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Analysis of Physical and Chemical Ignition Delay with Di-tert Butyl Peroxide in Diesel Engine using Hydrogen as Gaseous Fuel

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ABSTRACT

Ignition delay is the most crucial parameter that influences combustion and engine performance, but it changes with hydrogen as fuel. Sum of physical and chemical ignition delay is known as total ignition delay, are changes with hydrogen fuel due to high auto-ignition temperature and gaseous nature of fuel. In this present work, the physical, chemical and total ignition delay of diesel engines working on dual fuel mode has been examined, using hydrogen as gaseous fuel with additive di-tert butyl peroxide using diesel as base fuel. These mentioned observations were made on a 3.50 KW Kirloskar TV1, single cylinder 4 stroke direct ignition diesel engine at a constant speed of 1500 rpm with base fuel as diesel and hydrogen as secondary fuel. Physical and chemical ignition delay gets decreased with more than 2% of di-tert butyl peroxide addition. Fuel quality parameters such as density and viscosity influence physical ignition delay, whereas cetane number influences chemical ignition delay of diesel engines working on dual fuel mode.

Keywords: Hydrogen fuel; Dual-fuel diesel engine; Ignition delay; Additive; Physical and chemical ignition delay.

1. INTRODUCTION

Population explosion has increased energy demand all over the world (Akal *et al.* 2020). As the demand of energy increases due to increase in population, result in climate change and it is regarded as a major global problem. Rate of global warming can be reduced by reducing global formation of carbon di-oxide (CO_2) and other harmful gases like carbon monoxide (CO), unburned hydrocarbon (HC), and oxides of nitrogen (NO_x) but a stabilization of global temperature can only occur if CO_2 emissions approach zero. Usage of such technology, which not only provides sufficient energy but also gives out minimum emissions needs to be developed (Oreggioni *et al.* 2017). Limited stock of conventional sources of energy and increasing environmental concerns have increased people's interest in renewable sources of energy (Kanth *et al.* 2021).

All energy utilizing sector is trying to find out new alternative fuel but the major challenge is for the transport sector. Vehicles using renewable sources of energy or electricity aren't that efficient and indirectly harmful emissions are produced somewhere. So, research is being carried out to figure out ways in which emissions can be reduced from internal combustion (IC) engines(Salek *et al.* 2021). One way is to remove carbon from the scene and use such a fuel that would not generate other harmful gases. Hydrogen falls under these criteria as on its combustion, water is formed with minimum emissions. It serves as a clean energy source, which has great potential. It can also be directly used in internal combustion (IC) engines without much modification of the engines (Mishra *et al.* 2020). However, there are a few issues like uncontrolled ignition, surface ignites, backfiring and high rates of heat release leading to knock with hydrogen (H_2) combustion in diesel engines which needs to be resolved (Talibi *et al.* 2018). Ignition delay is defined as the time interval between the injection of fuel into the cylinder and the instant of the first detectable rise in cylinder pressure due to exothermic energy release within the change. It is an important parameter that impacts engine performance and later combustion process as well as influences exhaust emissions. Ignition delay displays trends that are significantly different in homogeneous gaseous fuelled dual fuel diesel engines with direct injection of diesel as pilot fuel from those observed in corresponding conventional counterparts. Injecting small quantities of liquid diesel fuel ensures the ignition of the charge (Talibi *et al.* 2018).

Diesel engine work on dual fuel mode with diesel as parent fuel and hydrogen as gaseous fuel, it leads to increase ignition delay due to decrease in mean gas temperature of the charge at the time of injection of parent diesel fuel (Neilsen *et al.* 1987). Ignition delay (ID) is one of the important parameters that make

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influenced on the combustion process inside the cylinder. This ignition delay affects not only the performances but also the noise and emissions of the engine (Goto and Lee, 1999).

Di-tertiary butyl peroxide (DTBP) is a common fuel additive used to increase cetane number of diesel fuel in diesel engine (Chen *et al.* 2009). The cetane number of diesel fuel poses a significant effect on the ignition timing, combustion, and engine-out emissions of diesel engines (Chen *et al.* 2009). As addition of DTBP increases in the fuel, its cetane number of fuel increases, further it reduces ignition delay period, stability of engine also enhanced (Goto and Lee, 1999). This may be due to sharp increase in heat release rate with more than 5% addition of DTBP.

DTBP advances the ignition timing of the diesel fuel under different conditions, and the effects become evident with a higher DTBP concentration. Kumar *et al.* (2021) were found that ignition delay decreases with increase in percentage of DTBP and hydrogen in air-fuel mixture. This may be due to cetane improver nature of DTBP, pre-ignition reaction rate and energy release rate of hydrogen fuel. Similar results were found with by Paneerselvam *et al*. (2021) with addition of cetane improvers ignition delay was significantly reduced.

To have an idea of the performance of dual fuel engines, combustion models are prepared. Necessary information regarding ignition delay of the pilot fuel is mandatory. Ignition delays comprises of physical and chemical ignition delays which occur simultaneously. Physical ignition delay consists of atomization, vaporisation and mixing of fuel with air mixture and the chemical ignition delay is pre-combustion reactions in fuel/air mixture of fuel (Tsujimura *et al.* 2003).

Many possible ignition delay correlations have been proposed. The first one was by(Hardenberg *et al.*1979) for heavy duty diesel engines. Their correlations fit perfectly for numerous conditions as well as cover several experimental parameters like cetane number, temperature, pressure, engine speed and also some kinetic parameters like activation energy and apparent activation energy with few adjustable coefficients.

Assanis *et al.* (2003) in his study on ignition delay formulated eight empirical relations. He used steady flow, constant volume bombs, diesel engines and single drop experiments and calculated many empirical constants for the correlations. The evolved correlations for the calculation of ignition delay in direct diesel engines are frequently used beyond the temperature pressure range of their validity or applied for different types of engines. The commonly accepted correlations for diesel engines are those suggested by Assanis and Watson. These empirical correlations are based on pressure and temperature data (Hardenberg *et al.*1979; Rodríguez *et al.* 2011).

Arrhenius equation was modified by (Vasil'ev, 2007) for multi fuels. He operated a binary fuel system on it. A correlation for ignition delay was also developed by (Kavtaradze *et al.* 2005)for dual fuel engines. For gaseous fuel, natural and synthesized gas was taken and for pilot fuel, diesel was used and the experiment was carried on a single cylinder four stroke diesel engine. Other correlations were obtained in volume bombs, steady flow reactors, rapid compression machines and engines.

Pischinger *et al.*(1988) observed that increased pressure dependence in Arrehenius ignition delay correlation could be derived from elementary reaction kinetics based on singles stage reaction mechanism. Certain elements like equivalence ratio, concentration of the reactants and engine speed are found in some correlations (Vasil'ev,2007).

Tsujimura *et al.* (2003) analysed a few attributes of the auto-ignition of hydrogen jets in a constant volume vessel. The auto-ignition delay in hydrogen jets was influenced by the thermodynamic conditions of ambient gas and its temperature. For temperature below 1100 K, a linear relation is seen between auto ignition delay and ambient gas temperature, while the relation vanishes above 1100 K, and the delay period reaches a finite value in Arrehenius coordinates.

Naber (1998) employed at a combustion vessel of constant volume and examined the outcome of hydrogen addition in the auto ignition process of dual fuel. A few variables include injecting pressure and temperature, ambient pressure, orifice diameters, temperatures and pressure of gas. Arrhenius correlation stood strong among temperature and ignition delay. For typical gas densities at top dead centres in diesel engines less than 1.0 ms ignition delay was obtained for gas temperatures greater than 1120 K. This certified that compression ignition of hydrogen is achievable in diesel engine at ratio TDC conditions (Catoire *et al.*1998; Tsujimura *et al.*2003).

Raine (1990) has formulated correlation to predict ignition delay period for dual fuel diesel engine with input parametres mean temperature and pressure of the charge. Minimal consent with experimental data on dual fuel ignition delay is seen via this method. This signifies that for dual fuel situations existing diesel ignition delay correlations could not be used. Based on experimental outcomes for diesel engines, ignition delay correlation had been attained for application in biogas diesel dual fuel engines.Governments across the world have set targets that aim to increase the renewable shows in the energy mix (such as the E.U. “2020” Strategic Energy Technology Plan). Hydrogen, a clean fuel sets perfect for the above target. It can be used in dual fuel mode with diesel as pilot fuel.

Ignition delay, as mentioned earlier, is influenced by fuel properties and is an important engine parameter. Hence, the content presented is an attempt to formulate an ignition delay correlation. Diesel engines working on dual fuel mode by attuning the mostly accepted ignition delay correlation for diesel engines proposed by Wolfer based on the Arrhenius equation. The work aims to estimate ignition delay in dual fuel mode by using certain parameters related to diesel operation, along with the knowledge of the concentration of inducted gaseous fuel in the charge (Senthil, 2003; Ghazal, 2013).

2. EXPERIMENTAL SETUP AND TESTING

The experimental set-up consists of a 4 – stroke engine, single cylinder diesel engine (Model Kirloskar TV1) of power 3.5 kW, running at a constant speed of 1500 RPM. The dual fuel engine comprises a stand type control panel box. A fuel tank, an air box, a manometer, a digital speed indicator, a fuel measuring instrument and a digital temperature indicator cooperated in the control panel box. The inlet and outlet temperature of the cooling water of the engine and calorimeter are indicated in the temperature indicator. Rota metres were employed to measure the flow of cooling water and calorimeter flow control panel data was used for further evaluation of engine performance.

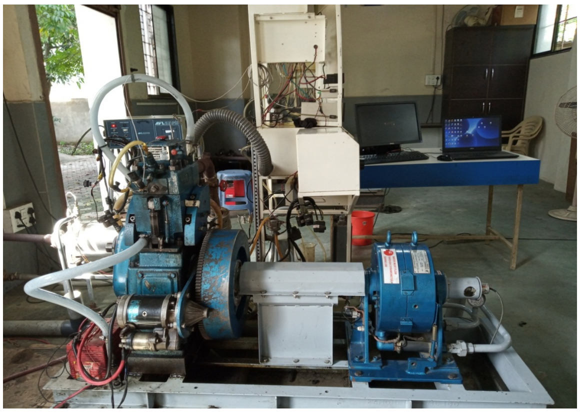

Fig. 1: Real view of the Experimental Setup

Real view of experimental setup is shown in figure 1. Specifications and parameters of diesel engines are tabulated in table 1. Conventional way was used to supply diesel fuel to the engine and intake manifold for hydrogen. Engine was attached to a cylinder containing hydrogen gas at 125 bar pressures while hydrogen supplied was at 2.5 bars regulated by a pressure regulator. Mass flow-meter of gas, gas detector, flame arrester, and gas injector are integrated to a non-return valve with intake manifold for supply of gaseous fuel. For load application to the engine an eddy current dynamometer is used.

Load varied from 0 kg to 18 kg. For cylinder pressure measurement, a piezo sensor with a maximum pressure measurement of 105,425 kPa and resolution of 0.69 kPa was attached. Recorded pressure data was there for put forward to the powering unit for further analysis. To measure crank angle, an angle sensor model kuldeep with an accuracy of 1^o was installed. A governor for supply of diesel fuel to engine was employed, whereas flow of hydrogen gas was checked manually. Through gaseous fuel system, a predetermined volume of hydrogen gas was subjected to an intake manifold and the engine was allowed to operate at stable condition for five minutes. Data of a hundred cycles was used to calculate average temperature and pressure. The flow rate of hydrogen was in kilograms per second.

3. EXPERIMENTAL ANALYSIS

The work presents analytical and experimental results of total ignition delay analysis. Using hydrogen as a secondary fuel, experiments were done on diesel engine running on dual fuel mode. To calculate ignition, delay analytically correlation of Arrhenius equation for diesel engine was applied. Total ignition delay was applied. Total ignition delay was also obtained experimentally for diesel and mixture of diesel and hydrogen. Heat release method was utilised to obtain experimental data.

Table 1. Details of parameters and specification of engine

Parameters	Unit	Specification
Make and model	-	Model Kirloskar, TV1
General detail	-	Single cylinder, four-strokes, Compression ignition engine,
No of cylinder	-	1
Bore	mm	87.50
Stroke	mm	110
Rated speed	RPM	1500
Swept Volume	cc	661.45
Compression Ratio	-	18
Injection Pressure	bar	224.11
Injection timing bTC	ºC	19
Rated power	KW	3.50
Inlet Pressure	bar	1.03
Inlet temperature	K	300

3.1 Analysis of Ignition Delay

Methods for estimating ignition delay are mostly based on Arrhenius equation (Raine, 1990; Hervás *et al.* 2011) of the form shown in equation 1. This equation is a modified version of the equation for global reaction rate. Increase of the reaction rate gives duration of the global reaction, representing chemical delay period. According to experimental data, equation 1 was then tuned to account for the total ignition delay period. Such ignition delay correlations have been popular for four decades for direct injection compression ignition engines. An experimental study by (Hiroyasu *et al.* 1983) in constant volume bombs produced ignition delay correlation for steady state conditions based on steady flow reactors, such as those by (Stringer *et al.* 1969).

$$\tau_{id}(ms) = Ap^{-n}\exp\left[\frac{E_A}{\bar{R}T}\right] \qquad \ldots (1)$$

Where, $\tau_{id}(ms)$ stands for ignition delay (time between the start of injection fuel to start of detectable heat release), E_A is apparent activation energy for fuel auto- ignition process, $\bar{R}$ signifies universal gas constant, and A and n are constants that dependent on the fuel (to some extent to the injection and air-flow characteristics). Air pressure and temperature at top dead position are derived from recorded cylinder pressure. So, it can see that $\tau_{id}(ms)$ is a function of mixture temperature, pressure, equivalence ratio, and properties of fuel (Hiroyasu *et al.*1983).

Table 2. Constant for Arrhenius equation for ignition delay

Investigator	Fuel	*A*	*n*	E_A / R	k	R-Sq.	Adj. R-Sq.
Stringer *et al*. (1969)	Diesel CN-(45-50)	0.04	0.75	5473	-	-	-
Wolfer, (1959)	Fuel with CN>50	0.44	1.19	4650	-	-	-
Modified	Diesel and H_2 fuel	5.87×10^{-8}	(-) 2.35	7324.17	(-) 0.042	0.96	0.897

Table 3. Percentage Variation of the load for four Cases (Stringer *et al.* 1969)

Case No.	Base Fuel	Secondary Fuel	Additive	Load Percentage (%)
I	Diesel Only	-	-	2,18,36,53,69
II	Diesel	Hydrogen	-	2,18,36,53,69
III	Diesel	-	Di-tertiary-butyl peroxide (DTBP)	2,18,36,53,69
IV	Diesel	Hydrogen	Di-tertiary-butyl peroxide (DTBP)	2,18,36,53,69

Table 4. Percentage Variation of Additive and H_2 with Load (Stringer et al. 1969)

Case No.	Base Fuel	Alternative fuel	Base fuel (Diesel) substituted with hydrogen gas (%) at each load condition
I	Diesel Only	-	-
II	Diesel	Hydrogen	14, 20, 26, 33, 40
III	Diesel	Di-tert butyl peroxide (Additive)	A-1%, A-2%, A3-%, A-4%, A-5%
IV	Diesel	Hydrogen and Di-tert butyl peroxide (Additive)	{M-1-(H-14,20,26,33,40)}, {M-2-(H-14,20,26,33,40)}, {M-3-(H-14,20,26,33,40)}, {M-4-(H-14,20,26,33,40)}, {M-5-(H-14,20,26,33,40)},
IV	Mixture (M)	-	M-1 = D-99% + A-1%, M-2 = D-98% + A-2%, M-3 = D-97% + A-3%, M-4 = D-96% + A-4%, M-5= D-95%+5%A

4. RESULTS AND DISCUSSIONS

While conducting experiments, four cases were separately considered: Case I, in which pure diesel was used and Case II, inwhich hydrogen was used as secondary fuel. The cases along with the load, additive (DTBP) and hydrogen fuel percentage are tabulated in Table 3 and 4. The experimental observations and results are systematically discussed for both cases, which were taken at rated power 3.50 KW, injecting pressure of 224.11 bar, 1500 rpm, injecting timing at 19° bTDC at a regulated load of 2%, 18%, 36%, 53% and 69% of the full load condition respectively. For engine performance analysis, 69% of full load capacity represented high load condition, respectively. Full load was not considered due to knocking of the engine (Stringer *et al.* 1969).

4.1 Ignition Delay (ID)

Ignition delay period starts with the injection of fuel and consist physical and chemical delay periods until the auto-ignition occurs (Fig. 2). It consists of physical and chemical delay period. During the physical delay period, process like fuel atomization, evaporation and mixing with air takes place. Thereafter, chemical reactions initiate auto-ignition which is known as chemical delay period. Arrhenius equations are mostly considered to express total ignition delay period. According to these equations ambient conditions and fuel injection pressures are important parameters of ignition delay. Numerous coefficients for ignition delay equations have been proposed by many authors (Payri *et al.*2009). New parameters like effect of injection pressure and nozzle geometry are added by some researchers. Inverse relation is seen between ignition delay time and ambient pressure, ambient temperature and ignition pressure.

Auto ignition and combustion process decides the air fuel mixing. Ignition of fuel states, the total ignition delay comprising of physical and chemical ignition delay until the actual combustion states. The process of fuel atomization, evaporation and mixing with air takes place in physical ignition delay period. Then chemical ignition delay begins slowly and ignites auto ignition. This period is called chemical ignition delay period. Rate of pressure rise is influenced by ignition delay. Knocking and emission formation are also influenced by ignition delay to some extent. Rise in NO_x emissions is observed because of high cylinder temperature. Rough engine running is also seen and it may cause knocking (Aggarwal, 1998).

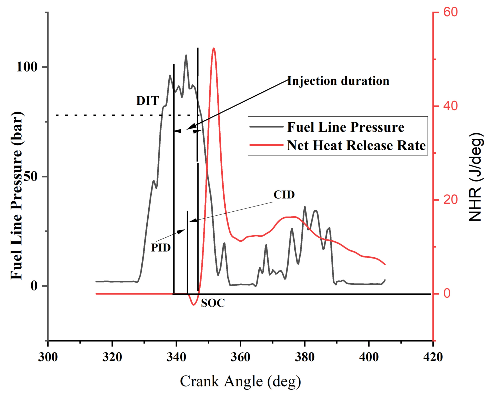

Fig. 2: Variation of fuel line pressure (bar) and NHR (J/deg) with Crank Angle (deg) for diesel fuel at higher load condition (69%)

Cetane number is a measure of the total ignition delay time; it is dependent on other fuel properties like viscosity, density, surface tension and distillation, in addition to the more fundamental chemical compositional effects. Considering ignition delay in terms of physical and chemical delay provides convenience, but it is not possible to separate the two in single engine experiment. The time required for atomization, vaporization, mixing and heating of injected fuel is known as physical delay, and the time utilised for completion of relatively slow pre-flame reaction before the flame or burning reaction takes place is called chemical delay. It is a fundamental property of the fuel and or fuel components.

4.1.1 Variation of Ignition Delay Period

The Fig. 3 depicts the variation of physical (PID), chemical (CID) and total ignition delay (TID) period of the diesel engine, operating on blends of diesel and additive (DTBP) and mixture of diesel and gaseous fuel (H_2) at higher (69%) load conditions.

Physical as well as chemical ignition delay period decreases with the addition of additive (DTBP) in the diesel fuel (Case-II), as compared with pure diesel fuel (Case-I), except 1% of addition additive (DTBP). Addition of 1% additive in the diesel fuel, increases the physical ignition period (PID). Physical ignition delay period at 0%, 1%, 3% and 5% is 3.75^o, 5^o and 2.5^o and 2.5^o respectively, whereas chemical ignition delay period is 2.5^o, 2.5^o, 2^o and 1^o at 0%, 1%, 3% and 5%. Pure diesel fuel condition is represented by 0% addition of additive. The total ignition delay period also decreases with addition of additives as it is the sum of physical and chemical ignition delay periods.

However, with addition of gaseous fuel in dual fuel mode (Case-III), physical ignition delay period is not too much affected but chemical ignition delay period increases with an increase in the gaseous fuel (H_2) substitution. Further, TID also increases with an increase in the substitution of diesel fuel with gaseous fuel (H_2). Physical ignition delay period at 0%, 14%, 20%, 26%, 33% and 40% is 3.75^o, 3.75^o, 4^o, 4^o, 4^o and 4^o, whereas chemical ignition delays period is 2.5^o, 2.5^o, 3^o and 3.5^o, 4^o and 4.5^o respectively. Pure diesel fuel condition is represented by 0% substation of diesel fuel with gaseous fuel (H_2). TID period for pure diesel fuel conditions is 6.25^o and 8.5^o with 40% gaseous fuel substations.

The variation in PID, CID and total ignition delay (TID) can be explained in literature. The temperature and pressure of the charge and type of fuel determine TID. Numerous ignition improvers' additives claim to enhance the ignition quality of diesel fuel. However, their precise role in promoting ignition remains uncertain. Some suggest that the physical processes contributing to the delay period are modified by the additives. For example, it's a popular thought that ignition additives would act in a similar way as water, when the latter is added to diesel in the form of emulsion. Additives remain at supercritical pressure, so they can evaporate very quickly, thereby shattering fuel droplets and assisting atomization. Others consider additives as heat flux improves, which aims to increase the heat transfer rate in nucleate boiling and then reducing evaporation time. It might be the basis to lessen the physical ignition delay by using additives (Case-II). In case of dual fuel mode (Case – III) when hydrogen is taken as secondary fuel slight increase in physical ignition delay is seen. This could be because of the high thermal conductivity of air hydrogen fuel compared to air.

Another school of thought believes that the main effect of additives is to accelerate the auto ignition chemistry. Mostly, the effective additives are thermally unstable and their thermal decomposition may yield free radicals. It has been suggested that these are effective in accelerating the chain branching reactions leading to ignition (Valdmanis *et al.* 1970). Heat released by the initial reaction of additive thermal decomposition products cause a rise in the local temperature which may be of equal importance in stimulating the auto ignition of the fuel (Satcunanathan *et al.* 1972). It could be the reason for the decrease in chemical ignition delay period with addition of additives in diesel fuel (Case – II). When diesel fuel is injected, in-cylinder temperature and pressure decrease in dual fuel mode with gaseous fuel. It could be the reason for increase in the chemical ignition delay period (figure 3) with an increase in the substitution of gaseous fuel (Case - III) as compared with diesel fuel operation (Case - I).

Fig. 4 depicts the variation of physical (PID), chemical (CID) and total ignition delay (TID) of the diesel engine, operating on dual fuel mode with H_2 (Hydrogen) as gaseous fuel and blends of diesel and additive (DTBP) as pilot fuel at higher (69%) load conditions. Both physical as well as chemical ignition delay period decrease with the addition of additive (Case-IV) in the diesel fuel along with hydrogen as secondary fuel as compared with dual fuel mode (Case-III), where gaseous fuel used as secondary fuel at 40% gaseous fuel (H_2) substitution. Physical ignition delay period is 3.75^{o}, 3.5^{o} and 2.5^{o} at 1%, 3% and 5% respectively as compared with 4^{o} (Case-III) at 40% hydrogen substitutions whereas chemical ignition delays period is 3^{o}, 2^{o}, and 1.5^{o} respectively as compared with 4.5^{o} (Case-III). However, physical, chemical (CID) and total ignition delay (TID) have a strong dependence on in-cylinder thermodynamic state of the charge at the end of compression stroke. Adding an additive (DTBP) to diesel fuel, in dual fuel mode with hydrogen as gaseous fuel, the mixture latent heat of vaporization is reduced due to instant heat release, atomization quality is improved, and preparation of combustible mixture is more uniform as compared to Case - III, which is beneficial to the generation and accumulation of active groups in the mixture during low-temperature oxidation reaction phase. Addition of an additive (DTBP) accelerates chemical reaction rate, and the ignition time is advanced with combustion taking place like constant volume condition due to presence of gaseous fuel. Although not entirely independent of the hydrocarbons present, since some kinetic interaction is inevitable, the principal initial contribution of peroxide decomposition and oxidation is to augment the local temperature rapidly and thus promote the initiation of the hydrocarbon fuel oxidation.

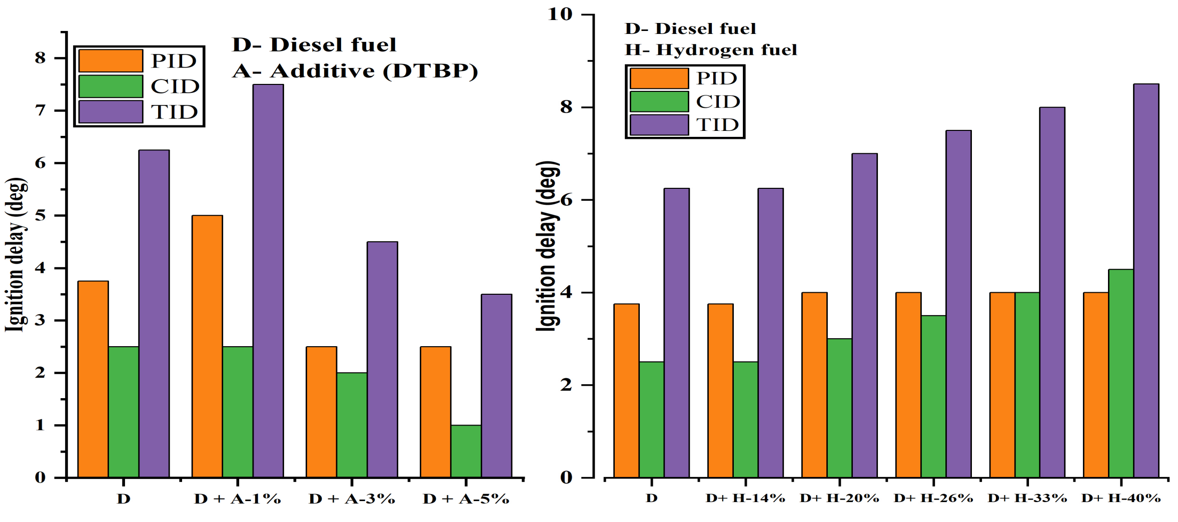

Fig. 3: Variation of Ignition delay (physical, chemical and total ignition delay) with DTBP (diesel + DTBP) and Hydrogen fuel (diesel + H2 fuel) at higher load condition (69%)

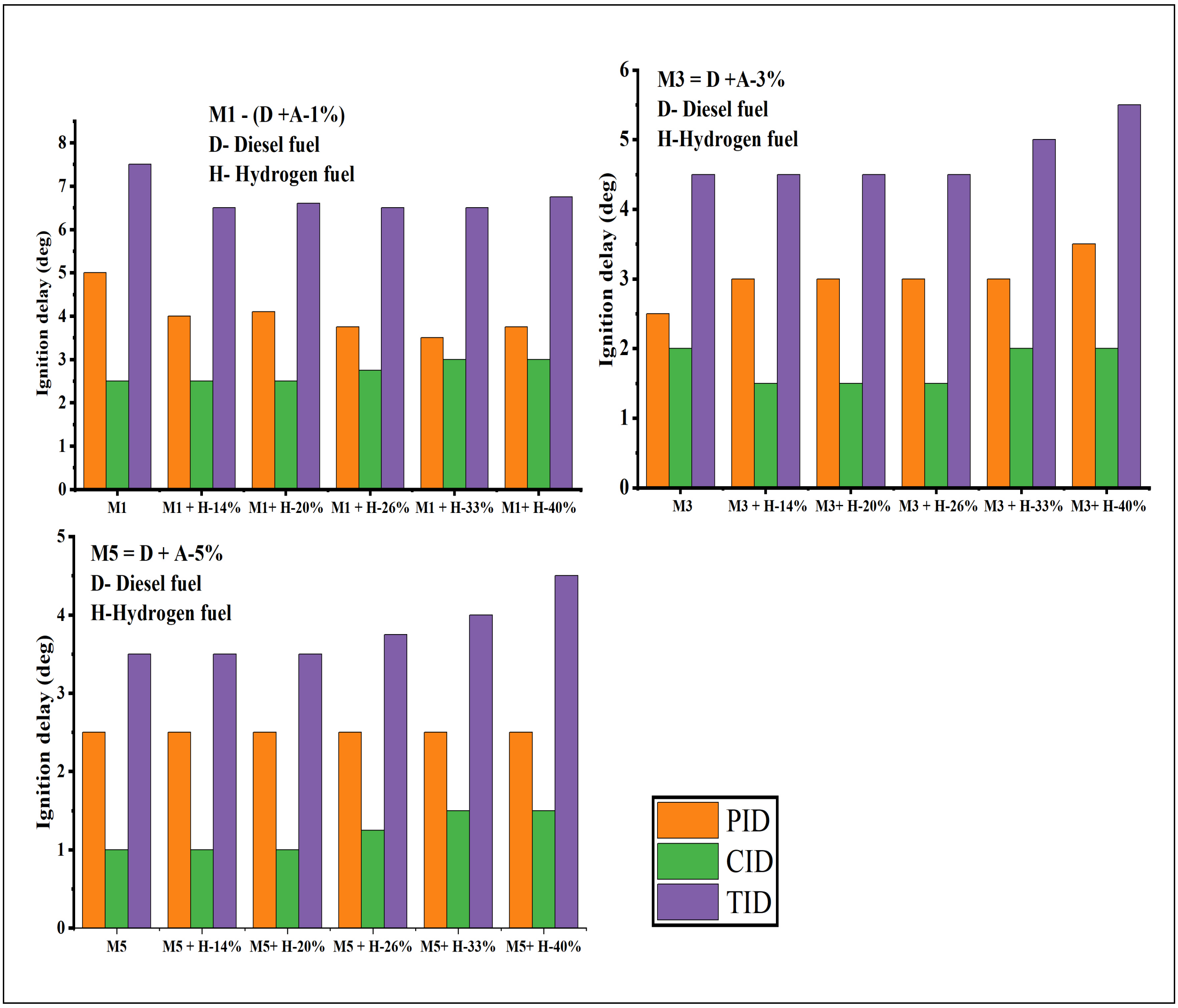

Fig. 4: Variation of Ignition delay (physical, chemical and total ignition delay) for dual fuel Case (Diesel + H2 + DTBP) at higher load condition (69%)

Table 5: Comparative study of theoretical and experimental ignition delay period

S. No.	H_2 Subst.	Pressure	Temp.	Ignition delay			{(D-A) / D} * 100	{(D-B) / D} * 100
				Wolfer, (1959) (A)	Stringer *et al.* (1969) (B)	Expt. (D)		
	(%)	(atm)	(K)	(ms)	(ms)	(ms)	(%)	(%)
1	0	20.17	777	4.80	4.71	0.83	- 478.31	- 467.46
2	14	18.35	757	6.34	6.14	0.94	-574.47	-553.19
3	20	19.32	751	6.25	6.24	1.06	-489.62	- 491.50
4	26	19.02	745	6.66	6.59	1.11	-500.00	- 493.69
5	33	19.06	749	6.24	6.29	1.16	-437.93	- 442.24
6	40	20.50	756	5.57	5.66	1.38	-303.62	-310.14

4.2 Theoretical and Experimental Ignition Delay (ms)

Comparison of the experimental ignition delay (ms) for the diesel engine working on dual fuel mode with hydrogen as gaseous fuel and other existing correlation are presented Table 5. Differences between experimental values and existing correlation at medium load (36%) for gaseous fuel (H_2) have used to compare ignition delay period.

5. CONCLUSION

An experimental study was conducted on a single cylinder, four strokes diesel engine, working on dual fuel mode; model Kirloskar TV1. The engine was connected with an eddy current type dynamometer for engine loading. The following inferences were concluded for the experiments mentioned above

- Physical, chemical and total ignition delay gets decreased by addition of more than 1% of additive (DTBP) in diesel fuel operation.

- DTBP have not impact much on Physical ignition delay, however chemical ignition delay get decreased in dual fuel mode with hydrogen as gaseous fuel by use of DTBP.

- Oxygen concentration plays the most significant role in determining the TID at all load conditions due to the induction of gaseous fuel hydrogen.

Fuel quality parameters such as density and viscosity influence physical ignition delay, while cetane number influences chemical ignition delay of diesel engines. Additive di-tert butyl peroxide (DTBP) increases the cetane number of the fuel.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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