Combustion Characteristics of Diesel Combustion System Using Blended Diesel: An Experimental Study

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Abstract: This paper deals with the experimental study of combustion characteristic of diesel blended with n-pentane and diethyl ether (DEE). The ignition delay Characteristic of diesel combustion system fuelled with n-Pentane and DEE blends with pure diesel is investigated. The experiment conducted at various pressures and temperatures of air inside the combustion chamber. An experimental set up was designed based on an optical method for the measurement of ignition delay. The result reveals that ignition delay of diesel fuel spray decreases with increases in the temperature and pressure of hot air. Results also show that the effect of methyl group being more dominant at low ignition temperatures whereas the alkyl groups are more effective at higher temperature. The temperature and pressure of hot air inside the combustion chamber are the main factors for ignition delay. Ignition delay of 10% and 20%, n-pentane blends is higher than pure diesel at low temperature while at high temperatures it is nearly equal to the pure diesel. However 30% and 40% n-pentane blends increased the ignition delay. Ignition delay of 10%, 20%, 30% and 40% blends of DEE is lower than pure diesel. DEE reduces the ignition delay of diesel fuel effectively at lower temperatures.

Keywords: Diesel Combustion System, Blended Fuel, Combustion, Ignition Delay, Optical Method, Hot Air Temperature and Pressure

1. Introduction

Diesel engines have high thermodynamic efficiency, therefore, they have always been the first choice for heavy duty vehicles. However, future emission regulation poses a challenge for upcoming diesel engine. Future emission regulations are becoming more restrictive, forcing engine designers towards lower exhaust values. With this perspective, knowledge of the injection and the combustion processes is currently being considered as a major research objective. Particularly, the analysis is focused on direct injection Diesel engines, where the fuel-air mixing process plays a dominant role. Only with a good understanding of this phenomenon, it will be possible to reduce the emission levels without impairing the engine performance and efficiency [1].

A substantial amount of work has been done in the field of diesel engine combustion as they areconsidered not only the major source of power but also exhaust emissions. So, the major attention of researchers is focused on the combustion process of the engine or in other words the main attention of researchers is on ignition characteristics of the fuel. Hasimoglu et al. [2], concluded that the higher viscosity of biodiesel reduced the engine power and also the lower calorific value of biodiesel increased the specific fuel consumption and decreased the combustion temperature. Agarwal et al. [3], have done an experimental investigation on diesel engine while using linseed oil and mahua oil with diesel reported that the blending of 50% linseed oil with diesel increased the smoke density and decreased the brake specific energy consumption. The mixing of 30% mahua oil with diesel reduced the smoke density and increased the thermal efficiency. Agarwal et al. [4] studied that the use of bio-diesel derived from rice bran oil reported the increase in NO_x emission due to the existence of molecular oxygen in

biodiesel and suggested the exhaust gas recirculation technique reduce NO_x emission even though the exhaust gas recirculation increases the brake specific fuel consumption and the emission of CO, HC, and particulate matters. Assanis et al. [5] have developed a correlation for ignition delay in a typical modern, heavy-duty, turbocharged, intercooler, DI diesel engine, operating under both steady state and transient conditions. The simulated and measured ignition delay histories were extremely close throughout the duration of transients. Chomaik et al. [6] studied the modified CFD model, based on the KIVA-3 code, to account for the auto-ignition of diethyl Ether. Constant volume simulations confirm high ignition quality of DEE in air. Temperature dependency of ignition delay is studied and results were presented for ignition delay. Kim et al. [7], studied the effects of intake pressure and intake oxygen concentration on combustion and emissions of diesel and soybean methylene ether biodiesel. Vijayaraj and Sathiyagnanam [8] studied combustion characteristics of a DI diesel engine fuelled with blends of methyl ester of cotton seed oil. It found that the peak cylinder pressure and heat release rate of diesel were higher when compared with those of methyl ester cotton seed oil blends. Xingcai et al. [9] investigated the influence of ethanol additives on the performance and combustion characteristics of diesel engines. The results show that the brake specific fuel consumption increased at overall engine operating conditions and found that engines fueled ethanol/diesel blended fuels have higher emissions of total hydrocarbon and lower emissions of CO, NO_X and smoke. Lee and Huh [10] validated the thermophysical properties against measured tip penetrations and sauter mean diameters (SMDs) of non-reacting sprays by using soy-based bio-diesel in a CI engine. Banapurmath et al. [11] found that the performance and emission characteristics were almost similar to that of the engine using diesel as fuel when using honge, neem, and sesame oil methyl esters as fuel. Balamurugan and Nalini [12] investigated the fact that increase the performance and reduce the emission by adding alkanes blending with diesel. Wang [13] investigated that the engine parameters needed some readjustments for getting the maximum output power and highest thermal efficiency when using the cottonseed oil as fuel. Kim et al. [14] investigated the characteristics of spray, auto-ignition, and combustion process of DME (Di-methyl ether) in a combustion vessel under high temperature and pressure and engine conditions. It was observed that the liquid phase length of DME spray

does not develop anymore at specific length when the ambient temperature and pressure is high.

Jung et al. [15] studied the influence of mixture stratification on homogeneous charge compression ignition combustion of di-methyl ether in a rapid compression and expansion machine. Im et al. [16] investigated the influence of tuning injection delay and EGR rate on the operational characteristics of a diesel engine. Tsutsumi et al. [17] studied the effects of mixing ratios and absolute quantities of di-methyl ether (DME) and methane blends on HCCI engine. The ignition timing and rapidity of combustion were investigated. Cool flame reaction behavior was deep analyzed on the basis of in-cylinder spectroscopic measurements. Kim et al. [18], investigate the performance and emissions of 20% biodiesel blended diesel fuel (B20) at various intake pressures and oxygen concentration levels to characterize the fuel for LTC application. Karikalan and Chandrasekaran [19] investigated the performance of Jatropha-Mineral Turpentine (JMT) and Jatropha-Wood Turpentine (JWT) blends were found close to diesel. JMT20 blend gives optimum results for brake thermal efficiency at 75% load.

In the present study, a system is designed in which the pressure and temperature inside the combustion chamber can be alter to optimize the ignition delay for the better performance of the system. Optical method is used to detect the three events i.e. start of injection, start and end of ignition. The influence of pressure and temperature of air inside the combustion chamber and various blends with diesel on the ignition delay have been investigated. Such as n-pentane and DEE were chosen as additives and blended separately with diesel in varying proportions such as 10%, 20%, 30% and 40% by volume. The ignition delay, while using n-pentane blends and DEE blends with different proportions compared with pure diesel at various high temperatures and pressures of air.

2. Methodology

2.1. Materials Used

DEE and n-pentane were taken as additives for blending with diesel. The blended fuel was prepared separately by blending n-pentane and DEE at different proportions, such as 10%, 20%, 30% and 40% by volume, with diesel. The various properties of diesel, n-pentane and DEE were given in Table 1.

Table 1. Properties of diesel, n-pentane and DEE.

S. No	Property	Diesel	n-Pentane	DEE
1	Molecular formula	$C_{14}H_{22}$	C_5H_{12}	$C_2H_5o\ C_2H_5$
2	Lower calorific value	43200kJ/kg	44945 kJ/kg	33892 kJ/kg
3	Latent heat of vaporisation	250 kJ/kg	375.5 kJ/kg	461.55 kJ/kg
4	Boiling point	250°C	36°C	34.6°C
5	Melting point	-30 to 18°C	-129°C	−116.3°C
6	Relative density	0.870.95g/cm^3	0.63(water=1)	0.7134 g/cm^3
7	Solubility in water	50-100mg/kg	None	69 g/L (20°C)
8	Vapour pressure	10 kPa at 38°C	53.3kPa at 18.5°C	70.92 k Pa at 25°C
9	Relative vapour density	4-6	2.5	5.946
10	Auto-ignition temperature	210°C	309°C	160°C

2.2. Experimental Set-Up

Combustion chamber for experimental set-up is a stainless steel cylindrical tank having a volume of 1.5 liters with the specifications given in Table 2. A pintle type nozzle is fitted on the head of the combustion chamber. An air compressor used to provide high-pressure air. The heating coil (1000 watt) is fitted inside the combustion chamber and connected to the secondary coil of a step-down transformer (output current 100 Ampere). Due to the heating effect of current, the heating coil is heated and temperature of the air is increased which could be measured by temperature indicator fitted on the combustion chamber. On one end of the tube, a light source is fitted. On the end of the second tube, a photosensor is attached to the chamber to detect the event of the start of ignition on the storage oscilloscope. For the measurement of fuel injected per stroke, a pipet is attached to the Bosch fuel injection pump. The layout of the experimental set-up is shown in Figure 1.
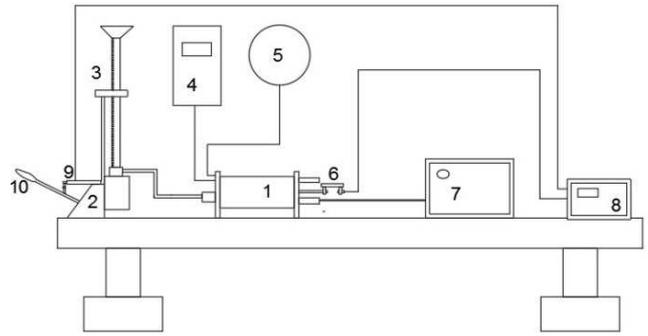
Table 2. *Specifications of Combustion Chamber.*

Parameters	Specifications
Dimensions	Diameter 9.3 cm, Height 22.3 cm, Thickness 8 mm
Material	Stainless Steel
Nozzle	Pintle Nozzle
Temperature Indicator	Digital Temperature Indicator (Cromel / alumel)
Sensor	Photo Sensor
Maximum Design Pressure	200 bar
Maximum Design Temperature	800°C

Figure 1. *Experimental layout. 1. Combustion chamber, 2. Fuel injection pump, 3. Fuel metering system, 4. Temperature indicator, 5. Pressure indicator, 6. Photo sensor, 7. Air compressor, 8. Oscilloscope, 9. NC switch, 10. Liver arm.*

2.3. Fuel Tested

In this work choose commercially available diesel fuel (Cetane no.55) as baseline fuel. This fuel is tested for the variation of ignition delay with the change in the temperature and pressure of hot air. Further, the diesel is blended with 10%, 20%, 30%, and 40% of n-Pentane and DEE. These blends are also checked for variation of ignition delay with a change in the temperature and pressure of hot air. Due to the blending, the density of the mixture differs from the baseline fuel (commercially available diesel) so the volume of the fuel injected per stroke is also different from that for the pure diesel. The density and volume for all blends were given in Table 3 and 4.

Table 3. *Test Conditions for n-Pentane Blends. (Density of n-Pentane=0.626 kg/l).*

Percentage of blending	Density of blend (kg/l)	Volume of blend injected per stroke (ml)	Temperature Range(k)
10	0.8336	0.10	583-663
20	0.8132	0.11	583-663
30	0.7898	0.11	583-663
40	0.7664	0.11	583-663

Table 4. *Test Conditions for DEE Blends. (Density of DEE=0.713 Kg/l).*

Percentage of blending	Density of blend (kg/l)	Volume of blend injected per stroke (ml)	Temperature Range(K)
10	0.8336	0.10	583-663
20	0.8132	0.11	583-663
30	0.7898	0.11	583-663
40	0.7664	0.11	583-663

2.4. Experimental Procedure

a. First of all, provide air into the combustion chamber at various high pressures by using Air Compressor and then an environment of air (maximum temperature 700K) is created hot inside the combustion chamber by using heating coil. When there is no spray burning inside the combustion chamber, there is no light intensity on the photo sensor so the output of the oscilloscope is zero.

b. As the lever is moved the fuel is injected into the chamber the NC switch triggers signal in the channel

(i) of the storage oscilloscope for the start of injection.

c. After the completion of ignition delay, the fuel ignites and a characteristic yellow flame is formed, which activates the sensor.

d. When the sensor detects the formation of the flame, after the completion of ignition delay, the oscilloscope shows the corresponding event.

e. Due to the ignition of spray, the light is emitted inside the chamber changes, due which the intensity of the light falling on the photo sensor, increases and hence the output of oscilloscope also changes to show starting of ignition.

f. Thus read three distinct events on the screen of oscilloscope viz. The start of injection, start of ignition and end of ignition.

g. The time difference between the event of injection and event of ignition gives the ignition delay of the tested fuel.

h. For all the fuel tested, the mass of the fuel injected per stroke is kept constant so that at a particular temperature the air-fuel ratio is constant for the comparison.

i. The process is repeated for the temperature range of 583-663 k. Thus a set of observation is completed for a diesel fuel.

j. The same procedure was then repeated to evaluate the ignition delay while using the blended fuels such as 10% n-pentane with diesel, 20% n-pentane with diesel, 30% n-pentane with diesel, 40% n-pentane with diesel, 10% DEE with diesel, 20% DEE with diesel, 30% DEE with diesel and 40% DEE with diesel. Evaluated data were compared and analyzed with that of the combustion chamber using pure diesel as fuel.

From the observed and recorded values, the ignition delays while using diesel and different blended fuels were reported in the form of graphs.

3. Results and Discussion

Study the characteristics of ignition delay; pure diesel used for generation of baseline characteristics. However, blends of diesel with n-Pentane and DEE are used. All samples were prepared after careful filtration and accurately measured blending. Most of the studies were conducted at elevated pressure; however, in this experiment, study at various pressures and temperatures were examined.

Ignition delay is decreased for all blends of n-pentane and DEE with diesel when increases the temperature (583-663K) and pressure (10-25bar) of air.

3.1. Ignition Delay for Pure Diesel

Basic studies in the constant volume bomb, in steady flow reactors, and in rapid compression machines have been used to study the auto-ignition characteristics of the fuel-air mixture under controlled conditions. In some of these studies the fuel and air are premixed; in some, fuel injection was used. Studies with fuel injection into constant temperature and pressure environment have shown that the temperature and pressure of the hot air are the most important parameters for a given fuel composition. Ignition delay data from these experiments have usually been correlated by Arrhenius equation given below [20]:

$$\tau_{id} = AP^{-n}\exp(E_A / RT) \qquad (1)$$

Where:

τ_{id} - Ignition Delay in a milli second.

P - Atmospheric pressure.

E_A - Apparent activation energy

R - Universal gas constant.

T - Temperature in Kelvin

A, n - Constants dependent on fuel

It is observed by J. D. Naber while investigated the effect of variation in natural gas composition on auto-ignition of natural gas under the diesel engine condition. They also reported that the reason for such phenomenon is the difficulty associated with the oxidation of alkyl group of lower hydrocarbons in natural gas at lower temperatures. The ignition delay also depends on upon the method of detection of the combustion process [20]. The same phenomenon is also observed by Wolfer and concluded that the alkyl group produced by the lower hydrocarbon does not oxidize easily and hence at lower temperatures ignition delay is longer. While as the temperature of the hot air inside the combustion chamber increases the alkyl group of the lower hydrocarbons present in the diesel fuel oxidizes as well as the higher hydrocarbons present in the diesel vaporizes easily hence causing relatively shorter ignition delay at a higher temperature. Wolfer [21] used Pressure Trace method for the measurement of ignition delay while we used optical method for the measurement of ignition delay.

Figure 2 shows the effect of various hot air temperatures and pressures on ignition delay of pure diesel. As increases the temperature of air in the combustion chamber (583K to 663K), the ignition delay was decreased and when we provide air in the combustion chamber at high pressure (10 to 25bar) the ignition delay was also decreased.
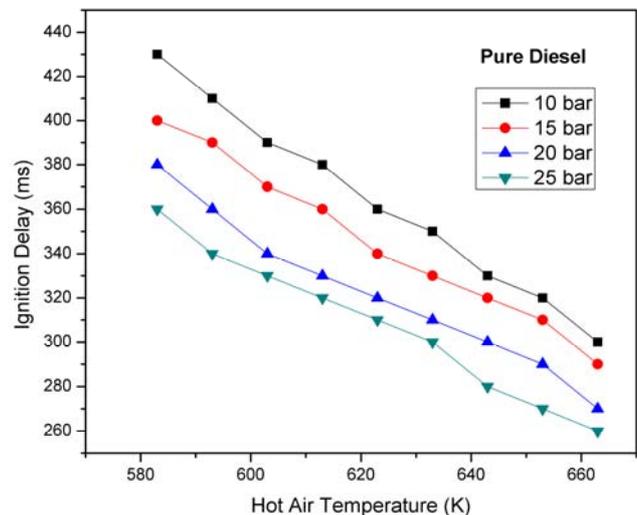

Figure 2. *Effects of various Hot Air Temperatures and Pressures on Ignition Delay for Pure Diesel.*

3.2. Effects of n-Pentane Blending on Ignition Delay

The effect of blending of pentane with diesel on ignition delay of fuel as the temperature of the air inside the combustion chamber was increased from 583 to 663K as shown in Figure 3, 10% pentane blends ignition delay at low temperatures is longer than pure diesel while in high-temperature operations, ignition delay is shorter than of pure diesel.
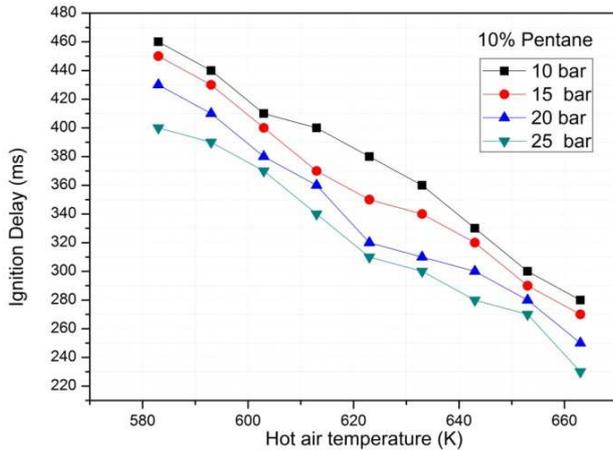
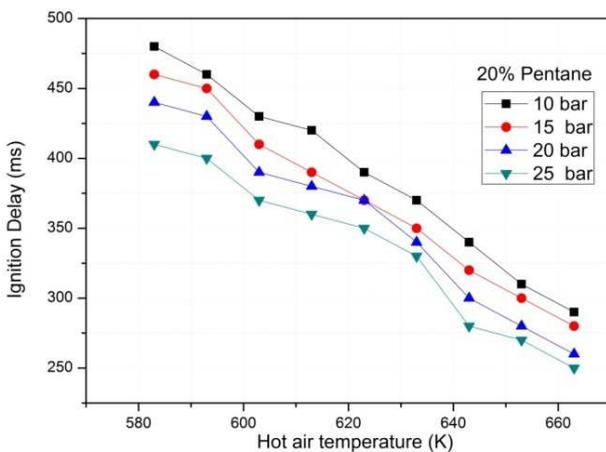*Figure 3. Effects of 10% n-pentane blends with diesel on ignition delay at various Hot Air Temperatures and Pressures.*

Due to the addition of pentane (n-paraffin), Cetane number decreases (which causes an increase in the ignition delay). The increase in the ignition delay at lower temperatures may be due to the fact that the small sized alkyl group of added pentane is not oxidized easily in comparison to the bigger size alkyl groups of diesel and thus causing higher ignition delay of the blend than pure diesel.

Figure 4. Effects of 20% n-pentane blends with diesel on ignition delay at various Hot Air Temperatures and Pressures.

However, at higher temperatures the effect of the presence of bigger molecule (high boiling point components) of alkyl group tends to reduce the ignition delay as the temperature was increased thus causing faster evaporation of bigger molecules in the process and temperature is also increased with increasing the pressure. A result is also reported by Naber [20] that on the addition of a lower hydrocarbon in the form of natural gas in an engine like environment at low temperatures causes an increase in its ignition delay or vice versa. As the concentration of pentane in the diesel is increased, this means to suppress auto-ignition characteristics of diesel at lower ignition temperature. The ignition delay of 20% n- pentane blends is higher than that of 10% n-pentane blends as shown in figure 4 for various hot air temperatures and pressures.
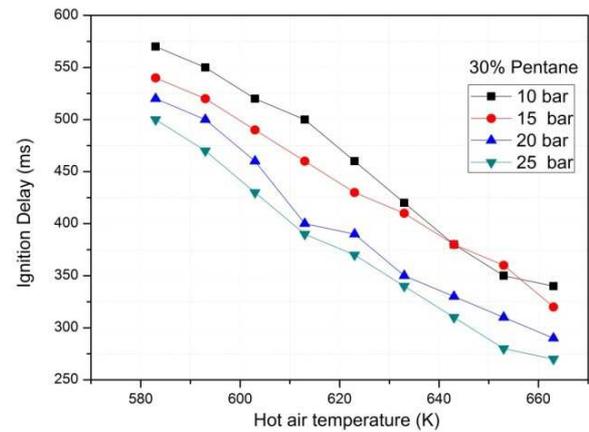

Figure 5. Effects of 30% n-pentane blends with diesel on ignition delay at various Hot Air Temperatures and Pressures.

It can also be observed from the Figure 2 that the ignition temperature for the pure diesel is 633 K while for 30% and 40% pentane blended diesel it is 653 K and 663 K respectively also, the ignition delay for 30% and 40% pentane blended fuel is much higher than that of pure diesel fuel. It may be due to the increased concentration of small sized alkyl group in the diesel fuel, which otherwise tends to have longer ignition delay than that of pure diesel. E. M. Sazhina et al., reported the similar trend of variation of ignition delay with hot air temperature [22].

Figure 5 and 7 shows the effect of 30% and 40% of n-Pentane Blends on ignition delay. The difference between the ignition delay for 10% and 20% pentane blend is small. As increasing the blend 30% and 40% of n-pentane the ignition delay is also increased. The variation of ignition delay of 30% and 40% pentane blends are much higher than 10% and 20% of pentane blends at low temperature, when increases the temperature the variation of ignition delay is decreased, it means the effect of the percentage of n-pentane is very small at high temperature (660K)
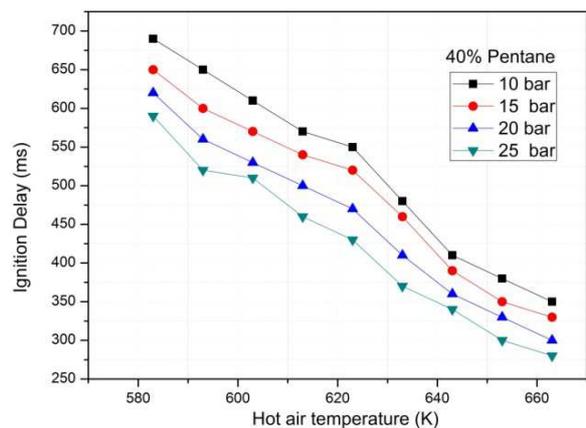

Figure 6. Effects of 40% n-pentane blends with diesel on ignition delay at various Hot Air Temperatures and Pressures.

3.3. Effect of DEE Blending on Ignition Delay

Diethyl Ether is considered to be a good combustion enhancer for diesel fuel. It is due to the fact that it is very

volatile compound. Boiling point and heat of vaporization at boiling point of DEE is 307.7 K and 6380cal/g-mol respectively, while the boiling point and heat of vaporization at the boiling point of diesel are 560K and 12240ca1/g-mol respectively.
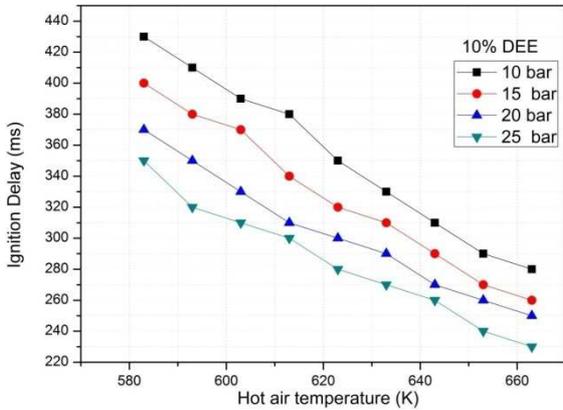

Figure 7. *Effects of 10% DEE blends with diesel on ignition delay at various Hot Air Temperatures and Pressures.*

This shows that the same amount of diesel requires nearly double amount of heat for its vaporization than DEE Hence, DEE is much more volatile than Diesel. DEE is used in the diesel vehicles as an additive to overcome the cold staring problem. But due to its low calorific value, its use in the engine is limited. Figure 7 shows the ignition delay variation with hot air temperature and various pressures for 10% DEE blended diesel fuel. It is very much clear from the Figure 2 and 7 that for almost every value of temperature the value of ignition delay for DEE blended diesel is lower than that of pure diesel that is why DEE is considered as good ignition enhancer for a diesel engine.

We anticipate that DEE will auto ignite first followed by auto-ignition of diesel. Because both the boiling point as well as the heat of vaporization of DEE are less than that of diesel. Chomaik et al. [6] stated that the excellent ignition quality of diethyl ether is attributed to the dominant role of peroxy radicals formed at low temperature. At low temperatures and under high pressures, the ignition process is controlled by the peroxide chemistry of DEE maintaining a radical branching.
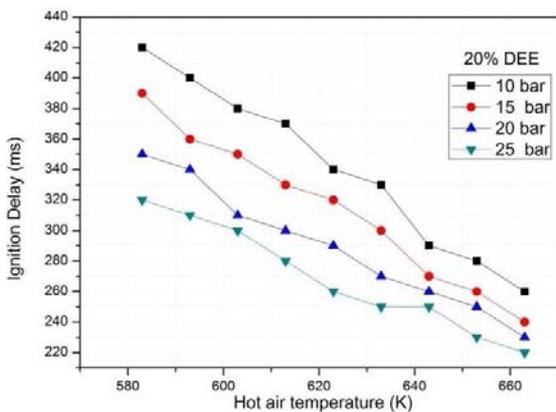

Figure 8. *Effects of 20% DEE blends with diesel on ignition delay at various Hot Air Temperatures and Pressures.*

Which result, a large difference in ignition delay of Diesel and DEE blend in low-temperature regions while at higher temperatures the difference is small because at higher temperatures.

It is clear from figure 7 and 8 the ignition delay of 20% DEE blends lower than that of 10% DEE blends but variation of ignition delay of 20% DEE blends is much higher than the 10% DEE blends.
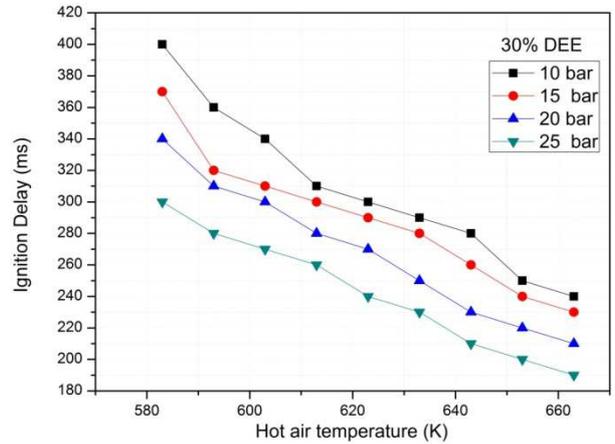

Figure 9. *Effects of 30% DEE blends with diesel on ignition delay at various Hot Air Temperatures and Pressures.*

It is clear from Figure 2 and 9 that for almost every value of temperature, the value of ignition delay for DEE blended diesel is lower than that of pure diesel. Figure 9 and 10 show that the variation of ignition delay of 30% and 40% DEE blends is much higher than the 10% and 20% DEE blends. In this case, the percentages of blends of DEE is increased the ignition delay is decreased while the result is opposite in the case of n-pentane blends.
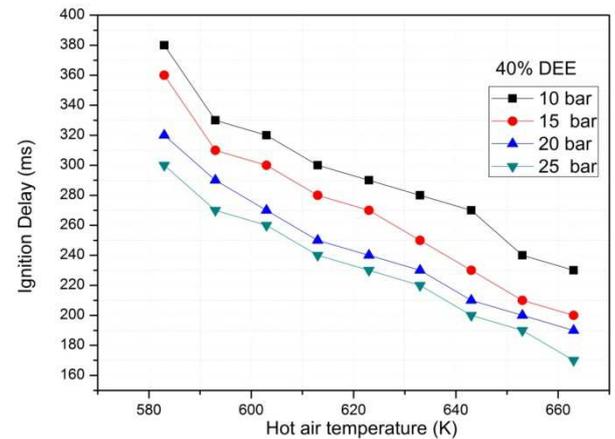

Figure 10. *Effects of 40% DEE blends with diesel on ignition delay at various Hot Air Temperatures and Pressures.*

4. Conclusions

The aim of this work is to study the effect of ignition delay by blending of n-Pentane and DEE in diesel at various temperatures and pressures of hot air in diesel combustion system. It is concluded that the temperature and pressure of

hot air inside the combustion chamber are the main factors for ignition delay. Ignition Delay of pure diesel, as well as all the eight blends studied here, decreases with increase in temperature and various pressures of hot air inside the combustion chamber. Ignition delay of 10% and 20%, n-pentane blends is higher than pure diesel at low temperature while at high temperatures it is nearly equal to the pure diesel. Ignition delay of 30% and 40% n-pentane mixtures is higher than pure diesel. For 10%, 20%, 30%, and 40% DEE blends the variation of ignition delay at high temperature is less. Ignition delay of all four blends of DEE is lower than pure diesel for the entire range of temperature.

Thus, it concludes that at lower temperatures, the addition of lower hydrocarbons can increase the ignition delay of pure diesel. DEE reduces the ignition delay of diesel fuel effectively at lower temperatures. The increase in the blending concentration of DEE also decreases the ignition delay accordingly. But at higher temperature the concentration have no significant effect on ignition delay.

References

[1] M. Nektaria, Experimental investigation of diesel ignition delay and soot formation in a high temperature pressure cell, Automot. Eng. Int. 110 (2002).

[2] C. Hasimoglu, M. Ciniviz, I. Ozsert, Y. Icingur, A. Parlak, M. S. Salman, Performance characteristics of a low heat rejection diesel engine operating with biodiesel, Renew. Energy. 33 (2008) 1709–1715. doi:10.1016/j.renene.2007.08.002.

[3] D. Agarwal, L. Kumar, A. Kumar, Performance evaluation of a vegetable oil fuelled compression ignition engine, Renew. Energy. 33 (2008) 1147–1156. doi:10.1016/j.renene.2007.06.017.

[4] D. Agarwal, S. Sinha, A. Kumar, Experimental investigation of control of NO x emissions in biodiesel-fueled compression ignition engine, Renew. Energy. 31 (2006) 2356–2369. doi:10.1016/j.renene.2005.12.003.

[5] D. N. Assanis, Z. S. Filipi, S. B. Fiveland, M. Syrimis, A Predictive Ignition Delay Correlation Under Steady-State and Transient Operation of a Direct Injection Diesel Engine, Trans. ASME. 125 (2017). doi:10.1115/1.1563238.

[6] J. Chomaik, V. Goloyitchev, N. Nordin, Computer evaluation of di Diesel engine fueled with neat DEE, SAE Pap. 2000-01-2518. (2000).

[7] J. Kim, J. Jang, K. Lee, Y. Lee, S. Oh, S. Lee, Combustion and emissions characteristics of Diesel and soybean biodiesel over wide ranges of intake pressure and oxygen concentration in a compression – ignition engine at a light-load condition, Fuel. 129 (2014) 11–19.

[8] K. Vijayaraj, A. P. Sathiyagnanam, Combustion characteristics of a DI diesel engine fuelled with blends of methyl ester of cotton seed oil, Int. J. Ambient Energy. 750 (2016). doi:10.1080/01430750.2015.1023841.

[9] L. Ü. Xingcai, H. Zhen, Z. Wugao, L. I. Degang, The influence of ethanol additives on the performance and combustion characteristics of diesel engines the influence of ethanol additives on the performance and combustion, Combust. Sci. Technol. ISSN. 2202 (2017). doi:10.1080/00102200490457510.

[10] Y. Lee, K. Y. Huh, Numerical study on spray and combustion characteristics of diesel and soy-based biodiesel in a CI engine, Numer. Study Spray Combust. Charact. Diesel Soy-Based Biodiesel a CI Engine Youngjae. 113 (2013) 537–545.

[11] N. R. Banapurmath, P. G. Tewaria, R. S. Hosmath, Performance and Emission Characteristics of a DI Compression Ignition Engine Operated on Honge, Neem and Sesame oil Methyl Esters., Renew. Energy. 33 (2008) 1982–1988.

[12] T. Balamurugan, R. Nalini, Experimental investigation on the effect of alkanes blending on performance, combustion and emission characteristics of four-stroke diesel engine, Int. J. Ambient Energy. 750 (2016). doi:10.1080/01430750.2014.915887.

[13] Y. D. Wang, An experimental investigation of the performance and gaseous exhaust emissions of a diesel engine using blends of a vegetable oil, Appl. Therm. 26 (2006) 1684–1691. doi:10.1016/j.applthermaleng.2005.11.013.

[14] Y. Kim, J. Lim, K. Min, A study of the dimethyl ether spray characteristics and ignition delay, A Study Dimethyl Ether Spray Charact. Ignition Delay. 8 (2007) 337–346. doi:10.1243/14680874JER02105.

[15] G. S. Jung, Y. H. Sung, B. C. Choi, M. T. Lim, Effects of mixture stratification on hcci combustion of dme in a rapid compression and expansion machine, Int. J. Automot. Technol. 10 (2009) 1–7. doi:10.1007/s12239.

[16] S. Y. Im, D. S. Choi, J. I. Ryu, Combustion and emission characteristics of bd20 reformed by ultrasonic energy for different injection delay and egr rate in a diesel engine, Int. J. …. 10 (2009) 131–139. doi:10.1007/s12239.

[17] Y. Tsutsumi, A. Iijima, K. Yoshida, H. Shoji, J. T. Lee, HCCI combustion characteristics during operation on DME and methane fuels, Int. J. Automot. Technol. 13 (2012) 293–300. doi:10.1007/s12239.

[18] J. Kim, J. Jang, K. Lee, Y. Lee, S. Lee, S. OH, Experimental investigation of B20 combustion and emissions under various intake conditions for low-temperature combustion, Int. J. …. 13 (2012) 293–300. doi:10.1007/s12239.

[19] L. Karikalan, M. Chandrasekaran, Influence of turpentine addition in jatropha biodiesel on ci engine performance, combustion and exhaust emissions, Int. J. …. 13 (2012) 293–300. doi:10.1007/s12239.

[20] D. L. S. J. D. Naber, Effect of natural gas composition on ignition delay diesel condition, 25th international symposium on combustion, in: UC Irvine, Irvine CA July 31-Aug 5, 1994.

[21] H. H. Wolfer, Ignition Lag in Diesel Engines, VDI-Forschungsheft 392, 1938; translated by Royal Aircraft Establishment, (1959) Farnborough Library No.358, UDC 621-436.047.

[22] E. M. Sazhina, S. Sazhin, M. R. Heikal, C. J. Marboney, Shell auto ignition model: Application to gasoline and diesel fuel, Fuel. 78 (1999) 389–401.