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STUDY OF IGNITION DELAY OF KEROSENE BLENDED DIESEL FUEL SPRAYS IN A CYLINDRICAL COMBUSTION CHAMBER

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Abstract: *An experimental study of the measurement of ignition delay (ID) characteristics of conical fuel sprays impinging on hot surface in cylindrical combustion chamber was carried out. The objective of the study was to investigate the effect of hot surface temperatures on ignition delays at various ambient air pressures. As power density of modern high speed direct injection (HSDI) diesel engines is increasing so is the increase in the piston's surface temperature of the engine. An attempt has been made to experimentally simulate the effect of ever increasing hot surface temperatures on ignition characteristics of conical sprays. Since diesel engines are considered to be capable of consuming a number of fuels therefore the effect of blending of kerosene in HS diesel was investigated. Hot surface temperature range chosen was 300°C to 450°C and ambient air pressure range chosen was 5 bar to 25 bar. The results here show that ignition delays of HS diesel fuel and various kerosene blends decrease with increase in the hot surface temperature. Optical method is used for measurement of ignition delays.*

Keywords: Surface temperature, Diesel engine, Ignition delay, Combustion chamber, kerosene Blending

1. Introduction

High power density of modern diesel engines in excess of 70 KW/liter of displacement is not only leading to an increase in the use of high temperature resistant alloys in pistons but also the increased cylinder pressures up to 180 bar. The temperature of the piston bowl rim within the cylinder of modern diesel engines is of the order of 400°C to 420°C. When temperature of diesel engine's piston increases beyond 400°C then its role in the ignition of spray also becomes an interesting aspect.

The pistons for modern diesel engines are now made of aluminum alloy. The second most prevalent material being silicon followed by other metals including copper and nickel. The alloying material helps not only in increasing the mechanical strength of the piston but also matches thermal expansion with that of liner. Increasing engine pressures are the consequence for the drive of high efficiency in small HSDI diesel engines. Since modern diesels have 180 to 190 bar pressure. The result of this high cylinder pressure is high specific output which means better fuel consumption [1].

Impingement of the fuel jet on the walls occurs in almost all of the smaller, high speed engines. For the 'M' system, this impingement is desired to obtain smooth pressure rise. In the M.A.N. 'M' system, hot surface ignition is realized since most of the fuel from the single-hole pintle nozzle is placed on the walls of the spherical bowl in the piston crown. Other studies have also shown that about 75% of fuel injected in the diesel engine cylinder gets deposited on the surface from where it evaporates, mixes with air and then supports combustion process.

Spray-wall interactions also depend on the distance from the nozzle to the impact surfaces as impacted conditions depends on momentum and energy exchanged as spray approaches the surface [2].

Use of hot surface ignition has emerged as a preferred combustion actuating mechanism for realizing the benefits of direct injection (DI). Key reasons for choosing the hot surface ignition approach include the combustion robustness of a continuous ignition source. Hot surface ignition is a preferred means of initiating combustion of diesel injected at or near TDC [3].

2. Experimental Set-Up

2.1 The block diagram of experimental set up is shown in Fig 2.1 given below.

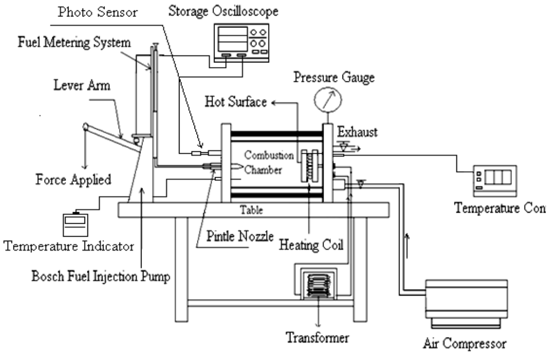

Figure 2.1: Block Diagram of the Experimental Set Up.

2.2 Various Components of Experimental Set Up-

2.2.1 Combustion Chamber

Combustion chamber in present experimental set-up is a stainless steel cylindrical tank having a volume of 890.641 cm^3.

2.2.2 Fuel Injection Nozzles-Pintle nozzle

2.2.3 Fuel Pump: Bosch fuel injection pump.

2.2.4 Pressure Indicator: Pressure gauges are used for the measurement of ambient air pressures developed inside the combustion chamber cylinder.

2.2.5 Universal Temperature Indicator and Controller: Temperature indicator used in present experimental work measures temperature of the hot surface of stainless steel plate inside the combustion chamber and it is a digital temperature controller and indicator.

2.2.6 Photo Sensor: The photo sensor is attached to the chamber to detect the event of start of combustion.

2.2.7 Heating Element: Heating element or coil used in present experimental set up act as a heater. The heating element of 500 Watt is placed between two stainless steel plates and heats the two surrounding stainless steel plates. The front plate act as the hot surface and the ambient air gets heated when comes in contact with these two hot plates.

2.2.8 Digital Storage Oscilloscope: The oscilloscope used in present experimental set up is a digital storage two channel oscilloscope. On one channel it shows the fuel injection process and on the other channel it shows the combustion process.

2.2.9 Centrifugal Air Compressor: Air compressor is used to supply compressed air to the combustion chamber at varying pressures.

2.2.10Temperature Indicator: Temperature indicator is used to display the temperature of the hot air as well as of hot surface.

Fuel Tested

In present work, commercially available HS diesel fuel having Diesel index-60 has been chosen as base line fuel. The HS diesel fuel is tested for the variation of ignition delay with the change in temperature of hot surface and ambient air pressures inside the combustion chamber. The available HS diesel fuel is blended with 10%, 20%, 30%, and 40% of kerosene.

Measurement of Ignition Delays

Since oscilloscope is a two channel oscilloscope therefore it can displays both these events i.e. fuel injection process and combustion process each on separate channel simultaneouslyon the screen of oscilloscope as shown in Fig. 2.2 given below.

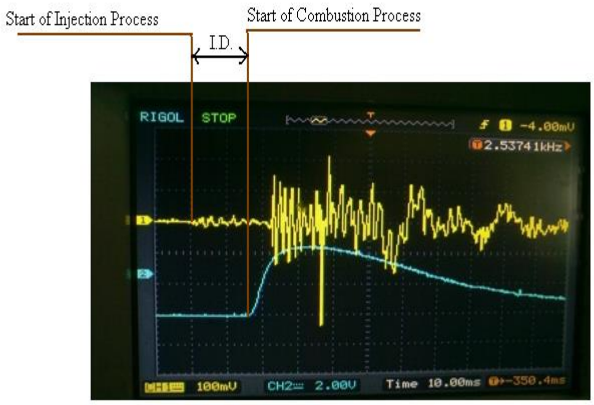

Figure 2.2: Ignition Delay Measurement.

3. Result and Discussions

3.1 Analysis of Diesel Ignition Delays:

Experiments were conducted on commercial HS diesel fuel for the measurement of ignition delays to generate base line characteristics. These base line characteristics of HS diesel fuel were then compared with the characteristics of blends of diesel with the kerosene fuel. In present study commercial HS diesel fuel was used which is available in the market. All the blends and samples were prepared after careful filtration and accurately measured blending. Experimentally, ignition delays results on hot surface were obtained for HS diesel and for different blends of HS diesel and compared with that in the literature available.

Most of the studies in the literature are conducted at high pressures and temperatures of hot air. Present study was conducted at high ambient air pressures and high hot surface temperatures to analyze the hot surface ignition in the real diesel engine combustion like environment. In present study, hot surface ignition are studied experimentally and the effects of hot surface temperatures and air pressures on the ignition delays of HS diesel fuels and its blends are studied. Since in the real HS diesel engine, combustion takes place in hot air. So in present study the effects of high temperatures and pressures of hot air developed in diesel engine combustion chamber on the ignition delay of fuels can also be analyzed.

Basic studies in the constant-volume bomb, in steady flow reactors, and in rapid compression machines have been used to study the auto ignition characteristics of the fuel air mixture under controlled conditions. In some of these studies the fuel and air are premixed; in some, fuel injection was used. Studies with fuel injection into constant temperature and pressure environment have shown that the temperature and pressure of the hot air are the most important parameters for a given fuel composition. Ignition delay data from these experiments have usually been correlated by Arrhenius equation given below [5]:

$$\tau_{id}(ms) = AP^{-n}\exp(E_A/RT) \qquad (4.1)$$

Where: τ_{id} = I.D. 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.

In present experiments, photo sensor was used to record the start of combustion as it senses the light falling on it due to combustion and sends this signal to the oscilloscope. Hence in present study optical method was used to measure the ignition delay.

It can be observed from the Fig. 3.11given below, that with increase in the temperature of the hot surface, measured ignition delays decrease continuously as reported [7]. Since ignition delay consists of two parts and is a sum of physical delay and chemical delay. With increase in the temperature of hot surface, chemical delay of the impinging fuel spray decreases because preflame chemical reactions occurring during chemical delay become fast. Thus chemical delay decreases with increase in hot surface temperature. The other reason for decrease in ignition delays with hot surface temperatures may be the faster mixing rate resulting from faster fuel evaporation on hot surface. The impingement of the spray on the hot plate will affect the fuel evaporation process and fuel-air mixing process.

In Fig. 3.12 given below, it can be seen that the same trends are there for variation of ignition delays with ambient air temperature. The line represents the average ignition delays of diesel fuel. Ignition delays decreases with increase in ambient air temperature. The reason is same as above, chemical delay decreases with increase in ambient air temperature. Another reason may be that since diesel fuel is a very complex mixture of thousands of individual's compounds [6] most with carbon number varying from 10 and 22. Most of these compounds are the members of paraffinic, napthenic and aromatic class of hydrocarbons. These three classes of hydrocarbons have different chemical and physical properties. The boiling range of the hydrocarbons contained in the diesel is 400-600 K [6]. At low temperature, the lower hydrocarbons present in the diesel fuel vaporized earlier than the higher hydrocarbons (boiling point of hydrocarbon increases with increase in the number of carbons atoms [8]). But the alkyl group produced by the lower hydrocarbon does not oxidize easily and hence at lower temperature therefore ignition delay becomes longer. While as the temperature of the ambient air increases the alkyl group of the lower hydrocarbons present in the diesel fuel oxidizes easily and rapidly as well as the higher hydrocarbons present in the diesel fuel vaporizes easily hence causing relatively shorter ignition delays at higher ambient air temperatures.

Figure 3.13 given below shows the variation of ambient air temperature as a function of hot surface temperature. It can be noted from Fig. 3.13 that ambient air temperature is increasing gradually with the hot surface temperature and ambient air temperature inside the combustion chamber is increasing only due to the increase in hot surface temperature. There is no other heat source inside the combustion chamber responsible for the increase in ambient air temperature.

It can be seen from the two Figs. 3.11 and 3.12 that with increase in ambient air pressure, the ignition delays of HS diesel decrease. Ignition delays are longest at lower air pressure and shortest at higher ambient air pressure i.e., at 25 bar. The reason is that with increase in intake pressure of air, the density of air increases and increase in density of ambient air reduces auto ignition temperature of fuel and hence the ignition delay decreases with ambient air pressure increase. From the above Fig. 3.12 it can also be noted that at high temperature irrespective of air pressure, the diesel ignition delays almost become constant.

3.2: Effect of Ambient Air Pressure and Hot Surface Temperature on Ignition Delays of n Kerosene Blended Diesel

Results in Fig. 3.21 given below show the variation of ignition delays with hot surface temperatures at different ambient air pressures for different blends of kerosene in HS diesel fuel. Four blends

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of kerosene in HS diesel fuel (10%, 20%, 30% and 40%) are studied to analyze other properties of diesel fuel oil in diesel engine combustion environment. Results in following Fig. 3.21 show that ignition delays of kerosene blends decrease continuously with increase in hot surface temperatures from 300°C to 450°C. The reason for decrease in ignition delays is that with increase in hot surface temperatures, the mixing rate of fuel vapor and air become fast due to the fast fuel evaporation on high hot surface of plate and faster rate of burning. The impingement of fuel spray on hot surface will affect the fuel evaporation process and mixing process [5]. Same results were reported [7] that with increase in wall temperatures inside the constant volume combustion bomb, ignition delays decrease gradually. Therefore shortest ignition delays of kerosene blends are obtained at highest hot surface temperature and longest ignition delays are obtained at lowest hot surface temperature.

Results in Fig. 3.21 given below show that at hot surface temperatures from 300°C to 450°C, the ignition delays decrease with ambient air pressures when increased from 5 bar to 25 bar for all blends of kerosene. The reason may be that increase in ambient air pressure increases the density of the compressed air resulting in closer contact of the molecules thereby reduces time of reaction when fuel is injected hence reduces the minimum autoignition temperature of the fuel and therefore the ignition delays decrease.

3.3: Comparison of Ignition Delays of Diesel with Kerosene Blended Diesel

The Fig. 3.31 given below shows the variation of ignition delays of HS diesel fuel with the kerosene blended diesel at various ambient air pressures (5 bar – 25 bar) for various concentrations of kerosene in HS diesel. In the Fig. 3.31, ignition delays of all blends (10%, 20%, 30% and 40% by volume in diesel) of kerosene at particular ambient air pressure are represented by an average line. It can be noted from the Fig. 3.31 given below that the ignition delays of all four blends of kerosene are shorter that the ignition delays of HS diesel at all ambient air pressures (5 bar to 25 bar) and at hot surface temperatures from 300°C to 450°C studied. Kerosene contains a variety of hydrocarbons but compounds having C_{10}-C_{13} dominates in its composition. As stated before overall average properties of kerosene are very roughly equivalent to dodecane [10], $C_{12}H_{26}$ which is a paraffinic compounds (high carbon number alkane) and therefore the addition of normal alkane improve ignition quality of blends i.e., cetane number increases and therefore ignition delays decrease [5]. The critical temperature and pressure of dodecane is 661 K and 1.81 MPa respectively [10].

Table 1.1: Properties of HS Diesel and Kerosene

HS Diesel		Kerosene	
Flash Point	43°C to 88°C	Flash Point	38°C to 74°C
Boiling Point	240°C to 370°C	Boiling Point	150°C to 300°C
Auto-ignition Temp	257°C	Auto-ignition Temp	210 to 227°C

The boiling point range of kerosene is 150°C to 300°C. While the boiling point range of HS diesel is 240°C to 370°C. Also flash point (the minimum temperature at which fuel vapor-air mixture ignite above a liquid fuel) of HS diesel (43°C to 88°C) is higher than kerosene (38°C to 74°C) as shown in Table 1.1 above. Therefore as in case of n-pentane and n-hexane blends, kerosene blends sprays vaporize fast in the low temperature ambient air and forms combustible mixture with ambient air and ignition occurs rapidly due to low flash point temperature of kerosene blends sprays as soon as it reaches the hot plate. Since boiling point of HS diesel fuel is higher than kerosene therefore spray of HS diesel reaches the hot plate and then vaporization and ignition occurs on surface of hot plate. Therefore during low temperature operation, ignition delays of HS diesel are longer than kerosene blends. However during high temperature operation, HS diesel fuel sprays also vaporize in the high temperature ambient air like that of kerosene blends sprays and ignition occurs as soon as it reaches the hot plate. Therefore ignition delays of HS diesel and kerosene blends are nearly equal at high hot surface temperature. So at higher hot surface temperature of about 450°C, blending effects on ignition delays of HS diesel are minimal.

The magnitude of ignition delays of HS diesel and kerosene blends measured in present study are higher (15 ms to 20 ms) than found in actual HSDI diesel engines at normal engine operating conditions. Because in present study ignition of conical spray was achieved on hot surface and nozzle to hot plate distance measured was 64 mm, which also play an important role in ignition because impact conditions depend on momentum and energy exchanged as spray approaches the surface. However in actual HSDI engines, hot air ignition of spray occurs which reduces ignition delays in HSDI diesel engine at same high ambient temperatures and ambient air pressures.

Results in Fig. 3.31 given below show that a reduction of nearly 50% was achieved in ignition delays of kerosene blends due to increase in hot surface temperature from 300°C to 450°C. Results from constant volume combustion bomb studies [7] show that ignition delay at 470°C and 25 bar was in between 10-15 ms however ignition delays of HS diesel fuel and kerosene blends found in present study were nearly from 15 ms to 20 ms at same operating conditions of DI engine. This validates the results of present study. The slight difference in magnitudes may be due to the difference in methods used to measure the ignition delays and size of combustion chamber used in the two studies.

3.4: Effect of Concentration of Kerosene Blending on Ignition Delays

In the present study, different amounts of kerosene were added in the HS diesel fuel. Kerosene was added in HS diesel fuel in percentages of 10%, 20%, 30% and 40% by volume. It can be seen from the Fig. 3.41 given below that with increase in hot surface temperature from 300°C to 450°C, ignition delays of all blends of kerosene in diesel fuel decrease due to the same reason as stated before. Decrease in ignition delays are larger at lower hot surface temperatures from 300°C to 350°C and at lower ambient air pressures from 5bar to 15bar with increase in concentrations. However as the hot surface temperature increases beyond 350°C and ambient air pressure beyond 15bar inside the combustion chamber there is little effect of the concentrations on ignition delays. At high hot surface temperatures from 400°C to 450°C and ambient air pressures from 20 bar to 25 bar, the ignition delays are almost constant with increase in concentration. No significant effects on ignition delays are there due to concentration at high hot surface temperatures and high ambient air pressures typical of normal HSDI diesel engine operation.

Kerosene is a common multicomponent liquid fuel in applications. Kerosene is a blend of relatively nonvolatile petroleum fractions. It typically consists of 60% of paraffins, 32% of naphthenes and 7.7% of aromatics by volume. The overall average properties of kerosene are very roughly equivalent to dodecane, $C_{12}H_{26}$. The critical temperature and pressure of dodecane is 661 K and 1.81 MPa respectively [10]. Kerosene contains a variety of hydrocarbons but compounds having C_{10}-C_{13} dominates in its composition hence very near to diesel as far as distillation of petroleum is concerned. The boiling point range of kerosene is 425 K-525 K. Since kerosene (high percentage of paraffins) properties are roughly equivalent to dodecane, which is an alkane and paraffinic compound therefore addition of alkanes (high carbon number alkane) improves ignition quality i.e., cetane number increases. Therefore addition of kerosene decrease ignition delays of the blends and as the concentration of kerosene increase in blends, the ignition delays decrease further. The other reason may be that with the increase in concentration of kerosene in blends, also concentrations of compounds having low boiling as well as flash point compared to HS diesel fuel increase in blends and hence the ignition delays of blends decrease.

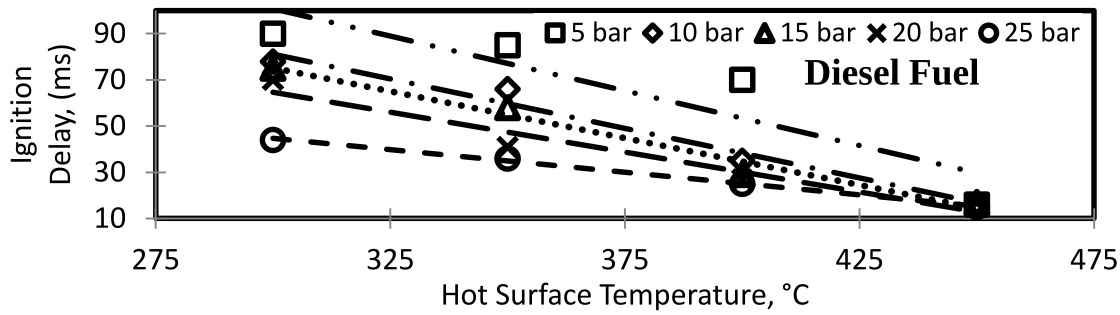

Figure 3.11: Ignition Delay versus Hot Surface Temperature

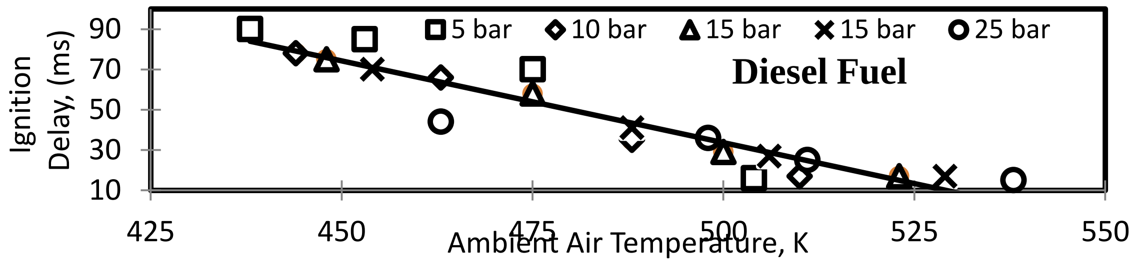

Figure 3.12: Ignition Delay versus Ambient Air Temperature

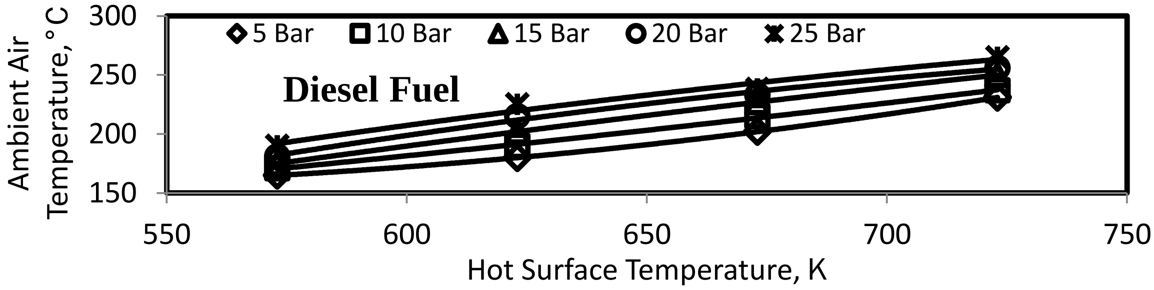

Figure 3.13: Ambient Temperature versus Hot Surface Temperature

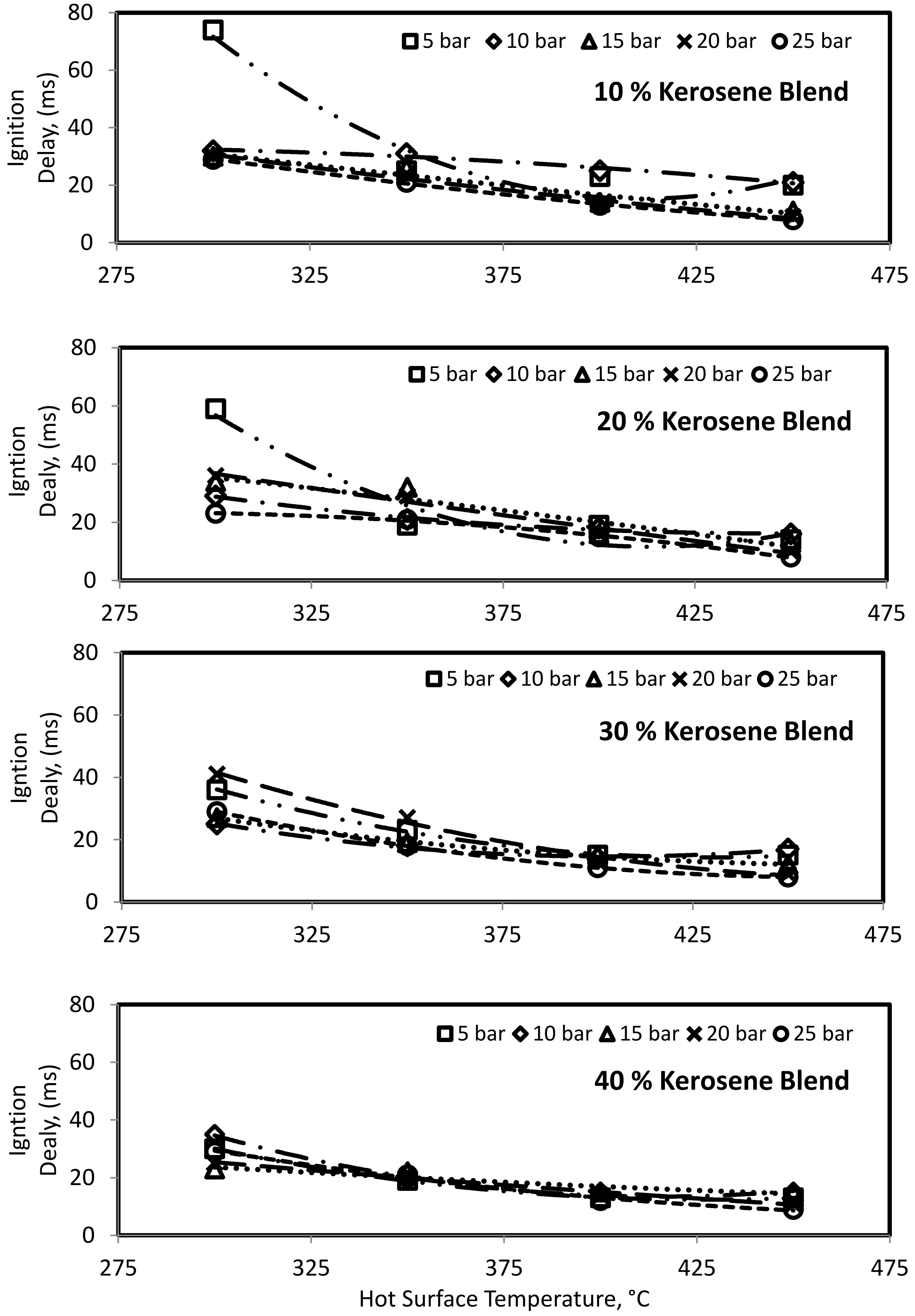

Figure 3.21: Variation of Ignition Delays of kerosene Blends with Hot Surface Temperatures at Different Ambient Pressures and Concentrations.

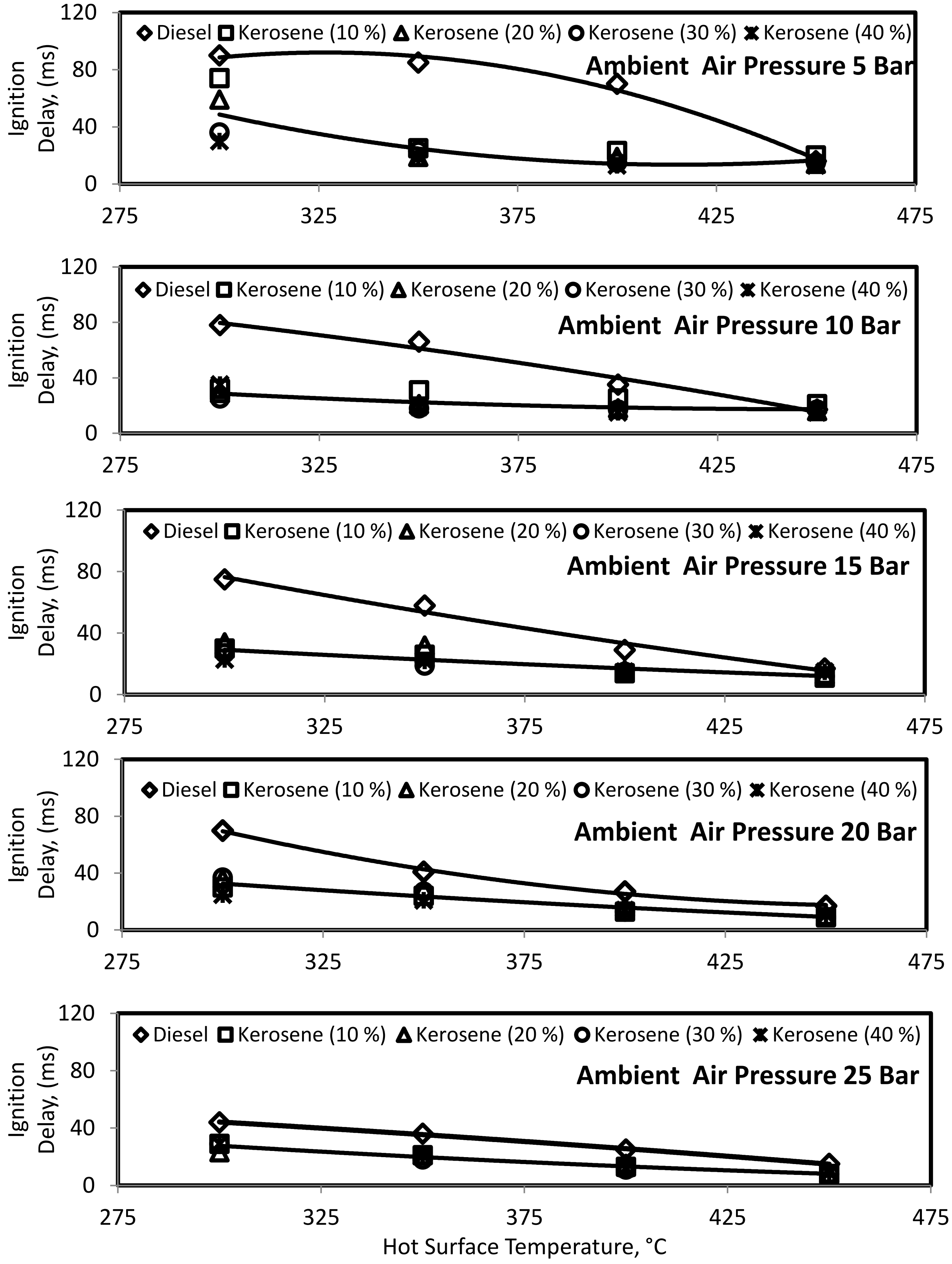

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Figure 3.31: Variation of Ignition Delays of Kerosene Blends and Diesel with Hot Surface Temperature at Different Ambient Pressures.

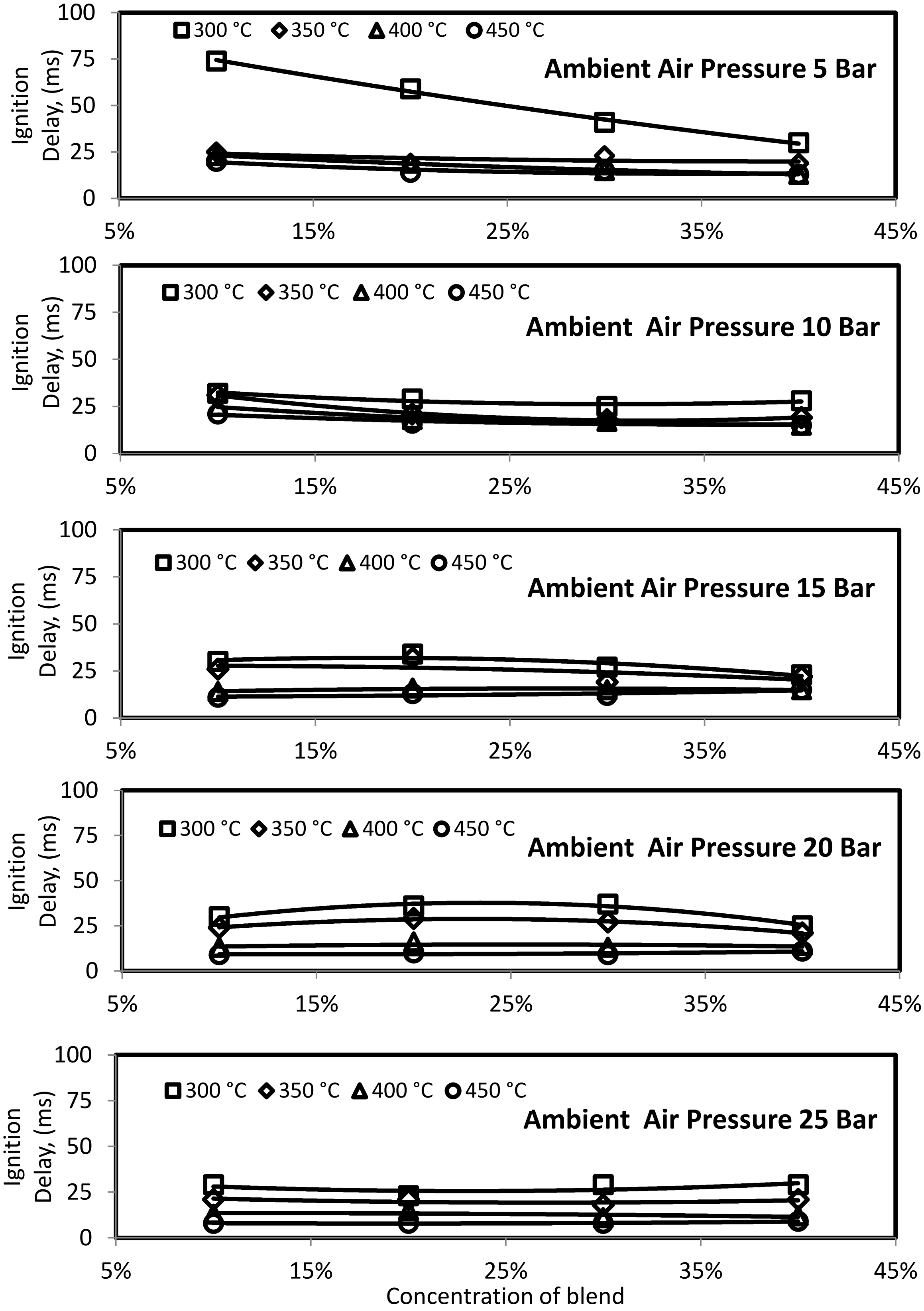

Figure 3.41: Effect of Concentration of kerosene Blend with Diesel on Ignition Delays at Different Ambient Pressures.

5. Conclusions:

The present study has shown that the effect of blending of fuel on ID on the hot surface mitigates as soon as the surface temperature exceeds 450°C. A temperature of 450°C of the hot surface is also coinciding with the ignition temperature of not only diesel but most of the HC fuels. Other studies have also shown that about 75% of fuel injected in the diesel engine cylinder gets deposited on the surface from where it evaporates, mixes with air and then supports combustion process. It is also important to note that as the power density of modern diesel engine has already reached from 30 KW/lit to 70 KW/lit, the piston surface temperature as a consequence of higher power density has also increased from 350°C to 450°C. It is therefore important to note that with the further increase in power density, the piston surface temperature is also likely to increase therefore the role of piston surface as a source of ignition cannot be ignored.

Ignition delays in real HSDI diesel engine are shorter than those found in present study at typical normal engine operating conditions. In HSDI diesel engine, hot air ignition takes place however in present study hot surface ignition was studied. However magnitude of ID matches more closely with that for large bore marine and stationary diesel engines.

The reduction in ignition delay with the increase in temperature of hot surface has also shown that 80% reduction in HS diesel ID was also achieved in only 50% increase in surface temperature. Any reduction in ID cause reduction in premixed combustion after the completion of ignition delay therefore it is reasonable to assume that a reduction in the amount of premixed charge burn after the completion of ID also leads to corresponding reduction in the amount of nitric oxide as most of the nitric oxide forms during premixed burning after completion of ID.

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