Experimental studies on combustion duration and ignition delay period for a newly synthesised gomutra emulsified diesel

Amit Jhalani*

Department of Mechanical Engineering,
Dr K.N. Modi University,
Newai, Rajasthan, India
Email: 2015rme9521@mnit.ac.in
Email: jhalaniamit@gmail.com
*Corresponding author

Dilip Sharma, Shyam Lal Soni,
Pushpendra Kumar Sharma and
Digambar Singh

Department of Mechanical Engineering,
Malaviya National Institute of Technology,
Jaipur, India
Email: dsharma.mech@mnit.ac.in
Email: shyamlalsoni@gmail.com
Email: pushpendra.mech@mnit.ac.in
Email: digisinsinwar@gmail.com

Abstract: Aligning to water-in-diesel emulsion technology, a newer work has been proposed in this study by introducing gomutra-in-diesel emulsion (GMD emulsion) fuel for application in CI engine. Experimental investigations have been performed in this study for ignition delay and combustion duration to understand the underlying mechanisms of combustion with this fuel. The complete work has been performed over a variable compression ratio (VCR) stationary diesel engine. Emulsions of different gomutra-in-diesel (5%, 10%, 15% and 20%) concentrations were taken for the study. The ignition delay was found to be 24º, 27º, 29º, 32º, and 34º crank angle (CA) with diesel, 5%, 10%, 15%, and 20% water-in-diesel emulsions respectively. The effect of injection timing on the engine performance was also analysed. It was observed that the combustion duration got decreased by a maximum of 12 degrees CA with 20% GMD emulsion. It is estimated that after the optimisation of other engine parameters like injection pressure and compression ratio, the performance of the engine could further be improved.

Keywords: diesel engine; gomutra; combustion duration; ignition delay; emissions; emulsified fuel.

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Biographical notes: Amit Jhalani is an academician and a researcher having more than 11 years of experience in this field. His area of specialisation is renewable energy technologies and alternative fuels for IC engines. He has published 10+ research papers in peer-reviewed international journals and has presented 15+ papers in different national and international conferences. He has one book published in his authorship on biogas utilisation in SI engines. He obtained his PhD and MTech from the MNIT Jaipur, India in 2019 and 2014, respectively.

Dilip Sharma is a Professor of Mechanical Engineering at the MNIT Jaipur. He has published more than 40 papers in national and international journals and presented 68 papers in national and international conferences. He has filed seven patents in the field of IC engines and alternate fuels and has published ten books. He has completed six major R&D projects. He has done more than 30 consultancy projects.

Shyam Lal Soni is a Professor of Mechanical Engineering at the MNIT Jaipur. He has published more than 80 research papers in different international journals and conferences and 28 research articles in national journals and conferences. He has supervised 17 PhD scholars.

Pushpendra Kumar Sharma is a research scholar in the Department of Mechanical Engineering, MNIT Jaipur. He is working over cleaner fuels for IC engines. He has published eight research papers in international journals and conferences.

Digambar Singh is a research scholar in the Department of Mechanical Engineering, MNIT Jaipur. He is working over different generations of biofuels. He has published ten research papers in international journals and conferences.

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1 Introduction

Today, when the whole world is grappling with the problem of continuously increasing air pollution and energy crisis, the fuel scientists are working to provide some cleaner fuels. Diesel engines are more popular due to their good thermal efficiency and heavy-duty application, but they are associated with problems of higher emissions of particulate matter (PM) and NO_x (Nayyar et al., 2017a; Sanjay et al., 2018). Researchers working over emission reduction techniques for the CI engines have found water emulsified diesel fuel to be a prominent alternative. Simultaneous improvement in engine performance and reduction in emission has been observed by most of the researches with water emulsification (Jhalani et al., 2019a). Gomutra emulsification is a similar kind of approach since it consists of around 95% water along with some other essential constituents. Hence, in this study, the benefits of water emulsification along with the other benefits of gomutra have been materialised through gomutra-in-diesel (GMD) emulsification.

Some important combustion features which are associated with the GMD emulsion approach are

1 Heat loss in vaporisation of the water content of GM lessens the combustion temperature, which results in the NO_x reduction (Ithnin et al., 2015).

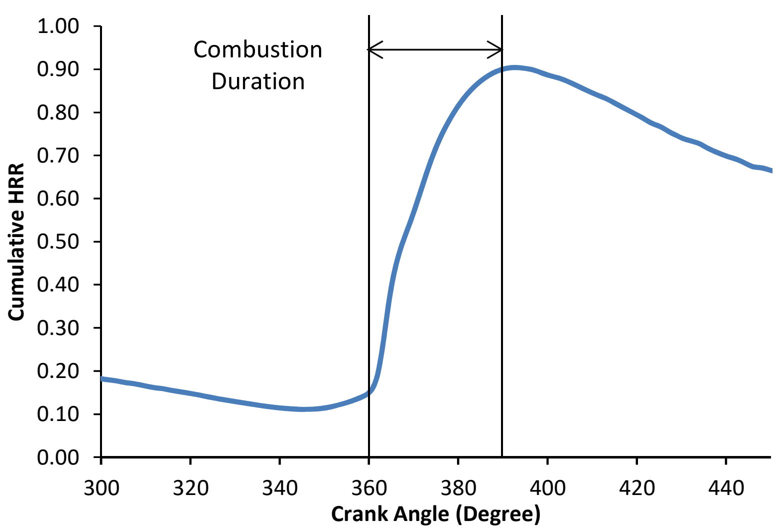
2 Further drop in NO emission due to urea content of gomutra, which converts NO into N_2 and water vapour.

3 Gomutra droplets entrapped inside the diesel results in micro-explosion phenomenon of emulsion.

It increases the volatility and surface to volume ratio of diesel fuel tending to improved combustion with lesser emissions (Attia and Kulchitskiy, 2014; Abdul Karim et al., 2019).

There are some points that should be taken care of while dealing with emulsion fuel. Increased ignition delay due to lower combustion zone temperature with gomutra may lead to diesel knock and hence could also affect the engine components adversely (Bedford et al., 2000). Changes in the fuel properties such as density and viscosity may significantly affect fuel spray pattern, air-fuel mixing, fuel filter, and hence the durability and combustion quality of the engine (Jhalani et al., 2018; Nayyar et al., 2019). Emulsion stability and the problem of cold-start may also rise with the use of emulsified fuel (Ismael et al., 2018).

Figure 1 Cumulative heat release curve for combustion duration analysis (see online version for colours)

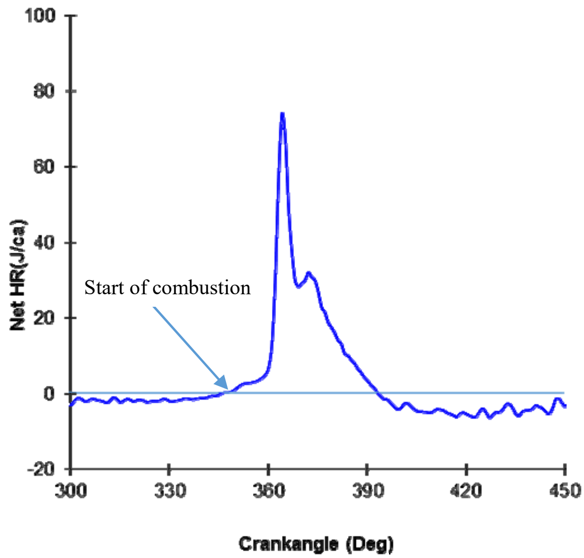


The physicochemical properties such as density and viscosity of fuel get affected in this strategy due to the use of surfactants and watery gomutra (Noor El-Din et al., 2013). Moreover, due to the heat loss in the vaporisation of water content results to lower down the combustion temperature, which affects combustion duration and ignition delay

(Basha and Anand, 2012; Suresh and Amirthagadeswaran, 2015). For the analysis of performance and emissions of an engine, these parameters are important to study in detail.

Hence, in this study, an effort has been made to analyse the effects of gomutra emulsification over combustion duration and ignition delay. The prolonged delay period leads to the accumulation of fuel in the combustion zone, which in turn results in excessive diesel knock. It adversely affects the engine components and their durability. Hence, it necessitates the requirement of optimising the injection timing (IT) of the engine for emulsified fuel.

Figure 2 Net heat release rate curve (see online version for colours)



The ignition delay during combustion is referred to the duration of time required by the fuel in showing a sign of actual combustion after the first droplet of fuel is entered inside the combustion chamber (Ganesan, 2015). In this work, the combustion duration is estimated from the cumulative heat release data. The lowest value obtained in the cumulative heat release indicates the start of combustion, while the maximum value indicates the end of combustion in the cumulative heat release curve (refer Figure 1). The instant at which the injector needle is lifted by a specific distance from its seat is termed as the initiation of injection. The start of combustion could be estimated from the point of abrupt change in the slope of the heat release rate curve, specifically when the HRR becomes positive (Dhole et al., 2016) (refer Figure 2).

2 Experimental setup

The present study was performed over a Kirloskar make diesel engine modified by Apex Innovations, India. Originally, the engine was a stationary compression ignition engine test setup. It was a 5.5 kW power rating engine which modified by Apex Innovations for variable compression arrangement to produce 3.5 kW at full load. An eddy current dynamometer is augmented to the engine for loading. Several thermocouples are connected at different locations to measure the temperatures of water, engine cylinder, exhaust gas, calorimeter, etc. Two control valve rotameters are provided to maintain constant water supply for cooling of engine and dynamometer. Various other engine specifications are tabulated in Table 1. The data acquisition device of the engine consisted of a proper analogue-digital-converter with an electronic interface unit. The pressure signals are obtained from the output of the charge amplifier and sent to the interface-unit, which after getting processed, were stored in the internal memory. After completion of every 10 combustion cycles, they are digitally displayed on the computer. In-cylinder pressure is one of the crucial parameters that has been recorded. Piezo-electric pressure transducers are the most commonly used form of pressure transducers to acquire in-cylinder pressure histories. Two piezo-sensors are installed on the cylinder head and fuel injector for the measurement of combustion pressure and fuel line pressure, respectively. Pressure pick-up assembly consisting of the piezo-electric transducer was mounted to the cylinder head and crank angle (CA) encoder, which was connected to NI USB-6210, 16 bit, 250 kS/s card, with digital input. The measured cylinder pressure was displayed on the computer after calibration and processing by the data acquisition system.

Figure 3 Experimental setup (see online version for colours)

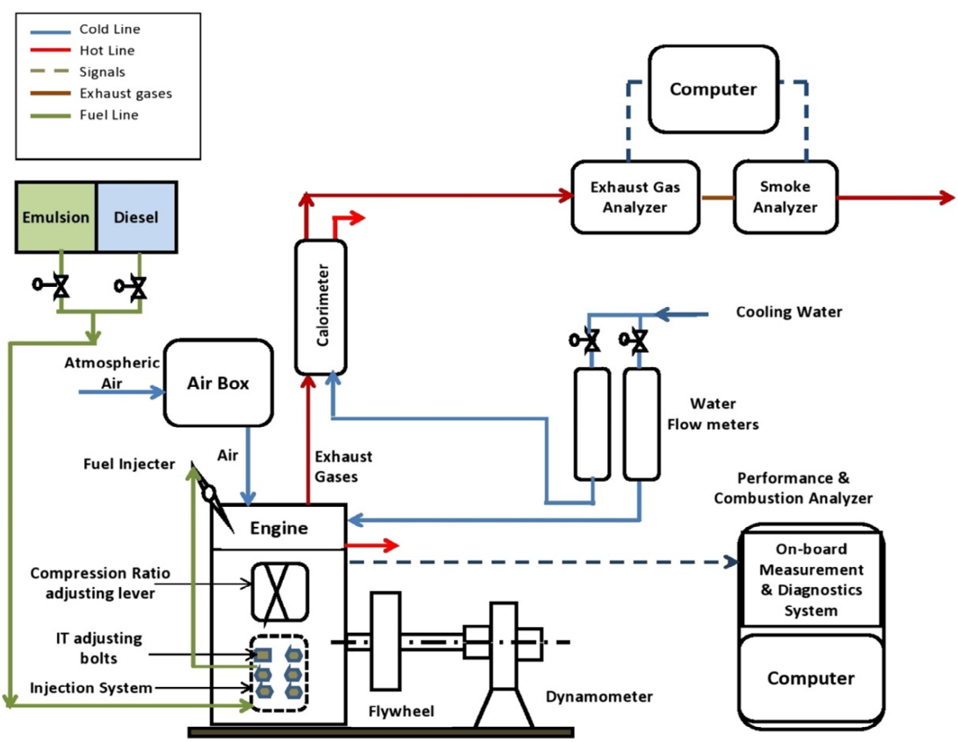


Table 1 Test engine specifications

Particulars	*Specification*
Engine type	4 stroke, single-cylinder, diesel engine mode
Model and make	TV1 engine of Kirloskar customised by Apex Innovation
Stroke length	110 mm
Bore diameter	87.5 mm
Cylinder volume	661 cc
Engine speed	1,500 rpm (constant speed) at full load
Connecting rod length	234 mm
Rated power	Maximum 3.5 kW at 1,500 rpm
Compression ratio	18:1 to 22:1
Type of cooling	Water cooled
Combustion chamber	Hemispherical bowl in piston type
Rotameters	Calorimeter 25–250 LPH; Engine cooling 40–400 LPH
Software used	‘Enginesoft’ supplied by Apex Innovation, India
Fuel tank	15 litres, dual compartment, glass fuel metering pipe

The exhaust gas emissions were measured by an AVL Ditest-gas analyser which is capable of measuring NO, HC, CO, O_2, and CO_2. PM emissions have a linear relationship with smoke. Hence, for the estimation of PM, an AVL smoke-meter was used to measure smoke. It gives the measurement in terms of absorptivity and opacity. Measurement of smoke is more comfortable as compare to particulate emissions (Sharma et al., 2019).

3 Gomutra emulsified diesel

Distilled *Bos indicus* urine (popularly known as *gomutra*) is easily and readily available in India because of its application for many other purposes, including medicinal and agricultural usage. Mainly it consists of water around 95%, and thereby its use in the engine is equally convenient as like water-diesel emulsion and in the same way. Other than water, it is constituted of around 2.5% urea and 2.5% other salts and minerals (Dhama, 2005; Kaneko et al., 2008). Magnesium, potassium, and sodium are also present in small proportions (Table 2). These are being used by various researchers as nano-particle additives in pure or combined form to enhance the fuel properties (Mehregan and Moghiman, 2018; Soudagar et al., 2018).

Elements such as K, Na, Mg, Ca are intentionally added to the fuels and lubricants during production due to their detergency and alkalinity properties. It helps to keep the engine components clean along with the neutralisation of the acids formed during combustion (Sharma et al., 2018). The difference in density and the surface tension within the gomutra and diesel components do not let them mix with each other. Due to the alkaline nature of the gomutra, its surface tension is lesser to provide better stability than water-in-diesel emulsion. A GMD emulsion is formed in mechanical homogeniser by high energy processing with the help of emulsifiers. The emulsifiers reduce the interfacial tension amid the diesel and *gomutra*, which helps to keep the *gomutra* content dispersed in the diesel matrix.

Table 2 Chemical composition of *Bos indicus* urine

S. no.	*Analyte*	*Standard range (%vol.)*
1	Allantoin	0.0152
2	Calcium	0.00062
3	Coproporphyrin	0.0021
4	Creatinine	0.0032
5	Magnesium	0.0027
6	Sodium	0.0021
7	Potassium	0.002
8	Urea	2.35
9	Ammonia	1.15
10	Uric acid	0.000423
11	Uroporphyrin	0.00015
12	Others micro-constituents	1.2
13	Water	95.28

Source: Kaneko et al. (2008)

4 Emulsion formation

Emulsions were formed taking four different proportions (5%, 10%, 15% and 20% GMD, i.e., GM05, GM10, GM15, and GM20 respectively) to optimise the content of the dispersed phase. 30 ml (25 ml of Span 80 and 5 ml of Tween 80) of emulsifier was used per litre of prepared emulsion to give a constant hydrophillic lipophillic balance (HLB) value –6. The proportion (3%) and the HLB value (6) of the surfactant were kept constant in all the prepared emulsions. The required amount of surfactant was first added in diesel. It was then mixed at 15,000 rpm in a mechanical blender. Then the gomutra phase was mixed in it gradually, and again it was subjected to high energy processing at 15,000 rpm. Irrespective of the GM percentage, an opaque milky-white emulsion was obtained in every preparation, as was given in most of the papers (Forgiarini et al., 2001; Mehta et al., 2015). All the emulsions prepared were found to be homogeneous and almost stable for more than 20 days of the observation period.

Table 3 Emulsifiers used in the preparation of emulsions

Emulsifier name	Tween 80	Span 80
Appearance	Yellow-pink	Amber liquid
HLB value	15	4.3
Chemical character	Non-ionic	Non-ionic
Molecular formula	$C_{32}H_{60}O_{10}$	$C_{24}H_{44}O_6$
Molecular weight	604.82	428.61
Make	Merck Life Science (Pvt) Ltd, India	Loba Chemie Ltd, India

Source: NCBI (2004, 2017)

5 Physicochemical properties of emulsified fuel

The density and viscosity of GM (dispersed phase) and surfactant are comparatively higher than that of the continuous phase (diesel) (Singh et al., 2020). Consequently, when mixed with diesel, they increase emulsion density and viscosity. As GM does not have its own calorific value (CV), its mixing decreases the overall CV of emulsion. It was observed equal to the CV of the diesel content of emulsion. Hence, the CV of the prepared emulsion as compared to the diesel alone was found to decrease. A redwood viscometer was used to measure the viscosity. It measures redwood seconds. It is the time period taken by 50 ml of emulsion to flow through a standard orifice within the viscometer. Further, these redwood seconds were used to convert the viscosity in centistokes. The following equation (1) was used to get the kinematic viscosity (Baukal, 2012).

$$\nu = At - \frac{B}{t} \tag{1}$$

here A and B are constants that are calibrated with the known viscosities of diesel and water at 25°C, i.e., $\nu_{diesel} = 2.98$ cSt; $\nu_{water} = 0.89$ cSt.

A = 0.1498 and B = 599.85; t = redwood seconds

The viscosity of GM05, GM10, GM15, and GM20 was obtained as 3.9, 4.24, 4.72, and 5.43 cSt, respectively. The effect of gomutra emulsification and surfactant over the density was analysed since it is an important parameter of any liquid fuel. The density of the diesel and emulsified fuel is measured with a digital density meter DS 7800, Kruss, Germany, with a specified measurement accuracy of 0.1 kg/m^3. The measurements were performed at different temperatures 20°C, 30°C and 40°C to assess the effect of temperature. It was observed that the addition of gomutra and surfactant increases the density of diesel. The density of diesel was found to be 829 kg/m^3 at 30°C. It was increased to 855 and 858 kg/m^3 with 10% and 15% gomutra respectively keeping a constant 3% surfactant.

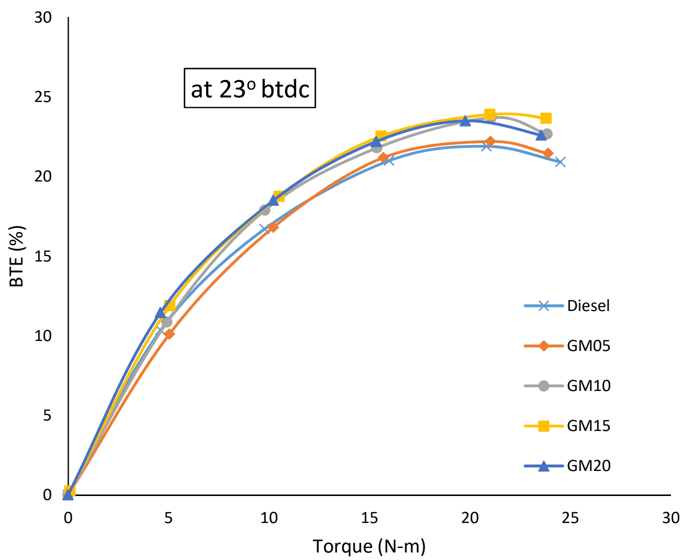
Further on increasing the surfactant to 4% in GM15, the density became 860 kg/m^3. The results indicate that the addition of either gomutra or surfactant affected the density of emulsions significantly. Moreover, emulsions showed the dependence of density on the temperature. The density was found to be decreased linearly with an increase in temperature. Most of the results were found to agree with El-Din et al. (2013), who worked over water emulsification in diesel. The CV of the emulsion was found equal to the diesel content of the emulsion, i.e., for GM15, it was observed as 36,200 kJ/kg, which is 85% of the CV of diesel (42,600 kJ/kg).

6 Performance analysis

All the experiments were carried out twice at any of the configurations to assess the effect of water emulsification on the performance of the engine. Average values of the readings were taken for better precision, although, any significant difference between any two sets was not found. All the prepared emulsions GM05, GM10, GM15, and GM20, were first tested, keeping all the parameters constant at IT 23^o btdc. A significant improvement in the brake thermal efficiency (BTE) was observed with emulsion fuels because of the micro-explosion phenomenon (Jhalani et al., 2019b). The BTE was increased as the percentage of GM increased up to 15%. Maximum 23.8% BTE was obtained with GM15 as compared to 21.9% with diesel alone.

Further increase in GM content to 20%, induced relatively high diesel knock, especially at higher loads. In addition, the high viscosity of GM20 emulsion affects the spray pattern and cause improper air-fuel mixture. It may also affect the injection system negatively (Singh et al., 2019). The larger amount of GM in GM20 emulsion lowers down the cylinder temperature, which makes a longer delay period (Suresh and Amirthagadeswaran, 2015). A more extended delay period promotes the accumulation of fuel in the combustion chamber, which ignites simultaneously, resulting in a high rate of pressure rise with increased heat release rate. It overtakes the effect of micro-emulsion, and hence lower efficiency is observed with GM20 (Figure 4). Combustion duration is also gets affected, which in turn affects the thermal efficiency of the engine (Khoa et al., 2019). It is discussed in detail in next section on combustion duration.

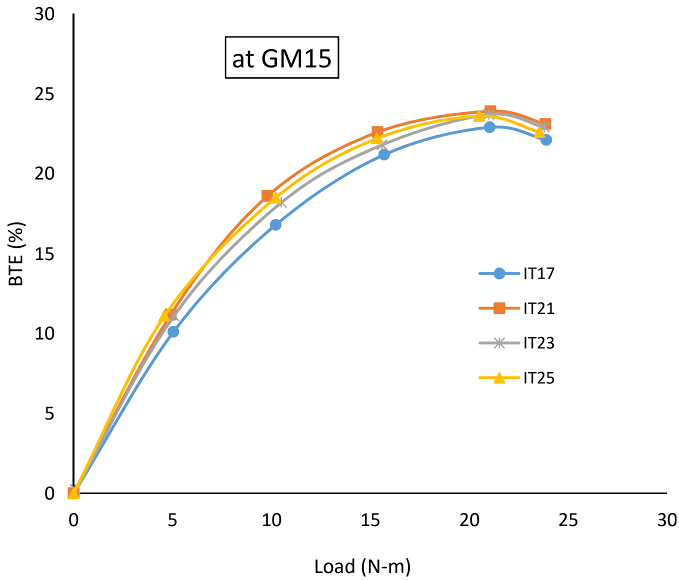
Figure 4 Effect of water concentration over BTE (see online version for colours)



The bsfc of emulsions was found higher as compare to the plain diesel because GM does not have any CV of its own; hence the CV of the emulsion lowered down. So for the same amount of energy input, high bsfc was required.

The optimised GM15 was then used to optimise the IT for GM emulsified fuel. The composition of emulsion and other engine parameters were kept constant, and only IT was varied in this process. The results for BTE were plotted at different settings of IT 19°, 21°, 23°, and 25° btdc. It was observed that due to IT variation, the BTE did not affect significantly, but the diesel knock was reduced substantially at IT 21. BTE (24.1%) was found to be improved marginally at IT 21 as compared to 23.8% at IT 23 (Figure 5). Retardation in the IT facilitates the fuel to enter a relatively higher temperature and pressure combustion zone (Debnath et al., 2015). It results in the early vaporisation and mixing of the fuel with air. The tendency of fuel accumulation got reduced in this case and thus, retardation provided a smoother engine run.

Figure 5 Effect of IT over BTE (see online version for colours)



7 Ignition delay

Ignition delay is an important parameter to analyse the combustion process inside the cylinder. GM emulsification enhances the physical as well as chemical delay. Lower temperature conditions of the combustion zone due to high water (GM) emulsification elongated the chemical-delay and required a longer time in vaporisation. The high density and viscosity of emulsion prolong physical delay. This ignition delay promotes diesel knock, and hence it is needed to be addressed and appropriately analysed (Nayyar et al., 2017b). The change in the ignition delay period with the addition of GM has been plotted on the curve as shown in Figure 6. It shows that the delay period was increased from 15º to 22º btdc when fuel was changed from diesel to GM20. High ignition delay allows the accumulation of a larger amount of fuel before combustion begins in the cylinder.

Further, when combustion occurs simultaneous burning of this more massive amount of fuel creates higher rates of pressure rise, which is responsible for diesel knock. The rate of pressure rise for different emulsion fuels has also been shown in Figure 7. Here too, it could be observed that the maxima of the rate of pressure rise shift to the right with an increase in the proportion of GM mixing. The effect over the ignition delay could also be depicted from here.

Figure 6 Variation in ignition delay (see online version for colours)

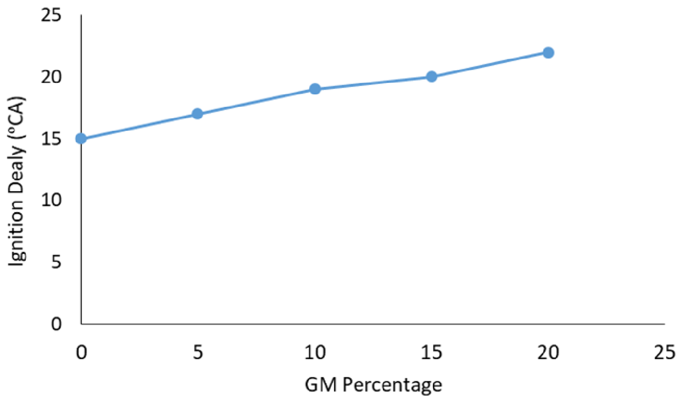
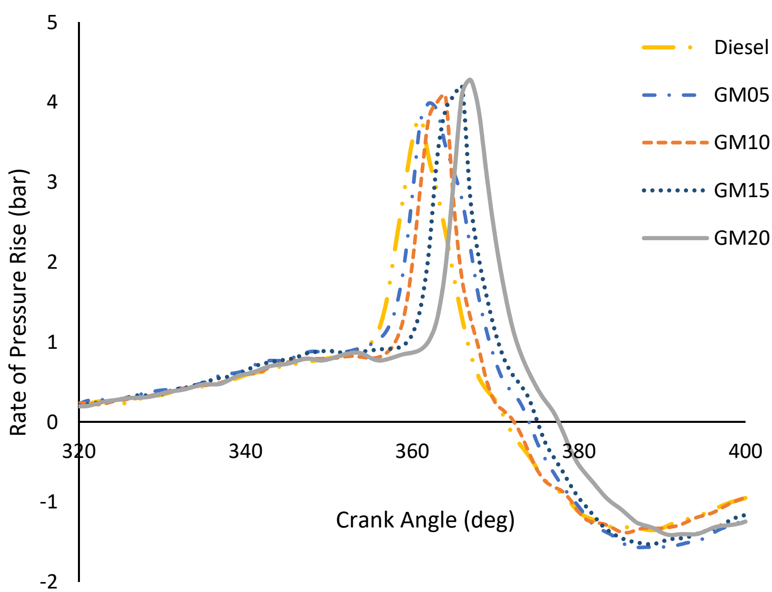


Figure 7 Effect of GM emulsification over rate of pressure rise (see online version for colours)



8 Combustion duration

It has been seen that gomutra emulsification tends to elongate the chemical delay as well as physical delay. Due to retardation of the IT, the fuel enters a relatively higher temperature and pressure conditions, which helps in early vaporisation and mixing of the fuel. It reduces the combustion duration with a high rate of pressure rise and heat release, as shown in Figures 7 and 8. Due to the increased ignition delay, the amount of fuel gets accumulated inside the combustion chamber before the combustion starts. It leads to the simultaneous burning of a larger amount of fuel, which causes a high rate of pressure rise.

Figure 8 Variation of rate of heat release with GM concentration (see online version for colours)

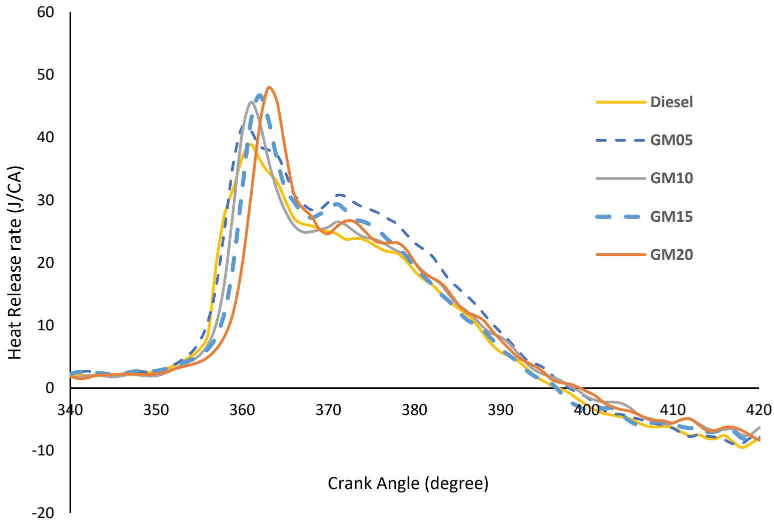
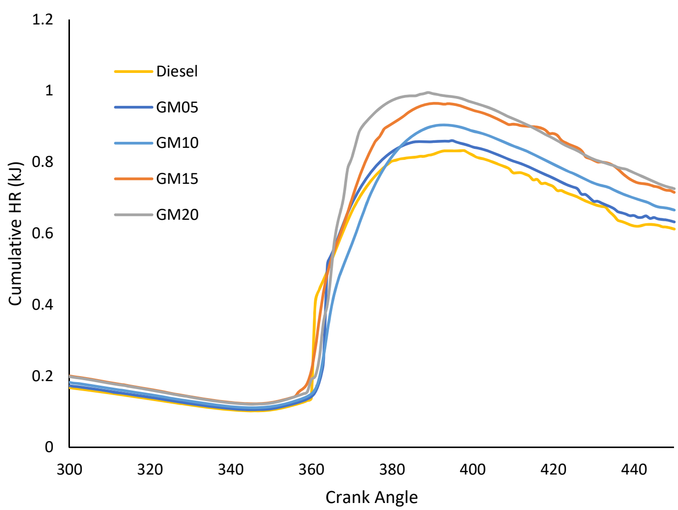
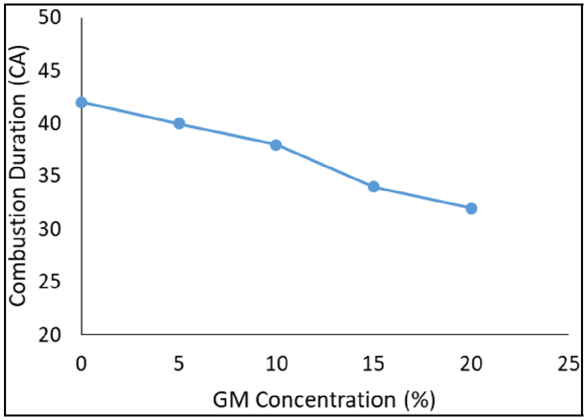


Figure 9 Effect of GM concentration over cumulative heat release (see online version for colours)



Moreover, due to the micro-explosion phenomenon and better combustion characteristics with GMD emulsion, higher heat release was obtained. It can be observed from Figure 9 that as the GM concentration is increasing, the amount of cumulative heat release is also increasing. Moreover, the peaks of the curves are also shifting leftward, which represents the reduction in combustion duration due to increased gomutra concentration. The variation in combustion duration has been plotted separately in Figure 10. The duration, which was 43º CA with diesel, was reduced to 31º CA with W20. This is because of the higher ignition delay. Due to high ignition delay with emulsion fuel, the accumulated amount of fuel burns instantly, and high temperature and pressure conditions shorten the combustion duration.

Figure 10 Effect of GM concentration over combustion duration (see online version for colours)



9 Conclusions

Results of experimental investigations for the gomutra emulsified diesel fuel have been discussed in this article. The study includes findings of combustion duration and ignition delay with GMD emulsion fuel. Moreover, the effect of the variation in IT has also been evaluated over the performance of the engine. Some important conclusions drawn from the study are mentioned below:

- Viscosity (5.43 cSt) of GM20 emulsion was very high, which elongated physical delay. The viscosity of GM10 emulsion (4.24 cSt) was found to be within permissible limits.
- GM15 emulsion was found to be optimum with 23.8% BTE as compared to 21.9% BTE with diesel along with lower diesel knock.
- Performance of the engine was found improved with reduced diesel knock by retardation in IT by 2º btdc, i.e., using IT 21º CA btdc in place of 23º CA btdc.
- Ignition delay of 5º CA and 10º CA was found with GM10 and GM20 emulsions, respectively. Combustion duration was reduced to 31º CA and 38º CA with a reduction of 12º CA and 5º CA with GM20 and GM10 emulsions, respectively.

From the combustion duration and ignition delay studies performed in this study, it is felt that the engine optimisation could be performed for GMD emulsion for better performance. Moreover, engine durability should also be assessed to analyse the effect of GMD emulsion over engine components.

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Nomenclature

BTE	Brake thermal efficiency
btdc	Before top dead centre
CA	Crank angle
CV	Calorific value
cSt	Centi stoke
GM	Gomutra
GMD	Gomutra-in-diesel
HLB	Hydrophillic lipophillic balance
IT	Injection timing
GM10	10% gomutra-in-diesel
GM15	15% gomutra-in-diesel
GM20	20% gomutra-in-diesel