Experimental and Theoretical Study for the Effect of Diesel Fuel Quality Produced in Iraq on Ignition Delay Period

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ABSTRACT

An experimental and theoretical investigation to evaluate the effect of diesel fuel produced in Iraq and blended with ethanol of four stroke single cylinder direct injection diesel engine was conducted. This study focused on the development of an empirical ignition delay equations based on engine experimental data and to analyse the dependency of ignition delay on equivalence ratio, engine brake power fraction, effect of engine speed, and cetane number .The experimental measurements was performed at compression ratio of 22:1 at engine speed ranging from 1100 to 2600 rpm with an increment of 500 rpm, and engine torque ranging from 2 to 10 N.m with an increment of 2 N.m. The experimental data from engine during test have been saved on the computerized program (ECA 100, VDAS) connected to the unit .The results show that the empirical equations of delay period are resulted as a function of ignition pressure, ignition temperature, fraction brake power with better agreement with the experimental data than an empirical equations of delay period which are resulted as a function of ignition pressure, ignition temperature, equivalence for all fuels at all speeds. E0 Basra has the highest value of the cylinder pressure with low speed at variable torque. E10 blended fuel has recorded the lowest value of ignition delay period in all speeds. The experiments also show that the ignition delay period has been found to be decreased with increase of cetane number, ignition pressure, ignition temperature, equivalence ratio, and the fraction brake power.

Keywords: Diesel engine, Ignition Delay, Cetane Number, Diesel Fuel, Ethanol.

INTRODUCTION

Ignition delay period measured in diesel engines is important parameters. Ignition delay period (IDP) in diesel engines have been defined in different ways depending on the criteria used to determine the beginning of combustion. There are two most common ways used to define ignition delay period such as pressure rise and illumination delay [1].Time delay period is critical between the commencement of fuel injection into the engine and fuel ignition occurring. The duration of this period called the ignition delay period. Ignition delay period can influence on brake power from engine, thermal efficiency, and engine maintenance [2].The ignition delay period can be divided into two parts such as the physical delay and chemical delay period. The Physical delay is the interval in demand for fuel atomization, evaporation and mixing with air [3].The chemical delay period is the pre-combustion reaction of air, fuel and residual gas mishmash which lead to auto ignition, chemical delay in more efficacious for the interval of the ignition delay period [4]. **Selvakumar, et al [5]**, studied theoretically the prediction of ignition delay (ID) using cetane number, compression ratio, engine speed, engine load, single cylinder, four stroke air cooled DI engi

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e. The results showed that the IDP of biodiesel decreased due to high cetane number. Also, these results showed that the ignition delay decreases with the increase in brake power. **Chen, et al [6],** studied the combustion of rapeseed biodiesel, diesel, and ethanol blend using a SC, diesel engine .They found that at small load peak combustion pressure is low and at the middle and large loads they increase with blending of ethanol. **Zhang, et al [7],** investigated experimentally ignition delay period by using dimethyl ether (DME) as an alternative fuel using direct-injection diesel engine. The results show that the predictions of ignition delay are in good agreement with experiment results. **Sahoo and Das [8],** analyzed the combustion of used Jatropha ,Karanla, and Polanga based biodiesel as fuel in a diesel engine .The results showed that lower IDP and higher peak cylinder pressure for all biodiesel when compared with diesel. **David, [9],** studied engine ignition delay for biodiesel prepared from modified feed stocks .The results indicated that of all the blends were similar to those of diesel fuel with lower ignition delay.

The objectives of this work are :

1. To develop an ignition delay empirical equations as a function of ignition pressure, ignition temperature, and equivalence ratio, and to develop an ignition delay empirical equations as a function of ignition pressure, ignition temperature, and engine brake power fraction.
2. To investigate the effect of engine speed and cetane number on the ignition delay.
3. To examine **Stringer [10], Wolfer [11],** present work as a function of (p_{ign}, T_{ign}, Φ), and as a function of (p_{ign}, T_{ign}, bp_f) empirical equations against experimental data

The Test engine

The experiments were carried out in a single cylinder four stroke variable speed air cooled direct injection diesel engine type (**TD 212**) made in UK. The basic data of the engine used are given in table (1). The engine was coupled with D.C electric dynamometer. A Kistler piezoelectric transducer (Type 6056A) has been mounted in the cylinder head to measure the cylinder pressure. The obtained cylinder pressure values and volume of a cylinder with a crank angle are taken from by the signal that comes from piezoelectric pressure sensor, and then fed to **ECA100** device Thermocouples were used to measure the exhaust temperature. Test engine and the schematic diagram of the engine test are shown in figure (1) and figure (2) respectively.

Table (1): Technical specifications the engine [12]

Item	Specification
Engine manufacture	TQ TD 212,UK
Fuel type	Diesel
Oil Type	Multi grade SAE 5W-40
Cylinder bore	69 mm
Stroke	62mm
Connecting rod length	104 mm
Engine capacity	232 cm^3
Compression ratio	22:1
No of strokes	4
No of cylinder	1
Maximum power	3.5 kW at 3600 rev/min
Maximum torque	16 N.m. at 3600 rev/min

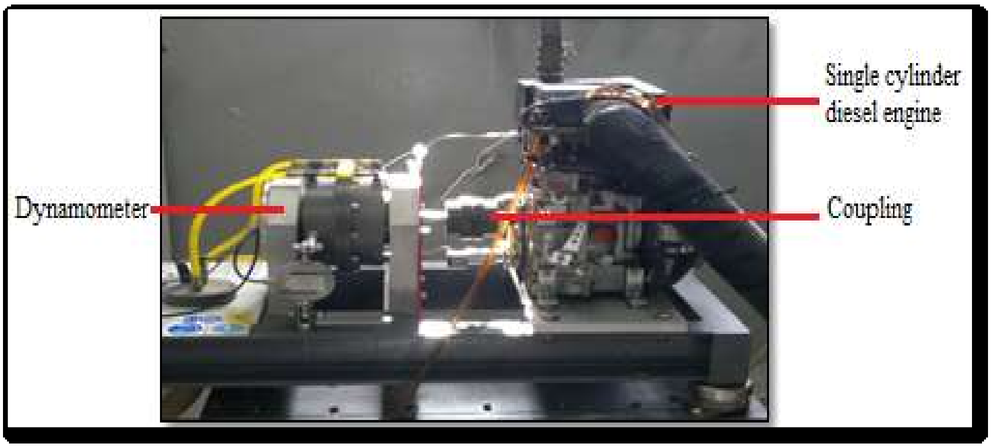

Figure (1): Test diesel engine.

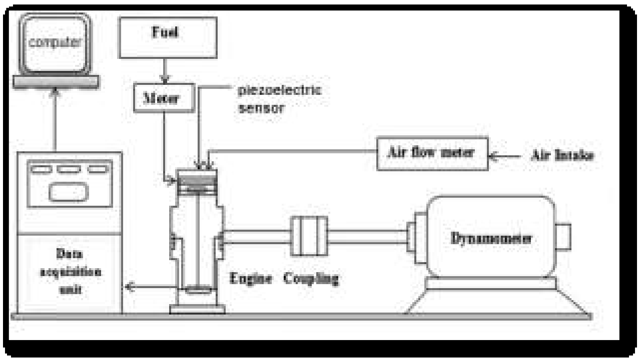

Figure (2): Schematic diagram of the test diesel engine.

Type of Tested Fuel

The use of ethanol as a blend with diesel fuel is increasing in recent years. It can be used as a fuel in a number of different ways as a blend with diesel (8% and 10%) and as a fuel in our experiments blended with Basra diesel fuel $C_{14}H_{30}$. The reason for using the Basra fuel blended is the higher value of cetane number of this fuel. The test fuels are denoted as E0 Beji (100 % diesel Beji fuel), E0 Basra (100% diesel Basra fuel), E0 Daura (100% diesel Daura fuel),E8 blended (8% ethanol and 92 % diesel Basra fuel), and E10 (10% ethanol and 90 % diesel Basra fuel), these samples were chemically analyzed before used in testing at midland refineries company AL- Daura - Quality Control and Researches Department in Baghdad. Results analyze of above five types of fuel which are in table 2. Figure (3) shows the pure diesel and the ethanol blends samples.

Table (2) Fuel Properties [13]

Lab . Insp. Data	E0 Beji	E0 Basra	E0 Daura	Ethanol	E8 Blended	E10 Blended
Density @15°C kg/m^3	841.3	830	838.8	789	828.5	829
Flash point °C	/	/	72.8	13	/	/
SP. Gravity @15.6°C	0.8418	0.8304	0.8393	/	0.8289	0.8294
API Gravity @15.6°C	36.6	38.9	37.1	/	39.2	39.1
Calorific Value MJ/kg	45.68	45.85	45.72	26.4	45.87	45.86
Cetane Number	55.5	58.0	56.0	8	58.5	58.5

Figure (3): Pure diesel and the ethanol blend samples

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Ignition Delay Theory

The ignition delay in direct injection diesel engines is of great interest because of its direct impact on combustion and the heat release, as well as its indirect effect on engine noise and pollutant formation. The indicator diagram (P-θ) diagram i.e. P=f(θ) is recorded at different engine speeds. The present work elucidates the measurement and indication of gas pressure within the combustion chamber as a function of crank angle [14]. From the indicator diagram (P-θ) the start of combustion point can be determined .The method used in determining the start of combustion in the present work is based on the sudden rise of cylinder pressure and the pressure at this point is the combustion pressure. This point was checked again using the log (p)-log (v) curve .In the present study, the compression process is polytrophic (pv^n = constant);so by taking the logarithm for both sides and drawing the log(p)-log(v) indicator diagram ,the curve will be linear and the end point of this curve shows the start of combustion point" .The derivative of the line is the polytrophic index (n) . Figure (4) shows indicator diagram pressure-crank angle (p-θ).Figure (5) the log (p)-log(v) curve.

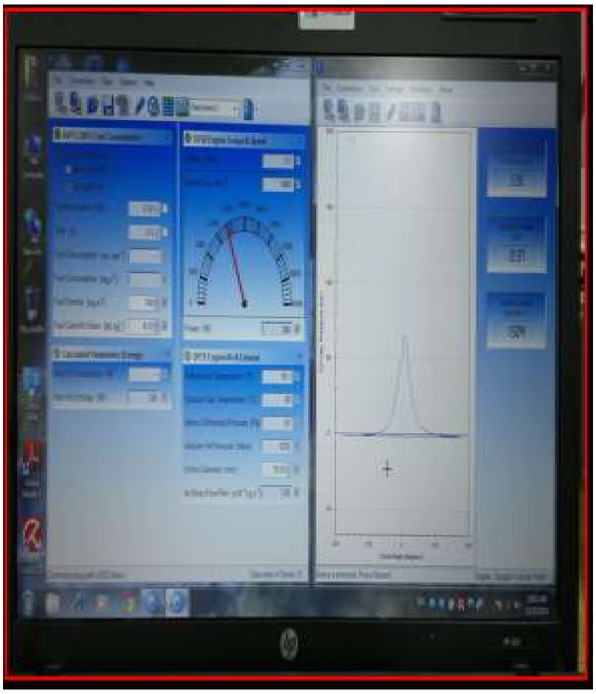


Figure (4): The Indicator Diagram (p-θ) from ECA100 device

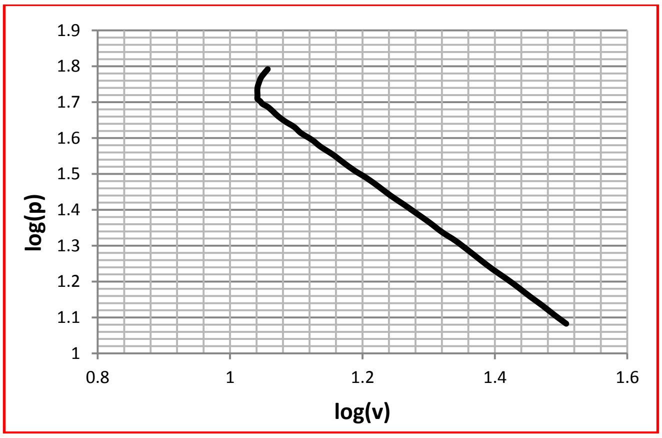


Figure (5): The log (p) -log (v) curve.

The fuel injection is set to be @20°(bTDC) for all experimental procedure, then determine the ignition delay angle (Δθ)which is the difference between the two angles in degree .From compression process, the combustion temperature can be determined. The atmospheric pressure and temperature have been considered at the start of the compression stroke i.e p_i=1.013 bar and T_i=15 C respectively. The air –fuel ratio AF is defined as the mass of air supplied per unit mass of fuel of fuel supplied. The actual mass flow rate of air and fuel are measured individually in the test engine .The theoretical air to fuel ratio is calculated by assuming stoichiometric combustion of the diesel and ethanol blended with theoretical air quantity.

The equivalence ratio (Φ) is defined as the ratio of to be equals (Air/fuel) theoretical/ (Air/fuel) actual [15]. The calculation of(Air/fuel) theoretical are shown in Appendix (A).

$$\Phi=\frac{(\text{Air/fuel})\ \text{theoretical}}{(\text{Air/fuel})\text{actual}} \qquad (1)$$

(Φ=1.0 is at stoichiometry, lean mixtures Φ<1.0, and rich mixtures Φ> 1.0).

Results and Discussion

Cylinder pressure

Figure (6) shows the measured pressure as a function of crank angle for diesel and ethanol-diesel blended at torque =10N.m at speed=2600 rpm.It is clear that the cylinder pressure of the engine with diesel fuel E10 blended and E8 blended recorded slightly higher than the engine running with diesel fuel E0 Beji, E0 Basra, and E0 Daura. This increasing in the cylinder pressure in the E8 blended and E10 blended may be due to high calorific value [16].

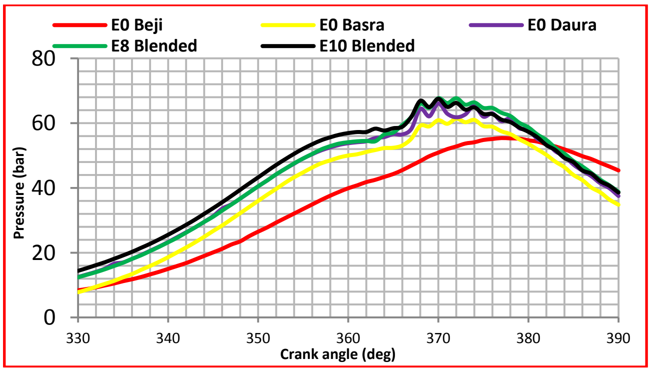
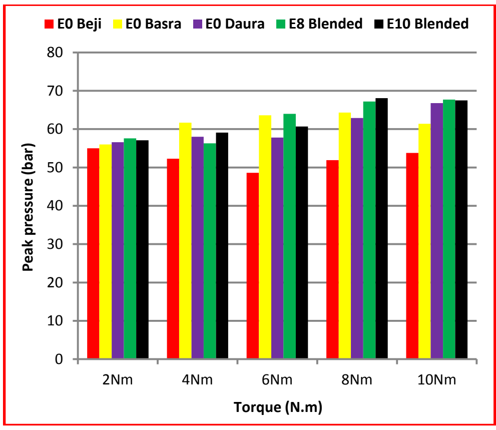


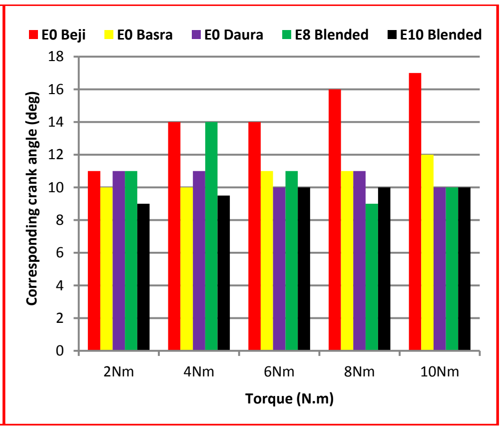
Figure (6): Measured pressure as a function of crank angle for diesel and ethanol-diesel blended at torque =10Nm at speed 2600rpm.

Peak cylinder pressure

Figure (7.a) shows the variation of peak cylinder pressure with engine torque for diesel and ethanol-diesel. E8 blended and E10 blended recorded higher value of maximum pressure than E0 Beji,E0 Basra, and E0 Daura at speed 2600 rpm, and at torque 6N.m,8N.m, and10N.m.This is due to the shorter ignition delay period of E8 blended and E10 blended as compared to E0 Beji,E0 Basra,E0 Daura. Figure (7.b) shows the effect for diesel and ethanol-diesel blended on the maximum crank angle (θ) for varying torque at speed 2600 rpm. A small but erratic change in maximum combustion pressure angle has been observed for diesel and ethanol-diesel blended.



(a)



(b)

Figure (7): Effect of diesel and ethanol-diesel blended on (a) maximum combustion pressure and (b) its corresponding crank angle for varying torque at speed 2600 rpm

Effect of blends on ignition delay:

Figure (8) shows the effect of speed on the ignition delay for diesel fuels and bioethanol-diesel blends. With an increase in engine speed, the loss of heat during compression decreases, resulting in the rise of both the pressure of the compressed air thus reducing the delay period in milliseconds. Ignition delay period is decreased with E10 blended and E8 blended at all speed as shown in Figure 8. This may be related to the effect of higher cetane number of E10 blended and E8 blended this result is agree with Gogoi [17].

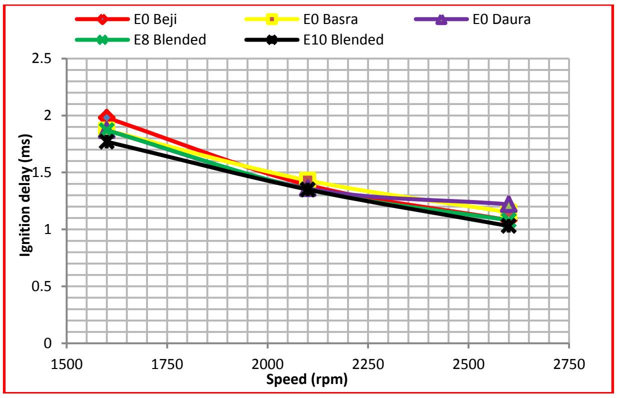


Figure (8): Effect of speed on the ignition delay for diesel fuels and ethanol- diesel blends.

Figure (9) shows the effect of cetane number on the ignition delay period .With increase in cetane number indicated that the ignition delay period has been decreased. This is because of the reduction in the self -ignition temperature. Self-ignition temperature is being responsible for chemical delay and it is the most important property of fuel .

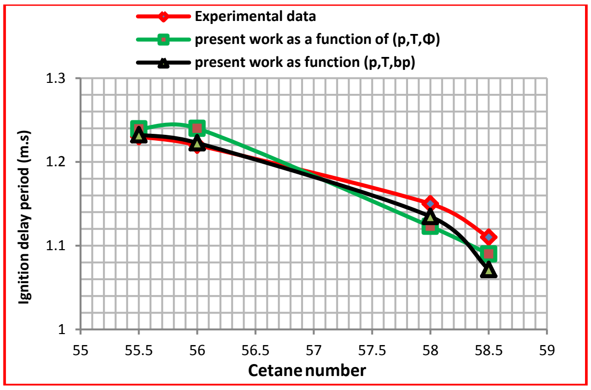


Figure (9): Effect of Cetane number on the ignition delay.

The empirical equations of delay period:

During the previous years, many empirical equations have been developed for prophesy of the IDP in internal combustion engines. They exist as a function of engine and charge parameters. A number of these empirical equations used an Arrhenius expression similar to that suggested by **Wolfer** [11], which measured the IDP using a CVB and expressed it as a function of pressure and temperature of the perimeter through the following semi-empirical equation

$$\tau_{id}=A_1.\,(p_{ign})^{-k}.\exp(E_A/R.T_{ign}) \quad (2)$$

$$E_A=\frac{618840}{CN+25} \quad (3)$$

The apparent activation energy increases with decreasing fuel cetane number .It was found that these constants vary by several orders of magnitude". An Arrhenius expression has a disadvantage that it could be used only for definition of the chemical ignition delay and could be recognized in an inadequate interpretation of the ignition delay. In order to determinate the complete ignition delay, it is necessary to incorporate definition of the physical ignition delay. Expressions integral the physical and chemical ignition delays have a more complex form than equation (2), [18].

Based on the semi-empirical equation developed by **Stringer** [10], developed an ID empirical equation using a compression ignition internal diesel engine which is still widely used ;

$$\tau_{id}=0.0405(p_{ign})^{-0.757}.\exp(5473/T_{ign}) \quad (4)$$

Wolfer [8] developed an ID empirical equation for diesel engine using constant volume bomb conditions which is still widely used;

$$\tau_{id}=0.44.(p_{ign})^{-1.19}.\exp(4650/T_{ign}) \quad (5)$$

In this work, the new effective parameters to develop ignition delay empirical equations can be used such as ignition pressure, ignition temperature, equivalence ratio, and engine brake power fraction. There are two cases are used in the present study to find ignition delay empirical equations.

Case (a)

EL- Bahnasy and El-Kotb [19], with the help of Heywood [20] proposed to develop the Arrhenus equation as mentioned previously to calculate the delay period of diesel fuels and bioethanol- diesel blends as a function of ignition pressure, ignition temperature, and equivalence ratio as follows:

$$\tau_{id}=F.(p_{ign})^{-V}.(\Phi)^{-C}\exp(E_A/R.\,T_{ign}) \quad (6)$$

The above equation is a non-linear equation forms. From the ignition delay results using least square fitting technique, one can get the coefficients F, V, c, by taking logarithm of both sides of that equation ,then we get ln(τ_{id}) = ln (F)-(V)ln (p)-(C)ln(Φ) +(E_A/R.T) .This equation has logarithms in it ,but they relate in a linear way. From the obtined data , the system of linear algebraic equations has been resulted. Now this system has been solved easily by computer program and the general empirical equation of each blend is shown below:

E0 Beji

$$\tau_{id}=3.089.10^{-7}.(p_{ign})^{3.6679}.(\Phi)^{-3.588}\exp(927.4/T_{ign}) \quad (7)$$

E0 Basra

$$\tau_{id}=1.276.10^{10}.(p_{ign})^{-6.057}.(\Phi)^{-0.0034}\exp(896.6/T_{ign}) \quad (8)$$

E0 Daura

$$\tau_{id}=1.126.10^{-32}.(p_{ign})^{17.236}.(\Phi)^{-10.406}\exp(918.7/T_{ign}) \quad (9)$$

E8 blended

$$\tau_{id}=234.87.10^{3}.(p_{ign})^{-3.321}.(\Phi)^{-0.564}\exp(891.2/T_{ign}) \quad (10)$$

E10 blended

$$\tau_{id}=31.34.(p_{ign})^{-1.933}.(\Phi)^{-7.9556}\exp(891.2/T_{ign}) \quad (11)$$

Case (b)

This is to calculate the delay period of diesel fuels and ethanol- diesel blends as a function of ignition pressure, ignition temperature, and engine brake power fraction. Engine brake power fraction (bp_f) is the ratio of the engine brake power at any point to the maximum brake power of the engine .

$$bp_f=\frac{\text{engine brake power at any point}}{\text{maximum brake power}} \quad (12)$$

$$\tau_{id}=c_1.(p_{ign})^{-c_2}.(bp_f)^{-c_3}\exp(E_A/R.\,T_{ign}) \quad (13)$$

Using least square fitting technique, one can get the coefficients, c_1, c_2, c_3, by taking logarithm of both sides of that equation ,then ln(τ_{id})= ln(c_1)-(c_2) ln (p)-(c_3) ln (bp_f) +(E_A/R. T_{ign}) are obtained .This equation has logarithms in it ,but they relate in a linear way. From data ,the system of linear algebraic equations has been resulted. Now this system has been solved easily by computer program and the general empirical equation of each ignition delay is as follows:

E0 Beji

$$\tau_{id}=2.27.10^{-2}.(p_{ign})^{0.8169}.(bp_f)^{-0.1736}\exp(924.4/T_{ign}) \quad (14)$$

E0 Basra

$$\tau_{id}=1.1917.10^{10}.(p_{ign})^{-6.0377}.(bp_f)^{-0.0059}\exp(896.6/T_{ign}) \quad (15)$$

E0 Daura

$$\tau_{id}=1.718.10^{-11}.(p_{ign})^{5.7963}.(bp_f)^{-2.5079}\exp(918.7/T_{ign}) \quad (16)$$

E8 blended

$$\tau_{id}=6.17.10^{-21}.(p_{ign})^{11.2543}.(bp_f)^{-2.326}\exp(891.2/T_{ign}) \quad (17)$$

E10 blended

$$\tau_{id}=4.8843.10^{-6}.(p_{ign})^{2.679}.(bp_f)^{-1.609}\exp(891.2/T_{ign}) \quad (18)$$

Results of the empirical equations of delay period calculations

The equations were obtained for diesel fuels and ethanol- diesel blends as a function of each parameter (p_{ign},T_{ign}, Φ), and as a function of (p_{ign}, bp_f, T_{ign}), as presented in Figure (10). As it is clear from the figure, the delay period decreases with the increase of pressure, temperature, and engine brake power fraction for all blends . This may be attributed to the fact that with increasing the pressure the mixture molecules become closer and the probability of increasing the active collisions between these molecules is higher, as a result the chemical reactions will be accelerated to complete the combustion with shorter delay period. The experiments are carried out in lean and slightly rich mixture zones, (Φ= 0.5–1.1), so the delay period decreases with the equivalence ratio and engine brake power fraction

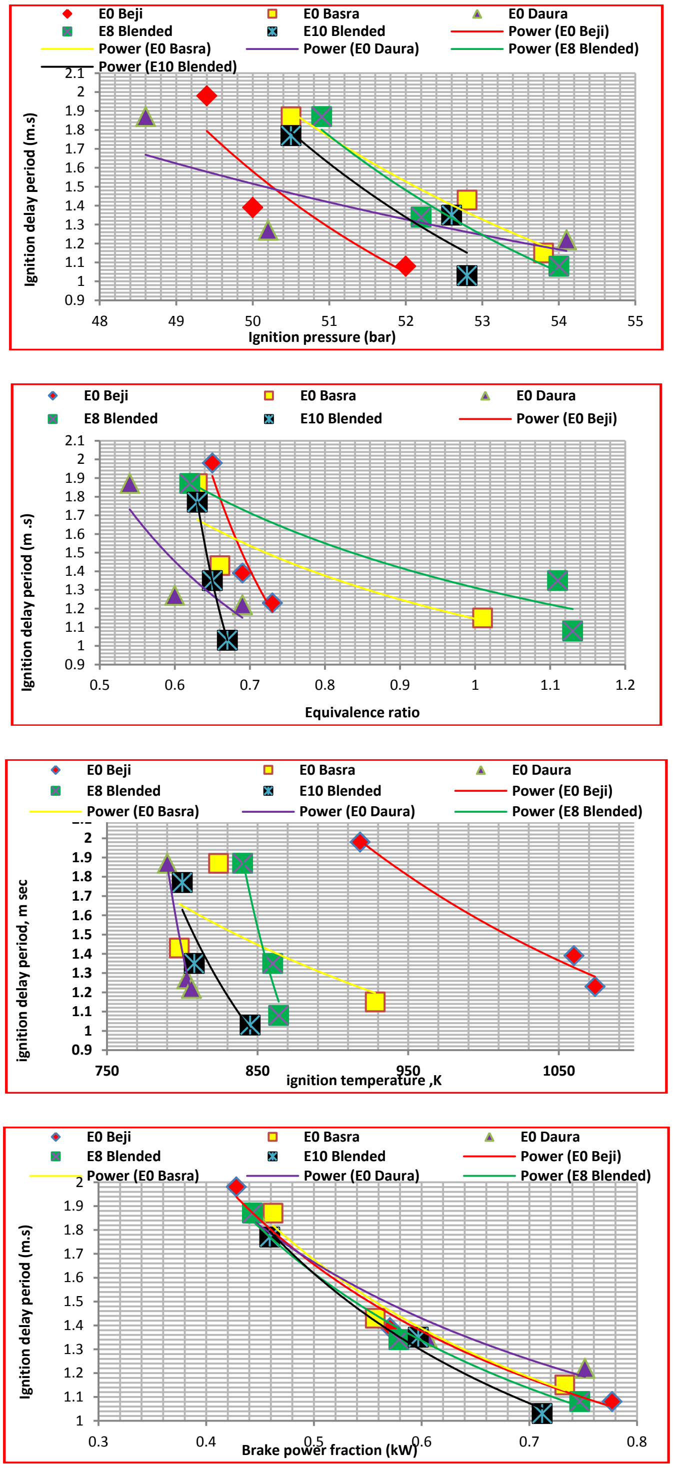


Figure (10): The ignition delay results obtained (a) ignition pressure (b) equivalence ratio, (c) ignition temperature, and (d) brake power fraction.

Figures (11) to (15), show that comparison of different ID empirical equations at all engine speeds for diesel fuels and ethanol- diesel blends at 10N.m.The results show that ignition delay period empirical equations resulted in the present study have showed better agreement with the experimental data than **Stringer[10],** and **Wolfer[11]** empirical equations. Ignition delay empirical equation as a function (p_{ign}, T_{ign}, bp_f) has better agreement with the experimental data than empirical equation as a function of (p_{ign},T_{ign}, Φ) for all speed. . Because of the engine brake power depends on engine speed and torque. Generally, using the engine brake power fraction instead of the global equivalence ratio has proven to result in a of ignition delay periods for the diesel engine in case direct injection in use.

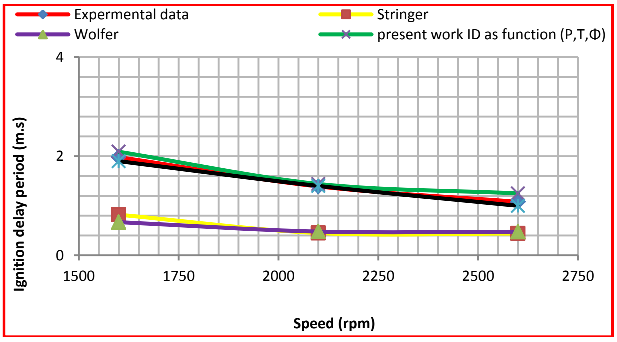


Figure (11): Variation of ignition delay for different ID empirical equations at all engine speeds using E0 Beji at 10N.m.

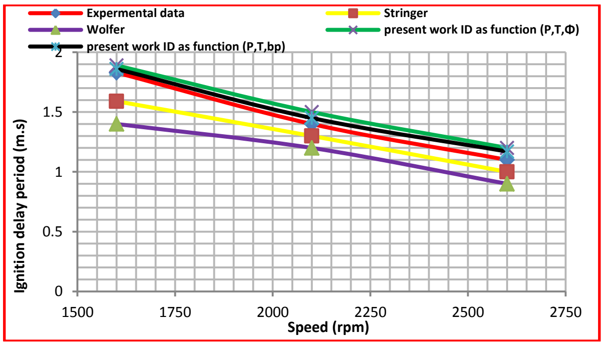


Figure (12): Variation of ignition delay for different empirical equations at all engine speeds using E0 Basra at 10N.m .

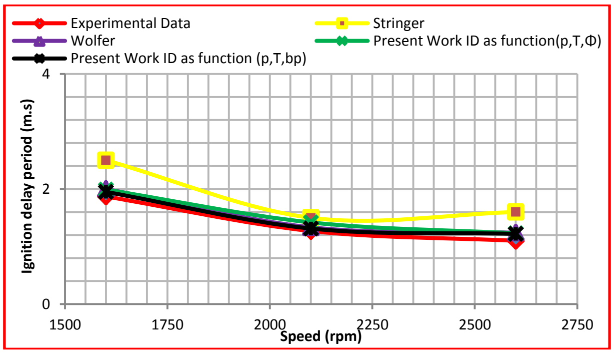


Figure (13): Variation of ignition delay for different ID empirical equations at all engine speeds using E0 Daura at 10N.m .

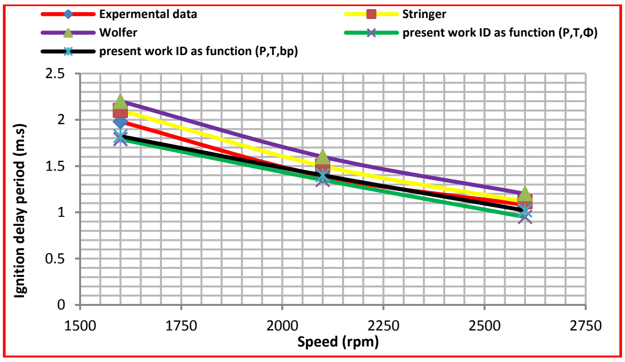


Figure (14): Variation of ignition delay for different ID empirical equations at all engine speeds using E8 Blended at 10N.m .

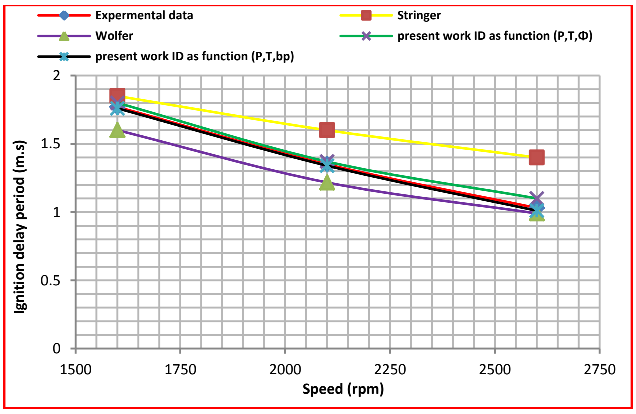


Figure (15): Variation of ignition delay for different ID empirical equations at all engine speeds using E10 Blended at 10N.m .

Nomenclature

Abbreviation	Meaning	Greek Letters	Meaning	Units
BTDC	Before top dead centre	θ	Crank angle	degree
ECA	Engine Cycle Analyzer	τ_{id}	Ignition delay	m.sec
E_A	Activation energy	Φ	Equivalence ratio	-----
ID	Ignition delay			
VDAS	Versatile data acquisition system			
Vol.	Volume			

Symbol	Description	Units
A_1	Constant	-----
bp_f	Engine brake power fraction	-----
c_1, c_2, c_3	Constants	-----
CH3–CH2–OH	Ethanol	-----
$C_{14}H_{30}$	Basra diesel fuel	-----
F	Constant	-----
P_{ign}	Ignition pressure	bar
T_{ign}	Ignition temperature	kelvin
T	Temperature	kelvin
R	Universal gas constant	kJ/kg K
V,C, k	Constants	-----
n	Constant	-----

CONCLUSIONS

The conclusions that are extracted from the present study are as follows:

1. The lowest value of ignition delay period is at ethanol blended diesel fuel (E10 and E8) with all speeds.
2. The developed ignition delay empirical equation as a function (p_{ign}, T_{ign}, Φ) was good agreement with the experimental data than **Stringer [10],** and **Wolfer [11]** for all fuels at all speeds.
3. The developed ignition delay empirical equation as a function (p_{ign}, T_{ign}, bp_f) was better closeness with the experimental data than the developed ignition delay empirical equation as a function (p_{ign}, T_{ign}, Φ) for all fuels at all speeds.
4. For E0 Basra fuel has a high value of peak pressure with low speed at variable torque followed by E0 Beji.
5. E10 blended fuel has recorded the highest of peak pressure with variable torque at medium and high speed.

Appendix (A)

1-Calculation of theoretical A/F for diesel Basra fuel .

$C_{14}H_{30}$+m_s(O_2+3.76N_2)→ d_1co_2+d_2H_2O+d_3N_2

 Balance for carbon

Hence, d_1=14

 Balance for hydrogen

Hence, d_2=15

 Balance for oxygen

Hence, m_s=21.5

 Balance for N2

Hence , d_3=80.84

$$(A/F)_{the} = \frac{21.5(32 + 3.76 * 28)}{14 * 12 + 30 * 1} = 14.906$$

2-Calculation of theoretical A/F for E10 blended fuel .

0.9$C_{14}H_{30}$+0.1(C_2H_5OH) +m_s(O_2+3.76N_2)→ d_1co_2+d_2H_2O+d_3N_2

 Balance for carbon

Hence, d_1=12.8

 Balance for hydrogen

Hence, d_2=13.8

 Balance for oxygen

Hence, m_s=19.65

 Balance for N2

Hence , d_3=73.8

$$(A/F)_{the} = \frac{19.65(32 + 3.76 * 28)}{0.9(14 * 12 + 1 * 30) + 0.1(12 * 2 + 6 * 1 + 16)} = 14.84$$

2-Calculation of equivalence ratio actual A/F

$$\Phi = \frac{\text{(Air/fuel) theoretical}}{\text{(Air/fuel)actual}}$$

$$\text{(Air/fuel)actual } \frac{\dot{m}_a}{\dot{m}_f}$$

Table (A): Calculated values for diesel and blended fuel equivalence ratio.

Fuel	speed	$\dot{m}_a$ (g/s)	$\dot{m}_f$ (g/s)	$(A/F)_{act}$	$(A/F)_{the}$	Φ
E0Beji	2600	3.072	0.149	20.6	14.989	0.72
E0Basra	2600	2.599	0.161	15.9	14.989	0.90
E0Daura	2600	3.14	0.145	21.66	14.989	0.69
E8 blended	2600	3.5	0.145	17.24	14.87	0.86
E10blended	2600	3.088	0.139	22.17	14.84	0.67

Appendix (B)

Table (B): Calculated values for diesel and blended fuel activation energy.

Fuel	E0 Beji	E0 Basra	E0 Daura	E8 Blended	E10 Blended
$E_A\ (\frac{kJ}{kg.K})$	7687	7456.1	7639.9	7411.2	7411.2

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