Development of Empirical Correlations for Ignition Delay in a Single Cylinder Engine Fueled with Diesel/Biodiesel Blends

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***Abstract*— Quantifying ignition delay for fuel-air mixture in compression ignition engines is very challenging as it depends on many factors such as: fuel properties, injection temperature and pressure, level of swirl and turbulence, and the mixture forming method. This paper presents an approach to develop empirical correlations for ignition delay in a single cylinder engine powered by diesel/biodiesel blends. The engine used here is retrofitted from a cetane testing CFR-F5 engine. The fuels tested in this study include commercial diesel (B0), pure biodiesel (B100) and blends of 20%, 40%, and 60% of the biodiesel in biodiesel-diesel mixtures (B20, B40, B60 and B100, respectively). The blends are injected into the cylinder under different physical conditions (temperature and pressure). Ignition delay time is experimentally investigated and used to develop empirical correlations for ignition delay.**

Keywords*— *ignition delay, diesel, biodiesel, CFR-F5 engine.

I. Introduction

In recent years, Vietnam has focused on studying the feasibility of production and use of biodiesels for diesel engines. Biodiesels have been known as cleaner fuels compared to the mineral diesel and other alternative fuels [1, 2, 3]. Utilising biodiesels also helps to decrease the dependency of fossil fuels which are known to be depleted soon [1].

Ignition delay in internal combustion engines is one amongst important parameters, it directly impacts the fuel-air premixing level, heat release rate noise and pollutant formation. Work has been done to measure ignition delay for diesel and biodiesel in general and empirical correlations for ignition delay have been developed worldwide [4,5].

R.P. Rodríguez [6] experimentally tested ignition delay of biodiesel (biodiesel derived from canola oil, crude palm oil) and diesel in a Volvo turbocharged diesel engine. The result shows that ignition delay of diesel is slightly longer than that of biodiesel and this is attributed to higher cetane number of biodesel. Addopting the experimental outcome, empirical correlations have been developed to determine iginition delay time (τ) for three fuels: diesel (see equation 1), biodiesel derived from canola oil, (see equation 2) and biodiesel derived from crude palm oil, respectively, (see equation 3):

$$\tau = \frac{\exp\left(\frac{950}{T}\right)}{p^{0.24}\phi^{0.04}} \tag{1}$$

$$\tau = \frac{\exp\left(\frac{1130}{T}\right)}{p^{0.34}\phi^{0.02}} \tag{2}$$

$$\tau = \frac{\exp\left(\frac{1145}{T}\right)}{p^{0.34}\phi^{0.06}} \tag{3}$$

EL-Kasaby and Medhat [7] investigated combustion characteristics, engine performance and exhaust emission levels for an engine when using diesel/biodiesel blends: B0, B10, B20, B30, B50 (biodiesel derived from Jatropha). The experiment was conducted in a single-cylinder variable compression-ratio engine. The authors have also investigated the effect of blending ratios on cylinder pressure and ignition delay. In addition, links between ignition delay time (τ) and injection conditions (pressure (p) and temperature (T)) are established for B0, B10, B20, B30, and B50 shown in equation (4) to (8), respectively.

$$\tau_{B0} = 26.06p^{-1.21}\phi^{-1.13}\exp\left(\frac{1038}{T}\right) \tag{4}$$

$$\tau_{B10} = 79.51p^{-1.45}\phi^{-0.81}\exp\left(\frac{1028}{T}\right) \tag{5}$$

$$\tau_{B20} = 74.32p^{-1.32}\phi^{-1.39}\exp\left(\frac{1022}{T}\right) \tag{6}$$

$$\tau_{B30} = 1{,}55.10^{3}p^{-2.12}\phi^{-1.01}\exp\left(\frac{1015.2}{T}\right) \tag{7}$$

$$\tau_{B50} = 3.461.10^{3}p^{-2.27}\phi^{-1.06}\exp\left(\frac{1003}{T}\right) \tag{8}$$

where E_a is the global activation energy estimated for each blend using the following relation E_a = 618840/(CN + 25), [7].

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Adopting the above mentioned approach in which ignition delay is a dependent parameter of injection temperature and pressure, equivalent ratio and activation energy, the article aims to develop correlations for ignition delays of an engine fulled with diesel/biodiesel blends. The biodiesel is derived from crude palm oil in Vietnam.

II. Experimental setup

In this study, a single-cylinder CFR-F5 diesel engine is used to investigate combustion characteristics and ignition delay. The engine was operated under a wide range of compression ratios, injection timing, and air-fuel equivalent ratio. The conditions tested here are two compression ratios (CR): 15 and 17, 7 different injection timings (IT) (8, 10, 12, 14, 16, 18, and 20 degree of crank angle before TDC, respectively); and four fuel flow rates (10.04, 11.30, 13.04, and 15.52 ml/m respectively). Engine specifications, main technical parameters, operating procedures and the method to measure ignition delay in the CFR engine are previously reported in detailed in [8]. The engine setup is schematically shown in Fig. 1. This is a cetane testing engine and further equipped to include combustion chamber pressure sensor and encoder. The experiments were conducted at the Gasoline-Oil-Gas Testing Laboratory of Quality Assistance and Testing Center 1, Viet Nam (Quatest 1).

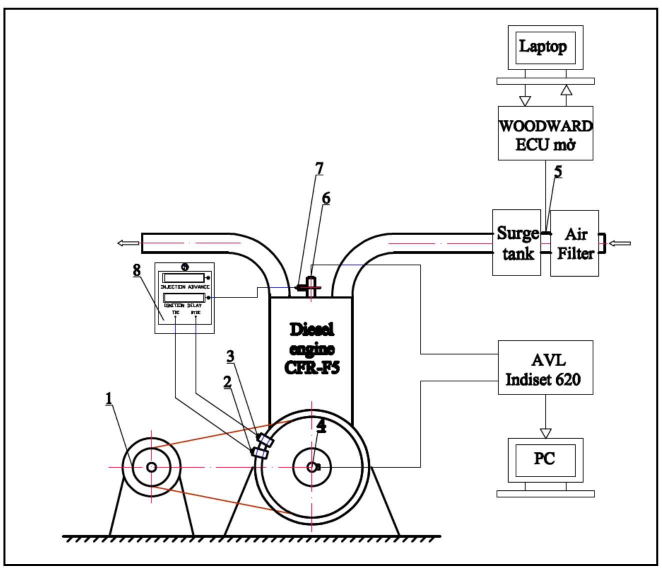

Fig. 1. Experimental set up

1-Electric motors; 2-Sensor position of TDC; 3- Sensor position of the 13 Crank angle deg (bTDC) ; 4-Encoder (E50S8-3600-3-T-24); 5-Air flow sensor; 6-Pressure sensor (AVL QC33C); 7- Combustion Pickup sensor on CFR-F5 engine; 8-Delay meter.

Piezoelectric of pressure sensor AVL QC33C (water-cooled) (6) measuring from 0 to 200 bar was used for tracing definitely the variation pressure in the cylinder. The cylinder pressure sensor is equipped additionally along to the combustion pickup sensor (7). Cylinder pressure sensor (6) and encoder E50S8 (4) were connected to the Data Acquisition System/AVL Indiset 620. Air intake was measured using a flow sensor and controlled by an ECU [9].

Biodiesel is produced from waste residue from refining crude palm oil into cooking oil (according to Process Technology of Vietnam Institute of Industrial Chemistry) and is the product of the project [8, 10]; Diesel is a commercial diesel product (0.05% S) on the market. B0 (pure diesel), B20, B40, B60 and B100 (pure biodiesel) were used in this study which correspond to 0, 20, 40, 60 and 100% of biodiesel volume fractions in biodiesel-diesel mixtures, respectively. Properties of diesel and biodiesel fuels are given in Table I.

TABLE I. PROPERTIES OF THE DIESEL AND BIODIESEL USED IN THIS STUDY

Fuels	Diesel	Biodiesel
Averaged H/C ratio (moles)	1.788	1.902
Lower heating value (MJ kg^{-1})	42.92	37.39
Molecular weight (g mol^{-1})	191.8	295.31
Cetane number	52.4	66.9
Density (at 15 °C) (g ml^{-3})	0.8216	0.8561
Viscosity (at 40 °C) (mm2 s^{-1})	3.14	4.6
Acid Number (mg KOH g^{-1})	0.023	0.06
Flash Point (°C)	68.50	183.5
Cloud Point (°C)	3	18

The C/H/O fractions of these fuels were determined separately by a high performance liquid chromatography technique (HPLC). C/H/O fractions of B0 and B100 are experimentally measured and shown in Table II.

TABLE II. PROPERTIES OF THE DIESEL AND BIODIESEL USED IN THIS STUDY

Fuel	C [%)	H [%)	O [%)	Others [%)
B0	86.93	12.96	0.07	0.04
B100	76.96	12.17	10.83	0.04

III. Results And Discussion

A. Cylinder pressure.

Fig. 2 shows the cylinder pressure versus crank angle at CR=17, IT=18 bTDC, ϕ=0.76 for diesel, biodiesel, and their blends. The motoring trace (in red and continuous colour) is also included in Fig. 2 to analyse the pressure trace characteristics. The Fig. shows that the pressure traces obtained by B10, B20, B40, B60 and B100 starts separating from the motoring trace and reach maximum values earlier than those of B0. This is mainly attributed to the higher cetance number of biodiesel compraded to diesel, as shown in Table III.

TABLE III. PROPERTIES OF THE DIESEL AND BIODIESEL USED IN THIS STUDY

Diesel/biodiesel blends	p_{cylmax} (bar)	Comparing with B0, (%)	Position of p_{cylmax} (bTDC)
B0	53.48		3.5
B20	51.54	-3.64	3.5
B40	50.64	-5.30	3.0
B60	49.44	-7.54	2.5
B100	48.43	-9.44	2

Table III reports values of maximum cylinder pressure and position in the cycle where the pressure reaches the values. It is clear that an increase in blending ratio decreases the P_{cyl_max} and the position that the pressure reaches at the maximum values is closer to TDC when increasing the blending ratio.

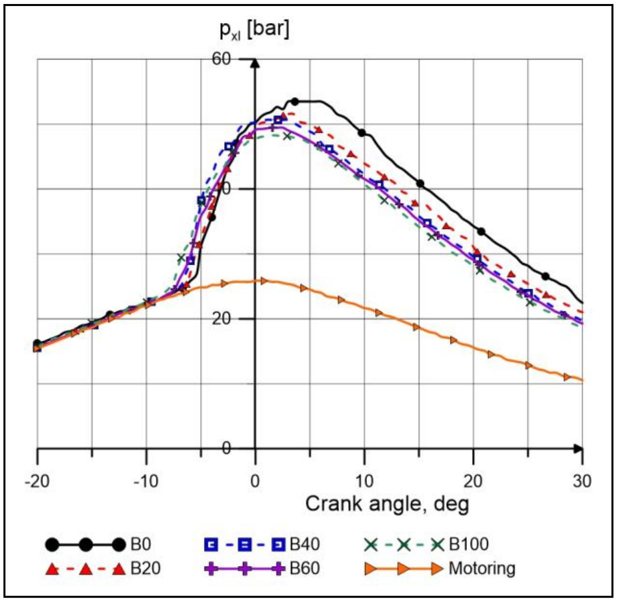

Fig. 2. Cylinder pressure traces of diesel/biodiesel blends at CR=17, IT=18 bTDC, ϕ=0.76

Table IV reports cylinder pressure for B60 at CR=17, IT=18 bTDC, and the equivalence ratios vary between 0.56 and 0.86. The Table shows that equivalent ratio has a significant influence on the maximum value of cylinder pressure. As shown in the Table, a maximum variation of 10.86% is observed for B60 at ϕ=0.56 compared to that at ϕ=0.86.The variation may be distributed to the changing in oxygen content in the air-fuel mixture which has critical effects on the ignition delay and this in turn impacts the fuel-air premixing fraction.

TABLE IV. THE PEAK OF CYLINDER PRESSURE VARIATION WITH THE EQUIVALENCE RATIOS

ϕ	$P_{xl\ max}$ (bar)	Comparing with ϕ =0.86 (%)	Crank angle (bTDC)
0.86	51.66		2.5
0.72	49.55	-4.28	3.0
0.63	47.69	-7.67	4.5
0.56	46.14	-10.68	6.0

Table V displays the maximum cylinder pressure at ϕ=0.76, and different CR and IT for B60. The Table shows that CR affects slightly maximum value of cylinder pressure. Comparing cylinder pressure obtained at CR=17 and CR=15, a biggest variation of 9% was observed corresponding with IT=8. It is also shown that IT has influenced significantly maximum cylinder pressure. Injecting fuel earlier results in a longer ignition delay and this increases the fraction of premixing and as such the rate of pressure rise.

TABLE V. THE PEAK OF CYLINDER PRESSURE VARIATION WITH IT AND CR.

IT (degree bTDC)	$p_{xl\ max}$, (bar)		Comparing with CR= 15 (%)	Comparing with IT=8 (%) (CR=17)	Crank angle (degree bTDC) (CR=17)
	CR= 15	*CR= 17*			
-8	37.73	41.12	9.00		10.5
-10	40.48	43.09	6.46	4.79	9.5
-12	41.98	45.18	7.60	9.85	8.0
-14	43.25	46.94	8.51	14.13	7.0
-16	46.01	47.88	4.04	16.41	6.0
-18	48.33	49.44	2.29	20.23	3.0
-20	49.81	50.99	2.36	23.97	2.5

B. Ignition Delay

Table VI reports ignition delay variation at CR=17, IT=18 bTDC, and ϕ=0.76 for diesel/biodiesel blends. The result shows that biodiesel has shorter ignition delay time than that of traditional diesel. The delay in ignition decreases as the biodisel perentage increases in the blends. The diference is due to higher cetane number of biodiesel with respect to that of B0.

TABLE VI. IGNITION DELAY VARIATION FOR DIESEL/BIODIESEL BLENDS

Diesel/biodiesel blends	The Ignition Delay		
	Crank angle deg	Real time, (µs)	Comparing with B0 (%)
B0	10.8	2000.00	0
B20	10.7	1981.48	-0.92
B40	9.8	1814.81	-9.25
B60	9.5	1759.25	-12.03
B100	9.4	1740.74	-12.96

Table VII reports ignition delay variation with equivalence ratios of 0.58, 0.66, 0.76 and 0.90 at CR=17, IT=18 bTDC for B60. The equivalence ratio of the blends has affected slightly ignition delay. Comparison of ignition delay amongst equivalence ratios shows a biggest change of 9.67%. The rich mixture has shorter ignition delay than that of the lean mixture and this can be explained that rich mixture can have an auto-ignition centre earlier than that of lean mixture.

TABLE VII. IGNITION DELAY VARIATION FOR THE EQUIVALENCE RATIOS

ϕ	The Ignition Delay		
	Crank angle deg	Real time, (µs)	Comparing with ϕ =0,86 (%)
0,86	9.3	1722.22	
0,72	9.5	1759.25	2.15
0,63	10.1	1870.37	8.60
0,56	10.2	1888.88	9.67

Table VIII reports ignition delay variation at varying IT and CR for B60. The Table shows that CR affects significantly ignition delay. A biggest change of 26.74% at IT=16 (Table VIII) is optained when CR=15. The CR became bigger leading to incresing pressure at injecting timing and as such ignition delay is shorter. IT had significant influences on ignition delay. Comparing ignition delay for for varying IT and the value for CR=17 at IT=8 DCA having biggest change by 27.71% and IT= 20 DCA. Because of injecting fuel too early in Chamber while ressure and temperate in cylinder is still low, resulted increasing ignition delay.

TABLE VIII. THE IGNITION DELAY VARIATION WITH IT AND CR

IT	Ignition delay		Comparing with CR= 15 [%)	Comparing with IT=8 (%) (CR=17)
	CR= 15	CR= 17		
-8	9.9	8.3	19.27	-
-10	9.9	8.3	19.27	0
-12	10.1	8.3	21.68	0
-14	10.2	8.4	21.42	1.20
-16	10.9	8.6	26.74	3.61
-18	11.9	8.5	25.26	14.45
-20	12.5	10.6	17.92	27.71

C. *Developing empirical correlations for ignition delay of diesel/biodiesel blends*

Ignition delay in IC engines has been traditionally expressed as using the Arrhenius correlation in which ignition delay is a dependent of temperature, pressure and activation energy as shown in equation (9), [7, 11]. In this study, the constants are estimated using the multiple linear regression (MLR) method [12].

$$\tau = Ap^{\alpha}\phi^{\beta}\exp\left(\frac{E_a}{RT}\right) \tag{9}$$

where, R=8314 (J/mol.K) is universal gas constant; E_a is global activation energy for the combustion process (J/mol); ϕ is fuel-air equivalence ratio; T (K) and p (bar) are temperature and pressure, respectively; and τ is ignition delay (µs).

First of all, in order to develop the empirical correlations using the above mentioned MLR approach, injection pressure and temperature in under varying conditions of equivalence ratios, blends and injection timing investigated here must be calculated. According to the injection timing selected for each operating condition, the injection pressure can be experimentally measured and then. The injection temperature is calculated using an ideal gas correllation as following:

$$\mathrm{T} = \frac{\mathrm{p.V}}{\mathrm{m.R_{hhnen}}};\ \mathrm{R_{hhnen}} = \left(\frac{\mathrm{V_c}}{\mathrm{V_a}} + \frac{\mathrm{V_h}}{\mathrm{V_a}}.\mathrm{x}(\varphi)\right)\mathrm{R_{spcs}} + \left(\frac{(\mathrm{V_a} - (\mathrm{V_c} + \mathrm{V_h}.\mathrm{x}(\varphi))}{\mathrm{V_a}}\right).\mathrm{R_{kk}} \tag{10}$$

$$\mathrm{x}(\varphi) = \mathrm{R}[(1-\cos\varphi) + \frac{1}{\lambda}(1-\sqrt{1-\lambda^2\sin^2\varphi})]$$

where, x (φ) is the displacement of piston in DCA; R_{kk} = 287.3(J/kg.K) is the gas constant of air; R_{spcs} = 286 (J/ kg.K) is the gas constant of combustion products (J/kg.K); V_h is the di s placement volume of the cylinder (m^3); V_a is the total volum e of the cylinder (m^3).

Experimental values of τ, T, p, and ϕ for B0 is presented in Table IX

TABLE IX. EXPERIMENTAL VALUES OF τ, T, P, AND ϕ FOR B0

CR	Measurement parameters	IT=8	IT=10	IT=12	IT=14	IT=16	IT=18	IT=20
15	τ(µs)	2074.07	2074.07	2074.07	2129.63	2277.78	2314.81	2444.44
	p(bar)	21.30	20.26	19.03	18.22	16.88	15.71	14.66
	ϕ	0.92	0.92	0.92	0.92	0.92	0.92	0.92
	T(K)	994.66	986.47	982.98	975.46	964.57	959.45	949.45
	τ(µs)	2074.07	-	-	2148.15	2314.81	2425.93	2500.00
	p(bar)	21.29	-	-	17.84	16.85	15.82	14.77
	ϕ	0.77	0.77	0.77	0.77	0.77	0.77	0.77
	T(K)	991.85	-	-	970.42	930.70	954.26	947.92
	τ(µs)	2092.59	-	-	2166.67	2314.81	2462.96	2555.56
	p(bar)	21.17	-	-	17.83	16.83	15.60	14.47
	ϕ	0.667	0.667	0.667	0.667	0.667	0.667	0.667
	T (K)	989.98	-	-	966.60	960.16	949.97	941.52
	τ(µs)	2092.59	-	-	2185.19	2296.30	2500.00	2666.67
	p(bar)	21.27	-	-	17.83	16.69	15.43	14.30
	ϕ	0.593	0.593	0.593	0.593	0.593	0.593	0.593
	T(K)	982.00	-	-	963.46	958.50	945.03	928.56
17	τ(µs)	1592.59	1592.59	1592.59	1611.11	1703.70	2000.00	2166.67
	p(bar)	23.75	22.62	21.15	19.59	18.48	17.07	15.86
	ϕ	0.92	0.92	0.92	0.92	0.92	0.92	0.92
	T(K)	1003.74	988.26	984.49	977.62	967.88	965.50	953.20
	τ(µs)	1629.63	1629.63	1629.63	1703.70	1796.30	1981.48	2166.67
	p(bar)	24.12	22.49	21.13	19.90	18.53	17.07	15.87
	ϕ	0.77	0.77	0.77	0.77	0.77	0.77	0.77
	T(K)	993.98	982.49	978.92	971.20	966.27	959.26	951.51
	τ(µs)	1740.74	1722.22	1740.74	1851.85	1944.44	2055.56	2185.19
	p(bar)	23.61	22.59	21.13	19.73	18.41	17.02	15.73
	ϕ	0.667	0.667	0.667	0.667	0.667	0.667	0.667
	T(K)	990.30	980.30	976.43	968.55	965.68	957.26	949.04
	τ(µs)	1777.78	1777.78	1814.81	1888.89	1981.48	2092.59	2222.22
	p(bar)	23.54	22.43	21.19	19.71	18.46	17.02	15.68
	ϕ	0.593	0.593	0.593	0.593	0.593	0.593	0.593
	T(K)	988.39	978.74	974.80	965.54	960.05	956.13	942.40

In this study, the global activation energy is identified using Hardenberg and Hase's correlation [13] shown in equation (11).

$$E_a = \frac{681840}{CN + 25} \tag{11}$$

Cetane number of the diesel/biodiesel blends has been experimentally measured and reported earlier in ref. [8]. From the outcomes, we can calculate activation energy (E_a) for the fuels B0, B20, B40, B60, B80, B100 and these values are shown in Table X.

TABLE X. ACTIVATION ENERGY FOR DIESEL/BIODIESEL BLENDS

Diesel/biodiesel blends	CN, [8]	Ea	$B = \frac{E_a}{R}$ (R=8.314 kJ/mol.K)
B0	52.4	7995.34	961.67
B20	54.4	7793.95	937.44
B40	57.4	7510.19	903.31
B60	62.4	7080.54	851.64
B100	66.9	6733.84	809.94

Applying natural log for both sides of Equation (9) then substituting $B = \frac{E_a}{R}$, we have:

$$\ln(\tau) - \left(\frac{B}{T}\right) = \ln(A) + \alpha \ln(p) + \beta \ln(\phi) \quad (12)$$

where: A is blocking coefficient; α, β are the regression coefficients; values T, p, τ, and ϕ were experimetnally determined as mentioned, B is determined from Table X and E_a, the activation energy (J/mol), shown in Table X is given in [12]:

$$b = \begin{bmatrix} \ln(A) \\ \alpha \\ \beta \\ \end{bmatrix}; \quad X = \begin{bmatrix} 1 & \ln(p_1) & \ln(\phi_1) \\ 1 & \ln(p_2) & \ln(\phi_2) \\ 1 & \ln(p_3) & \ln(\phi_3) \\ 1 & \ln(p_i) & \ln(\phi_i) \end{bmatrix}; \quad Y = \begin{bmatrix} \ln(\tau_1) - \frac{B}{T_1} \\ \ln(\tau_2) - \frac{B}{T_2} \\ \ln(\tau_3) - \frac{B}{T_3} \\ \ln(\tau_i) - \frac{B}{T_i} \end{bmatrix} \quad (13)$$

Applying Least Squares Method:

$$b = (X'X)^{-1}.X'Y \quad (14)$$

For fuel B0:

After subtituting the empirical values p, ϕ, T, τ and B of fuel B0 which are from experimental data into equation (14), we can determine the regression coefficients:

$$b = \begin{bmatrix} \ln(A) \\ \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} -5.196 \\ -0.701 \\ -0.104 \end{bmatrix}; \; A=0.00553$$

Subtituting the regression coefficients into the Equation (9), we have an empirical formula of the predicted ignition delay for B0 as follows:

$$\tau_{B0} = 0.00553 p^{-0.701} \phi^{-0.104} \exp\left(\frac{7995.349}{RT}\right) \quad (15)$$

Similarly, For B20:

$$\tau_{B20} = 0.00535 p^{-0.689} \phi^{-0.113} \exp\left(\frac{7793.955}{RT}\right) \quad (16)$$

For B40:

$$\tau_{B40} = 0.00577 p^{-0.724} \phi^{-0.171} \exp\left(\frac{7510.194}{RT}\right) \quad (17)$$

For B60:

$$\tau_{B60} = 0.00609 p^{-0.727} \phi^{-0.164} \exp\left(\frac{7080.549}{RT}\right) \quad (18)$$

For B100:

$$\tau_{B100} = 0.00497 p^{-0.664} \phi^{-0.194} \exp\left(\frac{6733.841}{RT}\right) \quad (19)$$

Thus, based on a set of experimental data (τ, T, p, and ϕ) used on the CFR-F5 diesel engine, empirical corelations for ignition delay have been established in this work.

IV. Conclusion

This article presents an approach to develop empirical correlations for ignition delay of diesel/biodiesel blends in a diesel engine. This work also investigates the variation of cylinder pressure and ignition delay for the diesel/biodiesel blends through a range of variable parameters such as CR, IT, equivalence ratios, and blending ratio.

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