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Experimental investigation on compression ignition engine powered with pentanol and thevetia peruviana methyl ester under reactivity controlled compression ignition mode of operation

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ABSTRACT

In the current study, an effort is carried out to study the influence of pentanol as low reactive fuel (LRF) along with diesel and Thevetia peruviana methyl ester (TPME) as high reactive fuels (HRF) in reactivity controlled compression ignition (RCCI) engine. The experiments are conducted on dual fuel engine at 50% load for RCCI mode of operation by varying pentanol percentage in injected fuels. The results revealed that RCCI mode of operation at 10% of pentanol in injected fuels exhibited higher brake thermal efficiency (BTE) of 22.15% for diesel and pentanol fuel combination, which is about 9.1% and 27.3% higher than other B20 and pentanol, B100 and pentanol fuel combinations respectively. As the percentage of pentanol increased in injected fuels, hydrocarbon (HC) and carbon monoxide (CO) emissions are increased while nitrogen oxide (NO_x) and smoke emissions are decreased. Among various fuel combinations tested diesel and pentanol fuel combination gives lower HC, CO and smoke emissions and higher NO_x emissions. At 10% pentanol in injected fuels, the highest heat release rate (HRR) and in-cylinder pressure are found for diesel and pentanol fuel combinations compared with other fuels.

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1. Introduction

With the improvement in the world's economy, the interest in raw petroleum is developing at a swift pace. The random utilization of fuel sources has led to an upsurge in GHG emissions, depletion of fossil fuels, increase in respiratory problems. These elements have led to the utilization of non-conventional energy [1–4]. The diesel engines inspire the researchers for their efficient mileage with higher CR [5,6]. Nevertheless, diesel engines experienced shows higher particulate matter and NO_x emissions [7]. The premixed charge compression ignition (PCCI) has resulted in expanding considerations in recent years because of lower emissions and higher efficiency. In the PCCI mode of combustion, the particulate matter could be diminished with an advanced blending of fuel and air before ignition [8]. The NO_x emissions were diminished by utilizing lean fuel and air mixture with a high exhaust gas recirculation rate (EGR) to reduce combustion temperature. As a result of higher combustibility and lower volatility of the diesel fuel, few issues have to be explained for the PCCI mode of combustion, including the homogeneous blend formation, ignition control, restricted working, high impingement to the walls of the combustion chamber, etc. [9,10]. To beat these issues related to the PCCI mode of combustion, RCCI mode of combustion has been developed recently, a viable and clean-burning system that utilizes two types of fuels with various physical properties and separate injection. The reactivity could be grouped into global reactivity, and the other is termed as reactivity gradient [11]. The global reactivity is controlled by using the fuel types along with the number of fuels injected into the combustion chamber. The reactivity gradient differs from the fuel injection methodology, including early and late addition of high and low octane number fuels. Thus, each fuel injection technique and injection rate could affect the RCCI mode of combustion [12,13]. Fuels with higher octane number (ON) were injected into a suction manifold, and the fuels with a high cetane number (CN) were injected into the combustion chamber so that a well-defined formation of the fuel reactivity was framed that prompts stratified burning [14]. Duraisamy et al. [15] found that the use of polyoxymethylene dimethyl ethers (PODE) as a high reactivity fuel (HRF) with the methanol as a low reactivity fuel (LRF) for RCCI combustion resulted in combustion duration shorter and reduced delay period as compared with methanol-diesel RCCI mode of combustion. Pan et al. [16] found that indicated mean effective pressure (IMEP) for iso-butanol-diesel, gasoline-diesel RCCI combustion considerably increased as the ratio of premixed combustion augments. IMEP in the case of iso-butanol-diesel fueled RCCI engine was constantly higher than gasoline-diesel RCCI mode of combustion at any premixed ratio. Yang et al. [17] found that diesel and methane injection timing (IT) had impact on the process of combustion for RCCI engine. An improved performance could be found for earlier diesel IT and later methane IT. Wang et al. [18] found that, thermal efficiency for gasoline-PODE fueled RCCI engine could be efficiently enhanced with air intake and dilution of EGR. The dilution of air for stable intake pressure showed results on thermal efficiency improvement. Zheng et al. [19] found that at medium and low loads, the RCCI showed a lower heat release rate (HRR). The indicated thermal efficiency of the engine reduced as the ratio of n-butanol was increased. Charitha et al. [20] found that NO_x emissions were decreased significantly by introducing cotton oil methyl ester (COME). The HC emissions were reduced at lesser proportions of COME, and these emissions were increased along with higher proportions of COME. Isik et al. [21] found that ethanol-fueled RCCI engine increased the peak values of pressure using B50 blend as HRF. The curves of HRR

Nomenclature

BSEC	Brake specific energy consumption
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
CO	Carbon monoxide
COME	Cotton oil methyl ester
CR	Compression ratio
CN	Cetane number
CRDI	Common rail diesel injection
ECU	Electronic control unit
EGR	Exhaust gas recirculation
HC	Hydrocarbon
HRF	High reactive fuel
HRR	Heat release rate
IMEP	Indicated mean effective pressure
IP	Injection pressure
IT	Injection timing
LRF	Low reactive fuel
NO_x	Nitrogen oxide
ON	Octane number
PCCI	Premixed charge compression ignition
PODE	poly oxymethylene dimethyl ethers
RCCI	Reactivity controlled compression ignition
TPME	Thevetia peruviana methyl ester

increased for ethanol-fueled RCCI engine for all fuels tested. Thiyagarajan et al. [22] found that BTE was higher for the engine with n-pentanol than methanol-fueled engine operation. Brake specific energy consumption (BSEC) was lesser in dual fuel mode when compared with neat biodiesel engine operation, and it was more than diesel. Radheshyam et al. [23] found that the delay period increased for all the fuel blends as the increase of EGR rate and pentanol concentration increased. The in-cylinder pressure decreased in case of 1-pentanol addition for minor loads and increased at major loads. Chen et al. [24] found that, diesel-n-pentanol-methanol blended fuels had shorter combustion duration and longer ignition delay resulted into additional HRR as compared with diesel. The diesel-n-pentanol-methanol blended fuels show lower emissions of soot than diesel, also higher NO_x emissions were produced. Huang et al. [25] found that, adding n-pentanol resulted into increased HRR and quickens the speed of combustion, shorten the duration of combustion. Brake specific fuel consumption (BSFC) was increased as the increase in EGR rate. Tian et al. [26] found that, adding n-butanol with gasoline would reduce the exhaust gas temperature of the engine as compared with pure gasoline. BTE and volumetric efficiency at low and medium engine speeds could be improved by n-butanol-gasoline blended fuels and pure n-butanol compared to pure gasoline. Adding n-butanol with gasoline could reduce the engine emissions of CO and NO_x.

The extensive literature review revealed that experimentation for the use of pentanol and Thevetia peruviana methyl ester in RCCI mode to study its performance is not carried out with the various percentages of pentanol in injected fuels. Hence, the current investigation's main objective is to study the combustion, performance, and emission characteristics of RCCI engine powered with pentanol and Thevetia peruviana methyl ester fuel combinations for various percentages of pentanol in injected fuels.

2. Physical properties of test fuels

Thevetia peruviana, known as yellow oleander or lucky nut or milk bush, is a little perpetual and evergreen and, for its most part, developed as a decorative plant. It is a dicotyledonous bush and has a place with the family Apocynaceae [27]. The fuel properties used are presented in Table 1.

2.1. *Thevetia peruviana (Yellow oleander)*

Thevetia peruviana is ordinarily found in the world's jungles and sub-jungles locations, yet it is local to Central and South America. The plant gives the fruits consistently, giving a consistent supply of seeds. The plant, developed as supports, can create 400 to 800 fruits for each annum, relying upon the plant's age. Flowers were like funnel-shaped, with their petals were spirally twisted. Fruits were fairly globular, and they had fleshy mesocarp and had 4–5 cm diameter. Fruits that had green color shading and became dark on aging. Every fruit contains a nut that is transversely and longitudinally divided. Matured fruit contained 2 to 4 seeds, and the plant bears milky juice at all parts [27]. The plant developed to around 2–6 m in tall, and leaves are spirally arranged, direct, and around 13–15 cm long [28]. Thevetia peruviana is a plant with no financial worth, under-utilized and lesser-known [29,30]. The seed contains 60–65% of oil, and the cake contained 30–37% protein [29,31]. The oil would be non-edible due to cardiac glycoside present in it. The seed has a health benefit and would thus be able to be utilized as an elective protein source in the creature feed plan [32]. It will decrease rivalry among humans and animals for the conventional protein sources if it is prepared healthily. The seed oil helps in oleo-chemical creation, for example, soaps, shampoos, and biodiesel. African nations are urged to include the resources for the development of that plant for diminishing the large dependability upon it. The plant could be developed in wastelands. The plant required least water when it is in the developing stage. Three thousand saplings could be planted in 1 ha, and out of that, around 52.5 tons of seeds (around 3500 kg of the kernel) could be gathered. Subsequently, around 1750 L of oil could be acquired from 1 ha of wasteland. Abhorred by herbivorous animals, the plant can be developed on side of the road and street dividers in interstates for beautification, ecological insurance and simultaneously for the creation of biodiesel. Because of high oil and protein substance, and its accessibility, the plant has a potential for different utilizations and it very well might be utilized for biodiesel creation [27,28,32].

2.2. *Transesterification process*

In the transesterification process, the raw oil of Thevetia peruviana is converted into biodiesel of Thevetia peruviana. Transesterification (TE) process involves heating the raw oil in a flask with three necks in which a magnetic stirrer is placed [33,34] (Fig. 1a). The required amount of methanol and sodium hydroxide catalyst is added to the flask. This mixture is kept for 2–3 h for the reaction purpose. After this, the mixture is placed in a separating flask overnight in which biodiesel and glycerol formation occur (Fig. 1b). The glycerol is removed out, and crude biodiesel is obtained. This unrefined biodiesel is washed with hot water so that there is the separation of phase in between water and biodiesel (Fig. 1c). This biodiesel consists of some water content removed by heating the

Table 1
Physical properties of test fuels.

Fuels → Physical properties ↓	Pentanol [25]	Diesel	TPME B20	TPME B100
Density at 20 °C (kg/m^3)	814	829	839	892
Calorific value (MJ/kg)	34.65	42.18	41.44	39.45
Flash point (°C)	49	52	76	177
Kinematic viscosity at 40 °C (mm^2/s)	2.88	3.51	3.95	5.73
Cetane number	18.2	52	48	47

(a) Round bottom flask with oil heating

(b) Separation of Ester and Glycerol

(c) Phase separation of water and biodiesel

Fig. 1. Synthesis of Thevetia peruviana biodiesel [13] (Adapted with permission from the publisher).

biodiesel in a heating oven so that all the water content is removed and pure biodiesel is obtained. In the present study, the TE reaction is referred to previous investigations [35–37]. The flow chart regarding the conversion of raw oil into biodiesel is shown in Fig. 2.

3. Experimental setup

The entire experiment tests were conducted on Kirloskar, single-cylinder, water-cooled, common rail diesel injection (CRDI) engine, which runs at 1500 rpm. The base test was carried out with the injection of diesel to warm up the engine. The existing engine was modified into a dual fuel mode of operation by modifying necessary arrangements. Initially, high ON fuel such as pentanol was injected into the inlet manifold at IP of 5 bar during suction stroke so that it could well be mixed with intake air and evenly distributed inside the combustion chamber. During the compression stroke, high CN fuel such as diesel was directly injected into the combustion chamber at IP of 900 bar so that there was a formation of fuel reactivity inside the combustion chamber. The injection of high ON fuel was controlled by an electronic control unit (ECU). High ON fuel injection was increased up to 10% at every step of experiments, and

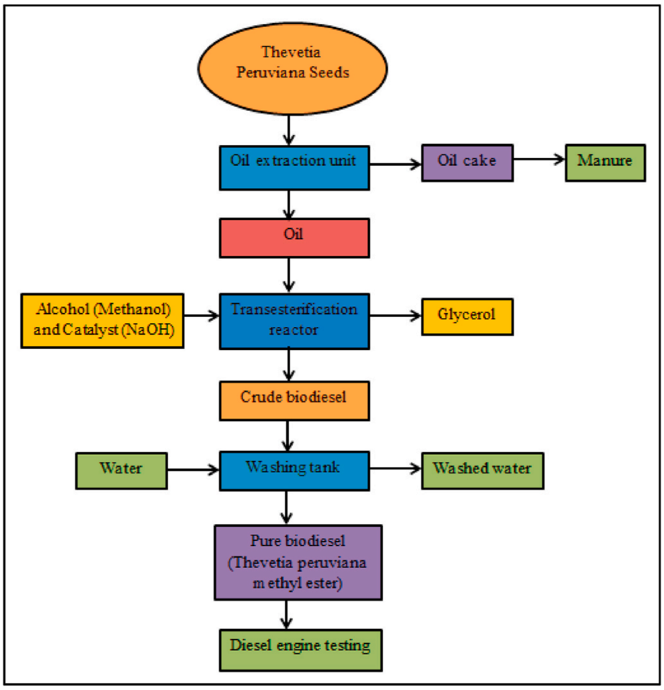


Fig. 2. Flow chart for biodiesel production from raw oil.

readings were noted down. In the next step, the high CN fuel was changed to B20 and B100 blends of TPME, tests were repeated with the same procedure. The entire tests were conducted at 50% of rated power to avoid the knocking phenomenon. The experimental line diagram is shown in Fig. 3. The actual experimental setup is shown in Fig. 4. The pentanol fuel injector is shown in Fig. 5. The toroidal combustion chamber was used for the experiment is shown in Fig. 6. The general specifications of the test engine are provided in Table 2.

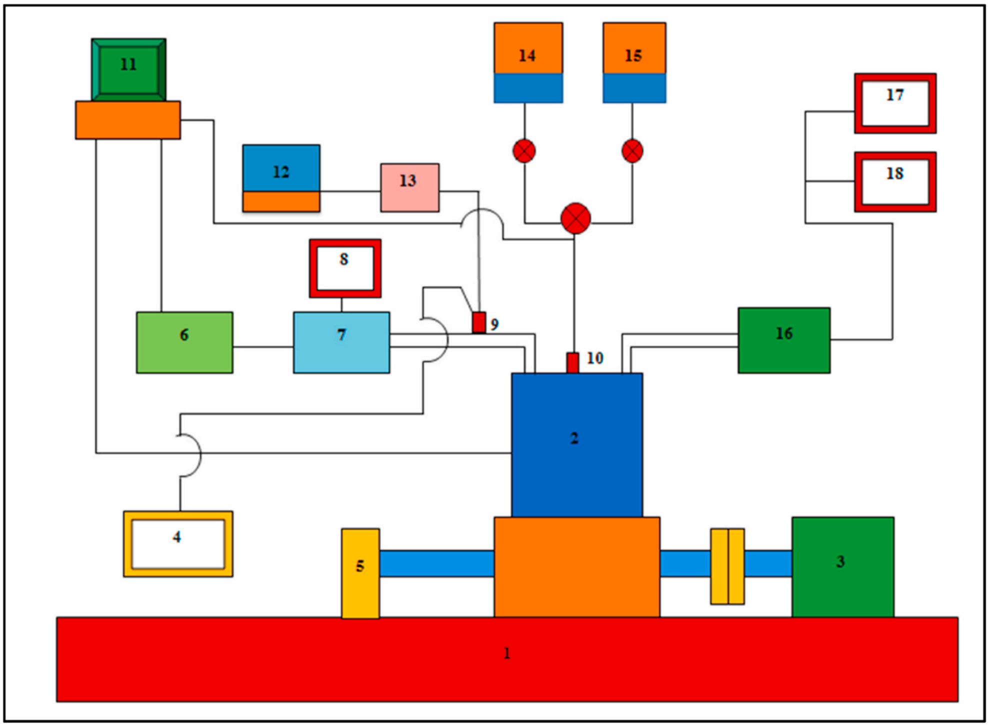
3.1. *Uncertainty analysis of the experimental data*

The experimental uncertainty analysis of the current work is presented in Table 3. To reduce the errors of calculated parameters, four readings are noted, and the results of average values are presented for the study [38,39].

4. Results and discussion

This segment presents the outline of the experimental results on a four-stroke, single-cylinder, dual-fuel engine operated under RCCI mode of combustion. In the current investigation, engine tests were performed when the engine arrived at settled working conditions. The experimental tests were directed with pentanol as LRF and diesel, TPME B20 and TPME B100 blends as HRF at 50% of rated power. The performance, combustion and emission characteristics of dual-fuel engine operated under the RCCI mode of operation are described.

Variation of BTE with the percentage of pentanol in injected fuels for various fuel combinations is shown in Fig. 7. BTE decreased with the increased percentage of pentanol [40]. That may be due to the formation of low-temperature combustion inside the combustion chamber with the addition of pentanol fuel. A Higher BTE of 22.15% is obtained for diesel and pentanol fuel combination at 10% of pentanol in injected fuels, which is about 9.1% and 27.3% higher than other fuel combinations. This is because diesel had a more calorific value that exhibits better combustion than biodiesel [5].



1-Base, 2-CRDI engine, 3-Eddy current dynamometer, 4-Pentanol injector ECU, 5-Crank angle sensor, 6-Air box, 7-Electric air heater, 8-Temperature controlling unit, 9-Pentanol fuel injector, 10-Diesel injector, 11-Computer interfaced to engine, 12-Pentanol tank, 13-Injector driver for pentanol, 14-Diesel tank, 15-Biodiesel tank, 16-Calorimeter, 17-Exhuast gas analyzer, 18-Smoke meter.

Fig. 3. RCCI engine line diagram [13] (Adapted with permission from the publisher).

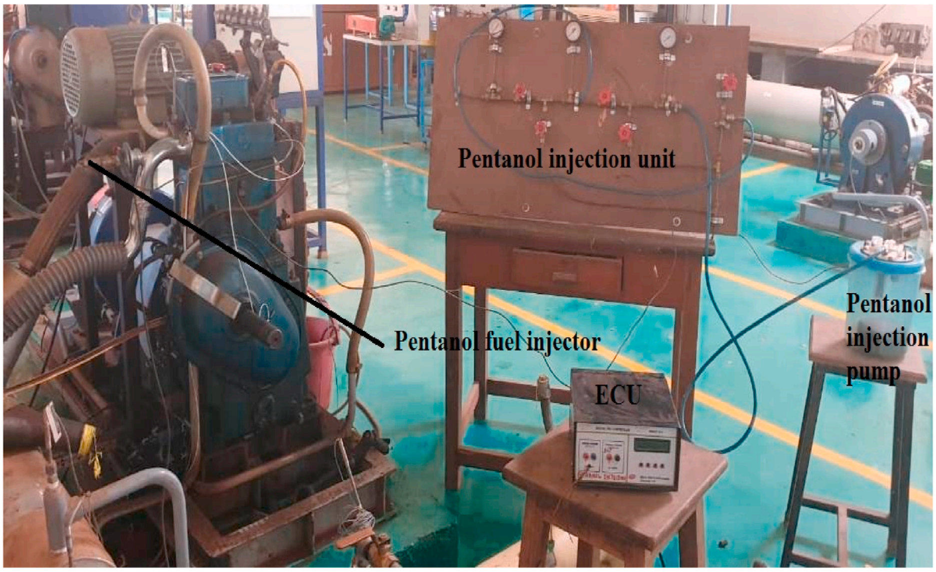


Fig. 4. Actual diagram of RCCI experimental setup [13] (Adapted with permission from the publisher).

Fig. 5. Pentanol fuel injector [13] (Adapted with permission from the publisher).

Variation of NO_x emissions with the percentage of pentanol in injected fuels for various fuel combinations is shown in Fig. 8. NO_x emissions are decreased with the increase in pentanol percentage. Highest NO_x emissions are obtained for diesel and pentanol fuel combination at 10% of pentanol. This is due to the lean mixture formation of pentanol with air, which leads to lower reaction duration and decreases NO_x emissions.

Variation of HC emissions with the percentage of pentanol in injected fuels for various fuel combinations is shown in Fig. 9. HC emissions are increased with the increase in pentanol percentage. Lowest HC emissions are obtained for diesel and pentanol at 10% of pentanol in injected fuels. This is due to incomplete combustion as the increase of pentanol in injected fuels.

Variation of CO emissions with the percentage of pentanol in injected fuels for various fuel combinations is shown in Fig. 10. CO emissions are increased as the pentanol percentage increases [40]. Lowest CO emissions are observed for diesel and pentanol at 10% of pentanol in injected fuels. With the addition of pentanol, there is not enough oxygen available for the complete combustion of fuel and air mixture, leading to higher CO emissions.

Variation of smoke emissions with a percentage of pentanol in injected fuels for various fuel combinations is shown in Fig. 11. As the percentage of pentanol increased, smoke emissions are decreased. Lowest smoke emissions are found for diesel and n-pentanol at 10% of pentanol in injected fuels. Because of highly premixed pentanol and more time of mixing for diesel, smoke emissions were very low [41].

Fig. 12 shows the variation of in-cylinder pressure with the crank angle at 10% pentanol in injected fuels. The highest pressure is

Fig. 6. Toroidal combustion chamber [13] (Adapted with permission from the publisher).

Table 2
Test engine specifications [13] (Adapted with permission from the publisher).

Engine parameters	Specifications
Engine	TV1 Kirloskar Engine
No. of cylinders	1
Software used	Engine soft
No. of strokes	4
Compression ratio	17.5: 1
Bore × stroke	87.5 × 110 (mm)
Combustion chamber	Toroidal
Dynamometer	Eddy current
Rated power	5.2 kW
Direct injection pressure	900 bar
Manifold injection pressure	5 bar

Table 3
Uncertainty analysis of the experimental data.

Measured variable	Accuracy
Load (N)	±0.1
Engine speed (rpm)	±2
Measured variable	**Uncertainty (%)**
Smoke	±0.3
Hydrocarbon	±0.2
Carbon monoxide	±0.1
Nitrogen oxide	±0.3
Calculated parameters	**Uncertainty (%)**
Brake thermal efficiency (%)	±1.2

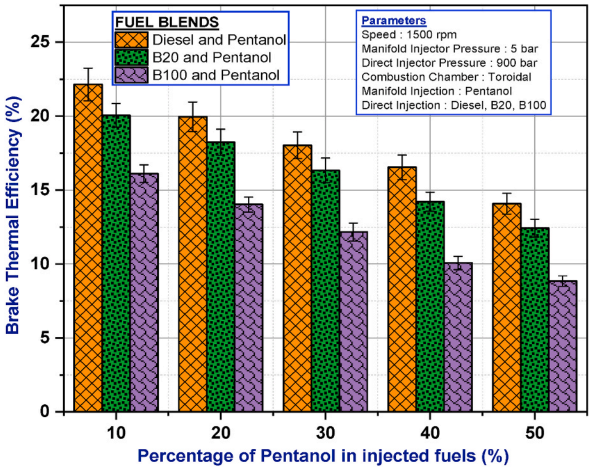


Fig. 7. Variation of BTE with a percentage of pentanol in injected fuels.

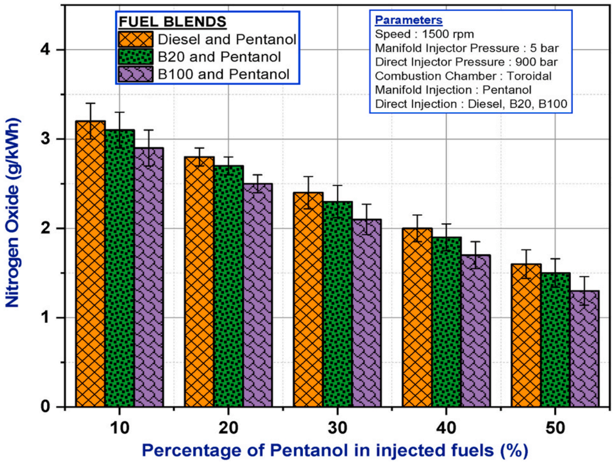


Fig. 8. Variation of NO_x emissions with a percentage of pentanol in injected fuels.

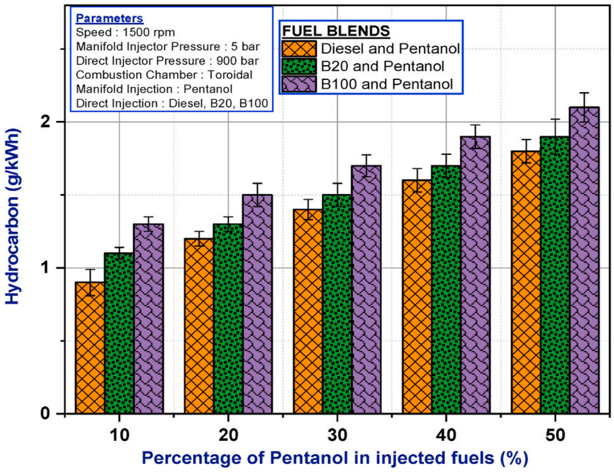


Fig. 9. Variation of HC emissions with a percentage of pentanol in injected fuels.

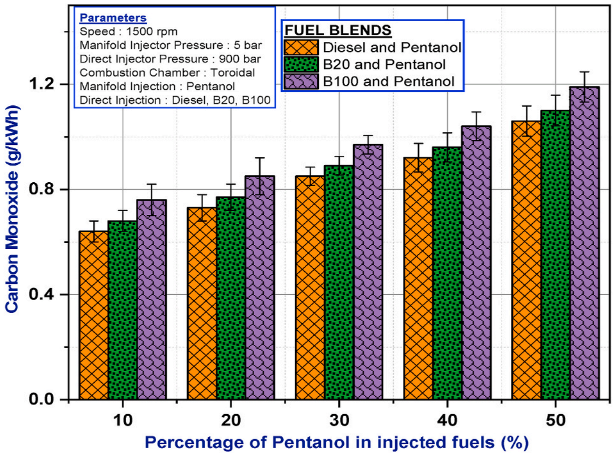


Fig. 10. Variation of CO emissions with a percentage of pentanol in injected fuels.

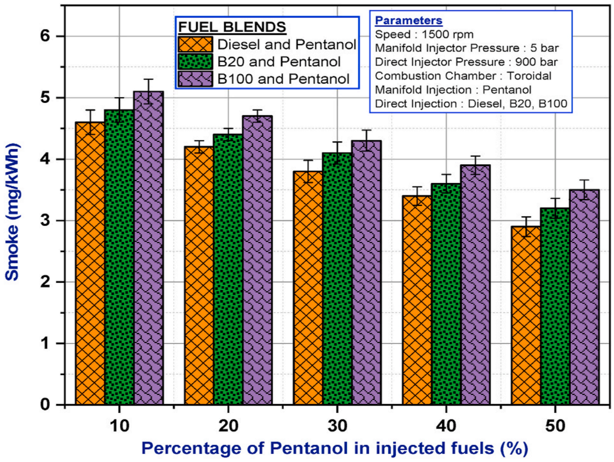


Fig. 11. Variation of smoke emissions with the percentage of pentanol in injected fuels.

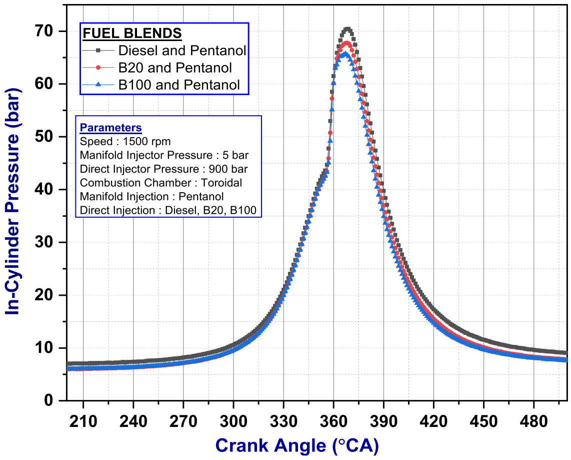


Fig. 12. Variation of in-cylinder pressure with the crank angle at 10% pentanol in injected fuels.

found for diesel and pentanol fuel combination mode as compared with other tested fuels. This is due to better combustion of fuel and air mixture inside the combustion chamber for diesel and pentanol fuel combination.

Fig. 13 shows the variation of HRR with the crank angle at 10% pentanol in injected fuels. Highest HRR is found for diesel and pentanol fuel combination mode as compared with other tested fuels. This is because diesel had more calorific value than biodiesel, and hence it burns effectively with the dosage of pentanol.

5. Conclusions

The experimental investigations on dual-fuel engines under the RCCI mode of combustion are performed at a different percentage of pentanol in injected fuels. Pentanol is injected along with air as LRF, and diesel, B20 and B100 blends of TPME are injected into the combustion chamber during compression stroke as HRF. From the experimental results following conclusions are drawn.

- As pentanol percentage increased in injected fuels, BTE decreased. Among various fuel combinations tested, diesel and pentanol give higher BTE as compared with other fuels. A Higher BTE of 22.15% is obtained for diesel and pentanol fuel combination at 10% of pentanol in injected fuels, which is about 9.1% and 27.3% higher than other fuel combinations.
- As the percentage of pentanol increased in injected fuels, HC and CO emissions increased while NO_x and smoke emissions are decreased. Among various fuel combinations, tested diesel and pentanol give lower HC, CO and smoke emissions and higher NOx emissions than other fuel combinations.
- At 10% pentanol in injected fuels, the highest in-cylinder pressure and HRR are found for diesel and pentanol fuel combinations compared with other fuel combinations.

Pentanol injection in RCCI mode of combustion as LRF with the diesel, B20 and B100 blends of TPME as HRF is carried out in the present work. Among different percentages of pentanol in injected fuels, 10% gives more efficient results in terms of efficiency and emissions. RCCI engine fueled with biodiesel exhibited lower performance as compared with diesel fuel. Nevertheless, biodiesel enables partial replacement for fossil diesel, decreasing the need for petroleum fuel and offers ecological energy supply.

6. Future scope

In the present work, the effect of pentanol as LRF and diesel, TPME B20 and TPME B100 blends as HRF on dual fuel engine under RCCI mode of combustion is performed at a different percentage of pentanol in injected fuels. The future scope of the research work includes the following.

- Study of RCCI engine fueled with various alcoholic fuels as low reactive fuels and various biodiesels as high reactive fuels.
- A study on the effect of exhaust gas recirculation and combustion chamber geometry on the performance, combustion and emission characteristics of RCCI engine needs to be carried out.

CRediT authorship statement

P.A. Harari and V.S. Yaliwal: Methodology, Writing-Original Draft, Conceptualization, Investigation. **Manzoore Elahi M Soudagar:** Writing-Original Draft, Review & Editing, Formal analysis. **N. R. Banapurmath and V.S. Yaliwal:** Supervision, Methodology, Conceptualization and Resources. **T.M. Yunus Khan**: Funding, Review and Editing. **Marjan Goodarzi and Mohammad Reza Safaei:**

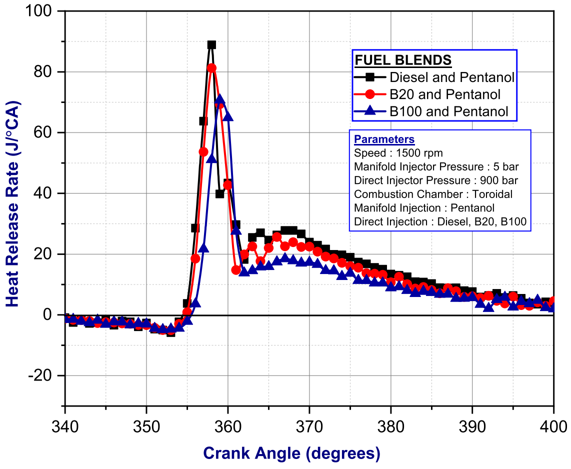


Fig. 13. Variation of HRR with the crank angle at 10% pentanol in injected fuels.

Supervision and Project administration. **MA Mujtaba and Naveed Akram:** Formal analysis, Review & Editing. **Ashraf Elfasakhany and Ahmed I. EL-Seesy:** Review & Editing and Methodology, Project administration, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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