Gas Processing Journal

Vol. 10, No. 1, 2022, pp. 85 - 94
http://gpj.ui.ac.ir

Research Paper

Performance Analysis of Iranian National Heavy-Duty Diesel Engine under RCCI Combustion Fueled with Landfill Gas and Diesel Fuel

Jafar Karbasi[*1], Seyed Ali Jazayeri[2], Mojtaba Ebrahimi[1],

[1] Department of Mechanical Engineering, Ayatollah Amoli Branch, Islamic Azad University, Amol, Iran
[2] Department of Mechanical Engineering, K.N. Toosi University of Technology, Tehran, Iran

Received: 2022-03-07 Revised: 2022-08-05 Accepted: 2022-06-18

Abstract: Landfill gas is one of the most important constituents in greenhouse gas production, but, it could be easily eliminated by using it in an engine as an alternative to conventional fuels. Because, there are several concerns about the use of LFG as fuel, therefore, the present study seeks to analyze the performance of the Iranian heavy-duty diesel engine (D87) under RCCI combustion fueled with diesel fuel and LFG. The main objectives of this study are to overcome the limitations of using LFG in the D87 engine as an alternative fuel, improve the D87 engine combustion characteristics, and reduce engine emissions. For this purpose, the effects of four major influential input parameters on the D87 engine performance were evaluated, namely, the IVC temperature and pressure, the diesel fuel SOI timing, and the LFG/diesel fuel mass ratio. The DOE concept-Factorial method was employed to predict the appropriate ranges of the selected four crucial parameters that lead to the desired performance. The simulation results show that the desirable engine performance would be achieved for the IVC temperature between 350 and 400K, for the IVC pressure between 2.6 and 2.9 bar, for the diesel fuel SOI timing between -75 and -30° ATDC, and the LFG/diesel fuel mass ratio between 70/30 and 85/15. Although, the hydrocarbon fuel consumption can be reduced by more than 80% byG, the downfall is that the EURO VI level for NOx, CO, and UHC and also the EPA 2007 level for Formaldehyde cannot be met.

keywords: RCCI Combustion; Heavy-duty diesel engine; LFG; DOE concept; Factorial method.

Nomenclature

ATDC	After top dead center	LFG	Landfill gas
CA10	Crank angle of 10% fuel burned	LHV	Lower heating value
CA50	Crank angle of 50% fuel burned	LTC	Low temperature combustion
CA90	Crank angle of 90% fuel burned	NG	Natural gas
CH2O	Formaldehyde	NOx	Nitrogen oxides
DESA	Iran heavy-duty diesel engine manufacturing company	PPRR	Peak pressure rise rate
DOE	Design of experiments	PCCI	Partially premixed-charge compression-ignition
EPA	Environmental Protection Agency	RCCI	Reactivity-controlled compression-ignition
EURO	European Emission Standard	RI	Ringing intensity
EGR	Exhaust gas recirculation	SOC	Start of Combustion
GIE	Gross indicated efficiency	SOI	Start of injection
HRR	Heat release rate	TDC	Top dead center
HCCI	Homogeneous-charge compression-ignition	UHC	Unburned hydrocarbon
IMEP	Indicated mean effective pressure	γ	CP/CV ratio

[*] **Corresponding Author.**
Authors' Email Address: [1] **J. Karbasi** (j.karbasi@yahoo.com ac.ir), [2] **S. A. Jazayeri** (jazayeri@kntu.ac.ir),
[3] **M. Ebrahimia** (m.ebrahimi1353@gmail.com)

http://dx.doi.org/10.22108/GPJ.2022.132943.1115

1. Introduction

The popularity and widespread use of heavy-duty diesel engines in the industrial sector such as electrical power generation and transportation is generally related to the desirable properties of these engines, such as the high compression ratio, engine performance in conditions of dilute fuel-air mixture, and absence of throttle losses. Diesel engines, although producing less carbon monoxide and unburned hydrocarbons than gasoline engines, , nitrogen oxides (NOx), particulate matter, and soot, due to the heterogeneous nature of combustion in conventional diesel engines could be significant, especially along with the lack of high-quality fuel which if these emissions are not controlled, major damage could be done to human health and the environment. One of the challenges facing these engines is the simultaneous reduction in NOx and soot emissions. The NOx formation is dependent on the high in-cylinder temperature and the source of soot formation is a locally fuel-rich zone existing in the engine combustion chamber. Therefore, high costs must be spent to provide after-treatment equipment such as selective catalytic reduction and diesel particulate matter filters to reduce a diesel engine emission. Although the sequential fuel injection system strategy in the last decade has drastically reduced NOx and soot at the same time in conventional diesel engines it should be noted that, to continuously meet the engine emission standards such as the European Emission Standard, the engine operating conditions and the performance of the used after-treatment devices must be regularly monitored. The operation of after-treatment equipment is very sensitive to fuel characteristics, therefore, if the consumed fuel is not standard, after-treatment systems will break down quickly and this damage is irreversible. Hence, to improve the engine performance in terms of emissions like NOx and soot, low-temperature combustion strategies were proposed for diesel engines such as HCCI and PCCI combustions (Pourfallah & Armin, 2019). Despite some of the benefits of these mentioned strategies in terms of combustion characteristics improvement and engine emissions reduction, there is a major problem in controlling combustion phasing and combustion durations (Reitz & Duraisamy, 2015; Paykani, Kakaee, Rahnama, & Reitz, 2015). Meanwhile, the promising RCCI combustion strategy as a flexible combustion strategy that takes advantage of a variety of fuels, increases engine efficiency and reduces engine emissions was introduced (Kokjohn, Hanson, Splitter, & Reitz, 2011). In this strategy, controlling the combustion phase is provided by using two fuels with different reactivity this combustion strategy injects a low reactive fuel with low cetane number ,e spatial stratification between the two fuels (Dempsey, Walker, Gingrich & Reitz, 2014). In this combustion strategy, a low reactive fuel with a low cetane number is injected into the air intake port during the engine intake stroke. Thus, a low reactive pre-mixed mixture of air and fuel is formed within the combustion chamber.

To generate the conditions appropriate to initiate combustion of the available low reactive air-fuel mixture, a highly reactive fuel like diesel fuel is directly injected into the engine combustion chamber using a high-pressure fuel injector, nearly at the end of the engine compression stroke.

In recent years, in the RCCI combustion field, many experimental and numerical works have been conducted with different fuels, one with high reactivity and the other with low reactivity, such as gasoline-diesel (Splitter, Wissink, Kokjohn, & Reitz, 2012; Lim & Reitz, 2013), ethanol and methanol-diesel (Dempsey, Adhikary, Viswanathan, & Reitz, 2012; Dempsey, Walker, & Reitz, 2013), Isobutanol-Isobutanol (DelVescovo, Wang, Wissink, & Reitz, 2015), and natural gas-diesel (Walker, Wissink, DelVescovo, & Reitz, 2015; Ebrahimi, Najafi, Jazayeri, & Mohammadzadeh, 2018; Armin, Gholinia, Pourfallah, & Ranjbar, 2021). Nowadays, due to rapid population growth especially in urban areas, and also ever-growing volume of solid waste where landfill is well known to be the most acceptable environmentally friendly, and cost-effective way of waste management, but the downfall would be generating massive landfill gas mostly Methane to the atmosphere with extreme greenhouse effect if not captured. The use of LFG which is mainly generated by chemical reactions and biological activities, not only resolves the greenhouse gas issues, but also, provides a cheap and very attractive alternative fuel source for heat and electricity generation (Ambarita, Widodo, & Nasution, 2017; Ambarita, 2018). The main elements of landfill gas are methane and carbon dioxide. The LFG composition is generally dependent on the landfill well conditions and the waste type as presented in Table 1, typical site data are presented by the Waste Management Organization of Shiraz and Mashhad in Iran.

The lower energy content of LFG is general, not high, and varies based on the composition of the landfill, one efficient way to increase its energy content is by adding hydrogen or natural gas to LFG. Recently, some studies have been conducted with the use of LFG enriched with hydrogen in heavy-duty diesel engines under RCCI combustion (Ebrahimi & Jazayeri, 2019; Kokabi, Najafi, Jazayeri, & Jahanian, 2021; Taghavifar, Nemati, Salvador, & Morena, 2021). The results of using LFG enriched with hydrogen are very promising and it is shown that the combustion characteristics would be improved and the engine emissions could be significantly reduced.

Table 1: Main components of LFG in two cities in Iran

City / Components	Shiraz	Mashhad
Methane (% by volume)	61	40-53
Carbon dioxide (% by volume)	24	20-28
Oxygen (% by volume)	2	1-6.5
Nitrogen (% by volume)	13	7-18
Sulfide Hydrogen (ppm)	300-320	

Although in recent years, several heavy-duty diesel engines have been simulated and tested using different fuels under the mode of RCCI combustion around the world, no research has been carried out to assess and evaluate the performance and emission of the newly developed Iranian national heavy-duty diesel engine, D87, under this new combustion strategy. Some researches related to this engine are investigation of the effects of diesel fuel injection characteristics on the D87 engine performance in the case of direct injection of diesel fuel(Jafari & Seddiq, 2019), investigating the effects of the number of diesel fuel injector nozzle holes on the D87 engine performance under the dual-fuel mode of combustion fueled with natural gas and diesel fuel (Jafari & Domiri Ganji, 2013) investigating the effect of exhaust gas recirculation (EGR) on the D87 engine performance and emissions under the dual-fuel mode of combustion fueled with diesel fuel and natural gas (Jafari, Domiri Ganji, & Mirsalim, 2013), and investigation of the effects of employing different fuel injection strategies on the D87 engine performance under RCCI combustion fueled with diesel fuel and natural gas enriched with synthetic gas or syngas (Jafari & Seddiq, 2021; Jafaria, Seddiq, & Mirsalim, 2021).

However, research on the use of LFG as a low-reactive fuel in the Iranian national heavy-duty diesel engine under RCCI combustion has not been studied in detail to date. Hence, in the present study, the D87 engine performance under RCCI combustion fueled with LFG and diesel fuel is to be assessed. Also, the effects of some influential items on the D87 engine output parameters would be studied based on the DOE concept-factorial method. The selected input parameters are the IVC temperature and pressure, the diesel fuel SOI timing, and the mass ratio of LFG to diesel fuel per cycle. On the other hand, the selected engine output parameters include the diesel knock occurrence, the engine output power, the engine efficiency, the CA50, the combustion duration, and the engine's major emissions such as NOx, CO, UHC, and Formaldehyde.

2. Specifications of National Heavy-Duty Diesel Engine (D87 Model)

The specifications of the heavy-duty diesel engine under investigation are listed in Table 2. The general view of the engine under development on the rig in DESA is depicted in Fig. 1. The D87 engine is designed to operate for different applications like power generation, marine sector, and railway sector. Although, the engine configuration is a V-type with twelve cylinders, , in the present study, as a standard practice in engine research a detailed study is carried out by simulation of a single cylinder under the RCCI mode of operation.

Table 2: The D87 heavy-duty diesel engine specifications (Jafari, Domiri Ganji, & Mirsalim, 2013)

DESA- D87 heavy-duty diesel engine	
Compression ratio	11.5:1
Bore × Stroke (mm)	150×180
Displacement volume (L)	18.3
Connecting rod length(mm)	282
Number of intake/Exhaust valves	2
Intake valve closing (° ATDC)	-150
Exhaust valve opening (° ATDC)	120
Engine speed (rpm)	1500
Diesel fuel injection pressure (bar) (bar)(((common rail mechanism)	1800
Diesel fuel injector holes number	6
Injector hole diameter (µm)	250
Nozzle included angle	150°

3. Computational Model

The three-dimensional computational grid of the D87 engine combustion chamber is shown in Fig. 2. In order to simulate the D87 engine operation, the proper number of cells in the 3D computational model should be checked. As listed in Table 3, several different average cell sizes were examined. The in-cylinder peak pressure difference between the obtained simulation results and the D87 engine experimental data (i.e. 106.76 bar) is depicted in Fig. 3 (Jafari, Domiri Ganji, & Mirsalim, 2013). As shown in Fig. 3, adopting the average cell size of less than 1.8 mm, i.e. 68880 cells at the TDC, would not lead to any more accurate simulation results, but also, increases 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.

Figure 1: A general view of the D87 heavy-duty diesel engine (Jafari, Domiri Ganji, & Mirsalim, 2013)

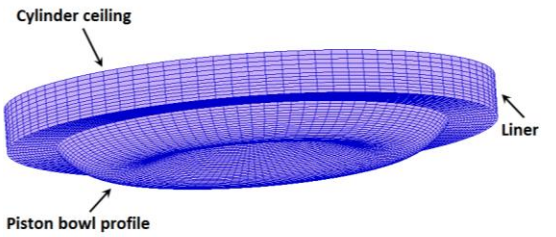

Figure 2: The 3D computational grid of the D87 engine combustion chamber at the TDC.

Table 3: 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

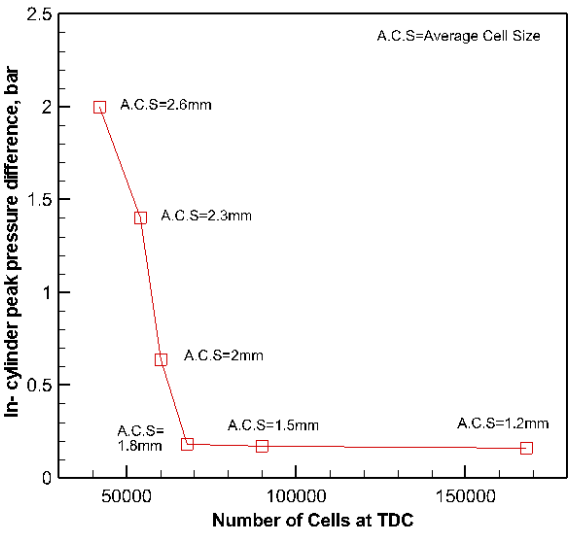

Figure 3: The 3D computational mesh independency assessment.

4. The D87 Engine Operating Conditions

4.1. Dual-Fuel Mode of Combustion Simulation Fueled with Natural Gas and Diesel Fuel

Based on the experimental data setup listed in Table 4, the D87 engine operates under the dual-fuel mode of combustion fueled with diesel fuel and natural gas (Jafari, Domiri Ganji, & Mirsalim, 2013). Thus, initially, the engine operation under dual-fuel mode is modeled where the experimental test data are available for validation of the simulation results obtained by the employed computational model.

Table 4: The D87 engine operating conditions under dual-fuel mode of combustion (Jafari, Domiri Ganji, & Mirsalim, 2013)

Engine operating parameters	Value
EGR (%)	0
Diesel fuel mass per cycle (mg)	44
Natural gas mass per cycle (mg)	206.7
Intake pressure(bar)	1.7
Intake temperature (K)	338
Diesel fuel SOI timing (°ATDC)	-22
Equivalence ratio	0.35

As aforementioned, since the D87 engine uses diesel fuel and natural gas in the dual-fuel mode of combustion, n-heptane as representative of diesel fuel and methane as representative of natural gas are used in the combustion simulation. Thus, to conduct the combustion simulation by the AVL FIRE CFD tool coupled with the CHEMKIN chemistry tool, a reduced kinetic mechanism containing 76 species and 464 reactions is employed to predict all the major reactions between methane and n-heptane (Rahimi, Fatehifar, & Khoshbakhti Saray, 2010). The flowchart of the combustion simulation is schematically presented in Fig. 4 using AVL Fire software.

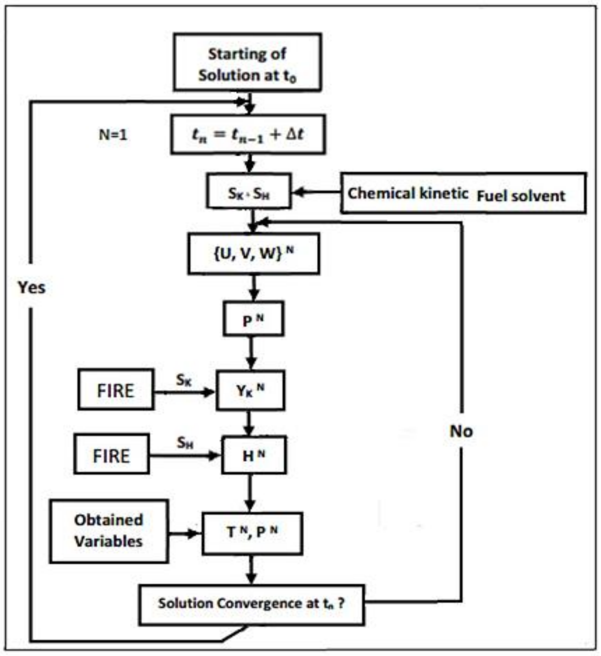

Figure 4: The simulation flowchart in the AVL FIRE CFD tool coupled with the CHEMKIN chemistry tool.

Also, for simulating the diesel fuel injection into the engine combustion chamber some sub-models are used including the turbulent dispersion model (Gosman & Ioannides, 1983), coalescence /collision of diesel fuel particles (Naber & Reitz, 1988), evaporation of diesel fuel droplets (Dukowicz, 1979), the break-up of diesel fuel droplets (Liu &

Reitz, 1993), and fuel flow from the injector nozzle (Kunsberg-Sarre, Kong, & Reitz, 1999).

Investigating the simulation results and the engine experimental data (Jafari, Domiri Ganji, & Mirsalim, 2013) which is depicted in Fig. 5 and Table 5 shows that the developed computational model has the potential to precisely predict the engine performance under dual-fuel mode of combustion; therefore, the modifies model can accurately be used to simulate the D87 engine operation under RCCI combustion.

4.2. The RCCI Combustion Simulation Fueled with Natural Gas and Diesel Fuel

Since the main objective of this study is the implementation of the RCCI combustion strategy in the D87 engine, therefore, after the validation stage, the D87 engine was set to operate under RCCI combustion fueled with natural gas and diesel fuel. For this purpose, the same mentioned operating conditions in Table 4 were used except for the diesel fuel start of injection (SOI) timing. The RCCI combustion strategy takes advantage of advanced diesel fuel SOI timing and the chemical reactions between some important species compared to the dual-fuel mode of combustion (Walker, Wissink, DelVescovo, & Reitz, 2015). Thus, based on the recent research in the field of RCCI combustion (Ebrahimi, Najafi, Jazayeri, & Mohammadzadeh, 2018; Walker, Wissink, DelVescovo, & Reitz, 2015), the diesel fuel SOI timing was set at -45° ATDC (i.e. 23° advance the diesel fuel injection). The results of the RCCI combustion simulation are also compared with the experimental results as depicted in Fig. 5 (Jafari, Domiri Ganji, & Mirsalim, 2013). As shown in Fig. 5, not only the used computational model has the appropriate potential to predict the performance of the engine under RCCI combustion, but also, the engine output power and GIE would be improved by more than 6% and 7%, respectively (Table 5).

4.3. The RCCI Combustion Simulation Fueled with LFG and Diesel Fuel

Finally, the study is carried out when the D87 engine operates under RCCI combustion fueled with LFG and diesel fuel. In the current study, landfill gas comprising 50% methane and 50% carbon dioxide by volume is considered a low reactive fuel. The LFG RCCI combustion simulation is done in detail and is also presented in Fig. 5. As shown in Fig. 5, LFG without any addition of enhancers such as hydrogen or natural gas has the potential to be used as an alternative fuel to natural gas in the D87 engine. Moreover, The results of the combustion simulations in terms of IMEP and GIE presented in Table 5 show that when employing the RCCI mode of combustion using LFG instead of natural gas, not only, natural gas consumption as fossil fuel and air pollution resulted from the greenhouse gases effect from the release of landfill gas can be reduced, but also compared to the experimental data (Jafari, Domiri Ganji, & Mirsalim, 2013), the decrease in the D87 engine output power and GIE are only less than 7% and 18%, respectively.

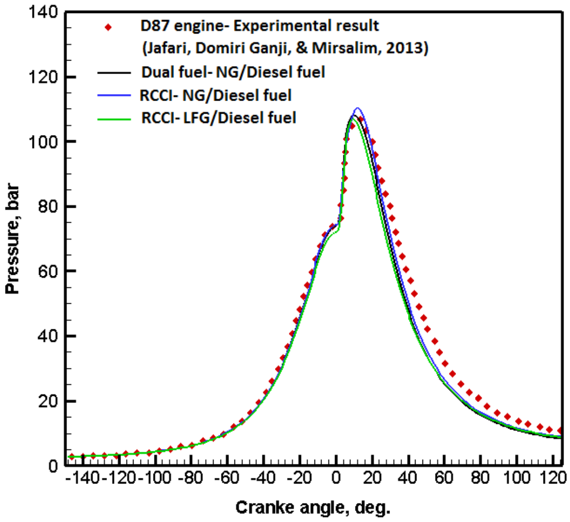

Figure 5: The simulation results validation with the experimental data (Jafari, Domiri Ganji, & Mirsalim, 2013).

Table 5: The comparison of the obtained IMEP and GIE from the RCCI combustion simulation with the experimental data (Jafari, Domiri Ganji, & Mirsalim, 2013).

Type of combustion strategy	IMEP (bar)	IMEP Error (%)	GIE (%)	GIE Error (%)
Dual-fuel mode of combustion- natural gas/ diesel fuel (Jafari, Domiri Ganji, & Mirsalim, 2013)	13.65	-	40	-
Dual-fuel mode of combustion- natural gas/ diesel fuel (Present study)	13.44	1.54	39.75	0.63
RCCI combustion- natural gas/ diesel fuel (Present study)	14.58	Enhanced 6.81%	43.13	Enhanced 7.83%
RCCI combustion- LFG/diesel fuel (Present study)	12.77	6.5	32.95	17.63

5. Application of the DOE Concept-Factorial Method

In this study, in order to overcome the restrictions of using LFG in the D87 engine as an alternative fuel, to improve the D87 engine combustion characteristics, and reduce the engine emissions level, based on the DOE concept-Factorial method, the effects of some effective input factors on the performance of the D87 engine under RCCI combustion fueled with LFG/diesel fuel are evaluated. The selected input factors are the IVC temperature (T_{IVC}), the IVC pressure (P_{IVC}), the diesel fuel SOI timing, and LFG/diesel fuel mass ratio. In order to use the Factorial Method, based on the D87 engine operating conditions, five levels are chosen for the four mentioned input parameters as listed in Table 6. Based on the DOE concept, the input parameter levels are randomly combined and used in simulating RCCI combustion by the AVL FIRE CFD tool.

Table 6: Five selected levels for four selected engine input parameters.

	Selected Level				
Input parameters	0	1	2	3	4
SOI timing (° ATDC)	-30	-45	-55	-65	-75
T_{IVC} (K)	320	340	360	380	400
P_{IVC} (bar)	2.3	2.5	2.7	2.9	3.1
LFG/diesel fuel mass ratio	90/10	80/20	70/30	60/40	50/50

6. Results and Discussion

6.1. The Misfire Occurrence Evaluation

Based on conducted research (Vasudevan, Davidson, & Hanson, 2005; Ebrahimi, Najafi, Jazayeri, & Mohammadzadeh, 2018), when methane is used as a fuel in an engine, two important species, namely, formaldehyde (CH2O) and hydroxyl radical (OH) have an effective role on the methane decomposition. Hence, these species have also a vital role in the decomposition of LFG as a fuel comprising a high percentage of methane. Based on the DOE concept, the RCCI combustion simulation results show that reducing IVC temperature below 340 K causes the poor formation of OH radical as shown in Fig. 6. Thus, the insufficient reaction between OH radical and CH2O does not lead to complete decomposition of methane contained in LFG, thus, the combustion process is hampered and misfire occurs. Also, the simulation results imply that in the D87 engine, the reduction in the mass ratio of the injected diesel fuel as the RCCI combustion initiation energy source to less than 30%, misfire risks intensify.

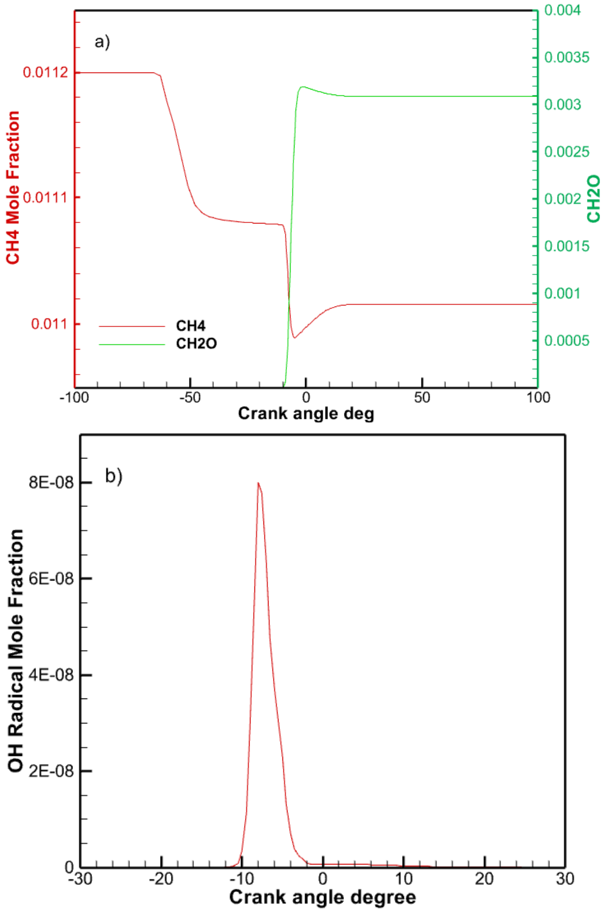

Figure 6: The role of OH radical and CH2O on the misfire occurrence at the IVC temperature below 340K.

6.2. The Diesel Knock Occurrence Assessment

In a heavy-duty diesel engine, diesel knock occurs due to excessive pressure rise rate resulting from the very rapid release of fuel energy. The occurrence of diesel knock in a diesel engine causes the engine parts damage and also reduces its efficiency. According to Eng criterion (Eng, 2002), at the PPRR above 15bar/° crank angle, diesel knock occurs. Also, the ringing intensity as another criterion in detecting the diesel knock occurrence can be calculated from Equation 1 (Eng, 2002).

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

Where $(dP/dt)_{max}$ is the maximum rate of pressure rise inside the combustion chamber in terms of KPa/msec, P_{max} is the maximum in-cylinder pressure in terms of Pa, T_{max} is the maximum in-cylinder temperature in terms of K, γ is the C_p/C_v ratio, and R is gas constant of the ideal gas. In a diesel engine operation without exposure to diesel knock, the maximum permissible amount of the ringing intensity is 5 MW/m² (Eng, 2002). In the present work, the obtained results based on the DOE concept are shown in Fig. 7.

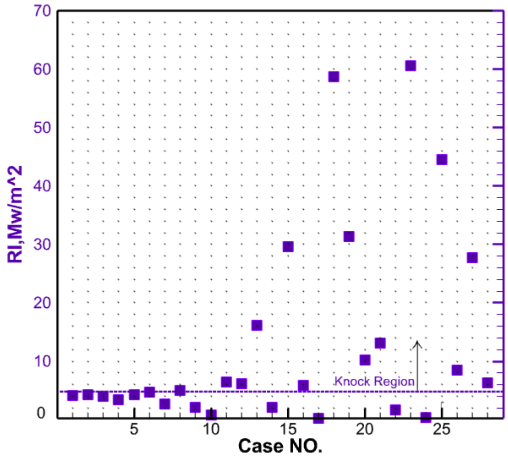

Figure 7: The obtained results for RI based on the DOE concept- Factorial method

The simulation results shown in Fig. 7 indicate that at LFG/diesel fuel mass ratios less than 70/30, the risk of the occurrence of diesel knock is drastically increased. Also, at the LFG/diesel fuel mass ratios higher than 80/20, the diesel fuel injection earlier than -30° ATDC has a major role in the diesel knock occurrence which should be avoided.

6.3. The Desirable Engine Output Power

Gross IMEP as a very good representative of engine output power can be calculated using Equation 2 (Nieman, Dempsey, & Reitz, 2012).

$$Gross\ IMEP = \frac{1}{V_d}\int_{-180^o}^{+180^o} PdV \qquad (2)$$

Wherein V$_d$ is the cylinder volume displaced per cycle. Moreover, another important performance parameter in a heavy-duty diesel engine is the gross indicated efficiency. The GIE can be calculated from Equation 3 (Nieman, Dempsey, & Reitz, 2012).

$$GIE = \frac{Gross\ work}{E_{in}} = \frac{\int_{-180^\circ}^{+180^\circ} P\,dV}{E_{in}} \qquad (3)$$

$$E_{in} = m_{fuel}\left[(x\cdot LHV)_{methane} + (x\cdot LHV)_{diesel\ fuel}\right]$$

Wherein E$_{in}$ is the total fuel energy, m$_{fuel}$ is the total fuel mass in each cycle, x is the mass fraction of each fuel used, and LHV is the lower heating value of each fuel used.

The eight desirable engine output powers which the engine operation would not be in the exposure of diesel knock are shown in Fig. 8. Based on the DOE concept, the appropriate range of four selected input parameters that lead to the desired engine performance is also listed in Table 7.

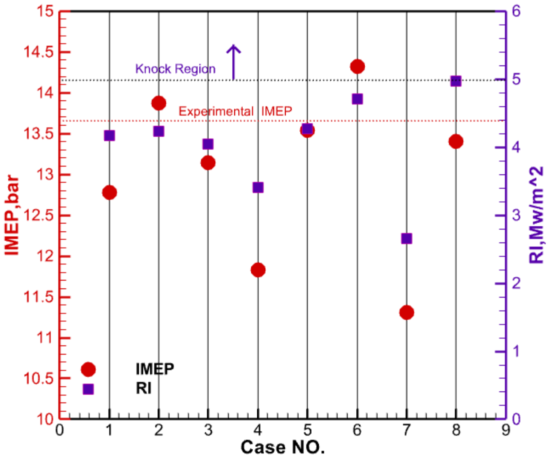

Figure 8: Desirable cases in terms of the RI and IMEP.

Table 7: The appropriate range of four selected input parameters.

Input parameters		SOI (°ATDC)	T$_{IVC}$ (K)	P$_{IVC}$ (bar)	Fuel mass ratio
Range	Min.	-75	350	2.6	70/30
	Max.	-30	400	2.9	80/20

Also, for these desirable cases, the calculated engine efficiency, IMEP, PPRR, and RI are listed in Table 8. As concluded in the D87 engine, when using LFG as an alternative low reactive fuel, the maximum losses in output power are below %18 compared to the experimental data (i.e. 13.65 bar) (Jafari, Domiri Ganji, & Mirsalim, 2013) and the maximum losses in the GIE would be about 26% compared to the experimental data (i.e. 40%) (Jafari, Domiri Ganji, & Mirsalim, 2013).

Table 8: The engine performance for desirable cases

Case No.	RI (MW/m^2)	PPRR (bar/° CA)	IMEP (bar)	GIE (%)
1	4.2	8.73	12.77	32.94
2	4.24	9.37	13.87	35.78
3	4.05	8.81	13.14	33.90
4	3.40	7.53	11.83	30.50
5	4.27	9.24	13.54	34.93
6	4.70	10.07	14.32	36.93
7	2.66	6.86	11.30	29.64
8	4.97	9.6	13.40	34.24

6.4. D87 Engine Combustion Characteristics Evaluation

6.4.1. Cool Flame Phenomenon

In an engine fueled with normal chain hydrocarbon fuel like diesel fuel, cool flame or low-temperature oxidation occurs before the SOC when the in-cylinder temperature is between 750 and 800 K (Ando & Yasuyuki, 2009). For the engine under investigation, the heat release rate versus the in-cylinder temperature is depicted in Fig. 9. As expected, the cool flame occurs under the same conditions.

6.4.2. The Low-Temperature Concept Criterion Assessment

When an engine operates under RCCI combustion as a low-temperature combustion strategy, the in-cylinder temperature should be below 1900 K (Dempsey, Walker, Gingrich, & Reitz, 2014). Figure 10 shows that for all eight desirable cases, the peak in-cylinder temperature in the D87 engine is below 1900 K, thus, the LTC concept is fully satisfied.

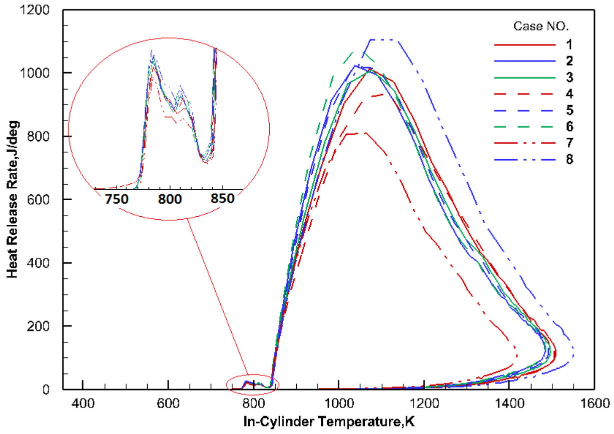

Figure 9: The cool flame occurrence for the desirable cases.

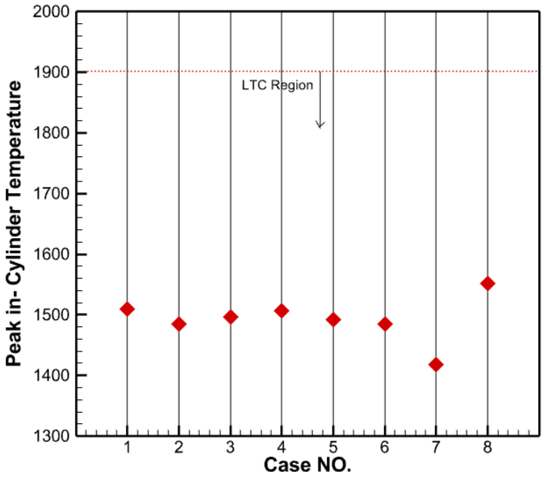

Figure 10: The peak in-cylinder temperature diagram for the desirable cases.

6.4.3. The CA50 and Combustion Duration

One of the important parameters in evaluating the performance of a diesel engine is the CA50. When the occurrence of this parameter shifts to after the TDC, more fuel energy is released during the engine expansion stroke; hence, the negative work resulting from releasing the fuel energy during the engine compression stroke is reduced. Figure 11 shows that in the D87 engine, the use of LFG comprising methane and carbon dioxide, the presence of CO2 causes to delay the SOC and also the CA50 occurrence. Moreover, the rate of combustion is slowed down due to the CO2 presence, thus, the combustion duration would be increased due to the gradual release of fuel energy in the engine combustion chamber.

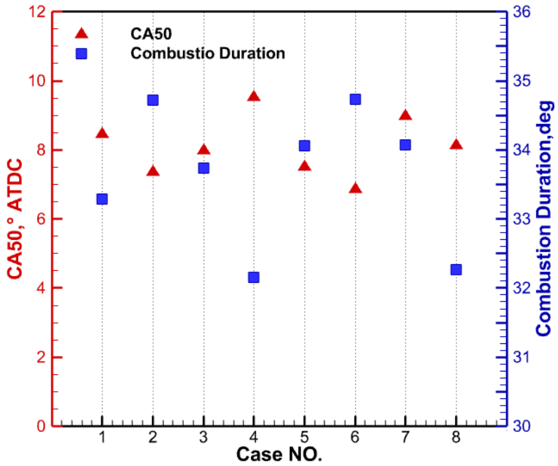

Figure 11: Combustion duration and the CA50 for the eight desirable cases.

6.4.4. Engine Emissions

For the desirable cases simulated in the present work, the D87 engine emissions under RCCI combustion fueled with LFG and diesel fuel were evaluated and shown in Fig. 12. Regarding the performance of heavy-duty diesel engines, the European Emission Standard, EURO VI, limits the maximum value for NOx to 0.4g/kWh, for CO to 1.5 g/kWh, and the unburned hydrocarbon to 0.13 g/kWh. Also, according to the U.S. Environmental Protection Agency, EPA 2007, the maximum value for Formaldehyde as a toxic component is limited to 0.012 g/kWh. Figure 12 shows that when LFG is used as a low reactive fuel instead of natural gas in the D87 engine under RCCI combustion, although the amount of fossil fuel consumption is reduced, but, the EURO VI level of NOx, CO, and UHC emissions and also the EPA 2007 level of Formaldehyde cannot be met.

8. Conclusions

In order to overcome the limitations of using landfill gas as an alternative fuel, in the present work, the performance of the Iranian heavy-duty diesel engine (D87) under RCCI combustion fueled with diesel fuel and LFG was evaluated. To improve the D87 engine combustion characteristics and reduce its emissions level, the DOE concept- Factorial method was employed to assess the effect of four decisive input parameters including the IVC temperature and pressure, the diesel fuel SOI timing, and the LFG/diesel fuel mass ratio on the D87 engine performance. Based on the obtained simulation results, the following remarks can be concluded:

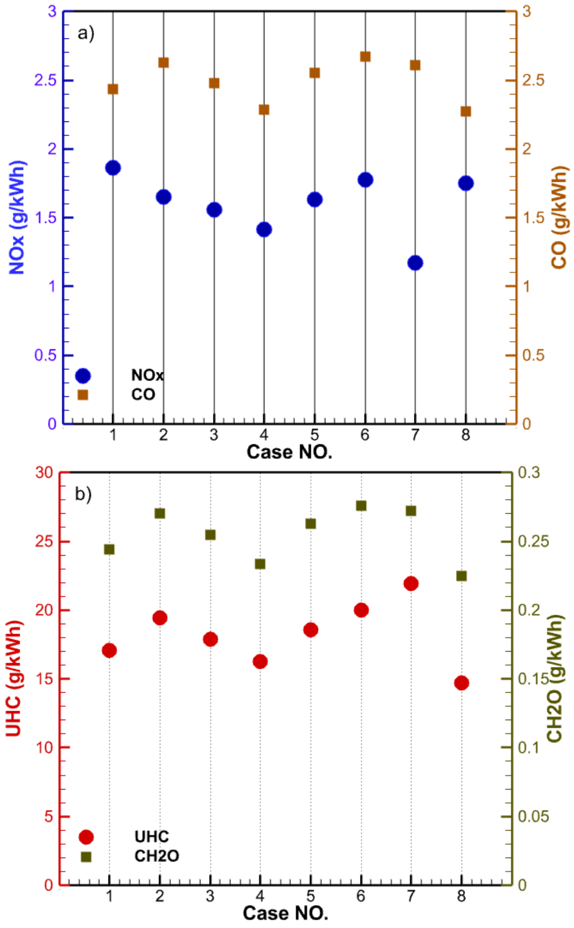

Figure 12: The D87 engine emissions: (a) NO$_x$ and CO (b) UHC and Formaldehyde for the desirable Cases.

1) When LFG is used as low reactive fuel in the D87 engine operation under RCCI combustion, lowering the IVC temperature below 330 K and the reduction in the injected diesel fuel mass share to less than 30% leads to misfiring occurrence.

2) At the LFG/diesel fuel mass ratios less than 70/30, the risk of the occurrence of diesel knock is drastically increased. On the other hand, at the LFG/diesel fuel mass ratios higher than 80/20, the diesel fuel injection earlier than -30° ATDC has a major role in the diesel knock occurrence.

3) The appropriate range of four selected input parameters to obtain desirable D87 engine performance is the diesel fuel injection timing between -75 and -30 °ATDC, the IVC temperature between 350 and 400 K, the IVC pressure between 2.6 and 2.9 bar, and the LFG/diesel fuel mass ratio between 70/30 and 80/20.

4) Although, using LFG instead of natural gas has the potential to reduce fossil fuel consumption by more than 80%, but, the EURO VI level of NOx, CO, and UHC and also the EPA level of Formaldehyde are not achievable.

Acknowledgments

The authors would like to thank the Research and Development department of IRAN Heavy-Duty Diesel Engine Company (DESA) for their preciously co-operating and for providing laboratory documents and the other information required for conducting the present study.

References

Ambarita, H, Widodo, T. I., & Nasution D. M. (2017). A numerical study on combustion process in a small compression ignition engine run dual-fuel mode (diesel-biogas). *Journal of Physics*: Conf. Series 801 (2017) 012095.

Ambarita, H. (2018). Effect of engine load and biogas flow rate to the performance of a compression ignition engine run in dual-fuel (dieselbiogas) mode. *IOP Conf. Series: Materials Science and Engineering* 309.

Ando, H. & Yasuyuki S. (2009). Universal rule of hydrocarbon oxidation. *SAE paper,* 2009-01-0948.

Armin, M., Gholini, M., Pourfallah, M., & Ranjbar A. A. (2021). Investigation of the fuel injection angle/time on combustion, energy, and emissions of a heavy-duty dual-fuel diesel engine with reactivity control compression ignition mode. *Energy Reports*, 7, 5239-5247.

AVL FIRE® VERSION 2013 Documentation.

DelVescovo, D., Wang, H., Wissink, M., & Reitz R. D. (2015). Isobutanol as Both Low Reactivity and High Reactivity Fuels with addition of Di-Tert Butyl Peroxide (DTBP) in RCCI Combustion. *SAE Int. J. Fuels Lubr.*, 8(2), 329-343.

Dempsey, A. B., Walker, N. R., Gingrich E., & Reitz R. D. (2014). Comparison of Low Temperature Combustion Strategies for Advanced Compression Ignition Engines with a Focus on Controllability. *Combustion Science and Technology*, 186 (2), 210-241.

Dempsey, A. B., Adhikary, B. D., Viswanathan, S., & Reitz R. D. (2012). Reactivity Controlled CompressionIgnition (RCCI) using Premixed Hydrated Ethanol and Direct Injection Diesel. *J. Eng. Gas Turbines Power*, 134 (8), 082806-082817.

Dempsey, A. B., Walker, N. R., & Reitz R. D. (2013). Effect of Cetane Improvers on Gasoline, Ethanol, and Methanol Reactivity and the Implications for RCCI Combustion. *SAE Int. J. Fuels Lubr.*, 6(1) 170-187.

Dukowicz, J. K. (1979). Quasi-Steady Droplet Change in the Presence of Convection. *Informal report Los Alamos Scientific Laboratory*, LA7997-MS.

Ebrahimi, M., Najafi, M., Jazayeri, S. A., & Mohammadzadeh A. R. (2018). A Detail Simulation of Reactivity Controlled Compression Ignition Combustion Strategy in a Heavy-Duty Diesel Engine Run on Natural Gas/ Diesel Fuel). *International journal of engine research*, 19 (7), 774-789.

Ebrahimi, M., & Jazayeri S. A. (2019). Effect of hydrogen addition on RCCI combustion of a heavy-duty diesel engine fueled with landfill gas and dieseloil. *International journal of hydrogen energy*. 44,7607-7615.

Eng, J. A. (2002). Characterization of pressure waves in HCCI combustion. SAE technical paper no. 2002-01-2859.

Gosman, A. D. & Ioannides, E. (1983). Aspects of Computer Simulation of Liquid- Fueled Combustor, *AIAA*, 7 (6), 482-490.

Iran Heavy Diesel Manufacturing Company (DESA) documents, 2019.

Jafari, B., & Seddiq M. (2019). An Experimental Investigation of the Effects of Diesel Fuel Injection Characteristics in a Heavy-Duty Direct Injection(HDDI) Diesel Engine. *Gas Processing Journal,* 1, 53-64

Jafari, B. & Domiri Ganji, D. (2013). Numerical Investigation in the Effect of Number of Nozzle Hole on Performance and Emission in Dual Fuel Engine. *Automotive Science and Engineering* (ASAE), *Iran University of Science & Technology*, 3 (2), 6.

Jafari, B., Domiri Ganji, D., & Mirsalim M. (2013). Experimental and Numerical Investigation of the Effect of Exhaust Gas Recirculation on Performance and Emissions of a Dual Fuel (Diesel–Gas) Engine. *Australian Journal of Basic and Applied Sciences*, 7(7), 668-678.

Jafari, B. & Seddiq, M. (2021). Effects of Fuel Injection Strategies in a RCCI Heavy-Duty Diesel Engine. *Springer*, 46, Article number: 6.

Jafari, B., Seddiq, M., & Mirsalim S. M. (2021). Impacts of diesel injection timing and syngas fuel composition in a heavy-duty RCCI engine. *Energy Conversion and Management.* 247, 114759.

Kokabi, H., Najafi, M., Jazayeri S. A., & Jahanian O. (2021). Hydrogen and propane implications for reactivity controlled compression ignition combustion engine running on landfill gas and diesel fuel. *International journal of hydrogen energy*. 46, 31903-31915.

Kokjohn, S. L., Hanson, R. M., Splitter, D. A., & Reitz R. D. (2011). Fuel Reactivity Controlled Compression Ignition (RCCI): A Pathway to Controlled High- Efficiency Clean Combustion. *International journal of engine research*. 12 (3), 209-226.

Kunsberg-Sarre, C. V., Kong, S. C., & Reitz R. D. (1999). Modeling the Effects of Injector Nozzle Geometry on Diesel Sprays. SAE Technical Paper 1999-01-0912.

Lim, J. H., & Reitz R. D. (2013). Improving High Efficiency RCCI Combustion with Diesel and Gasoline Direct Injection (GDI). *Proceedings of the Institution of Mechanical Engineers, Part D, Journal of Automobile Engineering*, 227, 17-30.

Liu, A. B. & Reitz R. D. (1993). Modeling the Effects of Drop Drag and Break-up on Fuel Sprays.*SAE paper* 930072, 1-13.

Naber, J. D. & Reitz, R. D. (1988), Modeling Engine Spray/ Wall Impingement, *SAE* 880107, 1-26.

Nieman, D. E., Dempsey, A. B., & Reitz R. D. (2012). Heavy-Duty RCCI Operation Using Natural Gas and Diesel. SAE paper , 01-0379.

Nieman, D. E., Dempsey, A. B., & Reitz, R. D. (2012). Heavy-Duty RCCI Operation Using Natural Gas and Diesel. SAE Int. J. Engines, 5(2), 270-285. https://doi.org/10.4271/2012-01-0379

Paykani, A., Kakaee, A. H., Rahnama, P., & Reitz R. D. (2015). Progress and Recent Trends in Reactivity-Controlled Compression-Ignition Engines. *International Journal of Engine Research.* 17 (5), 481-524.

Pourfallah, M. & Armin, M. (2019). Sensitivity Analysis of the Combustion Parameters in a Stratified HCCI Engine with Regard to Performance and Emission. SAE Technical Paper, 2019-24-0114, https://doi.org/10.4271/2019-24-0114.

Rahimi, A., Fatehifar, E., & Khoshbakhti Saray, R., (2010). Development of an Optimized Chemical Kinetic Mechanism for Homogeneous Charge Compression Ignition Combustion of a Fuel Blend of N- heptane and Natural gas Using a Genetic Algorithm. *Proc Institution Mech. Eng. Part D J AutomobEng*, 224 (9), 1141-1159.

Reitz, R. D., & Duraisamy, G. (2015). Review of High Efficiency and Clean Reactivity Controlled Compression Ignition (RCCI) Combustion in Internal Combustion Engines. *Progress in Energy and Combustion Science*. 46, 12-71.

Splitter, D. A., Wissink, M. L., Kokjohn, S. L., & Reitz R. D. (2012). Effect of Compression Ratio and Piston Geometry on RCCI Load Limits and Efficiency. *SAE Technical Paper*, 01, 0383.

Taghavifar, H., Nemati, A., Salvador, F. J., & Morena J. D. L. (2021). 1D energy, exergy, and performance assessment of turbocharged diesel/hydrogen RCCI engine at different levels of diesel, hydrogen, and compressor pressure ratio, and combustion duration. International Journal of Hydrogen Energy, 46(42), 22180-22194.

Vasudevan, V., Davidson, D. F., & Hanson, R. K. (2005). Direct measurement of the reaction OH+CH2O@HCO+H2O at high temperatures. Int J Chem Kinetics, 37, 98–109.

Walker, N. R., Wissink, M. L., DelVescovo D. A., & Reitz R. D. (2015). Natural Gas for High-Load Dual-fuel RCCI in Heavy-Duty Engines. *Journal of Energy Resources Technology*. 137(4), 1-7.

Waste Management Organization of Shiraz, https://waste.shiraz.ir.