MECHANICAL ENGINEERING | RESEARCH ARTICLE

Hot surface ignition and combustion characteristics of sprays in constant volume combustion chamber using various sensors

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Abstract: In present study, ignition and combustion characteristics of hollow conical diesel fuel sprays are studied experimentally in constant volume combustion chamber using hot surface ignition technique at various operating conditions. Sensor based measurement techniques like needle lift sensor, photo (optical) sensor and piezoresistive pressure transmitter sensor are used to measure the ignition, combustion and injection characteristics. In this study, hot surface temperatures (HST) varied from 623 to 723 K, cylinder air pressures (CP) varied from 20 to 40 bar and fuel injection pressures varied from 100 to 400 bar. It is found that ignition and combustion characteristics are significantly affected by fuel injection characteristics. Luminous ignition delays (ID) of the diesel sprays significantly reduced with the increase in hot surface temperatures and cylinder air pressures and variation is nonlinear. Effect on ID mitigates as hot surface temperature and cylinder air pressure rise to higher values. Rate of heat release (at maximum pressure) rises with increase in hot surface temperatures but decreases with rise in cylinder air pressures. Rate of heat release increment is minimized as hot surface temperature increases. Also,

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His research group are continuously developing and testing new innovative research facilities in the field of combustion system like Constant Volume Combustion System, Rapid Compression Machine, High Speed Diesel Engine Test Bed etc. In these systems performance and combustion characteristics are investigated at typical engine operating conditions. Constant volume system is a high pressure combustion system simulating diesel engine combustion. Supercritical combustion process of diesel sprays are recent research activities in constant volume combustion system. Present reported work for conventional diesel combustion provides a basis for comparison with supercritical diesel combustion.

PUBLIC INTEREST STATEMENT

Present scenario of world shows fast depletion of petroleum oil reserves and also increasing environmental concern regarding air pollution. Air pollution is causing numerous health problems in living beings. Since mostly air pollution is due to automotive engines emissions. Therefore these factors demand continuous research and development in field of automotive engines. Engines combustion systems are mainly responsible for engines emissions. Diesel engine emissions like nitrogen oxides and smoke are major pollutants of air pollution. Nitrogen oxides and smoke depend on ignition characteristics of fuel in diesel engines. Present research work focuses on factors affecting these characteristics which in turn effect air pollution. Present study reflects combustion process of small sized diesel engines. Present research work provides a basis for comparison with supercritical combustion system. Supercritical diesel combustion will be studied at same operating conditions as a part of future work. Supercritical diesel combustion is a promising technology in term of efficiency and emissions.
rate of heat release reduces with increase in cylinder air pressure. Duration of burn/combustion reduced with increase in cylinder air pressures and hot surface temperatures. At higher surface temperature, the effect of surface temperature on duration of burn mitigates. Peak pressure increases with rise in hot surface temperatures. Hence, hot surface ignition effect on ignition and combustion characteristics of sprays substantially mitigates at higher surface temperature, which are typical operating conditions of small size high-speed direct injection diesel engines.

Subjects: Mechanical Engineering; Thermodynamics; Power & Energy; Technology

Keywords: combustion and ignition characteristics; diesel sprays; hot surface ignition; constant volume combustion chamber; sensors

1. Introduction

Spray combustion phenomenon occurs in various power systems such as compression-ignition engines, gas turbine engines, furnaces, industrial burners etc. Spray combustion of fuels involves many phenomena such as diffusion, evaporation, convective mixing, jet and droplet breakup and heat transfer, which influence the ignition process. Spray combustion process affects the engine performance such as efficiency, power output, emissions and noise. Nowadays, spray combustion technology is common to automotive engines i.e. gasoline engines as well as diesel engines. Direct injection technology is commonly employed in modern high speed automotive engines. However, in diesel engines, injection of fuel controls the autoignition process unlike that of gasoline engine. Therefore in diesel engines, spray autoignition and combustion characteristics are of crucial importance for engine performance and in turn these characteristics depend on fuel injection system characteristics or parameters.

The ignition delay period is an important ignition characteristic of diesel fuels and diesel-like fuels. In diesel engines, a shorter ignition delay period is required. A large ignition is a disadvantage because during delay period substantial amount of fuel accumulates inside the combustion chamber and burn rapidly as ignition commence. This results in high peak combustion pressures and temperatures (Baczewski & Kalon’ski, 2008; Yanowitz, Ratcliff, McCormick, Taylor, & Murphy, 2014). Also, this cause increase in engine noise, wear and tear of engine and increase in oxides of nitrogen. Ignition delay period depends on auto-ignition properties of fuel, spray structure and air temperature at time of injection among others and have greatest impact. The atomisation of fuel depends on the parameters of fuel injection system (Kuszewski & Lejda, 2009; Park, Kim, & Lee, 2009).

There are many experimental methods and techniques have been used for the measurement of ignition characteristics of fuels such as shock tubes, rapid compression machines, flow reactors, and constant volume combustion chambers. Other methods are developing and continue to be developed (Al-Hamamr & Trimis, 2009; Edenhofer, Lucka, & Köhne, 2007; Haylett, Lappas, Davidson, & Hanson, 2009; Pickett, 2005). Constant volume combustion chambers are frequently used to study auto-ignition behaviour of fuels and fuel mixtures (Emberger, Hebecker, Pickel, Remmele, & Thuneke, 2015; Ghojel & Tran, 2010; Hu, Somers, Davies, McDougall, & Cracknell, 2013; Kuszewski et al., 2017; Lapuerta, Sanz-Arget, & Raine, 2014a, 2014b; Lee & Baik, 2014; Pekalski, 2004; Rabl, Davies, McDougall, & Cracknell, 2015) under different operating conditions. Constant volume method has several advantages over other methods such as pressure and temperature uniform at time of injection, thermodynamic analysis simplified due to constant volume configuration, and fuel injection process through a high pressure injection system similar to that of typical diesel engine. Ignition delay can of two types depending on the method of measurement of start of combustion i.e. pressure ignition delay and luminous ignition delay (Ghojel & Tran, 2010). Pressure ignition delay depends on pressure rise due to combustion and luminous ignition delay depends on luminosity of light produced due to start of combustion. In present study, luminous ignition delay is measured and analysed. In rest of the paper, ignition delay means luminous ignition delay.
Earlier several experimental studies have been done to investigate the effect of fuel injection pressure on performance, emission and combustion characteristics for the DI diesel engine (Jegan, Balasubbramanian, & Nagarajan, 2009; Khalid & Manshoor, 2012; Venkanna & Reddy, 2011). From these studies, it was found that high injection pressures decrease the injection duration thus maximizing the time available for fuel/air mixing prior to ignition. It is also reported that injection pressure has a great effect on the mixture formation, ignition delay, flame pattern, turbulence and therefore affects to the flame development, combustion characteristics and emissions. In a study (Khalid & Manshoor, 2012), the effects of mixture formation on ignition and combustion of a multi-hole diesel spray were investigated. The results of testing showed that increasing injection pressures makes spray tip penetration longer and promotes a greater amount of fuel-air mixing occurs during ignition delay as compared at lowest injection pressure (100 MPa).

Modern high speed DI diesel engines have high power density (70 KW/liter of displacement) and high cylinder air pressures (up to 180 bar) for achieving high efficiency (Stone, 2012). Due to high power density and cylinder air pressures, the piston surface temperature gets increased and its role in ignition of spray becomes important. Recent trends towards smaller engine sizes with high pressure common-rail injection systems have increased spray/piston interactions and cause extensive fuel spray impingement on piston bowl walls (Ladommatos, Xiao, & Zhao, 2005). Impingement of the fuel jet on the walls occurs in almost all of the small high speed diesel engines (Heywood, 2011). Rao, Winterbone, and Clough (1992) showed that almost 75% of the injected fuel reached piston bowl at high loads in high speed direct-injection diesel engine. Because of high piston temperatures, the pistons of modern diesel engines are made of aluminium alloy. Also piston surface temperature affects exhaust emissions (Ladommatos et al., 2005). Since, all of the small high speed DI diesel engines have high cylinder pressures and high injection pressures up to 1,600 bar, therefore hot surface ignition can play an important role in the combustion process in these engines. Present study basically simulates complex diesel combustion process occurs in small sized high speed direct injection diesel engines having mechanically operated fuel injection systems.

Spray auto-ignition characteristics of diesel fuel in typical hot air environment inside combustion chamber have been studied comprehensively in various studies (Assanis, Filipi, Fiveland, & Syrimis, 2003; Finesso & Spessa, 2014; Kobori, Kamimoto, & Aradi, 2000; Murphy et al., 2004; Rothamer & Murphy, 2013; Semin & Bakar, 2008; Sinha & Agarwal, 2007). However, studies have been conducted on diesel spray/wall impingement (Guerrassi & Champoussin, 1996; Miyamoto, Ogawa, Iemura, & Reksowardojo, 1997; Schunemann, Fedrow, & Leipertz, 1998) but ignition and combustion characteristics of diesel sprays using hot surface as a source of ignition in lean combustion environment typical of high speed direct injection diesel engines are limited (Chown, Habbaky, & Wallace, 2014; Ghadikolaei, 2014; Hiroyasu, Kadota, & Arai, 1980; Rehman, 2016; Rehman & Zaidi, 2012). Therefore, purpose of the present work is to study experimentally the auto-ignition and combustion characteristics of hollow conical diesel spray impinging on hot surface under lean burning environment at different operating conditions. This study may be helpful in understanding the complex combustion process and emissions formation related to high piston temperatures in small sized high speed direct injection diesel engines.

2. Experimental setup

2.1. Experimental setup

Present experimental set up and its various components are shown in the Figure 1. The set up is designed and fabricated to measure ignition and combustion characteristics of hollow conical diesel fuel spray in constant volume combustion chamber under different experimental conditions. Hot surface ignition is achieved by injecting the fuel spray on the hot plate inside the combustion chamber. Conventional combustion of diesel sprays impinging on the hot surface is studied under lean burning conditions.
The experimental setup has following components:

(1) Constant volume combustion chamber
(2) Bosch Fuel injector
(3) Fuel injection pintle nozzle
(4) Bosch fuel injection pump
(5) Hot surface plate for ignition inside combustion chamber
(6) Multi-stage air compressor
(7) Temperature controller and indicator
(8) Pressure gauge for fuel injection pressure
(9) Pressure gauge for cylinder air pressure
(10) Piezoresistive pressure transducer
(11) Photo transducer in the optical window
(12) Needle lift transducer for fuel injection duration
(13) Four channel digital storage oscilloscope (scopemeter)

Details of specification of each component are given in Tables 1–8.

**Table 1. Specification of combustion chamber**

| Material                  | Stainless steel |
|---------------------------|-----------------|
| Dimensions of combustion chamber | Diameter = 9.5 cm  |
|                           | Length = 17.3 cm |
| Hot plate diameter        | 7.3 cm          |
| Hot plate thickness       | 5.6 cm          |
| Hot plate distance from nozzle tip | 8 cm          |

**Table 2. Specification of Bosch fuel injection pump**

| Make                    | Bosch            |
|-------------------------|------------------|
| Type                    | Single Barrel    |
| Length of stroke        | 8 mm             |
| Bore                    | 7 mm             |
| Maximum fuel delivery/stroke | 0.2 ml          |
| Maximum injection pressure | 500 bar         |
2.2. Setup description
Cylindrical combustion chamber shown in Figure 2 having fuel injector on one side and hot surface plate of stainless steel on the other side of the chamber just opposite to each other. Fuel injector has pintle nozzle (shown in Figure 3) for producing hollow conical spray which is impinging on hot surface/plate. Bosch fuel injection pump is connected to fuel injector through high pressure fuel line. Fuel injection pump is operated manually with the help of lever mechanism. Fuel injection pressure is measured with pressure gauge mounted on pump as shown in Figure 1. Pressure gauge is mounted on combustion chamber for measuring initial (static) cylinder air pressure and piezoresistive pressure transducer senses pressure rise (dynamic pressure) before combustion and after combustion.
process. Temperature controller and indicator shows hot surface temperature and thermocouple indicates cylinder air temperature. Hot plate is heated with the help of heating element (heater wire) placed behind it. Inlet valve for compressed air and exhaust valve for exhaust gases are placed on the opposite side of hot plate at one end of combustion chamber. Highly compressed air is produced by multistage reciprocating air compressor. Various transducers (sensors) such as piezoresistive pressure transducer, photo transducer and needle lift transducer and their circuit diagrams are shown in Figures 4 and 5. These sensors are used for recording different signals during injection and combustion processes. Each transducer gives signal on separate channel of four channel digital oscilloscope (scopemeter) as shown in Figure 6. List of abbreviations and symbols with description/definitions used in present study is given in Table 9.

2.3. Experimental conditions
Several experiments have been performed at different fuel injection pressures and at different cylinder air pressures and hot surface temperatures in a constant volume combustion chamber using the pintle nozzle. Experimental conditions are given in Table 10. Different readings are taken at various sets of operating conditions. For each set of readings (for example, 100 bar-fuel injection pressure, 20 bar cylinder air pressure and 623 K-hot surface temperature), mean value is calculated from the four repeated readings to minimise the error in measurement.
2.4. Experimental methodology

A series of experiments on diesel fuel oil have been carried out for different combinations of experimental conditions. The commercially available diesel fuel oil is used in present study. Properties of diesel fuel are given in Table 11. The flowchart in Figure 6 shows details of work approach step by step in present study. The detailed experimental procedure followed in taking readings at each set of experimental conditions is as follows.

In beginning, temperature of hot surface plate inside the combustion chamber is increased by means of heating coil and then temperature of hot surface plate is controlled and maintained by temperature controller and indicator at 623, 673 and 723 K respectively. The highly compressed air from multi-stage reciprocating compressor is introduced into the combustion chamber through the inlet needle valve. The required cylinder air pressure (20, 30 and 40 bar) and hot surface temperature is maintained inside the combustion chamber for steady state. The temperature of hot surface is varied from 350°C (623 K) to 450°C (723 K) in steps of 50°C. Cylinder air pressure is varied from
20 to 40 bar in steps of 10 bar for every fuel injection point. Bosch fuel injection pump is used to inject the required amount of diesel fuel into the constant volume combustion chamber through injector having a pintle nozzle. Fuel is injected at various injection pressures (100, 200, 300 and 400 bar). The injection pressure levels are lower (from 100 to 400 bar) in present study as this study basically simulates the complex diesel combustion process occurs in small sized high speed direct injection diesel engines having mechanically operated fuel injection system. The combustion process occurs in very lean burning conditions. The amount of fuel injected at injection pressure of 400, 300, 200 and 100 bar are 0.12, 0.13, 0.14 and 0.15 ml respectively. At fixed injection pressure (say 100 bar), hot surface temperatures and cylinder air pressures are changed to obtain different sets of readings. All the injection, ignition and combustion events of impinging spray are recorded on the screen of four channel oscilloscope (digital scopemeter) with the help of various transducers (sensors) as shown in Figure 7. Some details of four channel oscilloscope are given in Table 12. Ignition delay is measured in millisecond by noting the difference between point of start of fuel injection and the start of combustion as shown in Figure 8. Duration of fuel injection (DOI) or needle lift (NL) is measured in ms by noting the difference between point of start and the end of injection as shown in Figure 8. Duration of combustion/burn (DOC) is measured in ms by noting the difference between point of start and end of combustion process shown in Figure 9. Rate of pressure rise corresponding to maximum pressure is calculated by dividing pressure rise (ΔP) by time taken (Δt) to reach maximum pressure as shown in Figure 9. After noting down the readings from oscilloscope, all exhaust gases are expelled out from the combustion chamber through exhaust valve. Four times each set of readings are repeated to minimize the error in measurement and then average is taken of four readings. Whole procedure is repeated again to note the other sets of readings.
Table 9. List of abbreviations and symbols with description

| Abbreviations and symbols | Description/definition |
|---------------------------|------------------------|
| CP                        | Cylinder pressure of air inside combustion chamber before combustion |
| DI                        | Direct injection type combustion chamber |
| DOB/DOC                   | Duration of burn or combustion gives total combustion period |
| DOI                       | Duration of injection of fuel |
| HRR/ROHR                  | Heat release rate gives rate of release of fuel chemical’s energy |
| ID                        | Ignition delay of fuel |
| IDI                       | Indirect injection type combustion chamber |
| NL                        | Needle lift gives duration of injection of fuel |
| HST                       | Hot surface temperature |
| ΔP                        | Maximum pressure rise due to combustion |
| Δt                        | Time taken to reach maximum pressure |
| ms                        | millisecond |
| mV                        | millivolt |
| Po                        | Calibration constant of pressure transducer |
| Pc                        | Critical pressure of fuel |
| Tc                        | Critical temperature of fuel |
| Qn                        | Heat Release due to combustion |
| γ                         | Ratio of specific heat |
For a given sample of spray combustion at a particular operating condition, following are the sampled parameters measured using four channel oscilloscope:

(a) Ignition delay (ID) in millisecond
(b) Duration of combustion (DOC) in millisecond
(c) Duration of fuel injection (DOI) in millisecond
(d) Maximum pressure ($P_{\text{max}}$) in millivolt
(e) Time taken to reach maximum pressure ($\Delta t$) in millisecond
2.5. Heat release analysis in direct injection engines

The heat release rate (HRR) or rate of heat release (ROHR) is an important parameter for the analysis of combustion phenomenon in diesel engine cylinder. The analysis of heat release rate was based on the changes of cylinder gas pressure and cylinder volume during the cycle. Also the analysis for the heat release rate is based on the application of the first law of thermodynamics for an open system (Heywood, 2011). It is assumed that the cylinder content is homogeneous mixture of air and combustion products. Also content is at uniform temperature and pressure at each instant in time during the combustion process. The first law for such a system can be written as

\[
\frac{dU}{dt} = \frac{dQ}{dt} - \sum m_i h_i - p \frac{dV}{dt}
\]  

(1)

where, \(dQ/dt\) is the heat transfer rate across the system boundary, \(p(dV/dt)\) is the rate of work transfer done by the system due to system boundary displacement, and \(m_i\) and \(h_i\) are the mass and enthalpy respectively of the flow into the system. \(p\) and \(V\) is the pressure and volume respectively of the cylinder and \(U\) is the internal energy of the cylinder content. If the crevice effect is neglected, the above equation can be reduced to
\[
\frac{dU}{dt} = \frac{dQ}{dt} + m_f h_f - P \frac{dV}{dt}
\]

(2)

where, \(m_f\) and \(h_f\) is the fuel mass flow rate and enthalpy respectively of the fuel entering the engine cylinder.

For an ideal gas this equation can be further reduced to

\[
\frac{dQ_n}{dt} = \frac{dQ_{ch}}{dt} - \frac{dQ_w}{dt} = P \frac{dV}{dt} + mc_v \frac{dT}{dt}
\]

(3)

where, net heat release rate \(dQ_n/dt\) is the difference between the gross heat release rate \(dQ_{ch}/dt\) and the heat transfer rate \(dQ_w/dt\) to the walls; after eliminating \(T\) from Equation (3) using ideal gas relation \((pV = mRT)\), Equation (3) can be written as

\[
\frac{dQ_n}{dt} = \frac{dQ_{ch}}{dt} - \frac{dQ_w}{dt} = \frac{\gamma}{\gamma - 1} P \frac{dV}{dt} + \frac{1}{\gamma - 1} V \frac{dp}{dt}
\]

(4)

this relation makes it possible to calculate the heat release rate; all the quantities on the right-hand side are known or can be easily derived once the pressure–time history has been recorded. All the Equations from (1) to (4) are taken from reference (Heywood, 2011).

2.6. Rate of heat release calculation

The equation for rate of heat release for the constant volume combustion chamber is given as

\[
\frac{dQ_n}{dt} = \frac{1}{\gamma - 1} V \frac{dp}{dt}
\]

(5)

keeping volume \((V)\) of combustion chamber as constant.

The equation derived from piezoresistive pressure transducer circuit diagram (Figure 5(b)) is given as

\[
p = \left(\frac{P_o}{8}\right) - \left(\frac{P_o}{4}\right)
\]

(6)

where \(P_o\) is the calibration constant of the Piezoresistive pressure transducer having value equal to 60 bar and \(p\) is pressure inside combustion chamber. Now differentiating Equation (6), we have

\[
\frac{dp}{dt} = \left(\frac{dV}{dt}\right) \left(\frac{P_o}{8}\right) = \left(\frac{60}{8}\right) \left(\frac{dV}{dt}\right) = 7.5 \left(\frac{dV}{dt}\right)
\]

(7)

where \(dV\) is rise in pressure due to combustion and measured on screen of oscilloscope on y axis in mV, \(dt\) is the time taken by pressure to reach maximum pressure point measured on screen of oscilloscope on x axis in ms.

Putting the value of \(dp/dt\) from Equation (7) into Equation (5), we get

\[
\frac{dQ_n}{dt} = \left(\frac{1}{\gamma - 1}\right) V \left(7.5\right) \left(\frac{dV}{dt}\right)
\]

(8)

\[V = 9.9*10^{-4} \text{ m}^3, \quad \gamma = 1.3\text{(Heywood, 2011)}.\]

Putting all these values of \(V\) and \(\gamma\) in Equation (8), we get rate of heat release \((dQ_n/dt)\) in J/s or kJ/s.
3. Results and discussions

3.1. Ignition delay (ignition characteristics)

Ignition delay is an important characteristic of diesel fuel and plays a crucial role in diesel engine combustion process. In diesel engines, ignition delay may be defined as the time interval between the start of fuel injection event and start of combustion event. The start of fuel injection is usually taken as the instant when the injector needle lifts off its seat (determined by the needle lift indicator) (Heywood, 2011) as in present study. The start of combustion is more difficult to determine precisely (Heywood, 2011). The best method to detect start of combustion is with the help of change in slope of heat release rate diagram which occurs at ignition (Heywood, 2011). Flame luminosity detectors are also used to determine the first appearance of flame. In present study, photo sensor (transducer) similar to flame luminosity detector is used to detect the start of ignition/combustion process. The point of start of fuel injection is detected with the help of needle lift indicator or sensor (transducer). The point of start of fuel injection into combustion chamber is shown on channel A of oscilloscope (shown in Figure 8). The point of start of combustion is shown on channel B of oscilloscope (shown in Figure 8). The time difference between start of two processes (fuel injection and combustion) gives ignition delay period in terms of ms (shown in Figure 8). Of course, the measured ignition delay here is luminous ignition delay.

3.1.1. Effect of injection pressure

Figure 10 shows graphs presenting the effect of fuel injection pressure on ignition delay at different charge conditions. Each graph of Figure 10 shows effect of hot surface temperatures on ignition delays at constant cylinder air pressure. Each graph of Figure 10 has isotherms of temperatures (623, 673 and 723 K). Similarly, each graph of Figure 11 shows effect of cylinder air pressures on ignition delays at constant hot surface temperature. Each graph of Figure 11 has isobars of cylinder air pressures (20, 30 and 40 bar). The results presented in graphs of Figures 10 and 11 indicate that the ignition delays of the hollow conical diesel fuel sprays impinging on hot surface decrease with the increase in the injection pressures from 100 bar to 400 bar for each isotherm and isobar. The reduction in ignition delays may be due to the reduction in physical delay as a consequence of better fuel atomization (Lapuerta et al., 2014b). The better atomization (finer droplets diameters) results in improved mixing of fuel and air during the physical delay period and hence the physical delay is mainly affected and gets reduced. The physical delay is greatly reduced by using high fuel injection pressures, higher combustion chamber temperatures and high turbulence. All these factors facilitate breakup of the jet and improves evaporation (Ganesan, 2012). The increased injection pressure also results in increased spray tip penetration. Increased and longer tip penetration enhances the fuel-air mixing process and leads to more complete diesel combustion. The injection pressure has a great influence on ignition delay, mixture formation, flame pattern and turbulence and therefore affects flame development, combustion characteristics and engine emissions (Khalid, Yatsufusa, Miyamoto, Kawakami, & Kidoguchi, 2009; Sasaki, Ito, & Iguchi, 2003).

3.1.2. Effect of hot surface temperature

Graphs in Figure 10 show the variation of ignition delays of the hollow conical diesel spray with respect to hot surface temperatures at constant cylinder air pressure. It is found from each graph that reduction in ignition delay is reduced at higher hot surface temperatures as compared to lower hot surface temperatures. At higher hot surface temperatures more that 673 K, the reduction in ignition delay is relatively small with increase in surface temperatures. This behavior can also be seen by noting the difference between isotherms of 623, 673 and 723 K. In terms of reduction in magnitudes of ignition delays. This indicates the non-linear behavior of ignition delay with the increase in hot surface temperatures. This also shows that the effect of hot surface temperature on ignition delay mitigates as the hot surface temperature is increased. The same results reported by Hiroyasu et al. (1980) that at high surface/wall temperatures and cylinder air pressures, the change in ignition delay is marginal. From the present results, it can be said that ignition delay period does not significantly affected at higher piston/wall temperatures (typical conditions inside the combustion chamber of small size high speed direct injection diesel engines). The results presented in these
graphs show the strong influence of initial charge conditions i.e. the hot surface temperatures and cylinder air pressures on the measured ignition delays. Initial air temperature is proportional to hot surface temperature as shown in Figure 12. The increase in hot surface temperature leads to increase in initial air temperature. The increase in hot surface temperature decreases the ignition
delay of diesel fuel spray as reported (Hiroyasu et al., 1980; Rehman, 2016). Cylinder air temperature and pressure strongly influence the auto-ignition characteristics of the diesel fuel (Heywood, 2011). Increase in the temperature of the hot surface results in decrease in ignition delays continuously as reported (Chown et al., 2014; Ghadikolaei, 2014; Hiroyasu et al., 1980; Rehman, 2016; Rehman &
Zaidi, 2012). The reason for reduced ignition delay with the high surface temperature may be the fast fuel evaporation of the impinging fuel sprays on high hot surface. Faster evaporation of fuel and improved air entrainment results in rapid fuel-air mixing near impingement surface. Rapid fuel-air mixing leads to the shorter delay period.

3.1.3. Effect of cylinder air pressure

Figure 11 presents effect of cylinder air pressures on ignition delays at constant hot surface temperatures. It is found in each graph of Figure 11 that ignition delay reduces with the increase in cylinder air pressure. Longest ignition delay is at low cylinder air pressure (20 bar) and shortest at high cylinder air pressure (40 bar). This may be due to fact that increases in intake pressure of air increases the density of cylinder air. Increase in density of cylinder air reduces auto ignition temperature of fuel and hence the ignition delay decreases with the increase in cylinder air pressure (Ganesan, 2012). Increased air density also causes more air entrainment into the spray. Therefore, it is found that increase in cylinder air pressure (from 20 to 40 bar) causes the decrease in autoignition characteristics of the diesel fuel. It is important to note from the each graph in Figure 11 that reduction in ignition delay period is reduced significantly at higher cylinder air pressures. Alternatively, it can be said that the difference among various isobars (20, 30 and 40 bar) is drastically reduced in terms of magnitude of ID as cylinder air pressure is increased. This shows non-linear behavior of ignition delay period with cylinder air pressure. Further increase in cylinder air pressure beyond 40 bar (typical diesel engines conditions) causes a marginal reduction in ignition delay period employing hot surface ignition. Figure 12 indicates that initial air temperature (charge temperature) is proportional to hot surface temperature. Increase in hot surface temperature leads to increase in initial air temperature. There is no other source of heat in combustion chamber for heating the compressed air. The difference between hot surface temperature and initial air temperature is slightly more at high temperature and less at low temperature. Also, increase in cylinder air pressure slightly reduces initial air temperature from 10 to 5 K.

Graphs of Figure 13 indicate variation of ignition delays with inverse of hot surface temperatures (1,000/T) for different cylinder air pressures (isobars of 20, 30 and 40 bar) at constant fuel injection pressures. Again, these graphs indicate strong effect of initial air pressure and hot surface temperature on ignition delay period as stated earlier. Also, reduction in ignition delay is non-linear with the increase in cylinder air pressure and hot surface temperature irrespective of injection pressures. This means that reduction in ignition delay is relatively less as cylinder air pressure or hot surface temperature is increased to higher values. This is due to fact that diesel fuel oxidation has different temperature dependent chemistries. These include low, intermediate and high temperature conditions for premixed diesel combustion. This behavior of ignition delay is observed elsewhere (Lapuerta et al., 2014b).
3.2. Rate of heat release (combustion characteristics)

Graphs in Figure 14 show the variation of rate of heat release (ROHR, kJ/s) corresponding to maximum pressure at different operating conditions. In present study, rate of heat release is basically rate of heat release corresponding to maximum pressure. Since, rate of heat release is calculated from rate of pressure rise using Equation (5) or Equation (8). Rate of pressure rise is measured corresponding to maximum pressure as shown in Figure 9. Therefore, in rest of the paper rate of heat release would be referred to as rate of heat release corresponding to maximum pressure. Figure 14 show rate of heat release variation with the fuel injection pressure for different hot surface temperatures (623, 673 and 723 K) and at constant cylinder air pressures. Rate of heat release is defined as the rate of release of fuel chemical’s energy or fuel burning rate during the diesel engine combustion process (Heywood, 2011). Piezoresistive pressure transmitter (dynamic pressure transducer or sensor) was used to sense the cylinder pressure before and during combustion process. This sensor indicates cylinder pressure rise and rise time of cylinder pressure on channel C of oscilloscope as shown in the Figure 9. Channel C of oscilloscope indicates rate of pressure rise during diesel spray combustion process on hot surface. Analysis of heat release rate in DI engines combustion chambers is shown in the Section 2.5. Sample calculation of the rate of heat release in the present study is shown in Section 2.6.

3.2.1. Effect of injection pressure

The graphs of Figures 14 and 15 predict general behavior of the trend between the rate of heat release and fuel injection pressure. It is found from these graphs at different hot surface temperatures (or isotherms) or at different cylinder air pressures (or isobars) that rate of heat release decreases with increase in injection pressure. The rate of heat release is dependent on rate of pressure rise during combustion process. Higher the rate of pressure rise higher will be the rate of heat release as these quantities are directly proportional to each other (see Equation (5)). Since, the injection
The quantity of fuel reduces with increase in injection pressure being lowest at highest injection pressure (as shown in experimental conditions, Table 10). Therefore, rate of pressure rise decreases due to less amount of fuel burning at higher injection pressure. Less amount of fuel burning results in small release of fuel chemical’s energy. The heat release rate decreases with the increase in fuel injection rate (which is increased by fuel injection pressure). Although, fuel injection rate increases the fuel-air
mixing rate within the spray and results in the increased heat release rate in the mixing controlled combustion phase and premixed-combustion phase (Heywood, 2011). In present study, burning rate decreases due to burning of less amount of fuel at high injection pressure. The net heat release rate in rapid compression machine (Balles, 1987), studies of DI combustion shows also increase net heat release rate with high injection pressures. The same trends of heat release rate with injection pressure.
pressures are reported elsewhere (Dent, Mehta, & Swan, 1982; Kamimoto, Aoyagi, Matsui, & Matsuoka, 1980). The effect of injection pressure on ROHR is relatively less significant at higher cylinder air pressure shown in Figure 14. Similarly effect of injection pressure on ROHR is relatively less significant at lower hot surface temperature as shown in Figure 15.

3.2.2. Effect of hot surface temperature and cylinder air pressure

Figure 14 presents graphs of various isotherms (623, 673 and 723 K) at constant cylinder air pressures. These graphs show the effect of hot surface temperatures on heat release rate during the combustion process. These graphs predict behavior of increase in heat release rate (ROHR) as the temperature of hot plate is increased at all cylinder air pressures. This behavior of the heat release rate is also predicted elsewhere (Lapuerta et al, 2014a). It is interesting to note that the increase in rate of heat release gets reduced at higher hot surface temperatures at all cylinder air pressures. In other words, isotherm of 723 K and isotherm of 673 K are close to each other at all cylinder air pressures as compared to isotherm of 623 K. This means that effect of hot surface temperature on rate of heat release mitigates at higher hot surface temperatures (673 K or above) as compared to lower hot surface temperatures irrespective of cylinder air pressure. Graphs shown in Figure 15 indicate the effect of cylinder air pressures on rate of heat release produced during the combustion process. Each graph presents effect of various isobars (20, 30 and 40 bar) on rate of heat release at constant hot surface temperature. The graphs of Figure 15 show rapid increase in rate of heat release as hot surface temperature is increased. The reason may be the faster fuel evaporation process and rapid fuel-air mixing near higher hot surface. It results in fast burning of fuel-air mixture in mixing controlled combustion phase. It is found from graphs of Figure 15 that rate of heat release shows a decreasing trend with the increase in cylinder air pressure irrespective of hot surface temperature. The reason for reduction in rate of burning may be reduced fuel-air mixing due to more resistance to spray tip penetration impinging on hot surface.

3.3. Fuel injection characteristics

Figure 16 shows the effect of fuel injection pressure on the duration of fuel injection (DOI) of the diesel fuel sprays at different hot surface temperatures at constant cylinder air pressure. The duration of fuel injection is defined as the time interval between the start of fuel injection and end of fuel injection process. The duration of fuel injection is measured with the help of needle lift sensor (transducer) as shown in Figure 8. The needle lift (NL) gives the duration of fuel injection into the combustion chamber through the fuel injector. The duration of injection can be seen on channel A on the screen of digital oscilloscope as shown in the Figure 8 and is measured in millisecond. The amount of fuel injected per stroke is varying with fuel injection pressure at full rack position of the injection pump. The amount of fuel injected as measured experimentally is approximately 0.15, 0.14, 0.13 and 0.12 milliliter per stroke at fuel injection pressures of 100, 200, 300 and 400 bar respectively.

3.3.1. Effect of injection pressure

The results presented in Figure 16 show the decrease of duration of fuel injection with the increase in fuel injection pressure from 100 to 400 bar at all hot surface temperatures and cylinder air pressures studied. The duration of fuel injection significantly decreases with the increasing fuel injection pressure as reported (Lapuerta et al, 2014b). High injection pressure decreases the injection duration thus maximizing the time available for fuel-air mixing prior to ignition (Lapuerta et al, 2014a). Although injection duration is varying slightly with surface temperatures at fixed fuel injection pressure but the variation is not due to hot surface temperature. The variation is due to the fact that fuel is injected manually by the injection pump. The plunger of the injection pump is operated manually with the help of lever. The same reasons are for variation of duration of fuel injection with cylinder air pressure. The variation in duration of fuel injection at fixed fuel injection pressure is around 1–2 ms. This variation is less significant as compared to total duration of fuel injection at any fuel injection pressure. The variation at 100, 200, 300 and 400 bar is around 2, 1, 1 and 0.5 ms respectively at all temperatures and pressures conditions.
3.4. Duration of burn/combustion (combustion characteristics)

Figures 17 and 18 present the results of experiments performed in constant volume combustion chamber to study the effect of fuel injection pressures on duration of burn (DOB) or duration of combustion (DOC). Duration of burn/combustion is defined as the time interval between the start of combustion process and the end of combustion process. Photo sensor (transducer) was placed in an
optical window on the side of combustion chamber wall in front of the hot plate. Photo sensor detects the point of the start of combustion process and the point of the end of combustion process inside combustion chamber by sensing the light luminosity due to combustion. In other words, this sensor presents whole duration of combustion on single channel of oscilloscope. Photo sensor displays the whole combustion process on the screen of digital oscilloscope on channel B as it is seen in Figure 9. Duration of combustion can be easily read from the screen of oscilloscope in terms of millisecond.

Figure 17. Variation of duration of burn with fuel injection pressure at different hot surface temperatures (623, 673 and 723 K).
3.4.1. Effect of injection pressure

Each graph of Figure 17 shows the variation of duration of burn or duration of combustion along different isotherms (623, 673 and 723 K) at constant cylinder air pressure. Similarly each graph of Figure 18 shows the variation of duration of burn along different isobars (20, 30 and 40 bar) at constant hot surface temperature. It can be seen from Figures 17 and 18 that duration of burn decreases with the increasing injection pressure from 100 to 400 bar. Higher injection pressure of...
Figure 19. Variation of peak pressure with fuel injection pressure at different cylinder air pressures (20, 30 and 40 bar).

the fuel initially generates a faster combustion rate (Ghadikolaei, 2014; Khalid & Manshoor, 2012). Faster combustion rate results in faster combustion and short combustion duration of the fuel jet. Higher injection pressure results in improved atomization of fuel, good mixing of fuel and air particles and larger penetration of fuel jet. All these factors cause complete and fast combustion of the fuel jet in the combustion chamber. High injection pressures having great impact on shorten
combustion duration (Khalid & Manshoor, 2012). It is found elsewhere (Agarwal et al., 2014) that combustion duration reduces with the increase in fuel injection pressures. However, at higher injection pressures, reduction in duration of burn with increase in injection pressure is relatively small at all hot surface temperatures and cylinder air pressures. The reason may be due to less amount of fuel injected at higher injection pressures. Figure 17 shows that at higher cylinder air pressure about 40 bar, the injection pressure effect on duration of burn is less significant. It can also be seen from Figure 17 that injection pressure has also less significant effect on duration of burn at higher surface temperatures at or above 673 K. Alternatively, injection has significant effect on duration of burn at low surface temperature (around 623 K) for all cylinder air pressures.

3.4.2. Effect of hot surface temperature and cylinder air pressure

Results presented in the graphs of Figure 17 show that duration of burn or combustion gets reduced with the increase in hot surface temperature from 623 to 723 K irrespective of cylinder air pressure. Similarly, graphs of Figure 18 show that duration of burn decreases with the increase in cylinder air pressure from 20 to 40 bar irrespective of hot surface temperature. The graphs of Figure 18 indicate that at high hot surface temperature above 673 K (400°C), the effect of injection pressure is less significant on duration of burn at all cylinder air pressures studied. There is relatively less decrease in duration of burn with increasing injection pressure at higher hot surface temperatures (673 K). Figures 17 and 18 show that at higher surface temperatures and cylinder air pressure (typical operating conditions of high speed, high power density direct injection diesel engines), hot surface temperature and cylinder air pressure effects on duration of burn mitigate. It means non-linear behaviour of duration of burn with respect to hot surface temperature and cylinder air pressure.

3.5. Peak pressure (combustion characteristics)

Graphs of Figure 19 show effect of fuel injection pressure on the maximum or peak pressure achieved during combustion process. These graphs show variation of peak pressure achieved during combustion process along various cylinder air pressures (isobars of 20, 30 and 40 bar) at constant hot surface temperature. It is seen from these graphs that increase in fuel injection pressure of diesel spray decreases peak pressure achieved during combustion process. This may be due to the fact that lower rate of heat release is associated with higher injection pressures because of less amount of fuel burning at higher injection pressures in a given time. But this effect is less significant at higher hot surface temperatures. These graphs clearly indicate the nominal increase in peak pressure developed due to combustion process above the initial cylinder air pressure. The increase in peak pressure is around 2–4 bar over and above the initial air pressure inside the cylinder. The peak pressure rise is maximum at lower cylinder air pressures. Small rise in peak pressure due to combustion shows ultra lean burning conditions of the hollow conical diesel fuel sprays inside the combustion chamber.

4. Conclusion

Ignition and combustion characteristics of the hollow conical diesel fuel sprays in the high pressure constant volume combustion systems are studied experimentally using hot surface ignition approach under various operating conditions. It is found that ignition characteristics of the hollow conical diesel fuel sprays are strongly dependent on hot surface temperatures like that of initial air temperatures. Ignition delays of the diesel sprays significantly reduced with the increase in hot surface temperatures and cylinder air pressures. Also ignition delay variation is non-linear with hot surface temperature and cylinder air pressure. Effect on ignition delay mitigates as hot surface temperature and cylinder air pressure rises to higher values (typical normal DI diesel engine operating conditions). Ignition and combustion characteristics of impinging sprays are also highly dependent on fuel injection characteristics. High fuel injection pressure results in lower ignition delays of sprays at all temperatures and pressures. High fuel injection pressure also causes decrease in injection duration of fuel. Rate of heat release (at maximum pressure) is highly affected by the injection characteristics. Rate of heat release reduces gradually with the increase in injection pressures but effect is more significant at higher surface temperature and lower cylinder air pressures. Rate of heat release increases with increase in hot surface temperatures and effect mitigates as surface...
temperature increases. Also, rate of heat release reduces with increase in cylinder air pressure. Duration of burn/combustion reduced with increase in cylinder air pressures and hot surface temperatures which means faster combustion occurs at these conditions. The effect of surface temperature on duration of burn mitigates as surface temperature rises. Duration of burn/combustion greatly affected by the injection pressure but effect is less significant at higher temperature and pressure conditions. Peak pressure increases with rise in hot surface temperatures. Peak pressure increment is higher at higher hot surface temperature but peak pressure is lower at high cylinder air pressure. Hence, hot surface ignition effect on ignition and combustion characteristics of sprays progressively mitigates at higher surface temperature conditions which are typical operating conditions of small size high speed direct injection diesel engines.

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