modes (IMEP), i.e., low (4 bar), medium (6 bar), and high (9 bar) load. Overall, this study investigated the separate and simultaneous impacts of DIT at low, medium, and high load operating conditions on the following characteristics:

- Combustion characteristics
- Stability of the combustion process
- Rich and high-temperature regions inside the combustion chamber
- Quality of the flame propagation inside the engine cylinder
- Level of NOx and soot emissions formation
- Regions of soot and NOx formation, and unburnt gasoline accumulation inside the combustion chamber
- Thermal efficiency

Figure 3(a) displays the influence of DIT on the ID period under low to high load operating conditions. It is observed that as DIT was postponed, the ID period was considerably shortened for all engine operating modes. In other words, as the piston bowl gets closer to the TDC point, the initial oxidation process becomes more intense and the tendency of autoignition increases with the development and propagation of the flame. Regarding diesel fuel, late DIT near the TDC point, where the in-cylinder pressure and temperature are higher, leads to the enhancement of initial oxidation of gasoline, and therefore, the ID period of diesel fuel becomes shorter. A comparison of the three engine operating conditions reveals that the ID period at high load operating mode is longer compared to other conditions, which can be related to the higher EGR rate (48%) and premixed fuel ratio (94%). A less diesel (high reactivity fuel) portion can decrease the total reactivity of the air-fuel mixture inside the combustion chamber. Thus, higher pressure and temperature are needed for the fuel mixture to reach the autoignition point, which extends the ID period. Also, a high EGR rate leads to a weak mixture formation and oxidation process. For these reasons, ignition timing at high load operating conditions is noticeably retarded.

The impacts of DIT on the combustion phasing under low to high load conditions are displayed in Figure 3(b). As can be observed in Figure 3(b), under low and medium load conditions, as DIT was postponed, combustion phasing was retarded and approached TDC point. At low load operating mode and DIT of 42.5 CA BTDC, it can be seen that combustion phasing occurred later. Besides, under high load conditions, from 60 to 39 CA BTDC, combustion phasing was noticeably advanced to TDC point as DIT was postponed. As discussed earlier, late DIT caused a shorter ID period, and ignition timing took place earlier. Therefore, combustion phasing advances to the TDC point. Nevertheless, at high load conditions, due to the higher premixed fuel ratio and weak mixture reactivity inside the combustion chamber, late DIT (32 CA BTDC) was accompanied by retarded combustion phasing. Also, by comparing all three operating conditions, it can be seen that combustion phasing occurred earlier. Therefore, according to Figure 3(b), it can be concluded that at part load operating mode since the high reactivity fuel portion is noticeable and mixture reactivity is higher and more sensible to in-cylinder pressure and temperature changes, the ID period is shorter and thus, combustion phasing takes place earlier, especially compared to high load conditions.



(a) (b)

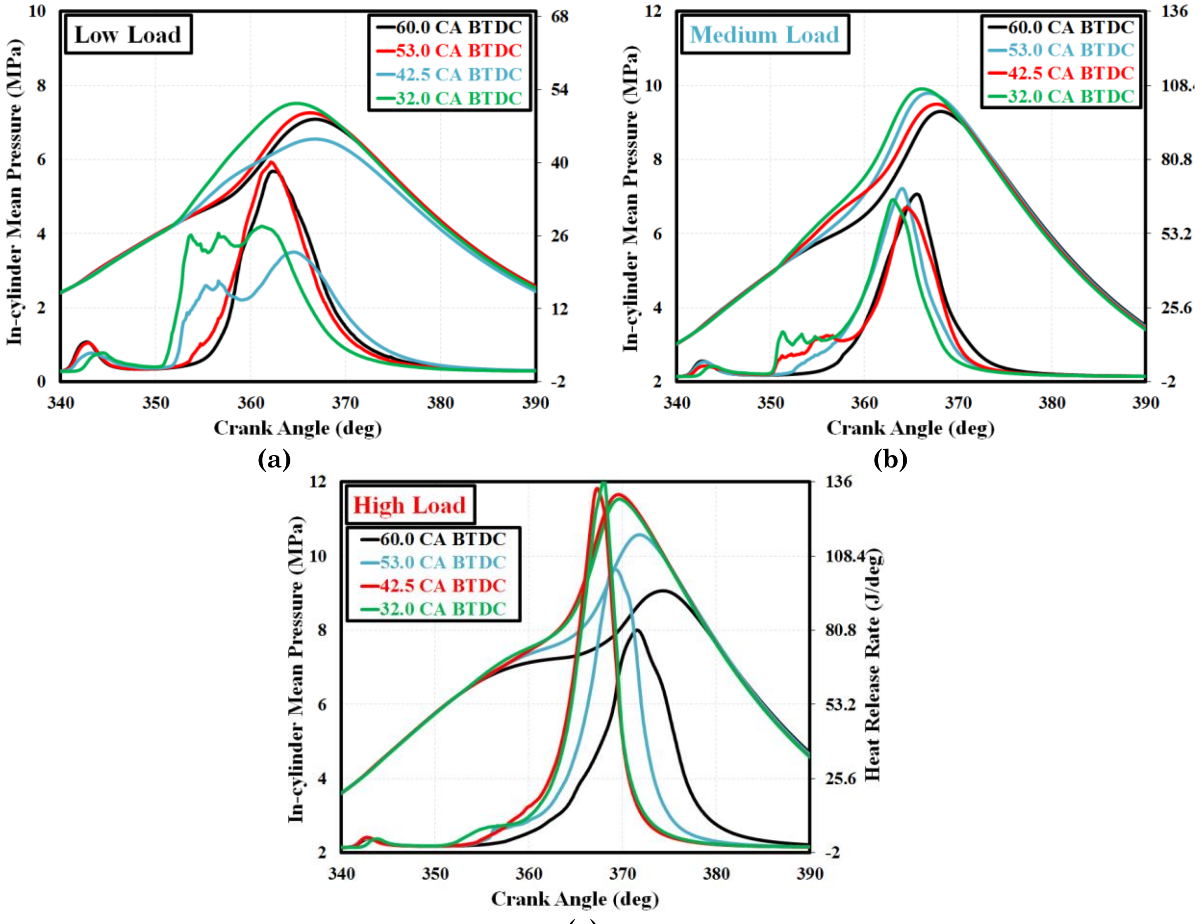
(c)

Figure 3. Effects of DIT on (a) ignition delay period, (b) combustion phasing, and (c) combustion duration under low to high load operating conditions

Figure 3(c) illustrates the influence of DIT on the combustion duration at low to high load operating conditions. Based on the results depicted in this figure, it can be noted that at low and medium load conditions, retarding DIT caused a longer combustion duration. The maximum value for combustion duration can be observed for part-load mode at DIT of 42.5 CA BTDC, which was significantly shortened at 39 CA BTDC and was then extended as DIT was retarded. By comparing the numerical achievements of all three engine operating conditions, it can be noticed that the combustion duration at low load operating mode is dramatically more prolonged, especially at 42.5 CA BTDC. At high load mode, retarding DIT shortened combustion duration noticeably but at DIT of 32 CA BTDC, it became more extended. According to Figure 3(c), it can be deduced that the combustion duration at low and medium loads depends on the ID period but under high load conditions, it is determined by the combustion phasing. In other words, under low and medium load conditions, since the portion of high reactivity fuel is noticeable, DIT has great impacts on the rate and mode of burning (premixed and diffusive combustion) and as direct injection timing is postponed and subsequently, the portion of diffusive burning is increased, combustion duration is prolonged. However, at high load operating mode, due to higher premixed fuel ratio and less diesel injection per cycle, the greatest portion of air-fuel mixture burnt in premixed mode. Hence, DIT has an insignificant effect on the mode of burning inside the combustion chamber. Nevertheless, postponing DIT led to the shortening of the combustion duration. This behavior is expected since combustion phasing got closer to the TDC point as DIT was retarded. The advancing of DIT toward the TDC point can cause combustion phasing to occur when in-cylinder pressure and temperature are higher and consequently, mixture oxidation is enhanced, and therefore, combustion duration becomes shorter.

Figure 4 depicts the effects of DIT on the in-cylinder mean pressure and the rate of heat release trends at low, medium, and high load conditions, respectively. As can be illustrated in Figure 4(a), by retarding DIT at low load operating mode, maximum in-cylinder pressure was increased. Nonetheless, at DIT of 42.5 CA BTDC, in-cylinder peak pressure was tangibly dropped off. As for the HRR, autoignition occurred earlier, the heat release period became more prolonged, and HRRPP was vastly decreased. In Figure 4(b), a repetitive scenario can be observed for medium load conditions compared to low load operating mode. As DIT was postponed, the maximum combustion pressure ascended, but HRRPP was slightly reduced. Similar to the part-load conditions, at DIT of 42.5 CA BTDC, the maximum in-cylinder pressure and HRRPP were dramatically dropped off. It can be deduced from Figures 4(a) and 4(b) that by retarding DIT and subsequently, shortening the ID period, the autoignition process occurred earlier and combustion phasing approached the TDC point. The combustion process took place when the in-cylinder pressure and temperature were higher, which favors the air-fuel mixture oxidation. Therefore, the maximum combustion pressure at low and medium load operating conditions was increased as DIT was postponed. However, since the ID period became shorter and the greatest portion of the fuel mixture burned in diffusive combustion mode, the heat release duration became more extended and HRRPP was reduced. As illustrated in Figure 4(c), the maximum combustion pressure and HRRPP were considerably increased as DIT was retarded, but at 32 CA BTDC, an opposite trend occurred. According to this figure, it can be concluded that at high load operating conditions, retarding DIT caused shorter combustion duration and the approaching of combustion phasing to the TDC point. For this reason, the combustion process occurred in favorable conditions and as a result, the maximum in-cylinder pressure and HRRPP were noticeably increased. However, at DIT of 32 CA BTDC, since the combustion phasing retarded and its duration became more extended, the maximum combustion pressure was reduced.

Figure 5 shows the impacts of DIT on the maximum combustion temperature at different engine operating conditions. As can be seen in this figure, by postponing DIT at low load conditions in the early period, the maximum combustion temperature was increased but at a late period, the direct injection timing had an imperceptible influence on the in-cylinder temperature. As the combustion phasing approached the TDC point, the mixture oxidation process was improved, and as a result, the combustion temperature was increased. Also, at DIT of 42.5 CA BTDC, the maximum combustion temperature was vastly reduced, which can be related to retarded combustion phasing and longer burning duration. At medium and high load operating conditions, by postponing DIT, the maximum combustion temperature was noticeably increased since the combustion phasing advanced to the TDC point where the in-cylinder pressure and temperature were higher and favored the oxidation process. Nonetheless, under high load operating mode, at DIT of 32 CA BTDC, the maximum combustion temperature was reduced since the combustion duration was prolonged and deteriorated the mixture oxidation process.



(a)

(b)

(c)

Figure 4. The effect of DIT on the in-cylinder mean pressure and HRR trends at (a) low, (b) medium, and (c) high load operating conditions

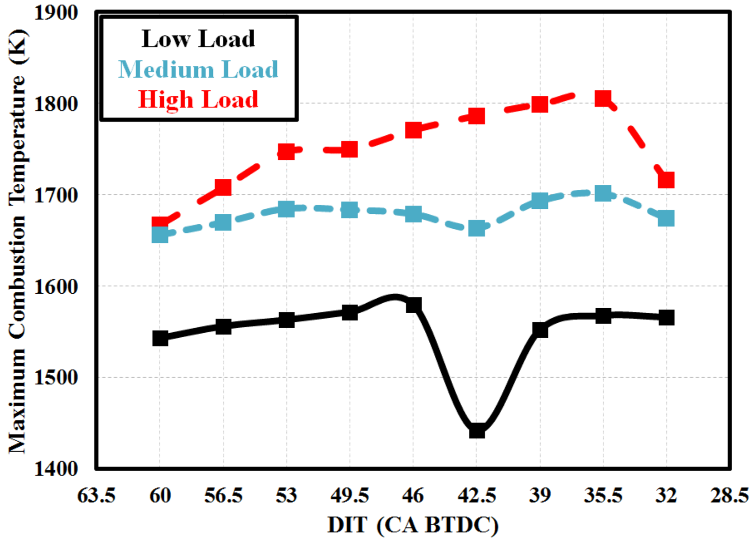


Figure 5. The maximum combustion temperature versus DIT under low to high load operating conditions

One of the critical and determinant characteristics of the operating range in diesel engines, which has been examined in various numerical and experimental studies, is called Ringing Intensity (RI). This parameter can also assess the level of noise pollution and the tendency of sudden ignition known as engine knocking (Eng 2002). The impacts of DIT on the RI at low to high load conditions are presented in Figure 6. As can be seen in this figure, at low load operating mode, RI was noticeably low, which can be ascribed to more extended combustion duration since by retarding DIT, the maximum combustion temperature and the pressure rise rate were insignificantly changed. At medium load conditions, RI under all DITs was higher compared to part load operating mode since the maximum combustion temperature was higher. By postponing DIT, it can be noticed that RI was slightly increased as a result of an increment in combustion temperature. Moreover, at DIT of 42.5 CA BTDC, RI was noticeably dropped off, which can be attributed to the more prolonged combustion duration that caused a lower pressure rise rate. According to Figure 6, it can be observed that RI was significantly sensitive to DI and as the injection timing was postponed, RI was dramatically increased and reached nearly 5 MW/m^2 at 35.5 CA BTDC. This can be related to the higher combustion temperature and also, the shorter combustion duration, which led to a higher pressure rise rate. However, at DIT of 32 CA BTDC, RI was tangibly decreased since the combustion phasing was retarded from the TDC point and caused a lower in-cylinder pressure and temperature. Totally, in this figure, it can be concluded that at high load operating conditions, late DIT can lead to an unstable combustion process since RI was vastly increased and this noticeably increased the chance of engine knocking and limited its operable load range.

Figure 7 depicts the effects of 60, 42.5, and 32 CA BTDC DITs on the in-cylinder equivalence ratio at low, medium, and high load conditions. As can be seen in this figure, early DIT caused more homogenous air-fuel mixture formation inside the combustion chamber. This behavior is expected since the ID period is noticeably more extended and provided enough time to increase the homogeneity of mixture formation; especially, under high load operating conditions at DIT of 60 CA BTDC, the ID period was nearly 55 CA long. On the contrary, late DIT that was accompanied by a significantly shorter ID period led to the formation of high rich regions near the cylinder walls, squish area, and bowl lip (ignition regions). Also, it can be observed that at DIT of 42.5 CA BTDC under low load conditions, a highly rich air-fuel mixture was formed near the cylinder walls, especially in crevices. Therefore, when combustion phasing was retarded, its duration was dramatically prolonged, and the maximum combustion temperature and HRRPP were decreased since most of the in-cylinder air-fuel mixture experienced misfire.

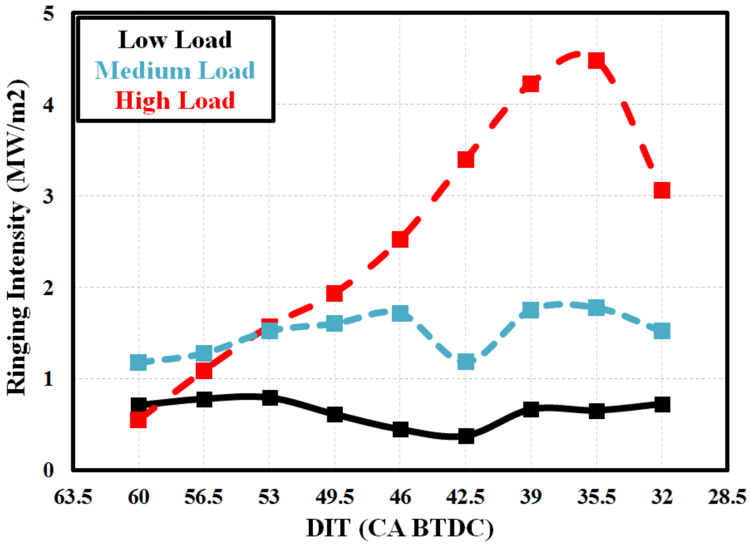


Figure 6. The effect of DIT on RI under low to high load engine operating conditions

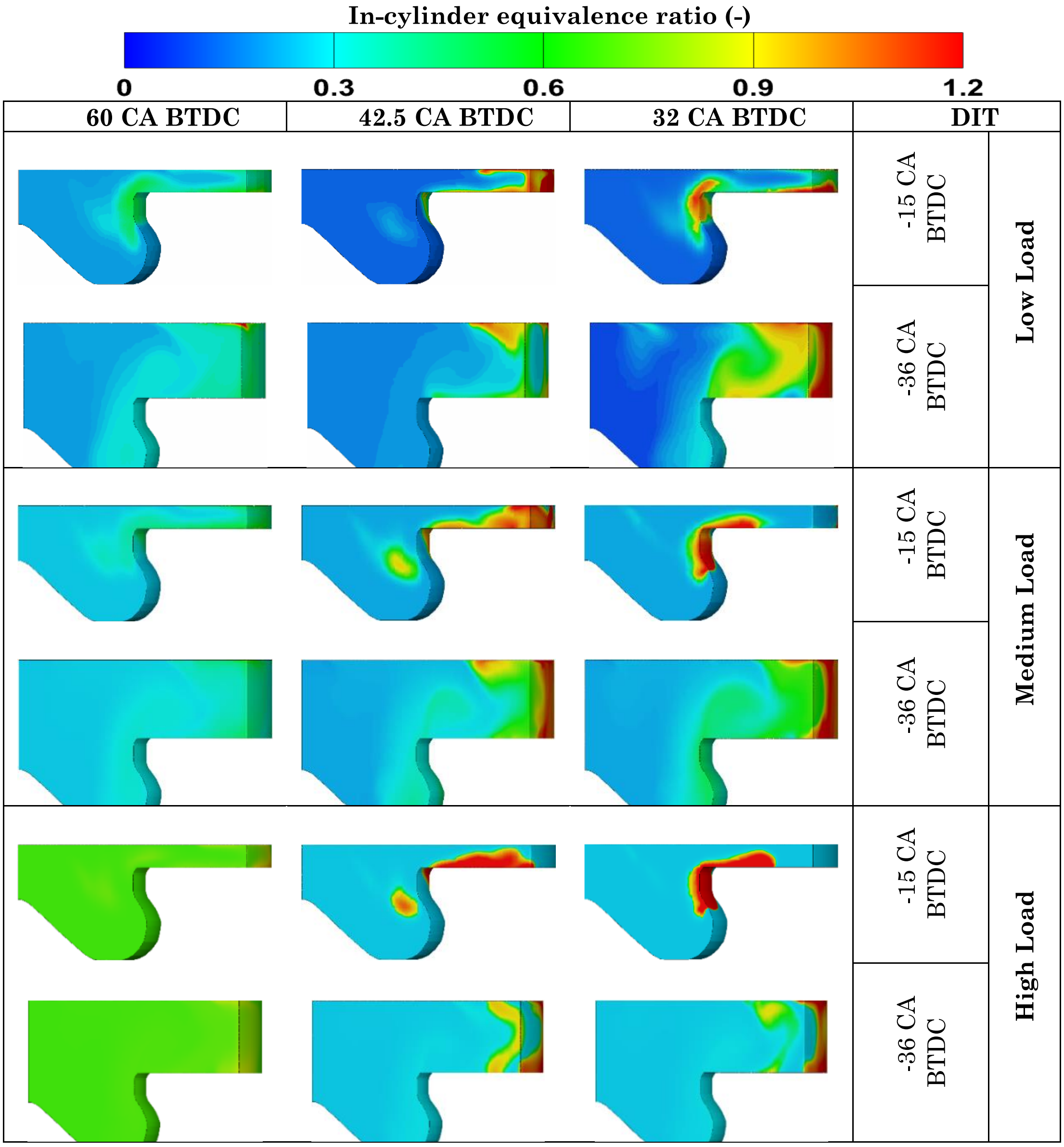


Figure 7. The effects of 60, 42.5, and 32 CA BTDC DITs on the in-cylinder equivalence ratio at low, medium, and high load operating conditions

Figure 8 illustrates the impacts of 60, 42.5, and 32 CA BTDC DITs on the in-cylinder temperature at low to high load engine operating conditions. In this figure, it can be seen that by retarding DIT, high-temperature regions were formed and increased inside the combustion chamber, advancing combustion phasing to the TDC point. At low load operating conditions and at DIT of 42.5 CA BTDC, most of the air-fuel mixture was burned in low oxygen concentration regions, such as near the cylinder walls and piston crevices, which was accompanied by low-temperature mixture oxidation and therefore, deteriorated combustion process. Also, it can be observed that the center of the combustion chambers is a low-temperature sector since it is far from the ignition regions and also, less high reactivity fuel (diesel) is distributed throughout this sector. Therefore, mixture oxidation at the center of the combustion chamber is deteriorated and causes low-temperature burning. However, late DIT under high load operating modeled to a significant increment in the in-cylinder temperature at the center of the combustion chamber compared to the other operating conditions and DITs. Thus, it can be deduced that the flame propagation was enhanced throughout the combustion chamber and penetrated more distance through the center of the piston bowl. This can be attributed to the more extended ID period (more homogenous air-fuel mixture formation) and higher flame temperature of combustion at high load operating conditions caused by late DIT.

Figure 9 shows the effects of 60, 42.5, and 32 CA BTDC on the OH distribution throughout the combustion chamber at low to high load conditions. Based on Yousefi et al.'s (2019) research work, OH formation is a product of the air-fuel oxidation process. According to this figure, at all operating modes, OH is formed in high-temperature regions, especially in ignition regions such as near cylinder walls, piston bowl lip, and squish area, its formation intensity is considerably higher (red zones). In these sectors, since the temperature is higher, the air-fuel mixture oxidation process occurred more efficiently. On the contrary, at the center of the combustion chamber, the level of OH formation is nearly zero. This may be related to the fact that these areas are low-temperature regions (about 800 K or less) and as a result, the oxidation process is weakened. At low and medium load operating conditions, by postponing DIT, OH formation intensity was reduced. This can be related to a decrement in HRRPP (flame temperature) in which retarding DIT extended the combustion duration and deteriorated the mixture oxidation, and as such, less OH was formed. It can be seen that at high load operating mode, OH formation intensity was increased as DIT was retarded since the flame temperature (HRRPP) noticeably became higher. However, at DIT of 32 CA BTDC, OH formation intensity was reduced as the flame temperature was decreased.

By comparing the numerical achievements, it can be observed that despite the higher flame temperature under high load conditions, OH formation regions were distributed more homogeneously throughout the engine cylinder even at the center of the combustion chamber under medium load operating mode. This can be due to the high EGR rate at high load conditions, which increased the mixture coagulation and as a result, OH was formed only in ignition regions, but at a higher intensity, since the flame temperature was considerably higher compared to medium load operating mode.

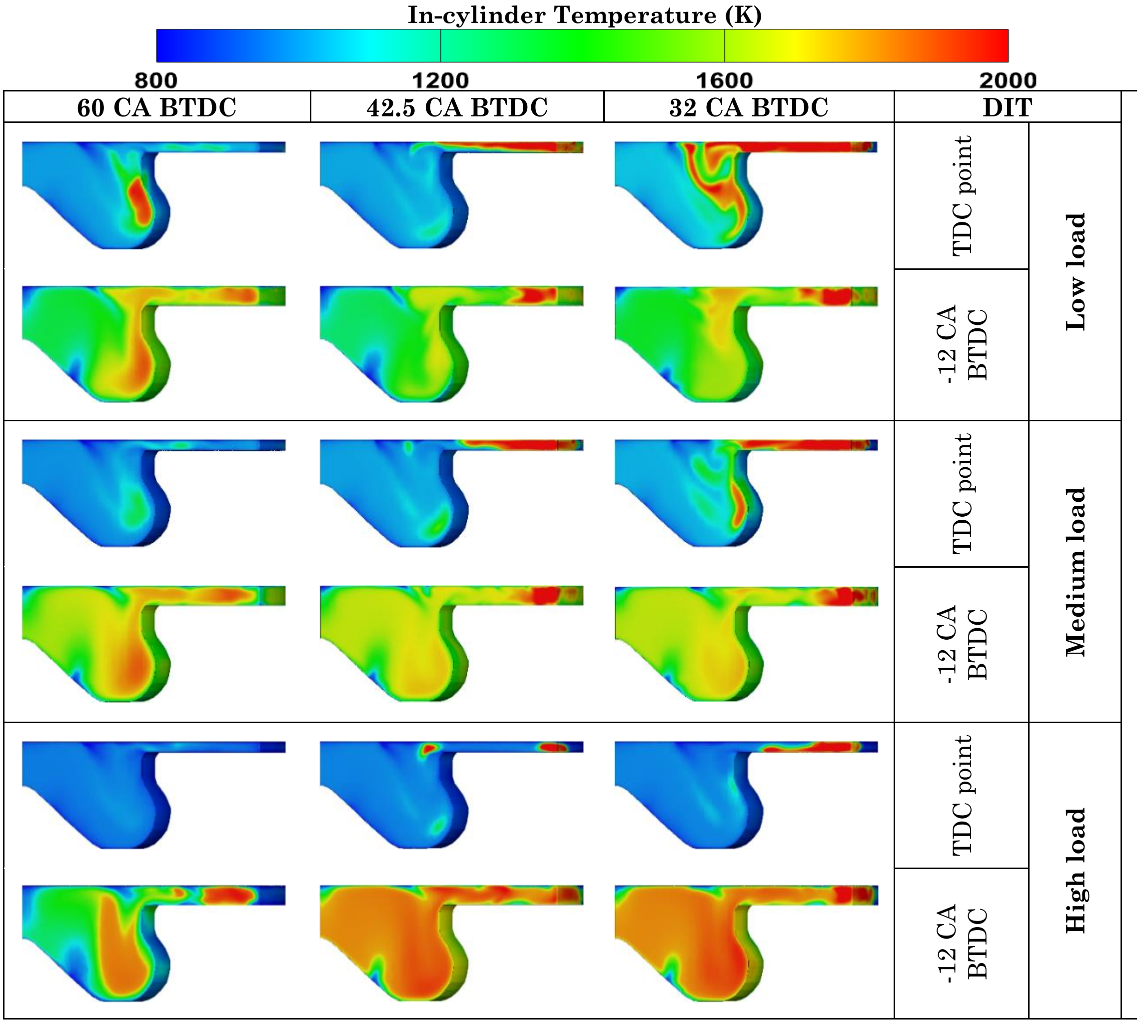


Figure 8. The effects of 60, 42.5, and 32 CA BTDC DITs on the in-cylinder temperature at low, medium, and high load operating conditions

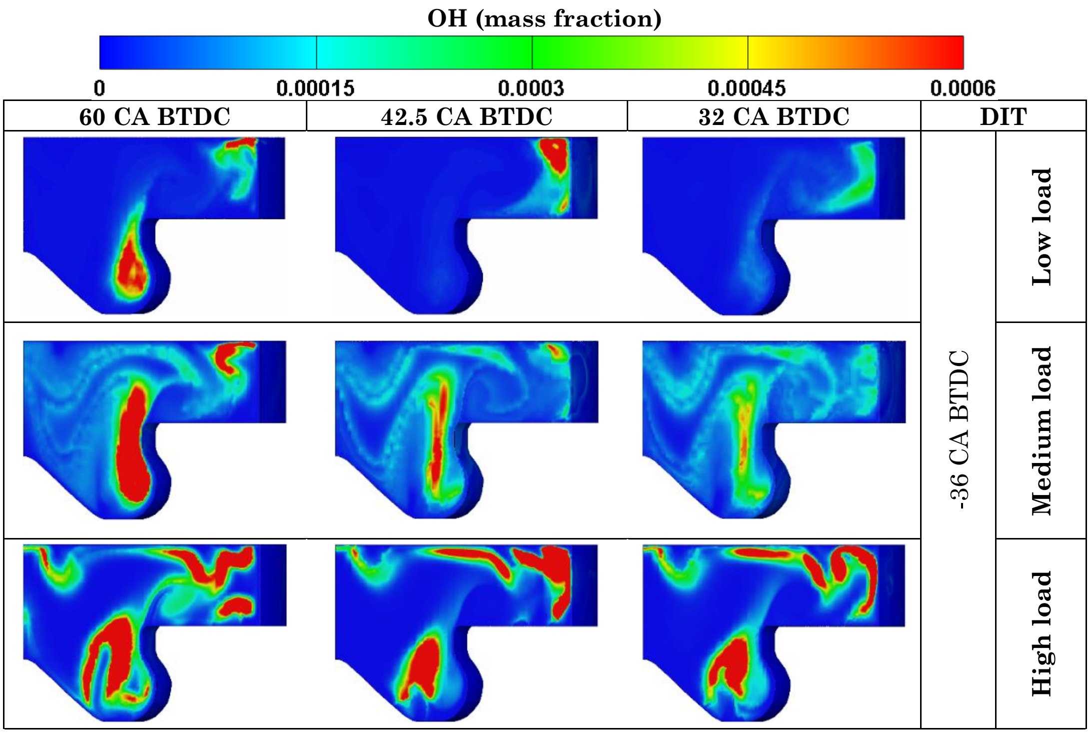


Figure 9. The effects of 60, 42.5, and 32 CA BTDC DITs on the OH distribution inside the combustion chamber at low, medium, and high load operating conditions

Figure 10 depicts NOx versus DIT at low to high load operating conditions. As it can be observed in this figure, by postponing DIT at low load conditions, the NOx level was slightly increased since the combustion phasing approached the TDC point and as a result, the thermal NOx formation was enhanced. Compared to the other operating conditions, fewer NOx emissions were formed under part load operating mode because the flame temperature and the maximum combustion temperature were considerably lower, which resulted in the deterioration of the thermal NOx formation process. The same trend can be seen for both medium and high load operating modes as DIT was retarded. Also, at high load conditions, despite the higher flame temperature, less NOx was formed compared to medium load operating mode, which can be attributed to applying a high EGR rate that significantly reduced the NOx pollutants in the exhaust gases. However, at DIT of 39 CA BTDC under medium load conditions, the NOx level was considerably decreased as the combustion phasing became shorter, and therefore, less time was available for more thermal NOx formation.

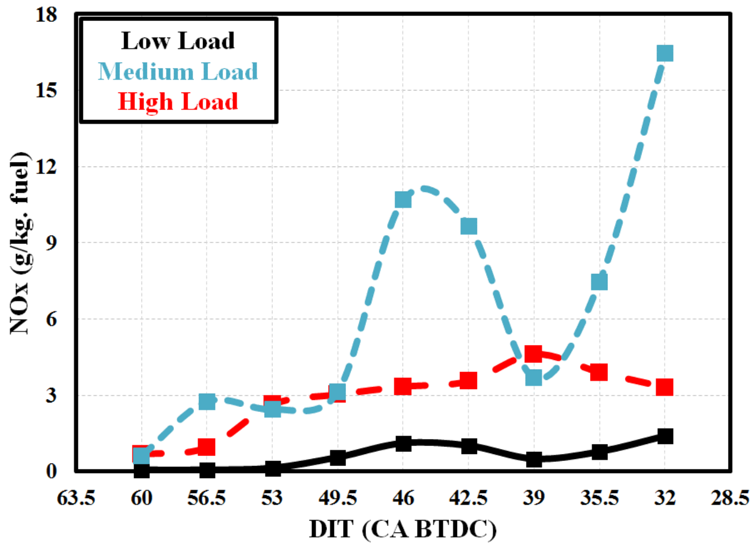


Figure 10. The effect of DIT on NOx emissions under low to high load operating mode

The effects of DIT on the formation and oxidation of soot emission inside the engine cylinder at various operating conditions are illustrated in Figure 11. As can be seen in this figure, the soot emission level reached nearly zero by early DIT at low load operating conditions. This can be related to the higher air-fuel ratio and longer ID period that considerably improved soot oxidation inside the combustion chamber. In other words, a prolonged ID period caused more homogeneous mixture formation and decreased the highly rich regions and also, provided enough time for nearly complete oxidation. Thus, for these reasons, the soot level was vastly decreased. Moreover, by retarding DIT in the late period, due to a decrement in mixture homogeneity, an increase in the fuel coagulation, and a decrease in flame temperature, soot emission was increased. At medium load operating mode, soot was initially reduced and then decreased as DIT was postponed. This can be attributed to the combustion phasing that as advanced to the TDC point, the maximum combustion temperature was increased and as a result, the soot oxidation was enhanced. However, as indicated earlier, late DIT caused a shorter ID period and an increment in mixture inhomogeneity. Therefore, the soot level raised despite an increment in flame temperature. At DIT of 39 CA BTDC under medium load conditions, soot level dramatically raised as a result of the shortening of the combustion duration since less time was available for efficient oxidation of carbon species inside the combustion chamber. At high load operating conditions, by postponing DIT, soot emission considerably reduced since the flame temperature was increased. However, diesel injection at 32 CA BTDC caused more soot emission in the exhaust gases as a result of retarded combustion phasing from the TDC point.

Figure 12 displays the influence of 60, 42.5, and 32 CA BTDC DITs on the in-cylinder NO and soot emissions formation under low to high load engine operating conditions at -36 CA BTDC. As can be observed in this figure, under low load operating mode, soot emission was slightly formed at the center of the combustion chamber since this was a low-temperature region compared to spray-wall interaction zones and led to a weak mixture oxidation process. Moreover, at medium and high load conditions, soot formation regions were distributed throughout the combustion chamber and the intensity of formation (red zones) was higher. This can be related to the fact that a lower air-fuel ratio and thus, higher fuel coagulation inside the cylinder deteriorated soot oxidation compared to low load operating conditions.

Based on the literature, thermal NO is the result of high-temperature region formation inside the combustion chamber. According to Figure 12, it can be seen that under low load conditions, NO emission formed only near the ignition regions (spray-wall interaction zones). However, under medium and high load operating modes, NO formation regions propagated throughout the engine cylinder and as a result, its level substantially raised. This can be due to the enhanced flame propagation and more extended flame front penetration through the center of the combustion chamber.

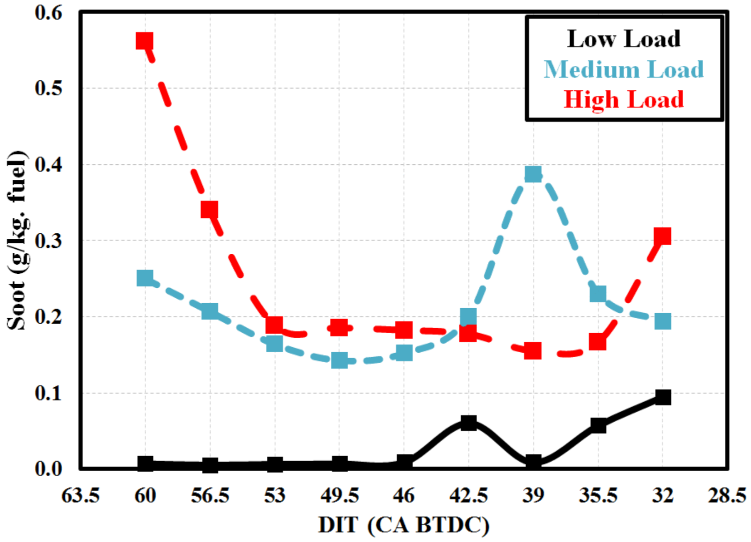


Figure 11. The effects of DIT on soot level under low, medium, and high load engine conditions

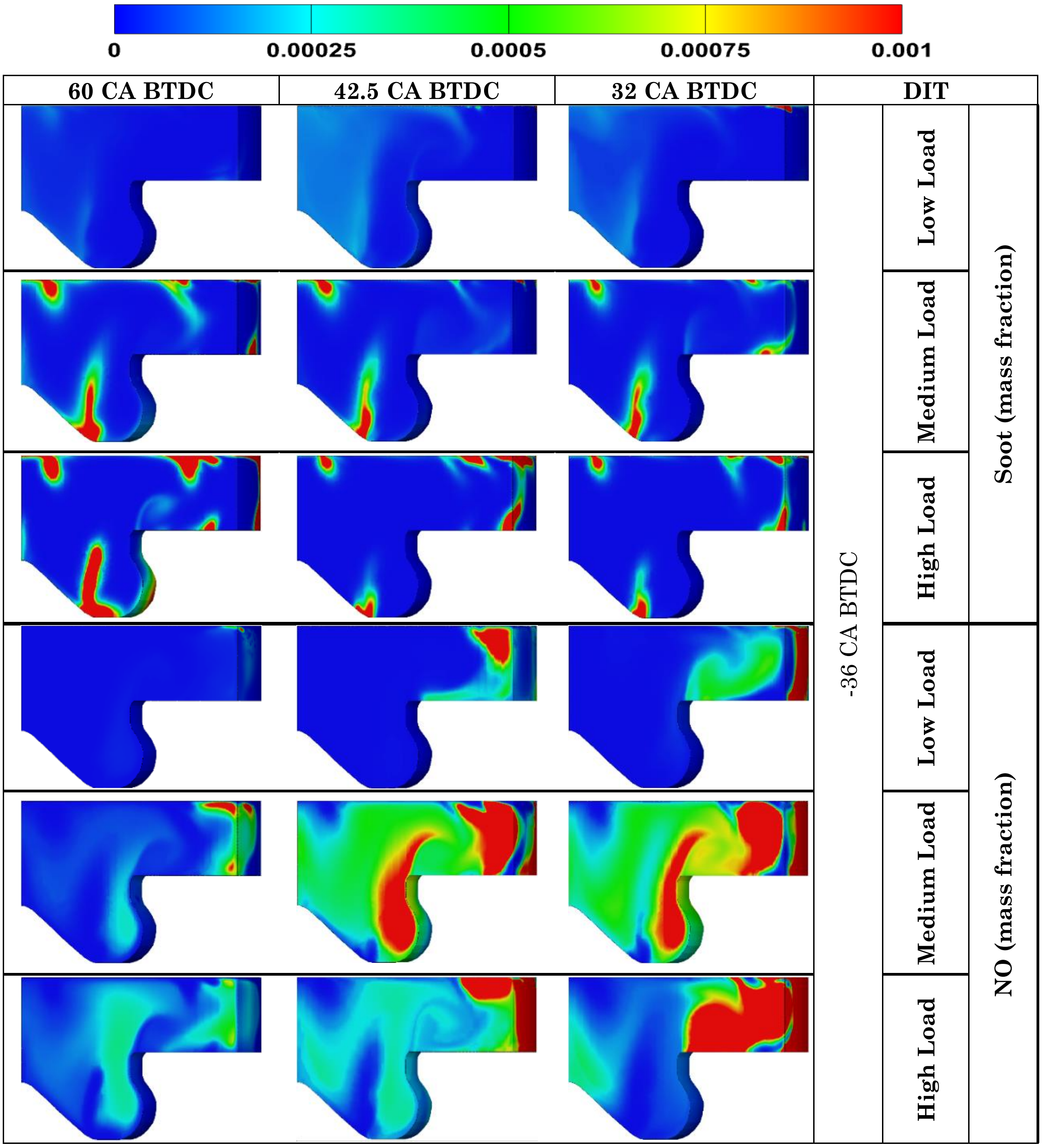


Figure 12. The effects of 60, 42.5, and 32 CA BTDC DITs on the NO and soot emission distribution inside the combustion chamber at low, medium, and high load operating conditions

Figure 13 depicts the effects of 60, 42.5, and 32 CA BTDC DITs on the unburnt gasoline emission at low to high load conditions. As can be noticed in this figure, at low load operating mode, a substantial amount of unburnt gasoline was accumulated at the center of the combustion chamber. However, under medium and high load conditions, the unburnt mixture (gasoline) was considerably reduced throughout the engine cylinder. The main reason for this behavior can be the flame temperature at part load conditions that caused incompetent flame propagation inside the piston bowl. Thus, the flame front only developed near the ignition regions, and most of the air-fuel mixture at the center of the combustion chamber experienced incomplete oxidation. On the contrary, at medium and high load operating conditions, since the flame temperature was higher, flame propagation throughout the combustion chamber was improved, and thus, the flame front penetrated more distance and reached even the center of the piston bowl. Hence, it can be seen that unburnt gasoline emission was noticeably reduced throughout the combustion chamber

Figure 14 displays the impacts of DIT on the Indicated Thermal Efficiency (ITE) under low, medium, and high load conditions. According to this figure, as DIT was postponed at low and medium load conditions, ITE was dropped off since the flame temperature

(HRRPP) was decreased and caused the deterioration of the mixture formation, especially at part load conditions in which unburnt gasoline was vastly accumulated at the center of the piston bowl. Also, at DIT of 42.5 CA BTDC under low load conditions, ITE was dramatically decreased since the combustion duration was noticeably prolonged and most of the air-fuel mixture experienced misfire. On the contrary, under high load conditions, by postponing DIT, ITE slightly raised as the flame temperature and maximum combustion temperature were increased. However, at DIT of 32 CA BTDC, it can be seen that ITE was dropped off since the combustion phasing retarded from the TDC point and the maximum combustion temperature was decreased. By comparing the numerical achievements of all three operating conditions, it can be noticed that the ITE under medium load operating mode for all DITs was higher despite the higher flame temperature and maximum combustion temperature of high load operating mode. This can be attributed to the use of a high EGR rate at high load conditions and lower flame temperature at part load operating mode, which impaired engine performance.

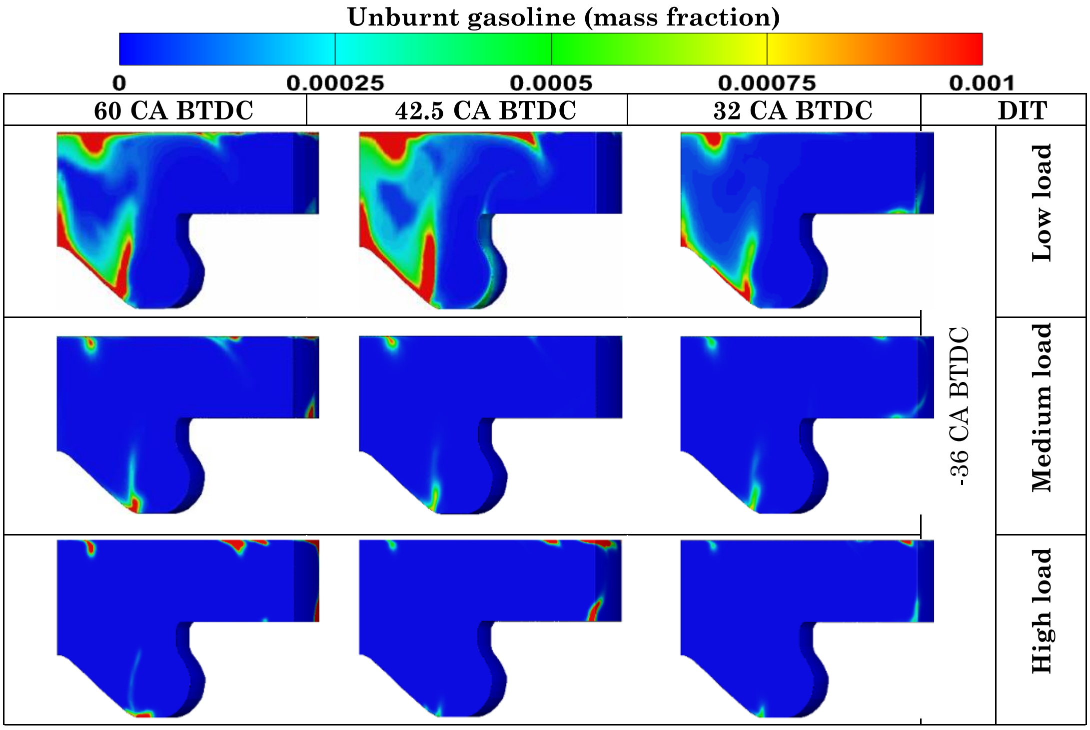


Figure 13. The effects of 60, 42.5, and 32 CA BTDC DITs on the unburnt gasoline distribution inside the combustion chamber at low, medium, and high load operating conditions

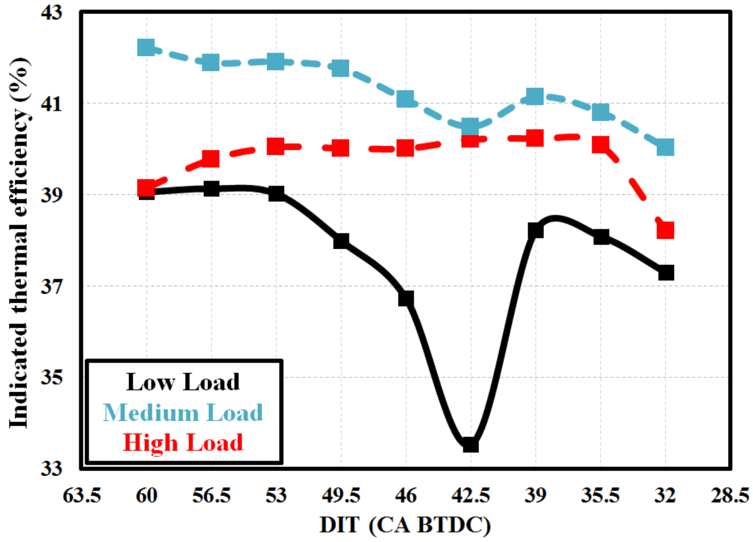


Figure 14. Indicated thermal efficiency versus DIT at low to high load operating conditions

The present numerical study evaluated the effect of nine DITs in the range of 60 to 32 CA BTDC on a high-speed RCCI engine, out of which two, including early (60 CA BTDC) and late (32 CA BTDC) injection timings, caught special attention due to their considerable impacts on the combustion characteristics, emission formation, and performance. Table 7 compares their advantages and disadvantages.

Table 7. Advantages and disadvantages of 60 and 32 CA BTDC DITs

Early DIT (60 CA BTDC)	
Advantages	Disadvantages
1. Stable combustion process 2. Homogeneous air-fuel mixture formation under high load conditions 3. Low NOx emission at all operating conditions 4. Nearly zero soot level under low load operating mode 5. Higher ITE at medium load operating conditions	1. Deteriorated combustion process at low load conditions (lowest maximum combustion temperature) 2. Substantial level of soot under high load condition 3. High level of unburnt gasoline under low load conditions

Late DIT (32 CA BTDC)	
Advantages	Disadvantages
1. Enhanced flame propagation 2. Low level of unburnt gasoline at high load conditions	1. Unstable combustion process and a high chance of engine knocking under high load operating conditions 2. High NOx level under medium load conditions

5. Conclusion

The current numerical research was conducted using the CONVERGE CFD code. The separate and simultaneous impacts of DIT from 60 to 32 CA BTDC with 5 CA steps under three operating loads (IMEP) conditions, i.e., low (4 bar), medium (6 bar), and high (9 bar), on the combustion characteristics, emission formation, and performance in a high-speed RCCI diesel-gasoline engine were investigated. The summary of the important achievements of this research is as follows:

- Early DIT leads to a more extended ID period and prevents the formation of rich and high-temperature regions inside the combustion chamber. Thus, the NOx level reaches nearly zero at all operating load conditions. In addition, diesel injection at 60 CA BTDC significantly decreases soot emission in the exhaust gases.
- Late DIT causes a shorter ID period and combustion phasing advances to the TDC point. In addition, rich and high-temperature regions are formed and increased throughout the combustion chamber, which leads to a simultaneous increment in both NOx and soot under low to high load conditions.
- By retarding DIT under low load conditions, flame temperature dramatically decreases and this leads to incompetent flame propagation and a substantial amount of unburnt gasoline accumulated at the center of the piston bowl.
- At high load operating mode, late DIT (35.5 CA BTDC) vastly increases RI to nearly 5 MW/m^2 and thus, the combustion process becomes unstable and the chance of engine knocking rises.
- At medium load conditions, OH formation regions are distributed throughout the combustion chamber even at the center of the piston bowl, leading to higher ITE compared to low and high load conditions. Also, diesel injection at 42.5 CA BTDC under low load operating mode dramatically decreases the ITE and deteriorates the engine performance level.

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Abbreviations and Symbols

BTDC	Before Top Dead Center
CA	Crank Angle
CFD	Computational Fluid Dynamic
CI	Compression Ignition
deg	degree
DI	Direct Injection
DIT	Diesel Injection Timing
EGR	Exhaust Gas Recirculation
EVO	Exhaust Valve Opening
g	gram
HRR	Heat Release Rate
HRRPP	Heat Release Rate Peak Point
ID	Ignition Delay
IMEP	Indicated Mean Effective Pressure
ITE	Indicated Thermal Efficiency
IVC	Intake Valve Closing
J	Jules
K	Kelvin
kg	kilogram
m^2	Square meter
mg	milligram
MPa	Mega Pascal
m/s	Meter per Second
ms	milliseconds
MW	Mega Watt
ns	nanoseconds
NOx	Nitrogen Oxides
RCCI	Reactivity Controlled Compression Ignition
RPM	Revolution per Minute
TDC	Top Dead Center

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