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Research Paper

Using the DOE Concept to Determine the Appropriate Operating Conditions for the D87 Heavy-Duty Diesel Engine under RCCI Combustion Fueled with Diesel Fuel and Natural Gas

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Abstract: The main purpose of this study is to determine the appropriate operating conditions for Iranian national heavy-duty diesel engines under RCCI combustion fueled with natural gas and diesel fuel. Therefore, in the RCCI combustion simulation, based on the DOE concept, the effect of changing six major parameters namely the IVC pressure, the IVC temperature, the diesel fuel SOI timing, the engine speed, the natural gas/diesel fuel mass ratio, and the effective compression ratio on the engine performance and combustion characteristics were assessed. The simulation results show that considering the IVC pressure between 2.3 and 2.7 bar, the IVC temperature between 350 and 380 K, the diesel fuel SOI timing between -30 and -50 ° ATDC, the NG/diesel fuel mass ratio between 70/30 and 90/10, and the engine speed between 1300 and 1600 rpm lead to optimal D87 engine operation. Where the GIE can be improved to more than 40% compared to the D87 engine operation under the dual-fuel mode of combustion. Although, the engine output power is noticeably reduced up to 17%, , the NOx emission level gets close to the EURO V level and the CO emission level gets close to the EURO VI level. At the same time, the UHC emission level is far from the EURO VI level and the Formaldehyde emission level is far from the EPA 2007 level.

keywords: D87 Heavy-duty diesel engine, Combustion, RCCI; Emission, Natural gas.

Nomenclatures

AEO	U.S. annual energy outlook	LHV	Lower heating value
ATDC	After top dead center	LNT	Lean NOx trap
CA	Crank angle	LTC	Low temperature combustion
CA10	Crank angle of 10% fuel burned	LFG	Landfill gas
CA50	Crank angle of 50% fuel burned	LPG	Liquefied petroleum gas
CFD	Computational fluid dynamic	NG	Natural gas
CI	Compression ignition	NOx	Nitrogen oxides
CNG	Compressed natural gas	P	In-cylinder Pressure
CO	Carbon monoxide	PCCI	Premixed-charge compression-ignition
Cp	Heat capacity at a constant pressure	PLTC	Premixed low temperature combustion
Cv	Heat capacity at a constant volume	PPRR	Peak pressure rise rate
DPF	Diesel particulate filters	PRF	Primary reference fuel
DOE	Design of Experiment	R	Gas constant
EGR	Exhaust gas recirculation	RCCI	Reactivity-controlled compression-ignition
EPA	Environmental Protection Agency	RI	Ringing intensity
EURO	European emission standard	SCR	Selective catalytic reduction

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EVO	Exhaust valve opening	SOC	Start of combustion
GIE	Gross indicated efficiency	SOI	Start of injection
H2	Hydrogen	SOx	Sulfur oxides
H2O2	hydrogen peroxide	t	Time
HCCI	Homogeneous-charge compression-ignition	T	In-cylinder temperature
HRR	Heat release rate	TDC	Top dead center
ICE	Internal combustion engine	UHC	Unburned hydrocarbon
IMEP	Indicated mean effective pressure	γ	Cp /Cv ratio
IVC	Intake valve closing		

1. Introduction

Heavy-duty diesel engines such as ICEs have been developed and used in many applications such as transportation, power generation, industrial, and so on due to their high efficiency. But, their applications are under tight restrictions by some important stringent emission standards and legislations, because of engine high emission levels which have adverse effects on human health and the environment. Therefore, these engines face many challenges in operation. In order to meet ever-increasing stiffer emission regulations on the aforementioned emissions, proposed by relevant organizations like the EPA and European emission standards, the present conventional diesel combustion needs a major upgrade to meet today's standards.

It should be noted important ICEs emissions are NOx, SOx, CO, UHC, Formaldehyde, and soot (CIMAC, 2008). The main factor in the NO_x formation is the occurrence of high in-cylinder temperature in the engine combustion chamber. Thus, lowering the in-cylinder temperature would significantly affect the NO_x level (CIMAC, 2008).

The SOx emission resulting from conventional fossil fuel consumption can be controlled by limiting the sulfur content in fuel as much as possible (CIMAC, 2008).

The CO, UHC, and Formaldehyde emissions are generally produced due to the incomplete combustion of fuels with carbon substances in an engine combustion chamber, especially in the cold regions near the engine cylinder wall and crevices (CIMAC, 2014). Recently, some researches show that these emissions levels can be reduced by improving the combustion characteristics such as the gaseous hydrocarbon fuel enrichment with hydrogen (Kakoee, Bakhshan, Motadayen Aval, & Gharehghani, 2018; Kalsi & Subramanian, 2017).

Moreover, the main source of soot formation is the occurrence of hydrocarbon fuel-rich areas in the engine combustion chamber (CIMAC, 2008). The soot emission level can be reduced by controlling the ignition timing. Using a longer ignition delay causes to creates a better homogeneous mixture before the combustion initiation. Hence, it prevents the fuel-rich areas occurrence in the combustion chamber and reduces the soot level.

In the past decades, emission reduction technologies known as after-treatment systems have been employed by researchers (Reitz, & Duraisamy, 2015). Some of the conventional after-treatment systems are DPF, LNT, SCR, and so on. Of course, the use of these technologies meant a decrease in fuel efficiency, and an increase in the maintenance, extra operation, and installation costs of heavy-duty diesel engines (CIMAC, 2008). Therefore, the use of a new combustion strategy known as the PLTC strategy was proposed to overcome the challenge of after-treatment device employment (Reitz, & Duraisamy, 2015). The HCCI, PCCI, and RCCI combustion strategies are the known types of the PLTC strategy.

Initially, the HCCI combustion strategy was introduced as an easy way to achieve lower NOx and soot emissions levels in CI engines that operate under conventional diesel combustion (Dempsey, Walker, Gingrich, & Reitz, 2014). Generally, in an HCCI engine, a homogeneous air-high reactive fuel mixture is induced to the engine cylinder prior to the combustion initiation during the intake stroke. Thus, the occurrence of hydrocarbon fuel-rich regions in the engine combustion chamber is completely prevented and the soot level is reduced, drastically (CIMAC, 2008). Also, in an HCCI engine, the maximum in-cylinder temperature will be below 1900 K, thus, the NOx level will also be reduced significantly. It should be noted that in the HCCI combustion strategy, a desirable engine output power is controlled by the equivalence ratio factor. Moreover, the thermodynamic conditions of gas composition inside the combustion chamber such as in-cylinder temperature and pressure could also be controlled by this factor (Reitz, & Duraisamy, 2015). But, the main challenges of an HCCI engine are controlling the combustion phasing and duration, especially at high loads also high levels of CO and UHC emissions (Reitz, & Duraisamy, 2015).

In order to overcome the HCCI combustion strategy challenges, the PCCI combustion strategy was proposed (Duan, Jia, Li, & Wang, 2021; Hardy & Reitz, 2006). In a PCCI engine, instead of inducing a homogeneous air-high reactive fuel mixture during the intake stroke, a highly reactive fuel is injected to coincide with the compression stroke to improve the combination of the air-fuel mixture. Unfortunately, this combustion strategy also suffers from controlling the rate of heat release and the combustion phasing and also high levels of CO and UHC emissions.

Therefore, in order to overcome the challenges of the two aforementioned combustion strategies, the RCCI combustion strategy was introduced (Kokjohn, Hanson, Splitter, Kaddatz, & Reitz, 2011). In this strategy, the combination of two fuels with different reactivity (low and high reactive fuels) is used. Thus, in an RCCI engine, the ratio of two fuels with different reactivity which are introduced through different fuel delivery systems is used to control the combustion phasing and the spatial stratification between the two fuels is also employed to control the combustion duration. Generally, in this mode of combustion, a low-reactive fuel such as natural gas or gasoline is entered into the combustion chamber through fuel injection into the intake port. Therefore, a mixture of air and low-reactive fuel is formed in the combustion chamber. After this stage, a highly reactive fuel like diesel fuel is directly injected into the combustion chamber. Thus, better control over the combustion phase and also engine emissions is achievable (Kokjohn, Hanson, Splitter, Kaddatz, & Reitz, 2011).

Since 2011, a wide variety of fuels with different reactivity were used in RCCI engines such as gasoline/ diesel fuel (Kokjohn, Hanson, Splitter, Kaddatz, & Reitz, 2011), hydrated ethanol/diesel fuel (Dempsey, Adhikary, Viswanathan, & Reitz, 2012), natural gas/ biodiesel fuel (Gharehghani, Hosseini, Mirsalim, & Jazayeri, 2015), natural gas/ diesel fuel (Walker, Wissink, DelVescovo, & Reitz, 2015; Ebrahimi, Najafi, Jazayeri, & Mohammadzadeh, 2018; Nieman, Dempsey, & Reitz, 2012; Hamdi, Agrebi, Idrissi, Mondo, Labiadh, Sadiki, & Chrigui, 2022), methanol/ diesel fuel, ethanol/ diesel fuel, n- butanol/ diesel fuel (Zou, Wang, Zheng, Reitz, & Yao, 2016), isobutanol/ isobutanol with the addition of di-Tert butyl peroxide (DelVescovo, Wang, Wissink, & Reitz, 2015), and so on.

Although crude oil resources are limited, in contrast, the resources of natural gas known as the cleanest hydrocarbon fuel (i.e. low-carbon hydrocarbon gaseous fuel) are abundant all over the world. As shown in Figure 1, based on the U.S. AEO 2022 forecast, among the different energy sources, the use of natural gas as an energy source will increase through 2050, significantly. Therefore, these days, in the RCCI combustion field, in many experimental and simulation studies, among low reactive fuels, natural gas is of a great degree of importance among researchers (AEO, 2022). Generally, natural gas consists of some important components like methane, nitrogen, carbon dioxide, ethane, propane, and so on. Of course, among the mentioned components, the dominant volumetric percentage is methane (approximately 89% by volume).

In RCCI engines fueled with natural gas and diesel fuel, the engine efficiency would be improved and a further reduction in the engine emission like NOx and soot would be possible, but, these engines still suffer from other important emissions like unburned methane, Formaldehyde, and CO. Because, in RCCI engines fueled with natural gas and diesel fuel, during the intake stroke, natural gas is injected into the engine intake port to form a pre-mixed air-low reactive fuel mixture in the engine cylinder. Hence, natural gas will be trapped in the engine crevice areas during the engine compression stroke, and the main sources of the formation of unburned methane, CO, and Formaldehyde emissions will be created due to occurring incomplete combustion process and the wall quenching effects near the engine cylinder wall (CIMAC, 2014).

Also, other low reactive fuels like Alcohol (Adzuan & Yusop, 2022), LFG (Ebrahimi & Jazayeri, 2019; Kokabi, Najafi, Jazayeri, & Jahanian, 202), biogas (Asadollahzadeh, Hamedi, & Jazayeri, 2020), biomethane (Baškovič, Vihar, Oprešnik, Seljak, & Katrašnik, 2022), CNG (Aydin, 2021; Harari, Yaliwal, & Banapurmath, 2021), LPG (Elkelawy, Shenawy, Mohamed, Elarabi, & Bastawissi, 2022), and natural gas enriched with hydrogen or syngas in the RCCI mode of combustion (Mabadi Rahimi, Jazayeri, & Ebrahimi, 2021; Kakoee, Bakhshan, Motadayen Aval, & Gharehghani, 2018; Sattarzadeh, Ebrahimi, Jazayeri, 2022) has been studied extensively.

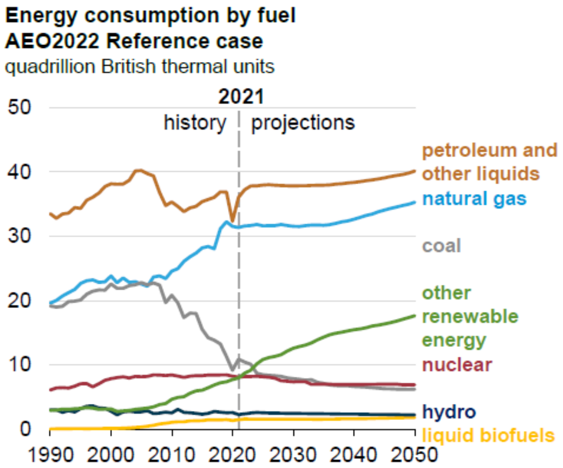

Figure 1: The energy production forecast (AEO, 2022).

Moreover, in this field, several types of heavy-duty and light-duty diesel engines were examined in order to improve their performance and reduce their emission levels (Khatamnejad, Khalilarya, Jafarmadar, & Mirsalim, 2017; Nieman, Dempsey, & Reitz, 2012; Gharehghani, Hosseini, Mirsalim, & Jazayeri, 2015; Aydin, 2021; Harari, Yaliwal, & Banapurmath, 2021).

One of these heavy-duty diesel engines is the Iranian national heavy-duty diesel engine, DESA 150-12V or D87 (DESA, 2019). This 12-cylinder V-type engine was designed for application in marine, railway, and power generation. The engine output power as conventional pure diesel combustion is 1000 kW and that for dual-fuel mode of combustion fueled with natural gas and diesel fuel is 850 kW (DESA, 2019).

Considering that the D87 engine is under its durability test, some limited studies have been conducted to assess the engine performance analysis. In the D87 engine operation under conventional diesel combustion, the effects of some important parameters such as diesel fuel injection timing, diesel fuel injection pressure, and the amount of diesel fuel mass on the combustion characteristics and the engine emissions were investigated (Jafari & Seddiq, 2019). Also, in the same engine under dual fuel mode of combustion, the effect of the number of diesel fuel nozzle holes and exhaust gas recirculation on the engine performance was assessed (Jafari & Domiri Ganji, 2021; Jafari, Domiri Ganji, & Mirsalim, 2013). Moreover, the effect of diesel fuel injection on the D87 engine performance and emissions under RCCI combustion fueled with diesel fuel/toluene/poly-aromatic hydrocarbons (PAH) was evaluated (Jafari & Seddiq, 2021). Recently, the performance of the D87 engine was also analyzed under RCCI combustion fueled with LFG and diesel fuel (Karbasi, Jazayeri, & Ebrahimi, 2022).

Based on studies that were conducted on the D87 engine and according to the RCCI combustion advantages in the engine performance improvement and the engine emissions reduction and also the demand for using natural gas as the cleanest fuel among the conventional hydrocarbon fuels, the current study; the DOE concept-Factorial method is employed to obtain the D87 engine appropriate operating conditions under RCCI mode of combustion fueled with diesel fuel and natural gas. The D87 engine operation is simulated through the AVL FIRE CFD tool coupled with the CHEMKIN chemistry tool. For implementing the DOE concept in the RCCI combustion simulation, six effective engine input parameters were selected including the IVC pressure, the IVC temperature, the diesel fuel SOI timing, the engine speed, the natural gas/diesel fuel mass ratio, and the effective compression ratio. The goals of this study are to maintain the D87 engine output power under RCCI combustion with satisfying the LTC concept, improve the combustion characteristics, and reduce the engine emission levels without engine exposure to diesel knock.

2. D87 Heavy-Duty Diesel Engine Specifications and Computational Model

The D87 engine under study its overview is depicted in Figure 2 is a designed Iranian national heavy-duty diesel engines family which can operate under conventional diesel combustion mode and also dual fuel mode of combustion fueled with diesel fuel and natural gas at a constant speed of 1500 rpm (DESA, 2019). The D87 engine's IMEP in the dual-fuel mode of combustion is 13.65 bar with a thermal efficiency of 38%. The D87 engine's technical specifications are listed in Table 1 (DESA, 2019).

Figure 2: An overview of Iranian national heavy-duty diesel engine (D87) on the test bed (Jafari, Domiri Ganji, & Mirsalim, 2013).

In this study, in order to simulate the RCCI mode of combustion in the D87 engine fueled with diesel fuel and natural gas, the AVL FIRE CFD tool coupled with the CHEMKIN tool is used. The used three-dimensional computational models for conducting the combustion simulation are presented in Figure 3.

Moreover, in order to assess the computational mesh independency and obtain the proper number of cells in the 3D computational model, several different average cell sizes were examined, as listed in Table 2. For each considered average cell size in Table 2, the difference between the in-cylinder peak pressure obtained in the RCCI combustion simulation and the D87 engine experimental data (i.e. 106.76 bar) is evaluated and depicted in Figure 4 (Jafari, Domiri Ganji, & Mirsalim, 2013).

Table 1: DESA 150-12V (D87) heavy-duty diesel engine specifications (DESA, 2019).

Displacement	38.1 L
Bore x Stroke	150 mm x180 mm
Connecting rod length	282 mm
Engine speed	1500 rpm
Number of intake/Exhaust valves	2
IVC timing	-150° ATDC
EVO timing	125° ATDC
D87 Conventional Diesel Engine	
Compression ratio	15:1
Diesel fuel injection mechanism	Common rail
Diesel fuel injector holes number	6
Injector hole diameter	290 µm
Included spray angle	140°
Rated power	1000 kW
D87 Dual Fuel Engine	
Compression ratio	11.5:1
Rated power	850 kW

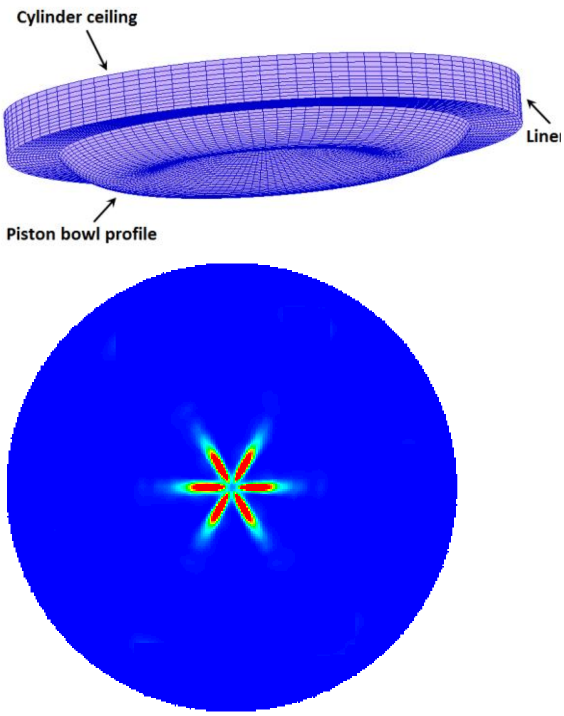

Figure 3: Three-dimensional computational grids of the D87 engine combustion and a top view of the diesel fuel spray axis.

As depicted in Figure 4, adopting the average cell sizes less than 1.8 mm, i.e. 68880 cells at the TDC, would not lead to any more accurate simulation results, but, it would increase the computation time unnecessarily. Therefore, in the present work, the average cell size of 1.8 mm is used to conduct the D87 engine combustion simulation.

Table 2: Different average cell sizes and the relevant number of cells at the TDC

mesh average cell size (mm)	Number of cells at the TDC
1.2	166776
1.5	91224
1.8	68880
2.0	10104
2.3	52632
2.6	42936

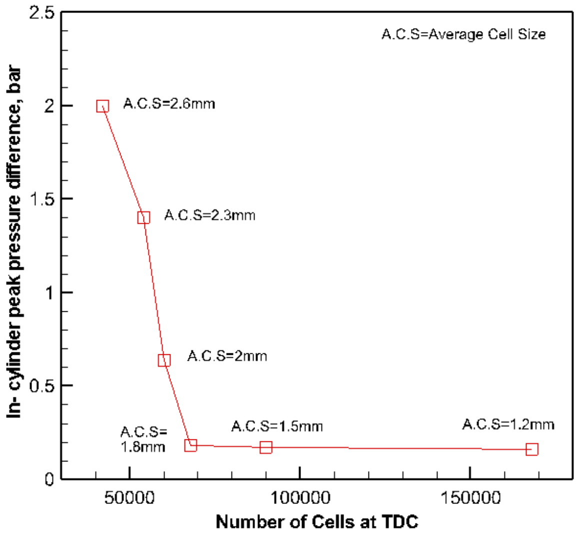

Figure 4: The 3D computational mesh independency assessment.

Since the D87 engine under the dual-fuel mode of combustion uses NG and diesel fuel, thus, these two fuels with different reactivity are also used in the D87 engine operation under the RCCI mode of combustion. Of course, in the present simulation study, in order to use a reduced PRF mechanism to predict all chemical reactions between NG and diesel fuel, Methane and N-heptane are considered tothe representative of NG and diesel fuel, respectively. The lower heating value of methane is 50 MJ/kg and that of n-heptane is 44.6 MJ/kg. Hence, an optimized reduced PRF mechanism including 76 species and 464 reactions is selected to predict the reactions between the two mentioned fuels (Rahimi, Fatehifar, & Khoshbakhti Saray, 2010). Also, in order to model the diesel fuel spray, some sub-models which were used are as follows:

- The turbulence dispersion model (Gosman & Ioannides, 1983) for modeling the interaction of the particles with the individual turbulent eddies.
- The wall jet model (Naber & Reitz, 1988) for modeling the diesel fuel spray–wall interaction.
- Dukowicz model (Dukowicz, 1979) for modeling the diesel fuel droplet evaporation.
- The wave standard model for modeling the diesel fuel droplet break–up (Liu & Reitz, 1993).
- The diesel nozzle model (Kunsberg-Sarre, Kong, & Reitz, 1999) for simulating the nozzle

flow such as injection velocities and initial droplet diameters due to cavitation.

The D87 engine operating setup under the dual-fuel mode of combustion fueled with diesel fuel-NG indicated in Table 3 is considered. The mathematical modeling simulation is validated by the experimental data available by DESA for in-cylinder pressure variation as presented in Figure 5 (Jafari, Domiri Ganji, & Mirsalim, 2013).

Table 3: D87 engine input setup data for validation purposes (Jafari, Domiri Ganji, & Mirsalim, 2013).

Parameter type	Value
Gross IMEP (bar)	13.65
Intake Pressure (bar)	1.7
Intake Temperature (K)	338
Diesel fuel mass per each cycle (mg)	46.5
Natural gas (Methane) mass per each cycle (mg)	173.6
Total fuel mass per each cycle (mg)	220.1
Diesel fuel SOI (° ATDC)- Dual-fuel mode	-22
EGR percentage (%)	0

As shown in Figure 5, the developed simulation model has the potential to predict the D87 engine in-cylinder pressure trace, accurately. Also, as presented in Table 4, the reduction in the obtained gross IMEP and the GIE resulted from implementing the dual-fuel combustion mode compared to that of the D87 engine experimental result is less than 1.6% and 0.7%, respectively (Jafari, Domiri Ganji, & Mirsalim, 2013).

As mentioned earlier, in the RCCI combustion strategy, two fuels with different reactivity are used. Generally, in this strategy initially low reactive fuel like NG mixed with intake air enters the cylinder, this is followed by a highly reactive fuel like diesel fuel which is directly injected into the engine combustion chamber earlier compared to conventional diesel engine.

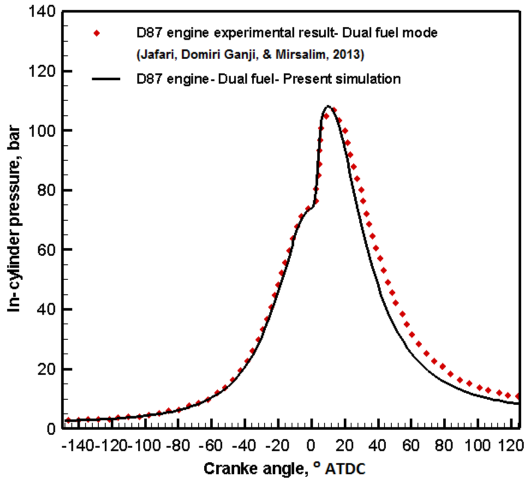

Figure 5: The D87 engine in-cylinder pressure in dual-fuel mode for validation purpose.

Table 4: The D87 engine gross IMEP and GIE for validation purpose (Jafari, Domiri Ganji, & Mirsalim, 2013).

Combustion type	Gross IMEP (bar)	GIE (%)
Dual-fuel engine (Jafari, Domiri Ganji, & Mirsalim, 2013)	13.65	40
Dual-fuel combustion simulation (Present work)	13.44	39.75
	Error 1.54%	Error 0.63%

This is because in the RCCI mode of combustion, the main combustion will be initiated due to the reactions between some important species in the combustion chamber such as hydrogen peroxide (H2O2), formaldehyde (CH2O), and hydroxyl (OH radical) (Reitz & Duraisamy, 2015). Therefore, in order to implement the RCCI combustion strategy in the D87 engine fueled with diesel fuel and natural gas, by using the D87 engine operating conditions mentioned in Table 3, the diesel fuel SOI is advanced and set at -45° ATDC. The D87 engine in-cylinder pressure resulting from the RCCI combustion simulation is shown in Figure 6 and compared with the experimental data (Jafari, Domiri Ganji, & Mirsalim, 2013). The result shows that not only the engine under investigation can optimally operate under RCCI combustion, but also, the D87 engine gross IMEP and GIE improves more than 6% and 7%, respectively, as listed in Table 5.

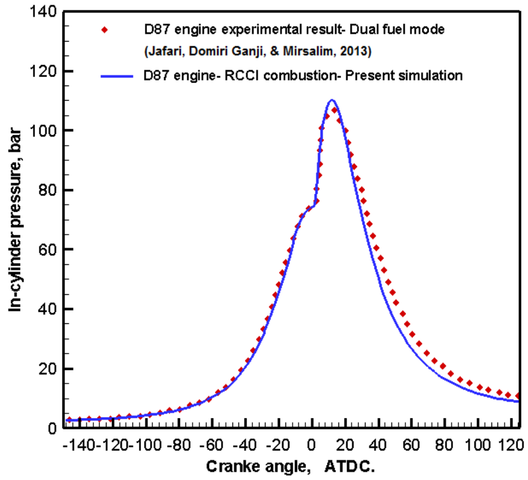

Figure 6: The D87 engine in-cylinder pressure under RCCI mode of combustion fueled with diesel fuel and natural gas.

Table 5: The D87 engine gross IMEP and GIE for validation purpose (Jafari, Domiri Ganji, & Mirsalim, 2013).

Combustion type	Gross IMEP (bar)	GIE (%)
Dual-fuel engine (Jafari, Domiri Ganji, & Mirsalim, 2013)	13.65	40
RCCI combustion simulation (Present work)	14.58	43.13
	Enhanced 6.81%	Enhanced 7.83%

3. The DOE Concept- Factorial Method

For implementing the DOE concept- Factorial method in the D87 engine performance evaluation under RCCI mode of combustion, the effects of several effective input parameters on the engine performance are evaluated. In the current study, six effective input parameters, namely, the IVC pressure and temperature, the diesel fuel SOI timing, the engine speed, the natural gas/diesel fuel mass ratio, and the effective compression ratio are selected. It should be noted that the main objective of the present work is to find appropriate initial conditions to maintain the D87 engine output power under RCCI combustion while satisfying the LTC concept, improving the combustion characteristics, and reducing the engine emission levels without the engine being exposed to diesel knock.

Based on the D87 engine operating conditions (Jafari, Domiri Ganji, & Mirsalim, 2013), five levels for the six selected input parameters are chosen as presented in Table 6.

Table 6: Selected input parameters at five levels.

	Level Number				
Input Parameters	0	1	2	3	4
IVC P (bar)	2.3	2.4	2.5	2.6	2.7
IVC T (K)	340	350	370	390	400
SOI timing (° ATDC)	-30	-40	-50	-60	-70
Engine Speed (rpm)	1000	1300	1500	1600	1800
Effective compression ratio (or IVC timing) (° ATDC)	-154	-152	-150	-148	-146
NG/diesel fuel mass ratio	50/50	60/40	70/30	80/20	90/10

Basically, for implementing the full factorial method, when five levels for the six selected input parameters are considered, a total of 15625 (i.e. 5X5X5X5X5X5) treatment combinations have to be examined. But, in the present work, some limited numbers of combinations are randomly chosen and used for the RCCI combustion simulation in the D87 engine.

4. Results and Discussion

4.1. The Misfire Occurrence Assessment

In an RCCI engine that uses n-heptane (i.e. diesel fuel) as a normal chain hydrocarbon fuel, the cool flame known as the CA10 generally takes place coincidence with direct diesel fuel injection into the combustion chamber about 10-20° CA before the SOC (Ando & Yasuyuki, 2009). Moreover, in an RCCI engine fueled with a normal chain hydrocarbon fuel, H2O2 plays a key role in oxidizing this type of fuel. H2O2 initiates to form coincident with the CA10 occurrence. The H2O2 loop reactions which are exothermic reactions cause enough heat will be accumulated in the engine combustion chamber and the SOC is initiated (Ando & Yasuyuki, 2009). Advancing the diesel fuel SOI timing causes that due to further effects of combustion air swirl on the diesel fuel spray, the concentration of diesel fuel-rich zone is reduced. Thus, the amount of fuel energy released in the CA10 stage is also reduced due to further dispersion of diesel fuel and its penetration into the available air-methane mixture. Hence, the result of advancing the diesel fuel SOI timing and the reduction of the amount of fuel energy released in the CA10 stage is that the start of the main combustion will be hampered.

In the present study, based on the DOE concept, the D87 engine's combustion simulation results show that for the engine speed between 1300 and 1800 rpm, when the diesel fuel SOI timing is advanced to more than -50° ATDC and the diesel fuel/NG mass ratio is also reduced to less than 50/50, the thermodynamic conditions is not right for initiation of the main combustion, thus, the D87 engine operation leads to the misfire occurrence.

4.2. The Diesel Knock Occurrence Assessment

Based on Eng research (Eng, 2002), the RI can be considered as a criterion that leads to the occurrence of diesel knock in a diesel engine. Generally, diesel knock occurs when the fuel energy is released very fast into the engine combustion chamber. This matter causes the PPRR in the engine cylinder increases, drastically. Therefore, a heavy-duty diesel engine operation will be exposed to excessive combustion noise known as diesel knock. This phenomenon causes damage to engine parts which should be avoided. A diesel engine operation is not the exposure to diesel knock when the PPRR or the RI values are below 15bar/° CA and 5 MW/m^2, respectively (Eng, 2002). In order to calculate the RI value, the same expression presented by Eng can be used (Eng, 2002).

$$RI = \frac{1}{2\gamma}\frac{(0.05({dP}/{dt})_{max})^2}{P_{max}}\sqrt{\gamma R T_{max}} \qquad (1)$$

In this equation, $(dP/dt)_{max}$ is the PPRR, P_{max} is the maximum in-cylinder pressure, and T_{max} is the maximum in-cylinder temperature.

According to the DOE concept, the RCCI combustion simulation results show that by decreasing the engine speed compared to the experimental conditions along with increasing the diesel fuel mass share up to 90%, the D87 engine operation is vulnerable to diesel knock. Also, by increasing the intake charge temperature to more than 380K along with increasing the engine speed relevant to the experimental conditions could easily lead to diesel knock occurrence.

4.3. The Low-Temperature Combustion Concept Assessment

Since the RCCI combustion strategy is known as the LTC strategy, thus, the maximum in-cylinder temperature should be below 1900 K (Reitz, & Duraisamy, 2015). By implementing the DOE concept, the D87 operation simulation results illustrate that in different engine speeds and effective compression ratios, when the diesel fuel mass share increases to more than 40% versus the natural gas mass share, increasing the intake charge temperature to more than 390 K leads to increase the peak in-cylinder temperature to more than 1900 K. Although the D87 engine operation is not exposed to diesel knock, , the LTC concept is not fulfilled. Thus, the engine operation under these conditions is undesirable.

4.4. The Desirable Situation for the D87 Engine Operation

By detailed assessment of six engine input parameters mentioned in Table 6, the simulation results show that in different scenarios the effective compression ratios, and the engine operation adjustment under the initial conditions listed in Table 7 leads to the desirable engine operation. It should be noted that under these mentioned conditions, the diesel fuel mass share reduction compared to the natural gas mass share is not an obstacle to obtain the desired engine performance. However, the obtained desirable NG/diesel fuel mass ratio is between 70/30 and 90/10. It is important that as mentioned earlier, for this proposed range of the NG/diesel fuel mass ratio, the diesel fuel SOI timing should be limited to below -50º ATDC to avoid misfire occurrence.

Table 7: The obtained desirable initial conditions.

	Selected input parameter range	
Input parameters	Minimum	Maximum
IVC Pressure (bar)	2.3	2.7
IVC Temperature (K)	350	380
SOI timing (° ATDC)	-30	-50
Engine Speed (rpm)	1300	1600
NG/Diesel fuel mass ratio	70/30	90/10

For the mentioned desirable conditions, the results for the D87 engine's IMEP and the GIE are depicted in Figure 7. As shown in this figure, for five desirable cases, the maximum loss in the engine power is approximately 17% compared to the dual-fuel mode of combustion experimental data (i.e. 13.65 bar) (Jafari, Domiri Ganji, & Mirsalim, 2013). At the same time, the GIE is more than the experimental data (i.e. 40%) (Jafari, Domiri Ganji, & Mirsalim, 2013). Moreover, for these desirable conditions, the PPRR values and the calculated RIs are depicted in Figure 8. As shown, in the D87 engine operation under the mentioned conditions in Table 6, the engine will not be exposed to the diesel knock occurrence.

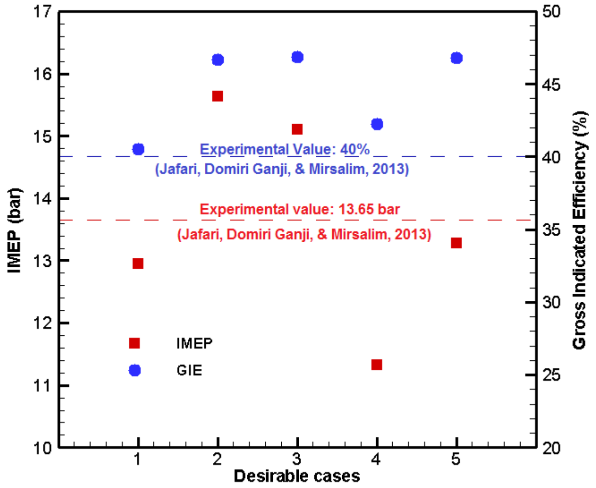

Figure 7: The D87 engine output power and GIE for the obtained desirable conditions.

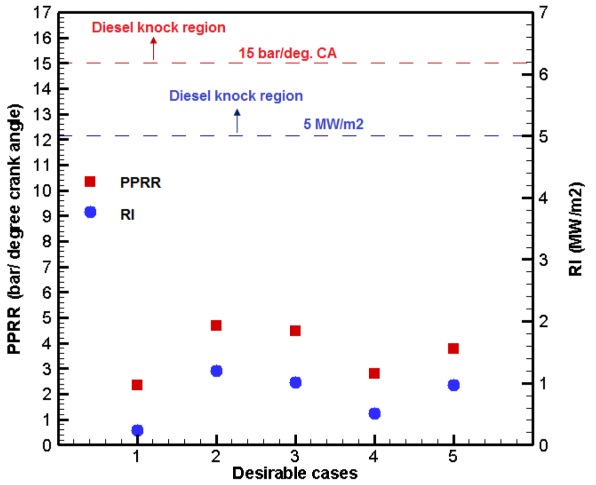

Figure 8: The PPRR and the RI values for the obtained desirable conditions.

4.5. The CA50 and Combustion Duration

The CA50 as an important combustion characteristic is the crank angle which 50% of the fuel energy is released into the engine combustion chamber. As depicted in Figure 9, the CA50 for the obtained desirable conditions takes place after the TDC. Therefore, the negative work resulting from the fuel energy release prior to the TDC, during the compression stroke, decreases.

Another important combustion characteristic is the combustion duration. In the RCCI combustion strategy that uses two fuels, a highly reactive fuel such as diesel fuel is used to supply the required energy for the combustion initiation. On the other hand, the combustion will be extended due to the presence of low reactive fuel. Hence, in the present study, by using natural gas as a low-reactive fuel in the D87 RCCI engine, it is expected that the combustion duration increases with the gradual release of natural gas energy. For the obtained desirable cases, the average combustion duration is about 31° crank angle.

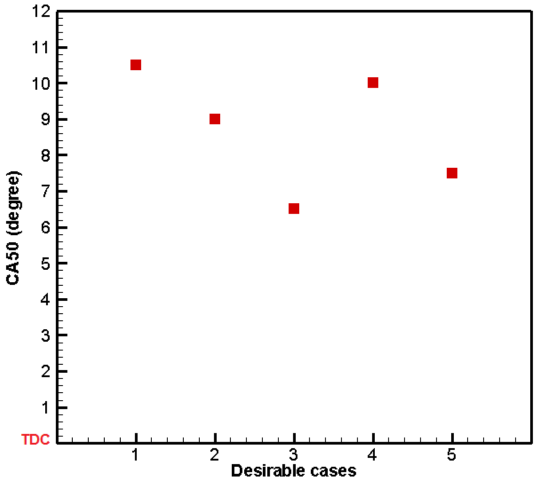

Figure 9: The CA50 for the obtained desirable conditions.

4.6. The D87 Engine Emission Evaluation

For all five relevant desirable cases, the D87 engine emissions are assessed. Figure 10 shows NOx and CO emissions results. In the D87 heavy-duty diesel engine under RCCI combustion fueled with diesel fuel and natural gas, the simulation results based on the DOE concept show that the NOx emission level gets close to the EURO V level (i.e. 2 g/kWh). At the same time, the CO emission level gets close to the EURO VI level (i.e. 1.5 g/kWh).

The UHC and Formaldehyde emissions are also depicted in Figure 11. As shown in Figure 11, for the mentioned desirable conditions, the UHC emission level is far from the EURO VI level (i.e. 0.13 g/kWh) and the Formaldehyde emission level as a carcinogenic emission is far from the EPA 2007 level (i.e. 0.012 g/kWh).

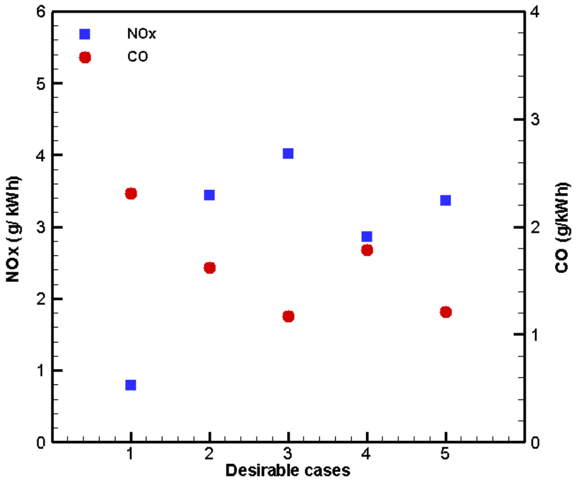

Figure 10: NOx and CO emissions for the obtained desirable conditions.

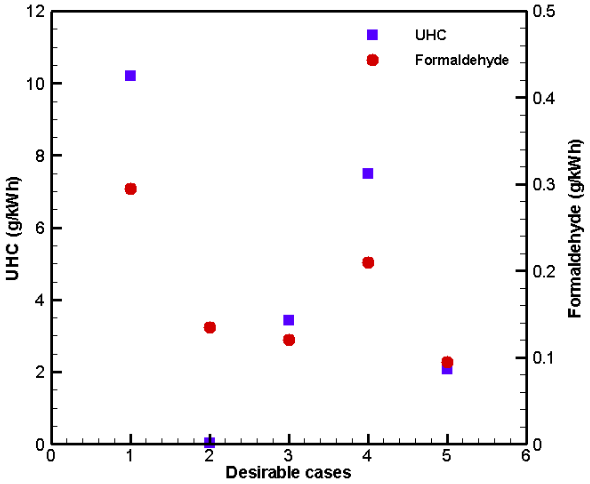

Figure 11: The UHC and Formaldehyde emissions for the obtained desirable conditions.

Conclusions

The present study aims to evaluate the performance of the Iranian national heavy-duty diesel engine (D87) under the RCCI combustion strategy fueled with diesel fuel and natural gas based on the DOE concept-Factorial method. The effect of six of the engine input parameters on the combustion characteristics and emissions were assessed. The selected input parameters are the IVC pressure, the IVC temperature, the diesel fuel SOI timing, the engine speed, the natural gas/diesel fuel mass ratio, and the effective compression ratio. Thus, in order to improve the D87 engine performance and combustion characteristics of D87, the following results can be derived.

1) The D87 engine operation leads to the misfire when at the engine speed between 1300 and 1800 rpm, the diesel fuel SOI timing is advanced to more than -50° ATDC, and the diesel fuel/NG mass ratio is also reduced to less than

50/50.

2) Under two different conditions, the D87 engine operation will be the exposure to diesel knock: (a) when the diesel fuel mass share is increased up to 90% along with decreasing the engine speed compared to the experimental conditions and (b) the intake charge temperature is raised to more than 380 K along with increasing the engine speed compared to the experimental conditions.

3) In contrast to the engine speeds and effective compression ratios, increasing the diesel fuel mass share to more than 60% versus the natural gas mass share and increasing the intake charge temperature to more than 390 K have significant effects on the LTC concept violation.

4) Compared to the dual-fuel mode of combustion, by operating the D87 engine under RCCI combustion, at various effective compression ratios, considering the IVC pressure between 2.3 and 2.7 bar, the IVC temperature between 350 and 380 K, the diesel fuel SOI timing between -30 and -50 ° ATDC, the NG/diesel fuel mass ratio between 70/30 and 90/10, and the engine speed between 1300 and 1600 rpm cause to improve the GIE to more than 40%. At the same time, the maximum loss in the D87 engine power is approximately not more than 17% compared to the dual-fuel mode of combustion experimental data.

5) Under the desirable conditions for the D87 engine, the CA50 takes place after the TDC. Thus, along with the reduction in negative work resulting from the fuel energy release prior to the TDC, the average combustion duration is about 31° crank angle.

6) Based on the proposed desirable situations for the D87 engine operation, the NOx emission level gets close to the EURO V level, and at the same time, the CO emission level gets close to the EURO VI level. But, the UHC emission level is far from the EURO VI level, and also the Formaldehyde emission level is far from the EPA 2007 level.

The D87 engine, 12-cylinder V-type engine, which is designed with the developed strategy, would lead to achieve the optimal application in marine, railway, and power generation purposes, can satisfactorily operate under conventional diesel combustion and also under the dual-fuel mode of combustion. In recent years, along with the significant success of RCCI combustion in reducing engine emissions, the reduction of hydrocarbon fuel consumption was also considered by the researchers. Thus, in order to the maximum reduction in hydrocarbon fuels consumption as the largest source of greenhouse gas emissions, the use of the RCCI combustion strategy in the D87 engine fueled with other renewable fuels such as landfill gas, biogas, hydrogen, syngas, and so on is suggested to reduce the engine emissions and also save the hydrocarbon fuels resources.

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