

# Variation in Ignition Delay with Changing the Environment inside the Combustion Chamber for Different Sprays

Tushar Gupta, M. Emran Khan

**Abstract:** Ignition delay is very important parameter which influences the entire combustion process and emissions generated inside the engine. An experimental study was conducted to observe the variation in ignition delay with changing environment inside the combustion chamber for different sprays. Two types of nozzles namely pintle nozzle and single hole nozzle were used for creating hollow cone spray and solid cone spray respectively. This study was carried at different injection pressures (100 bar, 150 bar and 200 bar), different HST (350°C, 450°C and 550°C) and different air pressures (10 bar, 15 bar, 20 bar and 25 bar) for obtaining the value of ID. A digital Oscilloscope is used to record ID and optical method was used for detecting the flame. Results of the experiments show that air pressure, injection pressure and HST all are responsible for variation in ID but HST is more strongly affect the ID compared to other parameters. However at high value of HST and injection pressures variation in ID is less. Variations in the values of ID are more for Solid cone spray than Hollow Cone spray although ID is decreased for both sprays at almost all injection pressures. The dependency of types of spray is more prominent in lower temperature ranges compared to higher temperature ranges.

**Keywords:** Diesel Engine, Injection Pressure, Air Pressure, Ignition Delay, Hollow cone spray, solid cone spray  
**Nomenclature:**

CVCC	Constant volume combustion chamber
HST	Hot surface temperature
ID	Ignition Delay
HSDI	High speed direct injection
SI	Spark Ignition
CI	Compression Ignition
ROHR	Rate of heat release
DME	Die Methyl Ether
HMN	Heptamethylnonane
DI	Direct Injection
IDI	Indirect Injection
CN	Cetane number
CO	Carbon mono oxide
CO <sub>2</sub>	Carban dioxide
UHC	Unburned hydrocarbons
NO <sub>x</sub>	Oxides of nitrogen
PM	Particulate Matter

RR	Rate of reaction
K <sub>f</sub>	Reaction rate constant,
O <sub>2</sub>	Oxygen concentrations are molar based
$\tau_{id}$	Ignition Delay in millisecond
E <sub>A</sub>	Apparent activation energy
P	Pressure in atmosphere
T	Temperature in Kelvin
R	Universal gas constant
A, m, n, j	Constants depend on fuel
ms	Milliseconds

## I. INTRODUCTION

In present days there are mainly two challenges in the development of engines. One is performance enhancement and other is air pollution generated by the emissions librated from the engines. Diesel engines have many advantages over petrol engine like high thermal efficiency, better fuel economy or low fuel consumption, low breakdown rate and hence diesel engines are more frequently used [1]. In case of diesel engines emissions librated is the primary problem. To deal with these problems several researches are ongoing now days and various policies are made by different countries to curb the emissions problem. The policies made in terms of various emission legislation norms like Euro norms and Bharat stage norms. Now India is looking towards Bharat stage VI norms based on Euro VI norms. Another big problem with diesel engines is increasing price of diesel therefore besides these policies, engineers are doing research to make better engine design and simultaneously improving the combustion process by optimizing the various parameters and emission characteristics of engine. Some parameters are combustion chamber design, geometry of nozzle, size of combustion chamber, position of injector. While emission characteristics are depending on many factors like spray pattern, injection pressure, inside cylinder temperature and pressure, injection quantity and injection timing. All these parameters or factors are directly or indirectly influence the ID in combustion process. Therefore understanding of ID and its influencing parameters is very important to improve the combustion process. Injection pressure is a very important parameter which varies the ID.

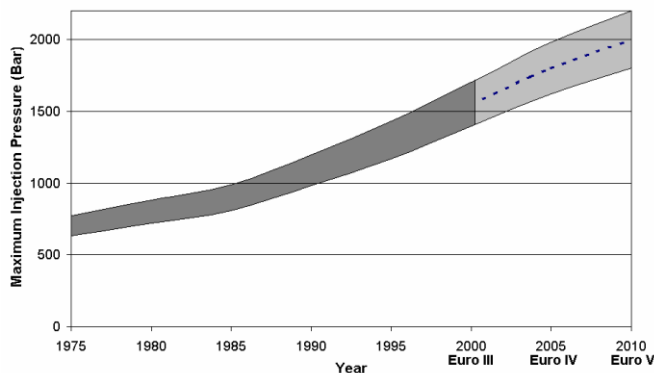
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Low injection pressure lead to larger fuel particles diameter and large ID which in turn lead to insufficient combustion and increase the NOx and CO level in the diesel engine. The data presented in Fig 1 shows how injection pressure of fuel has risen over in past few years. Research has shown that there are still benefits to be realized by further enhancing the injection pressure and rate, but these developments may proceed at a slower rate due to technical challenges of further enhancing the injection pressure within the constraints of low cost and high reliability. Along with this increased injection pressure lead to lesser homogeneous mixing and smoke formation at the exaust of engines. Simultaneously improvements in the injector nozzle geometry have been taken place for reducing the emissions. [2]



**Figure1: Past And Projected Trends In Fuel Injection Pressure [2]**

Since emission legislation drive cycles require operation within lower rail pressure ranges at lower load and speed operating points, research into these lower fuel pressure areas is of great importance. [2]

## A. Types Of Diesel Combustion Systems:

Two types of diesel engines are classified according to the combustion chamber design [3].

- **Direct-Injection (DI) engines:** In these engines fuel is directly injected in to a single combustion chamber. Direct injection engines usually used in both small and large latest diesel engines.
- **Indirect-Injection (IDI) engines:** In these engines, combustion chamber is divided into two parts and the fuel is first entered into the “pre chamber” thereafter in main chamber. IDI engines are only used in light automotive application.

## B. Ignition Delay Theory :

When the charge (fuel air mixture) is ignited with a spark plug (in case of SI Engines) or making contact with hot compressed gases (in case of CI engines), it doesn't get burned immediately, rather there is a time lag between the two stages known as ignition delay of the fuel.

Ignition delay in diesel engines is divided into two parts:

- Physical delay
- Chemical delay

In physical delay fuel-air mixing takes place and the resulting mixture is raised in temperature. In chemical delay pre-flame reactions occurs before start of ignition. At higher

temperatures chemical reactions are quicker and physical delay exceeds chemical delay otherwise generally chemical delay is larger compared to physical delay. Auto- ignition is the spontaneous combustion of a mixture of fuel and oxidizer in the absence of any ignition source. After some period of mixing between the fuel and oxidizer, ignition occurs. It is the initiation of overall chemical reaction. There is another way of indication of ID times either by a fixed temperature increase or an evolution of certain species.

Physical delay consists of different phenomena for either gaseous or liquid fuels before a combustible mixture is formed. Generally, for gaseous fuels, the physical processes include heating, diffusion, and mixing of air and fuel. For liquid fuels, the physical processes, which are more complicated, involve fuel atomization, fuel heating, fuel evaporation, diffusion and mixing with air. Chemical processes involve the kinetics of pre-flame reactions. In a lean premixed system, the goal is to minimize the physical processes in an effort to get a nearly homogenous mixture prior to combustion. As a result, in these systems, where the mixing time is relatively short compare to chemical delay, the ID time then depends largely on the chemical kinetics. For liquid fuels, the time to form drops, the time for the drops to heat up and vaporize and finally mix with the oxidizer adds considerable physical time to the process. However, once the physical delay has occurred, the chemical delay time dominates and depends upon the kinetics [3].

Ignition of reacting flows governed by the chemical processes composed of many interwoven reactions between fuel, air, intermediate species, and products. Describing the entire overall reaction in one step is a common simplification of the problem and has been proven to be a practical solution. The reaction rate of this overall or global reaction can be expressed as follows:

$$RR = K_f [O_2]^j [Fuel]^m [P]^n \quad \text{----- (1)}$$

Where,

$K_f \rightarrow$  reaction rate constant,

$O_2$  and fuel concentrations are molar based,

$P \rightarrow$  Pressure,

Since the delay time is proportional to the inverse of the reaction rate, it can be expressed as a combination of the above two equations:

$$\tau \propto \frac{1}{A} \exp \frac{-E_A}{RT} [O_2]^{-j} fuel^{-m} P^{-n} T^{-0.50} \dots \dots \dots (2)$$

Previous work by Lefebvre et al and others suggests that this global reaction approach can be utilized to determine global activation energies (or apparent activation energies) for different fuels as well as exponents describing the dependency upon fuel and oxygen concentration as well as temperature and pressure.

ID is strongly dependent upon the activation energy of the reactions that comprise the reaction mechanism. Activation energy is the barrier that must be overcome for the initial decomposition reactions within a chemical kinetic mechanism. From the ignition delay expression, temperature, pressure, fuel concentration (or equivalent ratio) and oxygen concentration all play a role in the process. Since activation energy varies with molecule type, fuel composition plays an important role as well [4].

**Table 1: Summary of Physical Factor Affecting Ignition Delay [4]**

Increases in variable	Effect on delay Period	Reason
Injection Pressure	Reduces	Reduces physical delay due to great surface volume ratio
Injection timing advance	Reduces	Reduced pressure and temperature when the injection begins
Compression Ratio	Reduces	Increases air temperature and pressure and reduce auto ignition temperature
Intake Temperature	Reduces	Increases air temperature
Jacket water Temperature	Reduces	Increases wall and hence air temperature
Fuel Temperature	Reduces	Increases chemical reaction due better vaporization
Intake Pressure	Reduces	Increases density and also reduces auto ignition temperature
Speed	Increases in terms of crank angle. Reduces in terms of milliseconds	Reduces loss of heat
Load(F/A Ratio)	Decreases	Increases the operating temperature
Engine Size	Decreases in terms of crank angle. Little effect in terms of milliseconds	Larger engines operate normally at low speed

**C. Fuel Ignition Quality:**

Auto ignition property is most promising ignition quality of diesel fuel and is expressed in cetane number. The cetane number is defined as

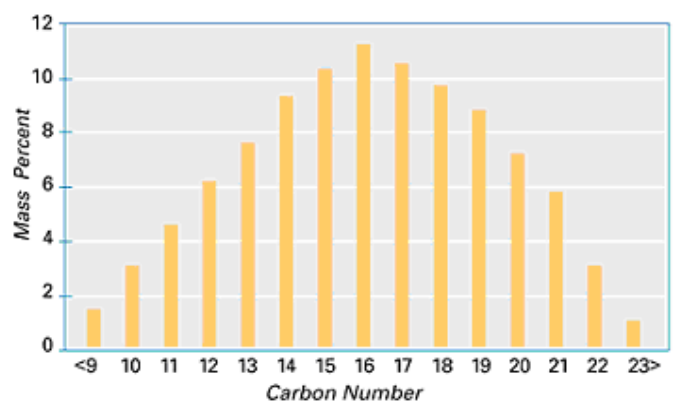
$$CN = \text{Percent n-cetane} + 0.15 \times \text{Percent HMN} \dots\dots (3)$$

A diesel index is also used to calculate the ignition quality of diesel fuels and is described as

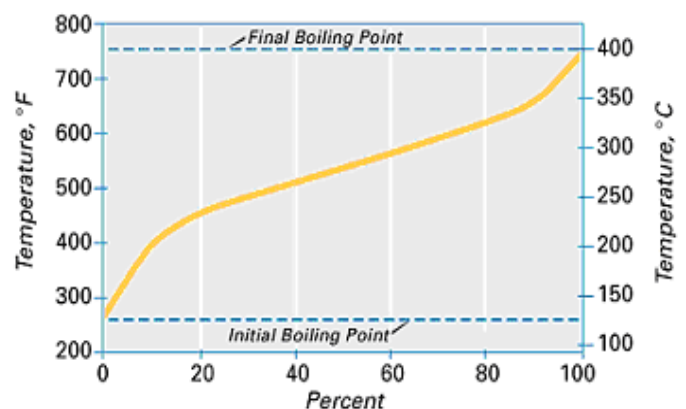
$$\text{Diesel index} = \text{aniline point}(\text{°F}) \times \frac{\text{API gravity}}{100} \dots\dots (4)$$

More API gravity denotes good ignition quality. The diesel index is slightly greater than Cetane number [5].

Diesel is a complex mixture of number of individual compounds mostly having carbon numbers between 9 to 23 and members of the paraffinic, naphthenic, or aromatic series having different physical and chemical properties. This chemistry of diesel fuel makes it different from other fuels. These physical and chemical properties are responsible for affecting the physical and chemical delay parts of ignition delay which can be understood by following figures.



**Figure 2: Carbon Number Distribution for Diesel Fuel [5]**



**Figure 3: Typical distillation profile for Diesel Fuel [5]**

**D. Necessity to Reduce Ignition Delay:**

Reduction in ID is required in diesel engines to enable adequate control over the combustion process such that the combustion stability of the engine can be maintained; when fuel is entered in the combustion chamber it doesn't get ignited quickly but rather requires a small but finite time to form a premixed combustible mixture for initiating the combustion. Since fuel is still

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continue to be injected during ID, therefore longer the ID, more will be the premixed burning and hence higher the peak of ROHR, leads to excessive NO<sub>x</sub> formation because of highest possible flame temp. Hence if the emissions of NO<sub>x</sub> are to be reduced, the ID also needs to be reduced.

### E. Effect of high pressure on Ignition Delay:

As we increase the pressure of combustion chamber, ID will decrease, due to high pressure better mixing and atomization is occur and in the way physical delay of combustion is reduce and lead to reduced ID because ID is sum of physical delay and chemical delay [4].

Earlier several experimental investigations have been done to know the ignition and emission characteristics of diesel engine based on various operating parameters. These experimental investigations and their findings are as follows:

The effect of nozzle size, nozzle cone angle and injection pressure were investigated on spray characteristics inside the HSDI engine using high speed photography and light extinction technique. The study concluded that injection pressure and nozzle size are the major influencing parameter compared to nozzle cone angle [6].

ID is small at high injection pressure due to the enhanced mixing as well as for high cetane number fuels at all injection pressure [7]. At different injection timings better spray atomization and evaporation takes place using very high injection pressures [8]. The ultrahigh injection pressure and microhole nozzle can be used to reduce the emissions [9]. Split injection can be used instead of single injection for faster reduction of soot at a particular injection pressure [10]. Fuel consumption and PM emissions can be reduced by employing higher fuel injection rate using increased nozzle hole number [11]. NO<sub>x</sub> and CO<sub>2</sub> emissions increased while there is lower smoke number, CO, and UHC emissions produced at high injection pressure [12]. The increasing injection pressure is in accordance with increasing power [13]. ID is significantly increased on advancing the injection timing [14]. ID is decreased with increase in injection pressure while it is less affected at high injection pressure and high surface temperatures [15]. Soot formation can be reduced by controlling the fuel injection timing [16]. ID of diesel and gasoline blended diesel fuel is strongly depending on HST [17].

## II. EXPERIMENTAL SET-UP AND TEST PROCEDURE

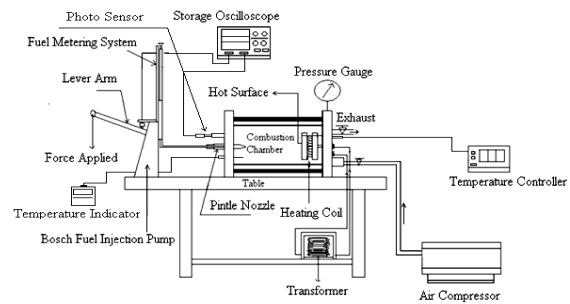


Figure 4: Block Diagram for the Experimental Setup

### A Various Components of Experimental Set Up

1. Bosch Fuel Injection Pump
2. Pump Plate:
3. Striking Pin
4. Rocker and Lever Arm
5. Fuel Metering
6. Piezo-electric Sensor
7. Photo Sensor
8. Injection Nozzle
9. Combustion chamber
10. Digital Oscilloscope
11. Temperature-Controller
12. Air Compressor
13. Temperature Indicator

### B Test Procedure

1. Initially the various components of the experimental setup are ensured to be well functioned and there should not any air in the fuel supply line before performing experiments.
2. Then metered fuel quantity is injected through the nozzle inside CVCC, when handle is manually given downward movement.
3. Then a signal appears in the digital oscilloscope which indicates the injection start event.
4. The oscilloscope shows the event when formation of the flame is detected by the optical sensor after completing the ID.
5. As ignition has been started the output can be seen on the oscilloscope.
6. Before each fuel injection sufficient fresh air is introduced in to the CVCC by opening the outlet valve after combustion.
7. Thus we can read on the of oscilloscope screen injection Start, injection stop and ignition start events.
8. The time interval between injection start to the ignition start gives the ID.
9. To minimize the error, the process is repeated five times at a given temperature and air pressure.
10. The mass of the injected fuel per stroke is kept constant.



### III. RESULTS AND DISCUSSION

An experimental study was conducted to know the variation in ignition delay with changing environment inside the combustion chamber for different sprays. Two types of nozzles namely pintle nozzle and single hole nozzle were used for creating hollow cone spray and solid cone spray respectively. Various studies have shown that the temperature and pressure inside the combustion chamber are the important parameters for a given fuel composition. Ignition delay data from experiments have usually been correlated by Arrhenius equation given below:

$$\tau_{id} (ms) = A P^{-n} \exp(E_A / RT) \dots\dots\dots (5)$$

Where:

$\tau_{id}$  = Ignition Delay in millisecond,

$P$  = Pressure in atmosphere,

$E_A$  = Apparent activation energy

$R$  = Universal gas constant,

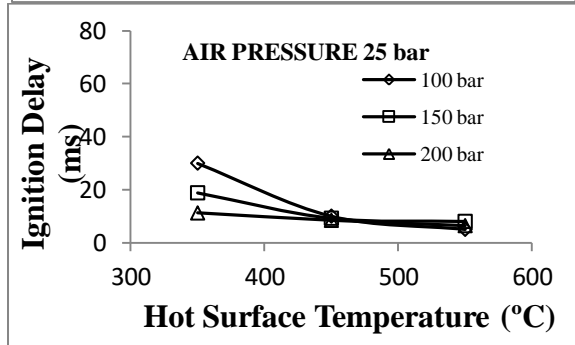
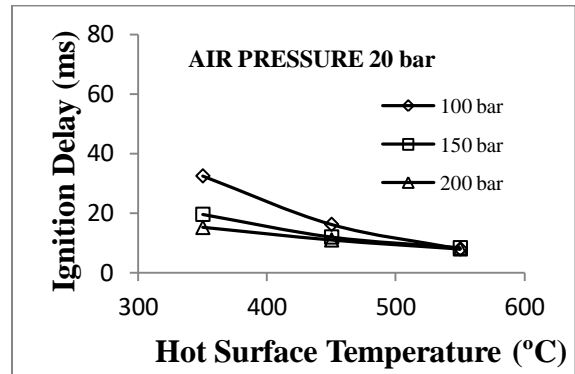
$T$  = Temperature in Kelvin,

$A, n$  = Constants dependent on fuel

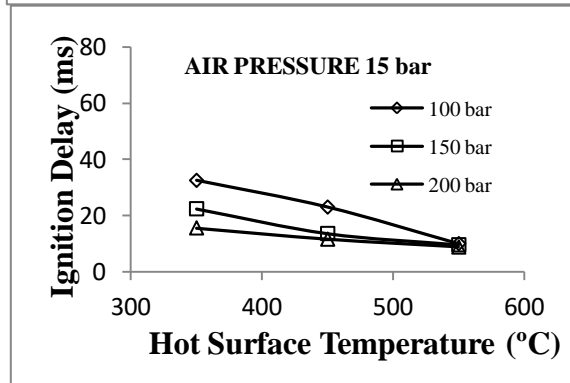
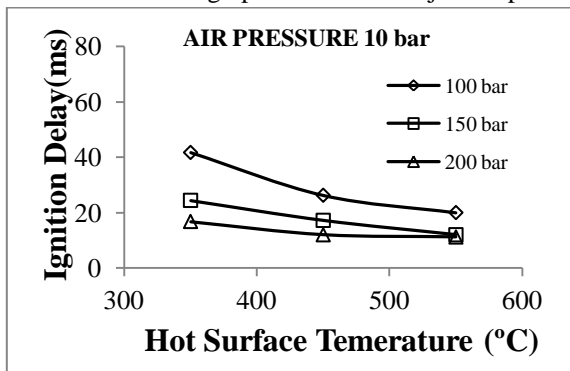
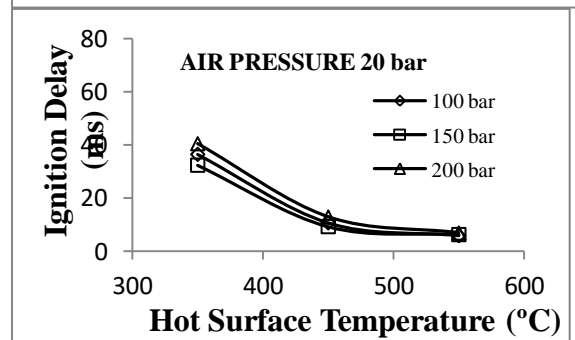
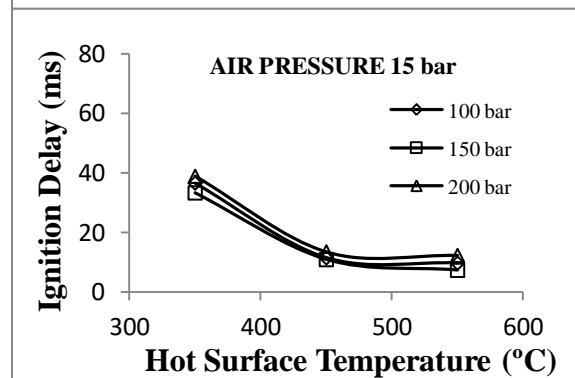
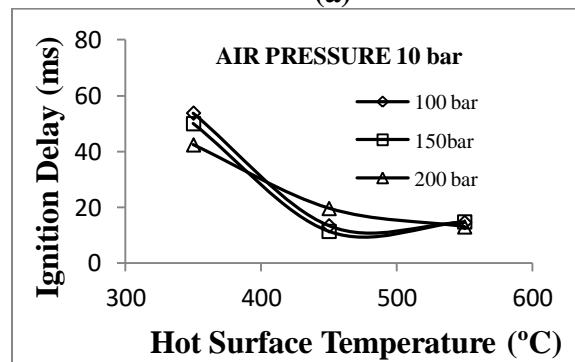
Several researchers gave the value of constants of above equation.

Our study were carried at different injection pressures (100 bar, 150 bar and 200 bar), different HST (350°C, 450°C and 550°C) and different air pressures (10 bar, 15 bar, 20 bar and 25 bar) for obtaining the value of ID.

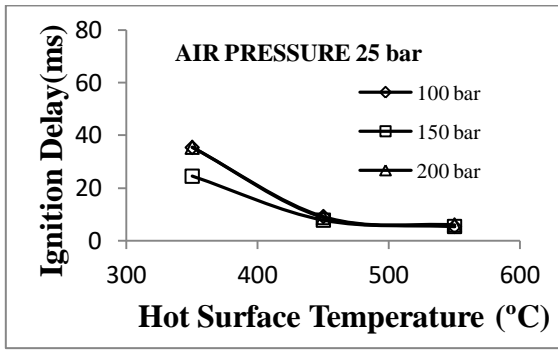
After executing the experiments, various results or findings are obtained which can be described by understanding the nature of different graphs for various injection pressures.



(a)



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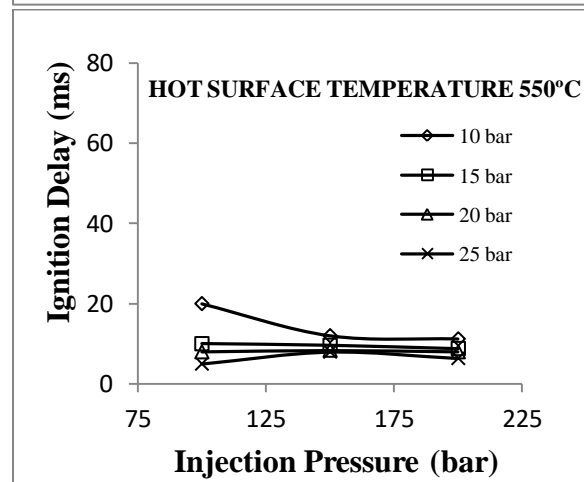
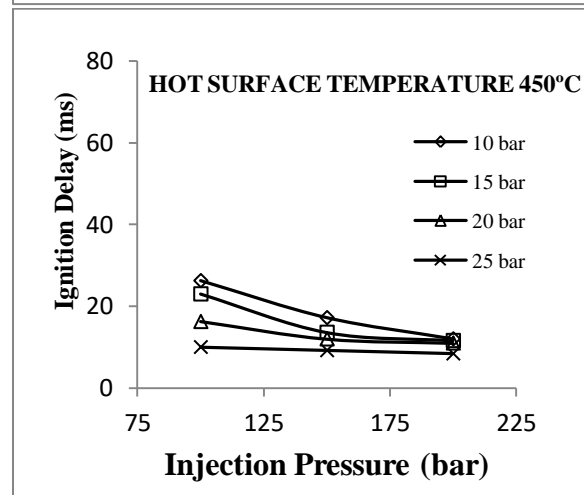
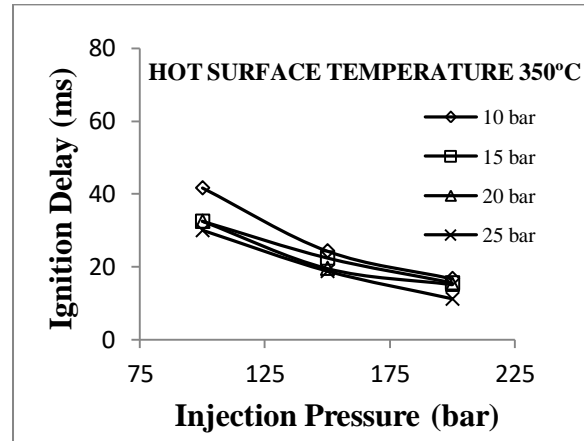
(b)

**Figure 5: Variation of ID with HST at Different Injection Pressure for (a) Hollow Cone Spray (b) Solid Cone Spray**

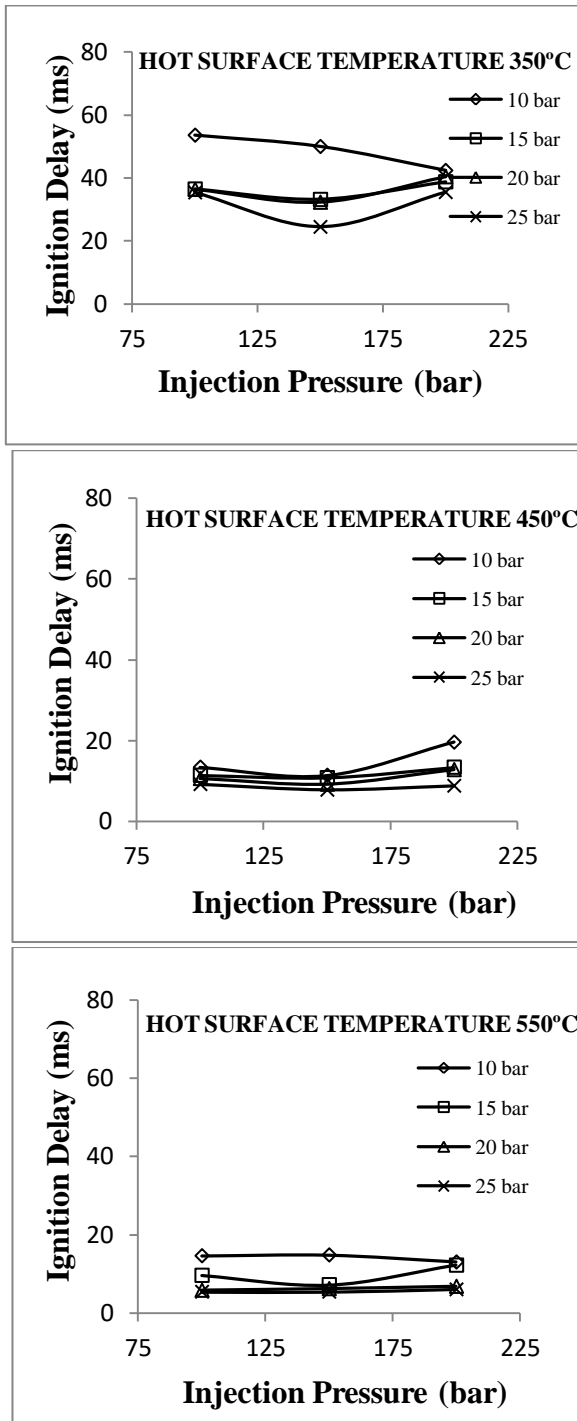
Figure 5(a) shows the variation of ID with HST for various Injection Pressures at a fixed Air Pressure for Hollow Cone Spray. At the Air pressure of 10 bar, as the HST increases, the value of ID is decreasing at a particular Injection Pressure. And as the Injection Pressure is increasing at a particular HST, the value of ID is also decreasing here. At the Air Pressure of 15 bar, as the HST increases, the value of ID is decreasing at a particular Injection Pressure. And as the Injection Pressure is increasing at a particular HST, the value of ID is also decreasing here. But at the HST greater than 450°C the difference in ID is less as compared to the HST lesser than 450°C. At the Air Pressure of 20 bar, as the HST increases, the value of ID is decreasing at a particular Injection Pressure but the decrease in ID is less at higher Injection Pressures. And as the Injection Pressure is increasing at a particular HST, the value of ID is slightly decreasing up to the HST of 450°C. But at the HST greater than 450°C the difference in ID is very less as compared to the HST lesser than 450°C. At the Air Pressure of 25 bar, as the HST increases, the value of ID is decreasing up to 450°C but after 450°C the decrease in value of ID is marginally, at a particular Injection Pressure. And as the Injection Pressure is increasing at a particular HST, the value of ID is also decreasing here up to the HST 450°C but after 450°C the value of ID is almost constant.

Figure 5(b) shows the variation of ID with HST for various Injection Pressures at a fixed Air Pressure for Solid Cone Spray. At the Air Pressure of 10 bar on increasing HST, ID value is decreasing up to 450°C and then it slightly increases, at a particular Injection Pressure. And as the Injection Pressure is increasing at a particular HST, ID value is also decreasing here. But there is less difference in ID in between 150 bar-200 bar than the ID obtained in range of 100 bar -150 bar. At the Air Pressure of 15 bar as the HST increases, the value of ID is continuously decreasing, at a particular Injection Pressure. But at the HST greater than 450°C the difference in ID is less as compared to the HST lesser than 450°C. And as the Injection Pressure is increasing at a particular HST, variation in the value of ID is following same pattern as in the case of Air Pressure of 10

bar. At the Air Pressure of 20 bar the pattern of variation of ID with HST and Injection Pressure is same as that of 15 bar Air Pressure. At the Air Pressure of 25 bar the ID is decreasing up to 450°C but after that it is almost constant at a particular Injection Pressure. And as the Injection Pressure is increasing there is marginal change in the ID but still it is decreasing.



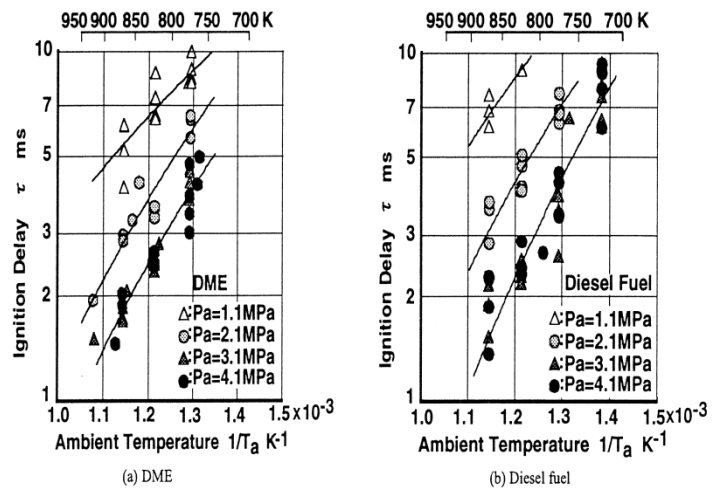
(a)



**Figure 6: Variation of ID with Injection Pressure at Different Air Pressure for (a) Hollow Cone Spray (b) Solid Cone Spray.**

Figure 6(a) shows the variation of ID with Injection Pressures for various Air Pressures at a fixed HST for Hollow Cone Spray. It is clear from the graphs in this figure that on increasing the Injection Pressure or Air Pressure, the value of ID is decreasing continuously at a fixed HST. On increasing the HST, the ID obtained is less and there is less variation among various Air Pressures. Figure 6(b) shows the variation of ID with Injection Pressures for various Air Pressures at a fixed HST for Solid Cone Spray. At HST of 350°C, the value of ID is first decrease then it slightly

increases on increasing the Injection Pressure at a particular Air Pressure. And as we increase the Air Pressure, ID is decreasing but there is marginally change for 15 bar and 20 bar Air Pressure. At HST of 450°C, the value of ID is first slightly decreases then it slightly increases on increasing the Injection Pressure at a particular Air Pressure. And as we increase the Air Pressure, ID is marginally decreasing. At HST of 550°C, the value of ID is first marginally decreases on increasing the Injection Pressure at a particular Air Pressure. And as we increase the Air Pressure, ID is decreasing. Wakai shows the Arrhenius expression of the ID of the DME and Diesel fuel sprays. In the Fig.8 the ordinate is the logarithmic ID and the abscissa is the reciprocal ambient temperature. This shows that the variation of ID with ambient temperature plays a important role and it decreases with increases ambient temperature. So the trend obtained in our results is also matched with the wakai results [18].



**Fig. 8 Ignition delay under various ambient pressures**

#### IV. CONCLUSION

By changing the environment inside the combustion chamber and injection pressure, value of ID is varying significantly. The results are concluded as follows:

- At all air pressure ID is decreasing with increasing HST at fixed injection pressure for hollow cone spray. For solid cone spray ID is decreasing with increasing HST on all air pressure except 10 bar at fixed injection pressure.
- ID is decreasing with increasing injection pressure on all HST at fixed air pressure in case of hollow cone spray. For solid cone spray from 100 bar to 150 bar, ID decreases but from 150 bar to 200 bar ID slightly increases (mainly at lower HST of 350°C).
- Although air pressure, injection pressure and HST all are responsible for variation in ID but HST is more strongly affect the ID compared to other parameters.

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However at high temperatures the strong dependency is diluted.

- The effect of injection pressure is also important at low and moderate range while for very high range its dependency on ID is less. The effect of air pressure on ID is significant at low temperatures but at high temperature its dependency on ID is marginal.
- The dependency of type of spray is also good on ID and this dependency is more in lower temperature ranges compared to higher temperature ranges.
- At all air pressure trend of variation in ID is same for both spray but at 10 bar air pressure, value of ID is decreasing for increasing HST at all injection pressure for hollow cone spray while for solid cone spray, ID is decreasing till 450°C but above 450°C it is slightly increases at lower injection pressure (100 bar and 150 bar).
- At low air pressure, high injection pressure and lower HST, the variation in ID high.
- At high air pressure, low injection pressure and higher temperature the variation is very less.

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