ABSTRACT

WU, ZENGYANG. Investigation of Spray and Combustion of a Piezo-electric Fuel Injector for Gasoline Direct Injection Engines. (Under the direction of Dr. Tiegang Fang).

In recent years, more stringent emission standard and high fuel economy demands have forced vehicle manufactures to seek alternative techniques to synchronize benefits of both gasoline and diesel fuels. In this work, experimental studies of spray characteristics and fuel auto-ignition properties from an outwardly opening piezoelectric gasoline direct injection fuel injector were conducted in an optically accessible constant volume combustion chamber (CVCC) experiment system.

Fuel sprays of light naphtha (LN), primary reference fuel (PRF), and E10 gasoline under different ambient pressures from 1 bar to 12.5 bar were investigated first. Spray was visualized by applying a Mie-scattering technique. A high-speed camera was employed to capture the spray images. Results show that a clear filamentary hollow-cone spray structure is formed for all three fuels at atmospheric conditions, and toroidal recirculation vortices are observed at the downstream spray edges. A higher ambient pressure leads to a stronger vortex located closer to the injector outlet. Larger spray angles are found under higher ambient pressure conditions for all three fuels.

Ambient pressure conditions were then extended to a lower range for iso-octane sprays. Five ambient pressure conditions were selected from 0.01 bar to 0.10 bar to evaluate the effect of superheated conditions on the spray structure from the piezoelectric fuel injector. Results indicate that spray under a superheated condition presents a distinct spray structure in the flash boiling regime. A lower ambient pressure within the superheated condition range results in a stronger deformation on spray structure, a faster spray front penetration velocity and a faster
liquid vaporization rate. These phenomena are dominated by ambient pressures. Effects of fuel the injection pressure and the fuel injection duration are relatively negligible.

Next, the auto-ignition characteristics of LN, primary reference fuels (PRF65, PRF95), gasoline (Haltermann CARB LEV III) and a gasoline surrogate under conditions similar to the spray G condition (3.5 kg/m³ gas density, 21% ambient oxygen concentration) were studied. Five different ambient temperatures from 650 K to 950 K with a 75 K step were investigated. Fuel auto-ignition was observed with noticeable ignition delay for five investigated fuels under all selected experiment conditions. Results show that the locations of the occurrence of auto-ignitions are randomly distributed in combustion chamber. Ignition delay of each fuel is always longer than fuel injection duration under all selected experiment conditions. Differences in ignition delay among the five fuels are more significant when the ambient temperature is lower than 750 K.

At last, two-color measurements were conducted for LN under diesel engine conditions. Five ambient oxygen concentrations varying from 10% to 21% and three ambient temperature conditions, 800K, 100K and 1200K, were selected to simulate both conventional diesel engine operation environment and low temperature and low oxygen concentration environment. Flame temperature distribution and KL factor distribution under different ambient conditions were calculated and discussed.
Investigation of Spray and Combustion of a Piezoelectric Fuel Injector for Gasoline Direct Injection Engines

by
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DEDICATION

To my love, Tian Peng, and my parents Yurong Zeng and Gaojin Wu
BIOGRAPHY

Zengyang attended University of Science and Technology of China and graduated in 2013 with a B.S. in Mechanical Engineering. Following graduation he was accepted into the North Carolina State University Ph.D. program in Mechanical and Aerospace Department under Dr. Tiegang Fang. While pursuing a Ph.D. degree, he earned his M.S. degree in Mechanical Engineering from North Carolina State University in 2015. His research interests include spray characteristics from piezo-electric fuel injectors for gasoline direct injection engines, and gasoline fuels auto-ignition in CI engines.
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1. Introduction

1.1 Motivation

Currently, gasoline used in spark-ignition engines and diesel used in compression ignition engines are two major types of road transport fuels. Most of commercial transport is run on diesel. The primary difference between these is the auto-ignition quality [1]. Diesel engine is well known as a significant source of pollution emissions, including nitrogen oxides, unburned hydrocarbons, carbon monoxide and particulate matters. Currently, more stringent emissions standards along with higher fuel economy demands have forced auto makers to achieve alternative combustion approach or alternative fuels.

Conventional diesel fuels used in current diesel engines mostly have cetane numbers greater than 40, and fuels get auto-ignited very soon after the start of fuel injection, before fuel and air are adequately mixed. Especially at high loads, diesel fuel auto-ignition usually occurs far before the end of fuel injection. Advance the fuel injection timing is the most common approach to achieve fully premixed fuel and air. However, combustion phasing is affected by conditions at the start of the compression stroke and the chemical kinetics of fuel/air mixture, which make the fuel auto-ignition timings control extremely difficult in CI engines. The lack of reliable ignition control has been a major challenge to extend the operation range. However, Spark ignition (SI) engines are much less efficient than compression ignition engines because they encounter throttling losses under part-load operation. It cannot be operated with lean mixtures and their compression ratio is limited by knock [2]. On this concern, it is more desirable to have a fully premixed combustion with high combustion efficiency and low emissions. Moreover, it has been demonstrated that diesel compression ignition engines can handle much higher load on gasoline-like fuels at given engine parameters, and maintain low
soot and NOx emission at the same time [2]. Hence running compression ignition engines on gasoline offers the potential for developing engines of high efficiency and low emissions at lower cost and complexity compared to other approaches. Meanwhile, NOx levels can be reduced by reducing combustion temperature by either running lean, pre-mixed or using EGR [3].

Naphtha fuels has drawn more attention recently due to its beneficial properties for the utilization in transportation sector. Naphtha is a kind of fuel with less processed refinery stream in the gasoline boiling and carbon number range, but with lower octane number. Generally, it is composed of C5 to C11 hydrocarbons and has a low research octane number (RON) value, roughly within the 40-70 range. Since naphtha requires much less processing in the refinery than either gasoline or diesel, there is an additional benefit in terms of well-to-wheel CO2 emissions and overall energy consumed [4]. It is of great interest to gain a more thorough understanding on the gasoline fuels auto-ignition in diesel engine environments, especially with the utilization of naphtha fuels.

1.2 Research objective and outline

This study is mainly focused on spray characteristics and auto-ignition process of gasoline like fuels from an outwardly opening piezoelectric gasoline direct injection fuel injector under different ambient conditions. The organization of this dissertation is summarized as follows:

In chapter 2, the background and approaches for the fuel spray characteristics and fuel auto-ignition investigation are described. An overview of the basic definitions involved in spray description and flame analyzation are given. The modeling techniques used to evaluate
the performance of fuel injector, and fuel flame temperature and soot distribution calculation are also described.

Chapter 3 describes the setup of the constant volume combustion chamber experiment system. Design of the experimental system is introduced with consideration of safety concern. Gas delivery system, fuel injection system, ignition system and data collection system are also described.

Chapter 4 investigates spray characteristics of light naphtha (LN), primary reference fuel (PRF) and E10 gasoline under different ambient pressures. Effect of ambient pressure on spray structure is discussed in detail. Spray angle, spray front penetration length, spray front penetration velocity and spray front fluctuation are compared quantitatively.

Chapter 5 studies the spray characteristics of iso-octane under superheated conditions by lowering pressure of the ambient environment. Effect of ambient pressure, fuel injection pressure and fuel injection duration on spray structure are evaluated. Spray penetration velocity is calculated and discussed.

Chapter 6 explores the possibility of auto-ignition of different gasoline like fuels under spray G condition first. LN, primary reference fuels (PRF65, PRF95), gasoline (Haltermann CARB LEV III) and gasoline surrogate are investigated in this section. Spray development before fuel auto-ignition are studied first. Ignition delay of different fuels are calculated and compared as well. Compression ignition of light naphtha under both conventional diesel combustion environment and low-temperature, low-pressure environment are then studied. Two-color pyrometry is employed to calculate flame temperature and KL factor distribution. Average temperature and average KL factor development under different ambient conditions are analyzed and compared.
Chapter 7 summarizes all experimental studies discussed in previous sections. Major conclusions and future work is presented.
2. Literature Review

2.1 Outwardly opening piezo gasoline direct injection (GDI) fuel injector

Currently solenoid-actuated inwardly opening multi-hole injectors and piezoelectric outwardly opening injectors are predominant injectors in GDI engines. Solenoid injectors are more economical than piezo injectors by sacrificing the precision and repeatability [5]. Piezo injectors draw attentions because of their sensitive and fast response, which are significant for small quantities or closely spaced multiple injections. Spray from a piezo injector has a hollow-cone structure with visible striations and filaments. Unlike hollow cone pressure-swirl sprays, no collapse arises with the spray development [6], and this spray pattern is quite repeatable. A typical spray form a piezo fuel injector is shown in Figure 2.1.

2.2 Spray front penetration Length

Spray front penetration length is defined as the distance from spray front to the injector nozzle. It is one of the key parameters that affect fuel spray combustion process in engines. Selections of spray front location impact the calculation of spray front penetration length a lot. For a single-hole fuel injector, several models are proposed to predict spray front penetration length. Pastor et al [7] come up with following 1-D model based on a mixing driven evaporation assumption:

\[ L = \frac{K_p \cdot C_{a}^{1/2} \cdot D_a \cdot \sqrt{\frac{\rho_f}{\rho_a}}}{C_{mv} \cdot \tan\left(\frac{\theta}{2}\right)} \]  

(2 - 1)

Where L is the liquid penetration length, \( K_p \) is a constant depending on ambient conditions, \( C_a \) is the area coefficient, \( D_a \) is orifice diameter, \( C_{mv} \) is a coefficient depending on fuel and
ambient air properties. \( \theta \) is the spray cone angle, \( \rho_f \) and \( \rho_a \) are fuel and air density. This could be used as an reference while evaluation spray front penetration for an piezo-electrical hollow cone fuel injector.

2.3 Spray cone angle

For sprays from a an piezo-electrical hollow cone fuel injector, spray cone angle is defined as the angle between the spray edges at the pre-determined locations near the injector tip at a specified time after the start of fuel (SOF) \([8]\). It can be measured by Mie-scattering imaging, shadowgraphy or extinction tomography. Spray cone angle of a piezo-electrical hollow cone fuel injector is mostly determined by injector inner structure.

2.4 Mie-scattering imaging

Mie scattering is elastic scattered light of particles that have a diameter similar to or larger than the wavelength of the incident light \([9]\). Mie scattering signal is proportional to the square of the particle diameter. Compared with Rayleigh scattering, which describes the elastic scattering of light by spheres that are much smaller than the wavelength of light, Mie scattering is much stronger. There is a strong angular dependency of the scattered intensity especially for smaller particles which has to be considered for successful Mie imaging experiments. Mie scattering is often used to measure flow velocities applying Particle Image Velocimetry (PIV). In this study, Mie scattering imaging is utilized to visualize sprays from a piezo-electrical hollow cone fuel injector.
2.5 Jet velocity

For a single-hole fuel injector, jet velocity at the nozzle exit is determined by the pressure different between fuel in injector and the ambient environment. Musculus et al [10] proposed the following model to predict jet velocity at nozzle exit:

\[ v = \frac{C_d}{C_a} \sqrt{\frac{2 \cdot \Delta P_{inj}}{\rho_f}} \]  

(2 - 2)

where \( C_d \) is the discharge coefficient, \( C_a \) is orifice area contraction coefficient, \( \rho_f \) is the fuel density, \( \Delta P_{inj} \) is the pressure difference. The discharge coefficient is an empirical coefficient that could only be determined experimentally. So far no clear model is proposed to describe the jet velocity from a piezo-electrical hollow cone fuel injector.

For jet with phase change, the calculation of the mass and the velocity at the exit of the nozzle strongly depends on the determination of the regime of the jet at the exit of the nozzle. To simplify the situation, the flow type at the exit could be described as a two-phase fluid in thermodynamic equilibrium as a liquid–vapor flow in non-equilibrium according to the thermodynamic behavior of the whole system [11]. Under this assumption, flow velocity of liquid and vapor phases can be predicted by using equations as follows:

\[ u_l = \sqrt{\frac{2(P_{inj} - P_{exit})}{\rho_l}} \]  

(2 - 3)

\[ u_v = \sqrt{2C_{p,v} (T_{inj} - T_{exit})} \]  

(2 - 4)

where \( P_{inj} \) is the fuel injection pressure, \( P_{exit} \) is the jet exit pressure, \( \rho_l \) is the density of fluid, \( C_{p,v} \) is the specific heat coefficient of the vapor phase. \( T_{inj} \) and \( T_{exit} \) are fuel temperature and
exit environment temperature. Solomon et al. [12] employed equation (2 - 3) and proposed the following equation to describe the discharge velocity.

\[
u = \sqrt{2 \left[ \frac{(P_{\text{inj}} - P_{\text{exit}})}{\rho_l} + C_{p,l} \left( T_{\text{inj}} - T_{\text{exit}} \right) - C_p \cdot T_{\text{exit}} \cdot \ln \left( \frac{T_{\text{inj}}}{T_{\text{exit}}} \right) \right]}
\]

(2 - 5)

where \( C_{p,l} \) is the specific heat coefficient of the liquid phase.

### 2.6 Droplet distribution

The representation of the actual droplet size distribution is usually referred to as a frequency distribution curve. There are different distribution functions based on theoretical or experimental fundamentals that are proposed to describe the number of droplets of a particular size. One of the most widely used distribution function is the Rosin-Rammler distribution, which represents a probability volumetric size distribution of droplet diameters [13]. It involves two parameters to determine the distribution.

\[
P = 1 - e^{-(d/X)^p}
\]

(2 - 6)

Where \( P \) is the distribution defining the accumulated volume fraction of droplets with diameters less than \( X \), \( d \) is the drop diameter. \( X \) is the characteristic drop diameter. It is the size of a drop in the distribution whose accumulated fraction is 0.6321.

### 2.7 Superheated fluid and flash boiling

Superheated is used to describe the situation for a liquid contained at conditions above the ambient saturation pressure is released to the atmosphere. Under this situation, rapid boiling of the resultant liquid jet occurs, producing two-phase flow. Meanwhile, dynamic expansion of vapor bubbles shatters the liquid stream to produce a finely atomized spray. This
phenomenon is also known as flashing. Flashing liquid gives rise to potentially explosive and certainly hazardous heterogeneous two-phase clouds. Typically, the flashing phenomenon has been observed in laboratory experiments where a liquid flows through a short nozzle into a low-pressure chamber at a pressure value considerably lower than the liquid saturation pressure at the injection temperature.

Superheated fluid flash boiling is closely related to fuel sprays in engines. Flash evaporation might take place inside or outside the injector nozzle, thus the liquid jet behaves following different mechanisms. Flashing conditions greatly influence atomization and vaporization processes as well as the mixture formation and combustion. The occurrence of flash vaporization might affect combustion performances, and even create the danger of vapor lock within the fuel line. In internal combustion engines, the expansion process of a liquid flowing through a constriction such as an orifice or a short nozzle may take the liquid into the saturation condition for certain combinations of pressure drop and thermodynamic properties of the fluid. This would trigger the phase-change process as dictated by equilibrium thermodynamics [14].

2.8 Two color pyrometry

2.8.1 Theory

Flame luminosity that caused by soot particles thermal radiation at high temperature has long been used to calculate flame temperature distribution in 1940s [15, 16]. It has been demonstrated that fuel combustion is dominated by soot particles radiations. Meanwhile, it has been shown that temperature difference between flame and soot particles in flame is less than
1 K when the ambient gas and soot particles have reached thermal equilibrium [16]. Therefore flame temperature could be measured by measuring soot particle temperature directly.

Two-color pyrometry is a technique that obtains flame temperature distribution by measuring flame thermal radiation at two different wavelengths. Generally, thermal radiation of a blackbody resource at a certain temperature and a given wavelength could be evaluated by Planck’s equation.

\[
E_{b,\lambda}(T) = \frac{C_1}{\lambda^5 \left[ e^{\left(\frac{C_2}{\lambda T}\right)} - 1 \right]}
\]

(2 - 7)

where \( E_{b,\lambda} \) is the monochromatic emissive power intensity of a blackbody at temperature T. \( \lambda \) is the light wavelength, \( C_1 \) and \( C_2 \) are the first Planck’s constant and the second Planck’s constant.

\[
C_1 = 3.7418 \times 10^{-16} W \cdot m^2
\]

\[
C_2 = 1.4388 \times 10^{-2} m \cdot K
\]

For non-blackbody resources, the monochromatic emissivity is defined as:

\[
\varepsilon_{\lambda} = \frac{I_{\lambda}(T)}{I_{b,\lambda}(T)}
\]

(2 - 8)

where \( I_{\lambda}(T) \) and \( I_{b,\lambda}(T_a) \) are the monochromatic emissive power of a non-black body and a blackbody surface at the same temperature and wavelength, respectively. For two-color pyrometry, the apparent temperature \( T_a \) is defined as the temperature of a blackbody, which emit the same radiation intensity as a non-black body at T [16]. Substitute this parameter into equation (2 - 8)

\[
\varepsilon_{\lambda} = \frac{I_{b,\lambda}(T_a)}{I_{b,\lambda}(T)}
\]

(2 - 9)
and combine with equation (2 - 7)

\[ \varepsilon_\lambda = e^{\frac{C_1}{\lambda T}} - 1 \]

(2 - 10)

For soot particles the monochromatic emissivity, Hottel and Broughton [17] proposed an empirical correlation as

\[ \varepsilon_\lambda = 1 - e^{-KL/\lambda^\alpha} \]

(2 - 11)

Where K is an absorption coefficient that is proportional to soot particle density, L is the geometric thickness of the flame along the optical axis. \( \alpha \) is parameter related to the physical and optical properties of soot particles.

Combining equation (2 - 10) and (2 - 11), if the emissive power at two different wavelength and a certain temperature is given, the real flame temperature and KL factor can be calculated by solving following two equations.

\[
\left(1 - e^{-KL/\lambda^\alpha}\right) \left(\frac{2C_1}{\lambda^5 \left(e^{\frac{C_1}{\lambda T}} - 1\right)}\right) = I_1
\]

(2 - 12)

\[
\left(1 - e^{-KL/\lambda^\alpha}\right) \left(\frac{2C_1}{\lambda^5 \left(e^{\frac{C_1}{\lambda T}} - 1\right)}\right) = I_2
\]

(2 - 13)

2.8.2 Implementation and calibration

According to equation (2 - 12) and (2 - 13), monochromatic emissive power of a black body at a certain temperature and wavelength need to be obtained to calculate flame temperature and soot KL factor. In this study, a Halogen Light Sources (LS-1-LL) with a 2800 K bulb was used to calibrate the relationship between image pixel intensity and monochromatic emissive power at selected wavelength. A 550 nm and a 650 nm band pass filter are applied
while capturing light intensity from the light source. Signals from this light source were captured at each camera setting that used in experiments. A linear development pattern is demonstrated between camera exposure time and image pixel signal intensity at all aperture that selected in this study. Plot of image pixel signal to camera exposure time is presented in Figure 2.2. Therefore the relation between pixel value and emissive power at each pixel could be evaluated by this calibration process.

2.8.3 Selection of $\alpha$

$\alpha$ is a parameter that relate to light wavelength, soot particle size, refractive index of soot and fuel type [16]. In visible wavelength region, selection of $\alpha$ is less critical on flame temperature evaluation, since flame temperature is not sensitive to $\alpha$. Thus in this study, the difference between $\alpha_1$ and $\alpha_2$ could be negligible. It is recommended to select 1.39 as the value of $\alpha$ with wavelength 550 nm and 650 nm by Yan and Barman [18].

2.8.4 Selection of Wavelength

In general, visible and infrared wavelengths have been widely selected in two color measurement. Currently visible wavelength is preferred for a few reasons. Firstly, measuring system is more sensitive to flame temperature changes in visible wavelength region. It has been demonstrated that in a temperature range of 1000K to 2000K, spectral radiance with respect to wavelength is higher in visible light region. Second, combustion experiments release considerable heat, which leads to a relative high temperature of the experimental system. Hot experimental system emits infrared radiation, which could introduce more error on temperature
calculation. Wavelength within 550 nm to 650 nm are widely selected to implement two color measurement [19 - 20].
2.9 Tables and figures

Figure 2.1 Typical structure of spray from an outwardly opening piezo gasoline direct injection fuel injector

Figure 2.2 Linear relationship between camera exposure time and pixel intensity
3. Experimental setup

3.1 Experimental System Design

Constant volume combustion chamber (CVCC) system is an experimental system that is able to simulate environment near top dead center for both spark ignition engines and compression ignition engines. It has been widely used in several research institutions, including Sandia National Laboratory, University of Wisconsin at Madison, Brigham Young University, Eindhoven University of Technology, and so on. It offers flexible optical access, wide range of operation condition and high repeatability, which make the CVCC system an ideal tool to details of reactive and non-reactive spray process.

3.1.1 Chamber body

The constant volume combustion chamber was made of alloy steel 4140 due to its good thermal stability and machinability. There were six ports in the chamber body. Optical access was enabled by quartz windows installed in one or two ports. Other ports were sealed by solid stainless steel plugs fitted with a gas inlet, an outlet, a fuel injector, a spark plug, a pressure sensor, and other necessary components. A 2D structure and a assemble structure of the chamber body were shown in Figure 3.1 and 3.2. Material of all metal plugs was stainless steel 304, and the material of quartz window was Dynasil 1100. Dynasil 1100 is a fused silica material which is optically bubble free. It has excellent transmission capabilities in the ultraviolet range and allows a transmission of 0.9~0.95 in the spectrums. The inner diameter of chamber body ports was 100mm. To prevent the crack of windows from possible thermal expansion of surrounding material, and to make metal plugs dismountable, the diameter of metal plug or quartz window was 99 mm at the inner perimeters. The outer diameter of metal
plug and quartz window was 130mm. The thickness of the metal plug or the window was 60 mm. To seal the high pressure and high temperature mixture inside chamber, Silicon RTV 60 was used in the gap between the perimeter surface of metal plug or window and chamber body ports. Stainless steel plugs and quartz windows were held and pushed by customized metal holders. Holders were fitted on chamber body by thread. When all ports were sealed, the inner chamber volume was 0.95L.

The chamber body was fitted on an optical table with four adjustable feet. In order to heat the chamber, several straight holes were drilled for heaters and thermocouple. Maximum allowable stress of different components on chamber body were presented in Table 3.1.

### 3.1.2 Gas delivery system

The simulated high temperature and high pressure engine combustion environment near top dead center was generated by a premixed combustion of acetylene prior to fuel spray combustion. Therefore a gas delivery system was constructed to supply required gas into chamber for premixed combustions. Three different gases, acetylene, O₂/N₂ (50%/50%) and dry air were selected to formulate proper mixtures to obtain the desired ambient temperature and ambient oxygen concentration. Acetylene was selected mainly because of its high C/H ratio, which produces less water in the premixed combustion. Other than pure oxygen, O₂/N₂ (50%/50%) is selected to ensure safety during experiments. Dry air could be used to enable wide range of stoichiometric conditions and to manipulate inner chamber gas density. A structure of the gas delivery system is shown in Figure 3.3.

Solenoid valves and 90° actuators associated with ball valves were utilized to achieve electrical control of the whole gas delivery system. Controlling of all valves was realized by
configuring the solid state relay array with the signal from timing board PCI-6602 and integrated in the system control programs. For a typical spray combustion experiments, acetylene, O\textsubscript{2}/N\textsubscript{2} and dry air were fed on to a gas accumulator (Parker ACP-05AA100E1KTC) in sequence for the first premix process. Gas feeding time was adjustable. The gas feeding pressure was controlled by regulator and monitored by a pressure transducer (Omega PXI-300). After a mixing time of 15 seconds, mixed gas was pushed into chamber by high pressure nitrogen. It took 15 seconds to pump mixture to chamber. This duration is also adjustable. The gas pressure in chamber before premixed combustion was monitored by a digital pressure gauge mounted on chamber top. Gas continued mixing in chamber for another 15 seconds.

3.1.3 Fuel injection system

The injector employed in this study was an outwardly opening piezo gasoline direct injection fuel injector, as shown in Figure 3.4. It was controlled by a piezo injector driver from Drivven (a subsidiary of National Instruments, Inc.). Trigger signal could be generated by an external pulse delay generator or an integrated Labview program via the signal from timing board PCI-6602. Fuel pressure was controlled by a gasoline common rail fuel system. A typical gasoline fuel filter is used to remove fuel impurities and protect high pressure pump. The high pressure pump is controlled by the pressure signal feedback from rail with a PID loop. The high pressure pump is driven by a 3 Horsepower motor (Marathon G590) which runs at its maximum speed. The highest rail pressure for gasoline fuels is 120 bar.
3.1.4 Ignition system

The ignition system was made up of a spark plug (Bosch Platinum 4++), a plasma ignition coil (Okada PD1002102R) and a 12V battery. The plug gas and the pulse width were tuned to 1.6 mm and 5 ms respectively to obtain the best performance according to experiment observation. The spark plug was mounted at the top of chamber body. In this study, the ignition system was mainly used to ignition premixed gases to generate desired experimental conditions.

3.2 Data acquisition and control system

3.2.1 Hardware and software configuration

All electrical devices on CVCC system could be remote controlled by employing NI PCI-6040E, PCI-6014 and PCI-6602 DAQ boards as the signal source. Both automatic and manual operation of the system were enabled by integrated NI Labview programs. A control box was constructed to accommodate all the electric parts including relays, power supply, protection circuits, DC power supply, injector and high pressure pump drivers and data communication interfaces, as shown in Figure 3.5. Power supply for fuel pump and spark plug were separated for safety considerations.

3.2.2 Pressure measurement

An Omega pressure sensor (PX209-300A5V) was utilized to measure gas pressure in inlet gas lines. According to experiment results, calibration of this pressure sensor is necessary before experimental measurements. Chamber static pressure before premixed combustion was measured by a digital pressure gauge. This gauge was designed to check possible gas leaking. Chamber pressure during premixed combustion and fuel spray combustion was measured by
Kistler 6041A transducer coupled with a Kistler 5004 charge amplifier. A water-cooling system was employed to avoid thermal shock. Typical pressure development during premixed combustions were illustrated in Figure 3.6.

### 3.2.3 Optical diagnostic system

Spray and flame images were captured by a Phantom V4.3 non-intensified high speed camera. Its spectral response spans from 400 to 800 nm, covering the visible light spectrum. Camera setting, including resolution, frame rate and exposure time, were set appropriately according to experiment requirement. Band pass filters (550nm and 650nm) with 10nm band pass width were employed to capture emissions at selected wavelengths. Neutral density filters sometimes were utilized to manipulate emission intensity.

### 3.2.4 Experimental procedure

For spray combustion experiments, the high temperature and high pressure environment was generated by a premixed combustion of a mixture of acetylene, O$_2$/N$_2$ (50%/50%) and dry air. A simplified experimental procedure is illustrated in Figure 3.7. Premixed acetylene/air mixture was filled into the chamber. After the ignition by a spark plug, combustion occurs, which results in a high temperature and a high pressure environment. The premixed combustion is lean to reserve extra oxygen for the second combustion. Ambient oxygen concentration is adjusted by the compositions of premixed gases controlled by partial pressure during the gas inlet process.

Pressure data was collected by the Kistler 6041A transducer. After the premixed combustion, ambient temperature development during premixed combustion was then
calculated by using corrected ideal gas equation. Fuel injection was triggered at desired ambient temperature. Both ambient oxygen concentration and ambient temperature before fuel injection are critical for fuel spray combustion. Gas density in the constant volume combustion chamber was constant. It could be manipulated by increasing or decreasing gas partial pressures proportionally. While studying transient spray combustion process, camera and fuel injector were triggered simultaneously by a pulse delay generator.
3.3 Tables and figures

Table 3.1 Maximum allowable stresses at different positions on chamber [21]

<table>
<thead>
<tr>
<th>NO.</th>
<th>Connection position/parameter</th>
<th>Max allowable stress (psig)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Steel Plug (Hoop stress)</td>
<td>10,559</td>
</tr>
<tr>
<td>2</td>
<td>Retainer (Thread shear stress)</td>
<td>11,159</td>
</tr>
<tr>
<td>3</td>
<td>Injector (Thread shear stress)</td>
<td>56,532</td>
</tr>
<tr>
<td>4</td>
<td>Spark plug (Thread shear stress)</td>
<td>23,567</td>
</tr>
<tr>
<td>5</td>
<td>Pressure sensor (Thread shear stress)</td>
<td>15,005</td>
</tr>
<tr>
<td>6</td>
<td>Spark plug support (Thread shear stress)</td>
<td>14,952</td>
</tr>
<tr>
<td>7</td>
<td>Intake/Exhaust (Thread shear stress)</td>
<td>15,005</td>
</tr>
<tr>
<td>8</td>
<td>Cleaning hole (Thread shear stress)</td>
<td>15,360</td>
</tr>
</tbody>
</table>
Figure 3.1 Experimental system: 1.fuel injector; 2.exhaust line; 3.chamber body; 4.quatz window; 5. plug/window retainer; 6. pressure transducer; 7.intake line; 8.metal plug; 9. spark plug; 10. combustion chamber.

Figure 3.2 3-D structure of the chamber body design
Figure 3.3 The diagram configuration of gas supply system

Figure 3.4 The diagram configuration of fuel delivery system.
Figure 3.5 The actual control and data acquisition system

Figure 3.6 Typical pressure development during premixed combustion
Figure 3.7 Experiment procedure
4. GDI Fuel Sprays Using a Piezoelectric Injector under Different Ambient Pressures

4.1 Introduction

It is well known that gasoline direct injection (GDI) engines have considerable benefits on reducing exhaust emissions and increasing fuel efficiency. Compared with conventional port-fuel injection (PFI) engines, GDI engines generally have around 5% - 10% higher miles per gallon (MPG), and lower greenhouse gas emissions [22 - 25]. In recent years, research on GDI engines is mostly focused on new alternative fuels and injection strategies.

Naphtha is a kind of fuel with less processed refinery stream in the gasoline boiling and carbon number range, lower octane number and higher heating values compared to commercial gasoline. It draws attentions due to its high volatility and stronger resistance to auto-ignition, which potentially could be used for high efficiency compression-ignition combustion with low emissions. Producing naphtha is significantly simpler in a refinery compared to gasoline [26]. According to the refining process, naphtha fuels generally can be categorized as heavy naphtha (HN) and light Naphtha (LN) [27]. Investigations have been performed on the thermal efficiency, combustion and emission characteristics of naphtha. The Saudi Aramco Fuel Technology research team has been extensively investigating the low octane (naphtha) fuels and gasoline compression ignition (GCI) engine interactions both experimentally [27-29] and numerically [30-33]. They have reported up to 26% increase in efficiency compared to gasoline spark ignition (SI) engines. Similar observation were found also by Han et al [34]. Their work demonstrated that the low octane gasoline-GCI pathway leads to a 24.6% reduction in energy consumption and a 22.8% reduction in greenhouse gas emissions. Wang et al. [35] compared naphtha and commercial gasoline on multiple premixed compression ignition (MPCI) mode. Their work demonstrated that naphtha MPCI can operate stably in a wide load range. With the
same experimental system and combustion mode, they also found that the combustion delay of naphtha fuel is extended with the increase of injection pressure. The soot emission decreases at high injection pressure with a penalty of higher CO and HC emissions [36]. Manente et al. [37] studied the effect of gasoline-like fuels’ properties on the performance and emissions of an engine running in partially premixed combustion mode (PPC). Engines operating on lower octane number gasolines were also capable to run idle without increasing the inlet temperature [38]. A more optimized combustion chamber design was also developed by Chang et al. [39] to improve idle and light load combustion stability of naphtha fuels. The application of low cetane number (CN) naphtha fuels on diesel CI engines were evaluated by Won et al. [19] and Chang et al. [40] with different bowl and nozzle designs. It turns out that diesel CI engine can run with low CN naphtha fuels without compromising comfort, drivability, emissions or power requirements. CN 35 naphtha fuel was recommended for its better robustness and lower HC and CO emissions. Viollet et al. [41] developed three newly designed pistons to enable naphtha compression ignition combustion. Zhang et al. [42] compared naphtha fuel and ultra-low sulfur diesel (ULSD) under both conventional and low temperature combustion modes. Naphtha fuels exhibited appreciably lower levels of soot compared to ULSD across the investigated engine operation range while maintaining a diesel equivalent fuel efficiency.

Meanwhile, the impact of injection strategies has been demonstrated to be significant on fuel combustion and particles emission [43]. Injection rate shaping is one of the most attractive alternatives to multiple injection strategies [44]. Currently, solenoid-actuated inwardly opening multi-hole injectors and piezo-electrically actuated outwardly opening injectors are predominant injectors in GDI engines. Solenoid injectors are more economical than piezo injectors by sacrificing the precision and repeatability [45]. Piezo injectors draw
attentions because of their sensitive and fast response, which are significant for small quantities
or closely spaced multiple injections [46]. Spray from a piezo injector has a hollow-cone
structure with visible striations and filaments. Unlike hollow cone pressure-swirl sprays, no
collapse arises with the spray development [47], and this spray pattern is quite repeatable [48].
Studies have been done on both types of injectors in GDI engines in the past few years. Smith
et al. [49] conducted a systematic performance comparison of two spray-guided, single-
cylinder, spark-ignited direct-injected (SIDI) engine combustion system designs with both
solenoid and piezo injectors and found that the two kinds of injectors have comparable
combustion stability and smoke emissions. Achleitner et al. [50] demonstrated the possibility
to develop a spray-guided combustion system to meet the requirements to the maximum
possible extent by using a piezo injector. Skogsberg et al. [48] and Wang et al. [51] explored
the atomization of sprays generated by a piezo injector. It was shown that a leading edge vortex
is formed at the outer periphery of the spray. The location of the leading edge vortex depends
on back pressure. Zhang and co-authors [52] demonstrated that the cone angles at the
developed phase for alcohol fuels and isooctane are consistently stable for a solenoid swirl
GDI fuel injector. Higher injection pressure helps reduce droplet size.

Multiple techniques were employed to explore the spray characteristics of a piezo
injector. Zigan et al. [53] applied a planar imaging technique to investigate the spray formation
and fuel evaporation of a piezo injector in direct injection spark ignition (DISI) engines. They
noted that fuel vapor and smaller droplets follow the recirculating flow and concentrate in the
reduced pressure regions. Shi et al. [54] carried out spray experiments using a Mie scattering
technique and a phase-Doppler anemometry (PDA) measurement in a conditioned pressure
chamber to provide data for computational fluid dynamics (CFD) simulation of piezo injector
spray. Stiehl et al. [55] used a time-resolved particle image velocimetry (PIV) technique to reveal significant spray-induced vortices perturbing the tumble flow. Recirculation vortices were found to form at both the inner and outer edges of the hollow cone. In addition, spray penetration length and spray angle follow a steep rise with linear slope as long as the nozzle is open, and the outer recirculation vortex therefore provides a favorable zone for ignition [56].

While studies of piezo injectors and naphtha fuels have been undertaken, little study was done on fuel spray characteristics of naphtha fuels with a GDI piezoelectric outwardly opening hollow-cone fuel injector under different back pressure conditions, and experimental validated data was insufficient for unconventional fuels. Therefore, light naphtha (LN), PRF95, and E10 gasoline sprays using a GDI piezo fuel injector are studied and compared in this study. The ambient pressure was changed from the atmospheric condition up to 10 bar for the three fuels. The spray angle, spray front penetration length, spray front penetration velocity, and spray front fluctuation were calculated and discussed.

4.2 Diagnostics and Measurements

The spray development during fuel injection process was visualized by applying a Mie-scattering technique, as shown in Figure 4.1. A high-speed camera (Phantom V4.3 from Vision Research Inc.) was employed to capture spray images of each selected fuel. The frame rate was set at 25,000 frames per second (fps) with a resolution of 128×128 pixels. The camera exposure time, aperture and other parameters were set appropriately and kept constant. Injector and camera were triggered simultaneously by an external pulse generator. More details of the chamber can be found in previous publications [57-58]. Experiments were repeated five times for each condition to ensure consistency. Data from five readings were averaged and the standard deviation was calculated to account for uncertainty.
Three fuels were selected including light naphtha (LN), primary reference fuel (PRF), and E10 gasoline. LN mostly consists of molecules with 5-6 carbon atoms. LN was obtained from Saudi Aramco, with an AKI value of 61. Conventionally, PRF is a binary mixture of iso-octane and n-heptane and is used as a surrogate for gasoline. PRF used in this work was PRF95, a blend of 95% iso-octane and 5% n-heptane by volume. The AKI of PRF95 is 95 [59]. The gasoline fuel (AKI = 87) was obtained by mixing fuels with equal volume ratios from three different local gas stations (Shell, Exxon and BP). It contains up to 10% ethanol by volume (often referred as E10). The tested gasoline fuel represents the commercially available regular grade gasoline on the market at most gas stations. For all experiments, the injection duration was set as 0.3 ms and the injection pressure was kept at 10 MPa (100 bar). Chamber and fuel temperature were the same as the ambient for all experiments, namely 298 K. Fuel mass per injection was around 10 mg per injection. Selected fuel properties are listed in Table 4.1 [60 - 62].

In order to characterize the spray of different fuels, the spray angle, spray front penetration length, spray front penetration velocity, and spray front fluctuation were calculated and compared. Since the spray developed freely and had no definite angle after the end of the injection (around 430 μs ASOIT), transient spray angles were calculated only from the beginning to the end of each single injection. The spray front penetration length, spray front penetration velocity and spray front fluctuation were analyzed in a much longer time interval (up to 790 μs ASOIT). Depending on the spray structure, certain key parameters may be defined differently. In following section, the influence of the parameter definitions will be discussed first.
4.2.1 Spray angle definitions

The spray angle is defined as the angle between two spray edges at pre-determined locations near the injector tip at a specified time after the start of fuel (SOF) [63]. Specifically, reference points are defined for each image at two different axial distances downstream from the injector tip. To calculate the spray angle, spray edges were detected using a Matlab code developed in-house with the same threshold for all transient images in each single injection. Two spray edges were marked red and blue separately as shown in attached figures. Multiple selections of the reference points were used in literatures. Wang et al. [51] selected the average angle between the whole detected spray edges as the spray angle, especially for spray under atmospheric conditions (Definition A). However, under an environment with a pressure higher than the atmosphere, an obvious vortex can be found at downstream of the spray edges. This vortex results in a swell on the spray edges and affects the spray angle calculation. Therefore, 5 mm to 15 mm downstream of the injector tip is recommended for defining reference points by SAE international [53]. Considering that the spray front penetration length at the end of the injection under high pressure is much shorter than atmospheric condition, the effective spray edges in this study used for spray angle calculation are limited within 5 mm to 10 mm downstream of the exit plane (Definition B). In our study, the vortex is even stronger since the ambient pressure was set up to 10 bar. In order to completely eliminate the effect of the vortex, a third spray angle, defined as the angle between the two spray edges located within 1-5 mm downstream of the exit plane, is also applied to spray angle calculation (Definition C). In this near-nozzle region, there is no or little occurrence of vortex at spray edges even for high ambient pressures. The schematics of the three definitions are illustrated in Figure 4.2. These different spray angle definitions are discussed and compared in this section. For LN, PRF95, and gasoline, only one properly selected spray angle definition was applied and will be discussed later.
LN is selected as an example to compare the differences in the spray angles obtained from the three definitions. The spray angle results under different ambient pressures are shown in Figure 4.3. Apparently, three definitions lead to distinct spray angle developments. For Definition A, the spray angle slowly increases with time, and the slope becomes larger for a higher ambient pressure. Meanwhile, higher ambient conditions lead to smaller spray angles at the beginning and larger spray angles by the end of the injection. Overall the spray angle ranges from 98° to 105° for this definition. For Definition B, the spray angle still increases with time. However, both the slope and the absolute value are much larger than the results in Definition A. In addition, a larger spray angle is found at both the beginning and the end of the injection under higher ambient pressures. The spray angle range rises from 100° to 113° for Definition B. While for Definition C, the spray angle variation among different ambient pressures is much smaller than Definitions A and B. The spray angle stays quite stable under each ambient condition for Definition C and only a slight increase is observed under the 10 bar condition.

The spray angles using different definitions were compared under selected ambient conditions in Figure 4.4. Definition B leads to a much larger spray angle compared with Definitions A and C, and the difference is getting larger with increasing ambient pressure. Results of Definitions A and C are quite close for most injection process, but a slightly higher spray angle is noticed with Definition A at the end of the injection. This phenomenon is expected because, in this study, the spray vortex is mostly located at the downstream for all selected ambient pressures, while the spray edge at the upstream is smooth and stable. Definition B mostly covers the vortex area, which apparently make the spray angle larger. Moreover, the location of the vortex moves toward the exit plane with increasing ambient pressure, which means more vortex regions are covered under higher ambient pressure conditions for Definition B. Thus the difference between Definition B and Definitions A and C is getting larger under higher ambient pressures. Definition A covers both the stable area and the vortex area. Before the occurrence of the vortex, Definitions
A and C have the same effective sprays edges. Therefore, during the early injection stage, the spray angle results of Definitions A and C are close. For the later injection process, Definition A gradually covers the vortex region. As a result, the spray angle using definition A is higher than definition C during this stage.

Overall, the largest spray angle is found for Definition B, which covers the most of swell area caused by the vortex. This indicates that the vortex is a key factor that has great influence on the spray angle calculation. In order to eliminate the effect of the vortex, Definition C is employed in this study for all three selected fuels to show the near-nozzle spray angles.

### 4.2.2 Spray penetration length definitions

Similar to the spray angle, the spray front is detected and marked by green lines for the spray front penetration length calculation. Generally, there are two different spray penetration length definitions widely used in literatures. In most cases, spray penetration length is defined as the average distance between the entire detected spray front and the exit plane (Definition A). The other definition adopts the distance between the exit plane and the furthest detected spray location as the spray penetration length (Definition B). Definition B is mostly used for spray plumes that are inclined to the spray axis [63]. The logic of two definitions is presented in Figure 4.5. Again, LN is selected as an example, and the spray penetration length is calculated using two different definitions, as shown in Figure 4.6. Comparison of the spray penetration length of the two definitions under different ambient pressure conditions is shown in Figure 4.7. Apparently the penetration length using Definition B is longer than Definition A for the entire process and all selected ambient conditions. The difference between the two definitions under each ambient condition increases with time.
The spray penetration velocity is also calculated based on two different penetration length definitions, as presented in Figure 4.8. As expected, the spray penetration velocity with different definitions develops distinctly. The spray penetration velocity development for Definition A is quite consistent for all the investigated ambient pressures. A velocity peak is observed at almost the same timing right after the end of the injection for all investigated ambient conditions. While for Definition B the spray penetration velocity has visibly stronger fluctuations than Definition A for all the ambient pressures, and the velocity peak location varies a lot for different ambient pressures. In order to make more reliable quantitative results comparison for different fuels, Definition A was used for all the penetration length and velocity calculations as shown in the following section.

4.2.3 Spray front fluctuation definition

The spray front fluctuation is defined as the standard deviation of the entire detected spray front in this study. This definition is independent from the selections of spray angle and spray penetration length definitions.

4.3 Results and Discussions

In this section, macroscopic spray features of LN, PRF95 and gasoline are presented and analyzed, respectively. Spray angle (Figure 4.2, Definition C), spray front penetration length (Figure 4.5, Definition A), spray front penetration velocity, and spray front fluctuation were calculated.
4.3.1 LN results

A set of LN spray images with marked spray edges and front under different ambient pressures are presented in Figure 4.9. It is seen that the spray develops smoothly with a clear filamentary hollow-cone structure at the atmospheric condition. The spray front stays quite evenly during the injection process. However, the filamentary structure gets blurred with increasing ambient pressure, and a noticeable toroidal recirculation vortex is observed at the downstream region of the spray, which deforms the hollow-cone shape. A shrinking spray dimension or size is also noted with increasing ambient pressure. Similar to the discussion in [51], an increase of fuel liquid signal at frames after the end of the injection is noticed for all the selected ambient conditions. This is believed to be caused by the shutting off of the injector pintle, which squeezes out the residual fuel in the gap between the pintle and the injector body. This may result in a velocity increase and more spray front fluctuation after the end of fuel injection as discussed later. In order to better understand the ambient pressure effect on the toroidal recirculation vortex formation, the spray structure is evaluated with contour-plots at selected ambient pressure conditions, as shown in Figure 4.10. The reduction in the spray radial and axial penetrations with increasing ambient pressure is distinctly observed in this figure. Martin et al. [56] described a parallel moving string shape at the spray front with GDI fuel injectors. A similar phenomenon is observed in this study for all the selected ambient conditions, which indicates a relatively uniform velocity distribution at the spray front. However, this string shape is getting more inconspicuous with increasing ambient pressure. As a result, the spray front fluctuation may become weaker under a high ambient pressure environment.
The edge vortex does not appear until the spray penetrates a certain distance from the exit plane. To compare the location of the vortex under different ambient pressures, the spray structure is plotted at different time steps with the same investigated ambient conditions used in Figure 4.11. Three time steps were selected in Figure 4.11, including 140 μs, 260 μs, and 380 μs ASOIT. Considering that the actual injection process ends at around 430 μs with a 300 μs injection trigger duration, these three timings could represent the beginning, the stable stage and the ending stage of a single injection. It is seen that the vortex can be neglected at 140 μs ASOIT, and just becomes recognizable for 5 bar and 10 bar conditions at 260 μs ASOIT. By the end of the injection, the vortex gets stronger than previous stages. More importantly, the vortex location under 10 bar ambient condition is apparently closer to the orifice than the 5 and 1 bar conditions. Two reasons may result in this phenomenon. Firstly, the formation mechanism of the vortex is believed to be related to the momentum exchange between injected liquid and the small droplets of the precursory spray. A higher ambient pressure, namely a higher gas density, generates a faster momentum exchange rate than normal atmospheric conditions, which may accelerate the vortex formation. Secondly, an increasing gas density can lead to a larger drag force experienced by the moving spray droplets. As a result, a shorter spray penetration length occurs for a higher ambient pressure condition with a vortex observed closer to the nozzle exit.

Detailed LN spray angle (Definition C) under different ambient pressures has been presented and discussed in previous sections as shown in Figure 4.3 (c). The spray angle of LN is quite stable for the entire injection process, which ranges from 99° to 101° for each single injection. The variation among different ambient pressures is small and only a slight increase is observed at the 10 bar condition.
The spray front penetration length (Definition A) was used for all three fuels in this study, and the LN result have been presented in Figure 4.6 (a). Overall, the spray penetration length increases quite linearly until the end of the injection for all the ambient conditions. A higher ambient pressure leads to a shorter penetration length at each time step, and the difference of the penetration length between two adjacent ambient pressure conditions decreases with increasing ambient pressures. Evaluated from Bernoulli’s equation, a change of ambient pressure difference of 10 bar with 100 bar injection pressure leads to less than 5% variation on exit velocity for incompressible flows. In our study, the spray penetration length at atmospheric condition is almost double of the result obtained under 10 bar condition. Therefore the reduction on spray penetration length is believed to be dominated by the increasing drag force experienced by the moving spray droplets with increasing ambient pressure, rather than the small reduction of spray exit velocity. Further, more entrained air is also expected for high ambient pressure conditions. The spray front penetration velocity was calculated based on the spray front penetration length result, as show in Figure 4.8 (a). For LN, the penetration velocity is quite consistent for all the investigated ambient conditions. At the beginning, the spray velocity increases slightly and then keeps stable with a tiny decrease for the whole injection process. This tiny velocity decrease is expected due to the increasing air entrainment to spray in this period that accelerates spray and ambient environment momentum exchanging. After the end of the injection (around 450 μs ASOIT), an obvious peak is found for all the ambient conditions. As mentioned before, this velocity peak is due to the shutting off of the injector pintle at the end of the injection. The closing pintle squeezes out the residual fuel in the gap between the pintle and the injector body, resulting in an increase in spray penetration velocity. This also helps explain the consistence of the velocity peak
locations under different ambient pressure conditions. After this peak, the spray penetration velocity decreases with time, and higher ambient pressure cases have slower velocity decaying process.

The spray front fluctuation of LN is shown in Figure 4.12. The development of the spray front fluctuation can be divided into two stages. Stage one is from the beginning of the injection to around 500 μs ASOIT, during which the spray front fluctuation increases slowly for each ambient pressure, and the fluctuation level is close for all ambient conditions. This is consistent with the discussion on spray structure under investigated ambient conditions. However, after 500 μs ASOIT the fluctuation firstly increases rapidly and then becomes stable by the end. This period is defined as Stage two. Overall, the differences of the spray front fluctuation among different ambient pressure conditions are quite small. No obvious relationship between the ambient pressure and the highest level of the fluctuation is found for LN.

4.3.2 PRF95 results

Compared with LN, PRF95 has more carbon atoms in molecules and the boiling points generally higher. Selected spray images with marked spray edges and front are presented in Figure 4.13. The spray images show similar development and spray structure to LN, therefore, it is not repeated in this section. The spray angle of PRF95 was calculated using Definition C (Figure 4.2) under selected ambient pressure conditions, as shown in Figure 4.14 (a). Similar to LN, the spray angle of PRF95 ranges from 98° to 102°, and the spray angle increases mildly with time for all the investigated pressures. Each ambient pressure condition has almost the same spray angle at the beginning and the end of the injection. However, the difference
between different ambient conditions becomes larger. A larger spray angle is found for higher ambient pressures during the injection process.

The spray front penetration length of PRF95 was calculated using Definition A (Fig. 5), and the spray front penetration velocity was obtained based on the penetration length results as shown in Figure 4.14 (b). Similarly, a longer penetration length is observed for a lower ambient pressure condition, and the penetration length increases almost linearly until the very end of the spray development. The penetration length difference between different ambient pressure conditions becomes smaller with increasing ambient pressure. As for the velocity, PRF95 has almost the same development as LN for all the ambient conditions, as presented in Figure 4.14 (c). The velocity peak after the end of the injection appears quite consistently. The velocity decreases faster for higher ambient pressures after the velocity peak.

The spray front fluctuation of PRF95 was shown in Figure 4.14 (d). Similar to LN, the spray front fluctuation development of PRF95 also has two stages. Compared with LN, it is noticed that the end of Stage one shifts earlier to 400 μs ASOI for PRF95. During Stage one the fluctuations are still almost the same for different ambient pressures. Moreover, the fluctuation slowly increases with time for all the ambient conditions. During Stage two, fluctuation of all ambient conditions increases faster than Stage one, and tends to become stable by the end. Unlike LN sprays, where the ambient pressure effect on the spray front fluctuation is not clear, stronger fluctuation is observed at lower ambient pressure for PRF95.

4.3.3 Gasoline results

The spray angle, spray penetration length, spray front penetration velocity and spray front fluctuation for gasoline fuel were calculated under different ambient pressures. Selected spray images of gasoline were presented in Figure 4.15. The spray angle (Figure 4.2, Definition
C) results are shown in Figure 4.16 (a). Overall, gasoline has a higher spray angle range than LN and PRF95 (from 100° to 105°). The ambient pressure impacts even more on the spray angle for gasoline than LN and PRF95. At each ambient pressure, the spray angle slightly changes from the beginning to the end of the injection. A higher ambient pressure leads to a larger spray angle for the whole injection process and the spray angle development is more distinctly separated.

Spray front penetration length (Figure 4.5, Definition A) and penetration velocity are shown in Figure 4.16 (b) and (c), respectively. Gasoline has almost the same penetration length and penetration velocity development as LN and PRF95. No obvious differences are observed for all the investigated conditions. The spray front fluctuation of gasoline is shown in Figure 4.16 (d). The two stage development is also found for gasoline. Stage one for gasoline begins from the start of the injection to around 500 μs ASOIT for all ambient pressures, which is the same as LN. However, the fluctuation of gasoline in Stage one is more consistent than LN for different ambient conditions. While in Stage two, the spray front fluctuation of each ambient condition increases faster than Stage one, and a higher ambient pressure gives rise to stronger spray front fluctuation except the atmospheric condition.

4.3.4 Comparison among three fuels

In order to compare the effect of different fuels on spray development and the toroidal recirculation vortex, spray structures of three fuels under selected ambient conditions and time steps were plotted in Figure 4.17. The ambient conditions and selected timing are the same as the discussion in LN results section. Since the profiles showed in Figure 4.17 are only one selected case for each fuel and each condition, the penetration length value from the figure
may vary from the averaged result discussed before. According to Figure 4.17, despite the slight difference of the spray front penetration length, spray edges of three fuels match quite well for all the selected ambient pressures and timings. At each ambient condition and each timing, the vortex appears at almost the same location for the three fuels. This indicates that the spray structure may not be mainly controlled by the fuel properties for current study. Higher ambient temperatures might reveal the differences between the spray characteristics due to the apparent differences in the fuels boiling characteristics.

The comparison of the spray angle at different ambient pressures is presented in Figure 4.18. As seen in Figure 4.18, LN, PRF95 and gasoline have quite similar spray angle development under different ambient pressure conditions. All three fuels have weak spray angle fluctuation during the injection process, and the variations are less than 3° for most cases. At the beginning and the end of the injection, all three fuels have a spray angle rise under all selected ambient pressures. The increase of spray angle at the beginning of the injection is believed to be related to the sudden opening of the injector pintle, which adds instability to the spray. The limited number of data points may also introduce errors to the spray angle calculation. Compared with LN and PRF95, the spray angle of gasoline is always the largest when the ambient pressure is higher than 1 bar. At the atmospheric condition, gasoline has larger spray angle than LN at the beginning and the end of the injection. However, during the middle stage (around 150 μs to 300 μs after the start of the injection), LN and gasoline have almost the same spray angle. The smallest spray angle is found for PRF95 under most of the selected ambient pressure conditions. The only exception is for the 10 bar ambient pressure condition, where LN and PRF95 has a quite close spray angle at the second half of the injection process. The lower spray angle of PRF95 may be caused by its higher viscosity than LN and
gasoline. Gasoline has the lowest initial boiling point (25°C) among three fuels. Normally a lower boiling point indicates a stronger evaporation and diffusion ability, and this may be a reason for the largest spray angle of gasoline for all the investigated ambient conditions.

The comparison of the spray front penetration length is shown in Figure 4.19. Unlike the spray angle, the liquid penetration lengths of the three fuels are nearly the same for all investigated ambient conditions during the injection process. Only small differences are noticed at the end of the injection (around 400 μs after the start of the injection) and the end of the whole penetration process (after 700 μs). Gasoline has a slightly longer penetration length than LN and PRF95 at the two periods mentioned above. The comparison of the spray penetration velocity is shown in Figure 4.20. The velocity developments of LN, PRF95 and gasoline are quite close for the entire penetration process under all the investigated ambient conditions. The velocity peak occurs at the same timing for three fuels. Before the velocity peak, gasoline has a slightly higher penetration velocity than LN and PRF95 at most time, while LN has the smallest velocity among three fuels except the 1 bar condition. An opposite tendency is found after the velocity peak. Gasoline spray penetration velocity drops much faster than LN and PRF95 and always has the lowest penetration velocity, and LN on the contrary has the highest velocity for all selected ambient conditions. Different fuel densities may be a reason that caused the difference in the spray penetration velocity. However, the differences of the penetration length and penetration velocity among the three fuels are almost negligible. In other words, the effect of fuel properties on spray front penetration length and penetration velocity is minimal in this study.

The spray front fluctuations of LN, PRF95 and gasoline are shown in Figure 4.21. It has been shown that the spray front fluctuation of all the three fuels has two stages, and the
timing of the first and second stages differs. The timing of the spray front fluctuation variation of LN, PRF95 and gasoline matches well for all the selected ambient pressures. For each condition, a slow increase in spray front fluctuation is noticed before a sharp rise in the second stage for all the three fuels. The beginning of the sharp increase is close for the three fuels at each ambient condition. In addition, the timing of the sharp increase shifts forward with increasing ambient pressures. For example, at 1 bar condition, spray front fluctuation has a low increasing rate until around 600 μs ASOIT. When the ambient pressure increases to 10 bar, the timing shortens to 450 μs ASOIT. One key factor that impacts the spray front fluctuation is believed to be the vortex at the spray downstream. A higher ambient pressure leads to earlier vortex occurrence. Considering that vortex could introduce more random spray motion at the spray front, this may result in a more erratic spray front distribution. Comparing the three selected fuels, it is found that PRF95 always has the weakest spray front fluctuation.

4.4 Summary and conclusions

Spray characteristics of LN, PRF95 and neat gasoline are investigated under different ambient pressure conditions in a constant volume chamber in this study. Major findings are summarized as follows:

1. A clear filamentary hollow-cone spray structure is observed for all three fuels at atmospheric condition. Toroidal recirculation vortex is noticed at the spray downstream, and a higher ambient pressure leads to a stronger vortex closer to the exit plane. Spray structures of three fuels are consistent at the same ambient condition. Vortexes appear at almost the same location for each fuel. This indicates that the spray structure has little dependence on the fuel properties.
2. A slightly larger spray angle is found with a higher ambient pressure for all three fuels. Among the three fuels, gasoline always has the largest spray angle at each ambient condition and PRF95 spray angle is the smallest at most time.

3. The spray front penetration length and penetration velocity reduce considerably with increasing ambient pressure for all fuels. For each ambient pressure and each fuel, spray penetrates nearly linearly until the end of the injection. After the end of the injection, the spray penetrates slower with time. LN, PRF95 and gasoline have close penetration length under all selected ambient pressure conditions. For each fuel, the spray penetration velocity first increases slightly and then keeps stable with tiny decrease until the end of the injection (around 430 μs ASOI) under all ambient conditions. A velocity peak right after the end of the injection is observed, which is believed to be caused by the shutting off of the injector pintle at the end of the injection. After the peak, the spray penetration velocity decreases for all three fuels.

4. The spray front fluctuation presents two distinct stages during the spray development. In Stage one the spray front fluctuation is close for all ambient pressures and increases slowly with time. During Stage two, the spray front fluctuation increases rapidly to a certain level and then becomes stable. A higher ambient pressure generally leads to weaker spray front fluctuation when the ambient pressure is higher than 1 bar.
### 4.5 Tables and figures

Table 4.1. Selected fuel properties

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Density (gm/liter at 25°C)</th>
<th>Viscosity (mPa/s)</th>
<th>Surface tension (dyn/cm)</th>
<th>Boiling Point (°C)</th>
<th>RON</th>
<th>MON</th>
</tr>
</thead>
<tbody>
<tr>
<td>LN</td>
<td>637</td>
<td>0.28</td>
<td>16.4</td>
<td>50-73</td>
<td>62</td>
<td>60</td>
</tr>
<tr>
<td>PRF95</td>
<td>692</td>
<td>0.47</td>
<td>18.39</td>
<td>99</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>Gasoline (E10)</td>
<td>752</td>
<td>0.36</td>
<td>22.0</td>
<td>25-190</td>
<td>91</td>
<td>83</td>
</tr>
<tr>
<td>Isooctane</td>
<td>707</td>
<td>0.50</td>
<td>18.77</td>
<td>99</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Heptane</td>
<td>679</td>
<td>0.38</td>
<td>20.14</td>
<td>98</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 4.1 Experimental system: 1. fuel injector, 2. exhaust line, 3. chamber body, 4. quartz window, 5. plug/window retainer, 6. pressure transducer, 7. intake line, 8. metal plug, 9. spark plug, 10. Combustion chamber, 11. high speed camera (Phantom V4.3). 12 lighting

Figure 4.2. Scheme of three different spray angle definitions

(a) Definition A  (b) Definition B  (c) Definition C
Figure 4.3 LN spray angle with different definitions
Figure 4.4 Comparison of different spray angle definitions

Figure 4.5 Scheme of two different spray penetration definitions
Figure 4.6 LN spray front penetration length with different definitions
**Figure 4.7** Comparison of different spray penetration length definitions

- **Definition A**
- **Definition B**

**Figure 4.8** LN spray penetration velocity with different definitions

- **Definition A**
- **Definition B**
Figure 4.9. LN spray images under selected ambient pressures
Figure 4.10. LN spray structure development under selected ambient pressures

Figure 4.11. LN spray structure development at selected time steps

Figure 4.12 LN spray front fluctuation
Figure 4.13. PRF95 spray images under selected ambient pressures
Figure 4.14. PRF95 spray characteristics: (a) Spray angle (b) Spray front penetration length (c) Spray front velocity (d) Spray front fluctuation
Figure 4.15. Gasoline spray images under selected ambient pressures
Figure 4.16. Gasoline spray characteristics: (a) Spray angle (b) Spray front penetration length (c) Spray front velocity (d) Spray front fluctuation.
Figure 4.17 Spray structure comparison among three fuels
Figure 4.18 Spray angle comparison among three fuels

Figure 4.19 Spray front penetration length comparison among three fuels
Figure 4.20 Spray front penetration velocity comparison among three fuels

Figure 4.21 Spray front fluctuation comparison among three fuels
5. Sprays under low pressure environment

5.1 Introduction

Superheated is used to describe the situation that a liquid contained at conditions above the ambient saturation pressure. Under this situation, rapid boiling of the resultant liquid jet occurs and produces a two-phase flow. Meanwhile, dynamic expansion of vapor bubbles shatters the liquid stream to produce a finely atomized spray. This phenomenon is also known as flashing [64]. Flashing liquid gives rise to potentially explosive and certainly hazardous heterogeneous two-phase clouds. Typically, the flashing phenomenon has been observed in laboratory experiments where a liquid flows through a short nozzle into a low-pressure chamber at a pressure value considerably lower than the liquid saturation pressure at the injection temperature [14].

Study of flashing boiling liquids started from 1960s. Brown et al [65] and Lienhard et al [66] revealed the importance of the superheated liquid jet effects on the atomization process. They successfully correlated fuel flashing with liquid jet breakup. Several studies has shown flash-boiling sprays consist of smaller drop sizes with an accelerated vaporization process compared to non-flashing sprays [67-70]. Vieria and Simoes-Moreira [14] in 2007 examined iso-octane flashing regime that takes place at very high ratios of injection to discharge pressures in flow restrictions by using the schlieren and the back-lighting methods. It is reported that flashing takes place on the surface of the liquid core through an evaporation wave process, which results from a sudden liquid evaporation in a discontinuous process [71-72]. And this discontinuous process leads to high velocities at downstream of the evaporation stream that could reach local sonic speed at high expansion condition. Steelant and co-workers [73] paper investigates the characteristics and morphology of a flash jet by means of high-
speed shadowgraphy. They found that the inception of flashing strongly depends on the level of superheat and on the transient heat conduction process within the depressurized liquid jet. Transition towards the fully flashing disintegration regime is observed by increasing the superheat of the liquid jet [74-76].

Superheated fluid flash boiling is closely related to fuel sprays in engines. Superheating conditions are likely to be found under partial load conditions in GDI applications, which definitely could enhance fuel atomization and vaporization [77]. The occurrence of flash vaporization might affect combustion performances, and even create the danger of vapor lock within the fuel line [78]. In general, the superheated conditions in engines could be reached when the fuel temperature increases in high pressure pump at a low discharge pressure, or caused by the heat exchange between injector and cylinder head. Investigations in several working scenarios have shown that superheated fuels can alter mainly depending on nozzle geometry, pressure regimes, superheating degree and heat transfer [79]. Zeng et al [80] studied the empirical correlations that describe the mechanisms associated with flash-boiling sprays with multi-hole fuel injector. They concluded that bubbles in fuel encounter rapid expansion process that result in a prompt disintegration of bulk liquid into smaller droplets during fuel injection process [81-85]. Multi-hole injector was also studied by Zhang and co-workers [83-84] to investigate flow fields of n-hexane spray in both vertical and cross-sectional directions. They found that that in axial direction, the vertical velocity increases while the radial velocity decreases with increasing superheat degree, which determines the convergent spray structure. Negro et al [82] proposed a homogeneous one-dimensional model to predict flash evaporation in superheated liquid fuel injections, which is compatible for both internal and external flashing.
Even that considerable researches have been done on fuel flashing boiling, less work were done with outwardly opening piezoelectric GDI fuel injector. In this study, spray of iso-octane from an outwardly opening piezoelectric GDI fuel injector was investigated under different ambient conditions. To form a superheated condition, ambient pressure from 10 KPa to 100KPa were selected. Effect of fuel injection pressure, fuel injection duration on fuel spray flash boiling and spray structure were discussed.

5.2. Diagnostics and Measurements

In this study, five fuel injection pressures including 100 bar, 80 bar, 50 bar, and 20 bar were selected to achieve different and fuel spray initial velocity conditions. An outwardly opening piezoelectric fuel injector was employed in this study for all experiments. This injector was controlled by a piezo injector driver from Drivven (a subsidiary of National Instruments, Inc.). Two fuel injection durations, 0.3 ms and 0.5 ms, were investigated. Fuel injection trigger and fuel injection duration was controlled by an external pulse delay generator. Fuel mass per injection under different injection pressure and injection durations were presented in Figure 5.1.

Fuel spray was visualized by applying a Mie-scattering technique. Transient spray images were captured by using a high-speed camera (Phantom V4.3 from Vision Research Inc.). The frame rate was set at 5,500 frames per second (fps) with a resolution of 400 X 256 pixels for spray structure analysis, and was set at 25,000 fps with a resolution of 400 X 32 for spray penetration velocity analysis. In order to ensure the consistence of spray signals in all experiments, camera exposure time, aperture and other parameters were set all appropriately and kept constant. Camera was triggered simultaneously with fuel injection by the same pulse
delay generator. To investigate the effect of ambient pressure on fuel spray characteristics, five different ambient pressure were selected, including 0.01 bar, 0.03 bar, 0.05 bar, 0.07 bar and 0.1 bar, respectively. The gas pressure in chamber was manipulated by a gas control system with a vacuum pump, solenoid valves and electrical actuators. Gas pressure was read by a pressure transducer mounted on the top of the chamber.

Pure iso-octane was selected in this study. Iso-octane has similar characteristics with gasoline and has an AKI of 100. AKI is the average of the research octane number (RON) and the motor octane number (MON). Selected fuel properties of iso-octane are listed in Figure 5.2. For all experiments, Chamber and fuel temperature were at 298 K. Experiments were repeated five times for each ambient condition. In order to account for the uncertainty, data from five readings were averaged, and the standard deviation was calculated and reported.

5.3 Result discussions

In this study, effect of low ambient pressure on spray macroscopic features will be analyzed and discussed. As mentioned above, ambient pressure conditions are controlled at 0.01 bar, 0.03 bar, 0.05 bar, 0.07 bar and 0.1 bar, respectively. Fuel spray structure and development are discussed first, fuel spray penetration length and spray front penetration velocity are measured and calculated for both fuels. Effect of ambient pressure, fuel injection pressure, fuel injection duration on spray characteristics are analyzed.

5.3.1 Spray images

Comparing with sprays at atmospheric condition, sprays under an extreme low ambient pressure present distinct structures and unique developments. A set of spray images of iso-
octane under different ambient pressures are shown in Figure 5.3. Generally, sprays generated by an outwardly opening piezoelectric fuel injector have clear and sharp hollow-cone shapes when the ambient pressure is atmospheric or higher. However, when the ambient pressure is lower than 0.1 bar, spray structures are completely changed in this study. Practically, fuel injection with 0.3 ms injection duration ends at around 0.45 ms after the injection trigger. The delay is caused by the opening and close of injection nozzle. According to the first three images, it is found that the original hollow-cone structure is still observable with strong liquid signals. However, spray edges are no longer straight and clear. Instead, spray edges now are curved and spray signals are no longer uniform. More importantly, spray deforms from hollow-cone structure to blurred diamond shape with a long tail at spray downstream at 0.01 bar ambient condition. Liquid signals at tail part are much weaker than the original hollow-cone shape part. The tail part extends the spray to downstream greatly and is almost symmetric. Meanwhile, considerable liquid signals are detected at left-side of spray edges, which is not observed before.

When the ambient pressure is increased to 0.03 bar, sprays no longer maintain a diamond shape. However, a similar tail structure is still noticed right after the original hollow-cone structure. Compared with the tail at 0.01 bar, tail at 0.03 bar is thinner and shorter. Both the original hollow-cone shape part and the tail part of the spray at 0.03 bar have stronger liquid signal than sprays at 0.01 bar ambient pressure condition. In addition, even though that liquid signals could still be noticed at the left of spray edges, the liquid area is shrinking compared with the 0.01 bar condition. For 0.05 bar and 0.07 bar ambient pressure conditions, spray structures are quite similar as the spray at 0.03 bar condition. Similar tail are also observed. A longer tail is found at a lower ambient pressure condition, and tail at a lower ambient pressure condition has weaker liquid signal. At the same time, liquid signals at the left-side of spray
edges are continue shrinking and getting weaker with increasing ambient pressure, and finally disappear at 0.07 bar condition. Once the ambient pressure is increased to 0.1 bar ambient pressure condition, the tail part disappears and the whole spray return to general hollow-cone shape with clear and sharp edges again. Therefore, 0.1 bar might be the upper limit for the existence of the abnormal spray structure in this study.

5.3.2 Penetration length

In this study, the appearance of the additional tail makes spray penetrates much longer. In order to explore the effect of ambient pressures on spray penetration length, spray front penetration length is calculated for each ambient condition. In this study, the spray front penetration length is defined as the distance between the location of the furthest detected spray signal and injector nozzle. In order to measure the furthest spray front, the camera resolution is modified to 400 X 32 so that it will focus on the centerline of the spray, and could clearly capture the front of the tail. A set of spray front images are illustrated in Figure 5.4 to present the schema of spray front penetration length calculation. For each image, the furthest spray front is detected and marked by a green line using a Matlab program. The threshold for spray front detection is kept constant to ensure all results are consistent. Since in this study we are interested more in the special tail part of sprays under low ambient pressures, spray penetration length with time at 0.01 bar, 0.03 bar, 0.05 bar and 0.07 bar are calculated and presented in Figure 5.5. Apparently, spray under a lower ambient pressure penetrates much longer than at a higher ambient pressure condition at the same time step. For example, spray penetration length at 500 μs after the start of injection trigger (ASOIT) is more than 90 mm at 0.01 bar ambient pressure, but it is less than 30 mm if the ambient pressure increases to 0.07 bar.
Considering that the fuel injection ends at around 450 μs ASOIT, it is found that even spray have an abnormal tail structure appended after the hollow-cone shape, spray still penetrates almost linearly before the end of the fuel injection for all investigated ambient pressure conditions except for 0.01 bar ambient pressure. At 0.01 bar, spray penetration length development has obvious fluctuation. Seen from the slope, spray under 0.01 bar ambient pressure penetrates faster before around 250 μs. At 250 μs a noticeable inflection point could be observed. After this point spray penetration length has a lower slope than before.

In order to better evaluate the effect of low ambient pressures on spray penetration process, spray front penetration velocity is calculated based on spray penetration length results, as shown in Figure 5.6. Recall the spray front penetration velocity results in previous parts where ambient pressure is atmospheric or higher, the highest spray front penetration velocity is found at around 60 m/s when the ambient pressure is 1 bar. In this study, the spray front penetration velocity results are all much higher. Generally, under investigated ambient pressures, a higher spray front penetration velocity is found at a lower ambient pressure condition, and sprays have similar velocity development except 0.01 bar condition. At 0.01 bar, the spray front penetration velocity first increases linearly to more than 390 m/s at 250 μs ASOIT. After that the velocity drop to 200 m/s and maintains at this level for a while, and then continue dropping until the end of the measurement. It should be noticed that 390 m/s is a very high speed since it has exceeded the sound speed. For 0.03 bar, 0.05 bar and 0.07 bar ambient pressure conditions, spray front penetration velocities has close patterns. First the velocity increases rapidly to a certain level, and maintains at this level until the end of fuel injection. The velocities in this period are around 170 m/s, 100 m/s and 70 m/s for 0.03 bar, 0.05 bar and 0.07 bar conditions, respectively. After this period spray front velocity decreases slowly until
the end of the measurement. For all investigated ambient pressures, spray front penetration velocity drops faster at a lower ambient pressure than at a higher ambient pressure environment.

5.3.3 Effect of fuel injection pressure

According to discussions in the previous section, the pressure difference among different ambient pressure conditions is only 0.02 bar or 0.03 bar, but the differences on spray velocity ranges from 30 m/s to more than 200 m/s. In order to explore the dominant parameter that results in this phenomenon, effects of fuel injection pressure and fuel injection duration are investigated and discussed in follow sections.

Fuel injection pressure determines the initial spray penetration velocity. Generally, a higher fuel injection pressure leads to a faster initial spray penetration velocity. In last section, fuel injection pressure is maintained at 100 bar with 0.3 ms fuel injection duration for all experiments by using a gasoline common rail system. In this section, five fuel injection pressures, including 100 bar, 80 bar, 50 bar, 30 bar and 20 bar, are selected to study the effect of fuel injection pressures on spray characteristics under different ambient pressure conditions. Other parameters are kept the same. Selected spray images with different injection pressure under different ambient pressures are presented in Figure 5.7. It is found that sprays at the same ambient pressure have quite similar structure for all selected injection pressures. All sprays have the original hollow-cone structure and a tail appends after that. The hollow-cone part has much stronger liquid signals than the tail. Main differences are found with overall size of the spray and the length of the tail. Firstly, despite that all sprays have quite similar structures, a lower fuel injection pressure leads to a smaller spray size for all investigated ambient pressures and fuel injection pressures. This is expected since a lower fuel injection pressure results in a lower initial spray penetration velocity, which apparently reduces fuel mass for a single
injection. As a result spray penetrates shorter and has smaller size. In addition, distinct phenomenon is observed with the tail part. For all selected ambient pressures, a lower fuel injection pressure results in a longer tail for the whole measurement. For example, at 0.05 bar the spray tail part with 30 bar fuel injection pressure is longer than spray with 50 bar and 100 bar fuel injection pressures. Furthermore, at different fuel injection pressures, fuel spray front penetration lengths are quite close. In other words, a lower fuel injection pressure leads to a smaller hollow-cone spray size but longer tail length, and the results in the similar spray front penetration length. This is verified by the spray penetration length results discussed next.

Spray penetration length with different fuel injection pressures under 0.01 bar, 0.03 bar, 0.05 bar and 0.07 bar are calculated using the same definition in chapter 4. Results are illustrated in Figure 5.8. It is found that the effect of fuel injection pressure on spray penetration length is different at different pressure range. Firstly, when fuel injection pressure is higher than 30 bar, namely, variations on fuel injection pressure have minor effect on spray penetration length. Within this fuel injection pressure range, fuel sprays have close spray penetration length and development pattern under all investigated ambient pressures. Moreover, before 600 μs ASOIT where spray penetration length could well overlap. However, when fuel injection pressure is lower than 30 bar, namely 30 bar and 20 bar in this study, an obvious delay on spray penetration is observed for all selected ambient pressures, within which spray penetrates much slower in a period than sprays with higher fuel injections. Spray with 30 bar fuel injection pressure has shorter fuel penetration delay than spray with 20 bar fuel injection pressure. After this penetration delay, sprays penetration rate increases rapidly. Comparison of spray penetration at different ambient pressures with 30 bar fuel injection pressure is presented in Figure 5.9. It is seen that the spray penetration delay is almost the same.
with the same fuel injection pressure under different ambient pressures. At 30 bar fuel injection pressure, this delay is around 200 μs, and spray penetration lengths are quite close within this period even at different ambient pressures. This indicates that this delay is mainly dominated by fuel injection pressure and is irrelevant with ambient pressure conditions.

Spray front penetration velocity is also calculated based on spray penetration length results in this section and is shown in Figure 5.10. As we discussed previously, sprays at 0.01 bar have unique penetration velocity development, and this unique development pattern is still observed for all fuel injections pressures at the ambient condition. Meanwhile, spray front penetration velocities could well match when fuel injection is higher than 30 bar until very end of the measurement. For other ambient pressure conditions, spray front penetration velocities with different fuel injection pressures are quite close before 400 μs when fuel injection pressure is higher than 30 bar. Within this period spray front penetration velocity increases briskly until 200 μs ASOIT, and then drops slowly and almost linearly. After 400 μs ASOIT, spray front penetration velocity of spray with a higher fuel injection pressure drops faster than a lower fuel injection pressure. Obvious delay on spray front penetration velocity is also observed when fuel injection pressure is lower than 30 bar. During this delay, spray front penetration velocity is kept at a very low level compared with the sprays with higher fuel injection pressure. Normally the velocity is between 20 m/s to 40 m/s for all investigated ambient pressures. It is noticed that spray front penetration velocities has obvious fluctuations during this period, and this fluctuation is also quite consistent for each ambient pressure condition. After this delay, spray front penetration velocities begin to increase until reach the peak. One thing interesting is that the spray penetration velocity peak with 30 and 20 bar fuel injection pressure at 0.01 bar ambient pressure condition is even higher than sprays that have higher fuel injection
pressures, while the development pattern are still similar. For other ambient pressures, spray penetration velocity of sprays with 30 bar and 20 bar fuel injection pressures first boosts to similar level as sprays with higher fuel injection pressures and then begin to drop until the end of the measurement. Therefore the variation of fuel injection pressure mainly introduces the considerable fuel penetration delay for all ambient pressures, but has limited effect on spray penetration velocity afterwards. Comparison of spray front penetration velocity is presented in Figure 5.11. Previously we have concluded that spray with 30 bar fuel injection pressure have similar penetration delay, and this is also verified by the velocity results. Sprays at different ambient pressures have almost the same velocity development before 200 μs ASOIT, even for the velocity fluctuation. In addition, the observation that a lower ambient pressure leads to stronger velocity increasing rate dropping rate is still valid for 30 bar fuel injection pressure condition.

5.3.4 Effect of fuel injection duration.

Fuel injection duration controls fuel mass of a single fuel injection. At the same fuel injection pressure, a longer fuel injection duration results in a higher fuel mass with the same initial fuel penetration velocity. In order to evaluate the effect of fuel mass on spray characteristics under different ambient pressures and different fuel injection pressures, sprays with 0.5 ms fuel injection duration are studied and compared with previous results. Selected spray images with 0.3 ms and 0.5 ms fuel injection durations under different ambient conditions are presented in Figure 5.12. For each figure, five consecutive images are listed with time step marked on the top right corner.
Generally the third image in each select image set is at around 450 μs ASOIT, which is the end of fuel injection with 0.3 ms fuel injection. It is found that sprays with 0.3 ms and 0.5 ms fuel injection durations have similar spray structures for the first three images in each image set. Under each selected ambient condition, sprays with both injection durations have almost the same size and shape for the hollow-cone part and the tail part. In addition, spray liquid signals distributions are also close for the whole area. After the 450 μs ASOIT the fuel injection with 0.3 ms injection duration has ended and spray liquid signal becomes weaker, while continuous liquid signal could be observed for sprays with 0.5 ms fuel injection duration. In summary, spray fuel injection duration has little effect on spray structure with different ambient pressures and different fuel injection pressures.

Spray penetration length results with different injection duration under selected ambient pressures and 100 bar fuel injection pressure are shown in Figure 5.13. According to Figure 5.13, sprays with different fuel injection durations have almost the same spray penetration length and similar development pattern at all time steps for each selected ambient pressure. Only tiny differences are found after 800 μs ASOIT at 0.05 bar and 0.07 bar ambient pressures, where spray penetration length of spray with 0.5 ms injection duration is slightly longer than spray with 0.3 ms injection duration. To better explain this difference, spray front penetration velocity at the same ambient conditions are calculated based on spray penetration length results and are show in Figure 5.14. The spray front penetration velocity results are consistent with our discussion on spray structures and spray penetration length in this section. Sprays with different fuel injection durations still have quite close front penetration velocity all the time when ambient pressure is 0.01 bar or 0.03 bar. The difference on spray penetration length after 800 μs ASOIT at 0.05 bar and 0.07 bar conditions is also noticed in Figure 5.12.
In this time period spray with 0.5 ms injection duration has higher spray front penetration velocity than spray with 0.3 ms injection duration. This may due to the decreasing dominant effect of ambient pressure on spray structure when ambient pressure is higher than 0.05 bar. Then a longer fuel injection duration could offer a spray more initial momentum, and results in a slower velocity dropping rate after the end of fuel injection.

Spray penetration length and spray front penetration velocity results with different injection duration under selected ambient pressures and 30 bar fuel injection pressure are shown in Figure 5.15 and Figure 5.16. Similar phenomenon is observed for sprays with different injection durations when ambient pressure is lower than 0.05 bar. Sprays with 0.3 ms and 0.5 ms share almost the same spray penetration length and spray front penetration velocity development for the whole measurement. Specifically, the spray penetration delay are also observed when fuel injection duration is increased to 0.5 ms, and the duration of this delay does not change with increasing injection duration. However, the difference of spray penetration length and spray front penetration velocity is much more obvious and considerable at 0.05 bar and 0.07 bar ambient pressure conditions when fuel injection pressure is reduced to 30 bar. The starting point of the appearance of spray penetration length difference is forwarded to around 400 μs ASOIT. After this spray penetration length of spray with 0.5 ms injection duration is found larger than spray with 0.3 ms injection duration, and the penetration length difference is increasing with time. This difference could also be seen in Figure 5.15 (c) and (d). Spray front penetration velocities no longer close in (c) and (d), and spray with 0.5 ms injection duration has a more stable spray front penetration velocity development. Compared with sprays with 100 bar fuel injection pressures, it may indicate that fuel injection duration has stronger
effect on spray structure at an environment with a higher ambient pressure and/or a lower fuel injection pressure.

5.4 Summary

In this study, sprays of iso-octane under low ambient pressure conditions were studied. Effect of ambient pressure, fuel injection pressure and fuel injection duration were investigated. Major conclusions could be summarized as follows.

1. Spray presents distinct structures when the ambient pressure is lower than 0.1 bar. While the original hollow-cone structure is still observable, spray deforms from hollow-cone structure to blurred diamond shape with a long tail at spray downstream. Liquid signals at the tail part are much weaker than the original hollow-cone shape part. Within this pressure range, a higher ambient pressure leads to a shorter tail on spray.

2. Spray penetration length is greatly enlarged due to the deformation on spray structure. Spray under a lower ambient pressure penetrates much longer than a higher ambient pressure condition at the same time step. Fuel injection pressure and fuel injection duration have little effect on spray front penetration length development.

3. A higher spray front penetration velocity is found at a lower ambient pressure condition. Spray penetration velocity first increases rapidly and maintains at a stable level until the end of fuel injection for most ambient pressure conditions. Specially, the highest spray front penetration velocity at 0.01 bar could exceed local sound speed. Spray structure, spray penetration length and spray penetration velocity are mainly dominated by ambient pressure conditions in this study.
5.5 Tables and Figures

![Graph showing Fuel Mass vs. Injection Pressure](image1)

**Figure 5.1 Fuel quantity per injection**

![Graph showing Saturation pressure vs. Liquid temperature](image2)

**Figure 5.2 Saturation pressure of iso-octane at different temperature**
Figure 5.3 Selected spray images under different ambient pressures
Figure 5.4 Selected spray front images at 0.01 bar ambient pressure
Figure 5.5 Spray penetration length at different ambient pressures

Figure 5.6 Spray penetration velocity at different ambient pressures
Figure 5.7 Spray images with different injection pressure at selected ambient pressures
Figure 5.8 Comparison of spray penetration length at different fuel injection pressure

Figure 5.9 Comparison of spray penetration length at 30 bar injection pressure
Figure 5.10 Comparison of spray penetration velocity at different injection pressures

(a) 0.01 bar ambient pressure
(b) 0.03 bar ambient pressure
(c) 0.05 bar ambient pressure
(d) 0.07 bar ambient pressure

Figure 5.11 Comparison of spray penetration velocity at 30 bar injection pressures
Figure 5.12 Spray images with different injection durations at selected ambient conditions

(a) 0.01 bar ambient pressure, 100 bar injection pressure

(b) 0.05 bar ambient pressure, 100 bar injection pressure

(c) 0.01 bar ambient pressure, 30 bar injection pressure

(d) 0.05 bar ambient pressure, 30 bar injection pressure

Figure 5.12 Spray images with different injection durations at selected ambient conditions
Figure 5.13 Comparison of spray penetration length with different injection durations

Figure 5.14 Comparison of spray penetration velocity with different injection durations
Figure 5.15 Comparison of spray penetration length with different injection durations at 30bar injection pressure

Figure 5.16 Comparison of spray penetration velocity with different injection durations at 30bar injection pressure
6. Auto-ignition of gasoline fuels under different ambient conditions

6.1 Introduction

Researches has shown that in both large and small cylinder research engines [85-86] gasoline ignites much later than diesel fuel, which left more time for fuel and air to mix. Sufficient ignition delay for forming a near-homogeneous fuel/air mixture has been identified as critical to enable such clean combustion [87]. And the use of gasoline fuels in compression ignition engines has shown encouraging progress in engine efficiency and emissions. [88] Furthermore, the low temperature combustion (LTC) in diesel engines is capable of producing diesel-like efficiency while emitting simultaneously low NOx and soot emissions [89-91].

Two compression combustion modes, premixed charge compression ignition (PCCI) and homogenous charge compression ignition (HCCI) are most widely used in research. Both combustion mode could achieve low-NOx and low-smoke in a compression ignition engine, and solve a great part of shortcomings derived of the use of diesel fuel by using low cetane fuels.

PCCI engine has been manufactured experimentally and evaluated in terms of fuel economy and NOx reduction in 1990s by Aoyama and co-workers with a compression ratio of 17.4 [92]. Spontaneous ignition was observed at unspecified locations. By using a single-cylinder light-duty compression ignition engine with PCCI combustion mode, Hildingsson .et al [93] investigated the necessity of high volatility of different fuels to achieve more premixed combustion with low NOx and soot emission. They demonstrated that if the combustion phasing and delay of two fuels are equivalent, their emission behavior is also matched in spite of the differences in fuel volatility and compositions. Kalghatgi and co-workers [94] used similar experimental setup and studied auto-ignition quality of gasoline fuels at different
operation conditions. They proposed that a good surrogate for gasoline in partially premixed compression ignition engines is a mixture of toluene, iso-octane and n-heptane with the same RON and MON. Both experimental and numerical parametrical study was performed with varying EGR, injection timing and fuel type in a high speed direct injection diesel engine by Benajes et al. [95], and confirmed that use of gasoline could introduce much longer ignition delay in this engine than any other engine setting with diesel fuel.

HCCI is an alternative combustion approach for both the SI-engine and the CI-engine and is more wide used than PCCI in current gasoline fuels compression ignition studies. Benefits of HCCI includes low cycle to cycle variations, higher combustion efficiency, and low concentrations of particulates. Yoshizawa and co-workers [96] has been using HCCI mode in 2002 to perform multi-zone engine cycle simulations and investigate the characteristics of compression ignition combustion in gasoline engines. In general, air-fuel distribution in cylinder has large impact on combustion characteristics, Knocking could be well prevented by creating a fuel rich zone at the center of cylinder even under high load conditions. Experimental study has shown that stable gasoline compression ignition (GCI) engine operation was achieved down to idle speed and load on a multi-cylinder compression ignition engine with gasoline [97]. The use of gasoline in compression ignition engines offers significant advantages in terms of increased efficiency and reduced emissions compared to either conventional diesel compression ignition or gasoline spark ignition engines. Lots of work were done by Kalghatgi and co-coworkers [98] in investigating gasoline like fuels auto-ignition quality in HCCI engines.

The auto-ignition quality of a fuel of any chemistry at a given engine condition is described by an octane index defined as, \[ \text{OI} = (1-K) \text{RON} + K \text{MON}, \] where RON and MON
are the Research and Motor Octane numbers respectively and K depends only on the engine design and operating conditions [98]. Approaches like direct injection, higher compression ratios, downsizing and turbocharging will reduce the unburnt gas temperature for a given pressure and push the value of K downwards [99]. Fuels with high resistance like gasoline has a significantly higher ignition delay for the same combustion phasing and hence results in very much lower NOx and smoke for a given load compared to diesel fuels [100]. However, in HCCI mode gasoline cannot be run with very early injection in HCCI mode. Even that the HCCI combustion mode usually indicates simultaneously ignition of the whole fuel air mixture, in fact, the experiments have shown that it does not occur while running gasoline like fuels in diesel engines. The occurrence and development of auto-ignition are strongly affected by the residual gas and thermal distributions. It is shown that a heterogeneous combustion has large spatial and temporal variations, even with a homogeneously premixed charge [101]. The thermal inhomogeneous distribution correlates well with that of the residual gas, and a higher residual gas fraction level advances the auto-ignition occurrence [102]. In addition, higher temperature inhomogeneity could also result in earlier auto-ignition timing at the same average condition inside the cylinder [103-106].

In spite on alternation combustion mode, naphtha fuels has drawn more attention recently. Naphtha is a kind of fuel with less processed refinery stream in the gasoline boiling and carbon number range, but with lower octane number. Generally, it is composed of C5 to C11 hydrocarbons and has a low research octane number (RON) value, roughly within the 40-70 range [107]. Naphtha requires much less processing in the refinery than either gasoline or diesel [108], greenhouse gas emissions of the well to pump process are reduced, being 18 g/MJ fuel energy of gasoline and only 12 g/MJ fuel energy for naphtha. Thus there is an additional
benefit in terms of well-to-wheel CO2 emissions and overall energy consumed, thus it can also be considered as a way of increasing the efficiency of a Gasoline powertrain system [109]. It has been demonstrated that both light and heavy naphtha could be able to commercial diesel engines with both PCCI and HCCI modes [110-111]. Chang et al [112] developed more optimized combustion chamber design to improve idle and light load combustion stability in HCCI mode with a compression ratio of 14 by using naphtha fuels, and achieved 26% average fuel consumption reduction over a range of part load operating points. Compression ratio and derived cetane number effects on naphtha fuels compression ignition is then further studied by Viollet and co-workers [112]. Their work shows that heavy naphtha makes low load operation even at the lower compression ratio easier, and the light naphtha enables the engine to be run at a higher compression ratio at higher loads and gives higher efficiency. Kolołdziej [113] compared engine combustion, performance, and emissions between naphtha and E10 gasoline on a Gen 2 single-cylinder GDCI engine, and proved that naphtha fuels has lower hydrocarbon and carbon monoxide emissions at low loads.

In present study, auto-ignition of gasoline fuels, including light naphtha, primary reference fuels, gasoline and gasoline surrogate were investigated under different ambient conditions. Fuel auto-ignition delay at spray G condition of different fuels were compared and discussed. Two-color pyrometry was employed to evaluate flame temperature and KL factor distributions.
6.2 Auto-ignition of gasoline fuels under spray G condition

6.2.1 Diagnostics and Measurements

In this study, fuel injection pressure was maintained at 100 bar by a gasoline common rail fuel system through all experiments. Injection duration for all investigated fuels was kept as 0.3 ms by an external pulse generator. Temperature of both chamber and fuel were controlled at 90 °C. In order to generate a high-temperature high-pressure environment, a premixed combustion of acetylene was conducted prior to the fuel injection. Three different gases, acetylene, O$_2$/N$_2$ (50%/50%) and dry air were used to formulate appropriate mixtures to obtain the desired ambient temperature and ambient oxygen concentration. Premixed reactants were ignited by a spark plug. In this study, the ambient oxygen concentration was set as 21% for all experiments before fuel injection. The compositions of the gas mixture before and after the premixed acetylene combustion are listed in Table 6.2.1.

A Kistler 6041B transducer coupled with a Kistler 5004 charge amplifier was utilized to measure the transient pressure during premixed combustion, and the ambient temperature was calculated based on the pressure data using a corrected ideal gas law. In this study, a monochrome high-speed digital video camera (Phantom V4.3 camera from Vision Research Inc.) was used to capture both fuel spray and fuel auto-ignition process, as shown in Figure 6.2.1. The camera was set with 5500 fps and a resolution of 320×312 pixels. A 50 mm fixed focal length lens was used to collect signals. Camera exposure time and the aperture number were selected based on the flame intensity under different ambient conditions for fuel auto-ignition experiments. For fuel spray experiments, the spray development during fuel injection process was visualized by applying a Mie-scattering technique, and all camera settings were kept constant to ensure result consistency. In current investigation, a pulse delay generator was
used to enable external trigger to synchronize the image capturing of the high-speed camera and the fuel injection. Rising edge of the triggering pulse was used for all the devices. Experiments were repeated five times for each ambient condition. In order to account for the uncertainty, data from five readings were averaged, and the standard deviation was calculated and reported.

For all experiments, gas density in chamber was set as 3.5 kg/m$^3$ to keep consistent with the non-reacting spray G condition suggested by Sandia National Laboratories. Five different ambient temperatures ranged from 650 K to 950 K with a 75 K interval were selected in this study, with equivalent pressures of 6.8 bar, 7.6 bar, 8.4 bar, 9.2 bar and 10 bar, respectively. Five different fuels were investigated: light naphtha (LN), two primary reference fuels (PRF65, PRF95), gasoline (Haltermann CARB LEV III) and gasoline surrogate (Haltermann surrogate). Naphtha is a kind of fuel with less processed refinery stream in the gasoline boiling and carbon number range, lower octane number and higher heating values compared to commercial gasoline. LN used in this study was obtained from Saudi Aramco, with an AKI (the average of the research octane number (RON) and the motor octane number (MON)) value of 61. Conventionally, PRF is a binary mixture of iso-octane and n-heptane and is used as a surrogate for gasoline. PRF used in this work was PRF65, a blend of 65% iso-octane and 35% n-heptane by volume, and PRF95 that contains 95% iso-octane and 5% n-heptane by volume. The AKI of PRF65 is 65, and the AKI of PRF95 is 95 [59]. Gasoline used in this study is obtained from Saudi Aramco. Gasoline surrogate used in experiments is made in lab. Fuel mass per injection is around 10 mg per injection. Detailed compositions of gasoline surrogate and selected fuel properties of all five investigated fuels are listed in Table 6.2.2 and Table 6.2.3.
6.2.2 Results and Discussions

In this section, auto-ignition characteristics of different fuels and fuel spray development before auto-ignition will be discussed. Firstly, the auto-ignition images were presented and discussed. For each set of auto-ignition images, locations of the injector, pressure transducer and the chamber view boundary are all the same, as marked in Figure 6.2.2. Fuel ignition delay, spray angle, spray front penetration length and time-averaged spray front velocity were calculated and analyzed.

6.2.2.1 Auto-ignition images.

Fuel auto-ignition was observed for all selected fuels under each investigated ambient condition in this study. As mentioned above, experiments under each ambient condition were repeated five times. In this section, one set of auto-ignition combustion images of PF65 under different ambient temperatures are presented as example in Figure 6.2.3. For each temperature, twenty consecutive images with noticeable flame are selected, and the first image indicates the first appearance of flame. Fuel type and image timing after the start of the injection trigger are marked at the left top corner. The ambient temperature is noted at the left bottom corner. Since ignition delay results that presented in the next section are an average among five experiment runs, time marked on images in this section may differ slightly from the averaged ignition delay results.

Seen from PRF65 auto-ignition images, it is found that the location of the occurrence of auto-ignition is randomly distributed in combustion chamber. In most experiments, the first detected flame is observed at top-half area. It could be note that sometimes there are more than one auto-ignition events in one single experiment. For example, in Figure 6.2.3 (b), two disjoint
flames are observed in first five images. Unlike diesel compression ignition or gasoline spark ignition where most injected fuel is ignited almost simultaneously, obvious flame propagation process is observed in this study. The flame spread rate heavily depends on ambient conditions. Under a lower ambient temperature, flame spreads much slower than a higher ambient temperature. Specifically, flames occupies mostly the top-half area with no specific shape when ambient temperature is lower than 800 K. Once the ambient temperature is higher than 800 K, the flame moves left and present an eclipse shape. This phenomenon could be better explained combined with the discussion of ignition delay.

Ignition delay is defined as the time interval between the start of the injection trigger and the occurrence of auto-ignition. In this study, the camera and the injector are triggered simultaneously by a pulse delay generator. Therefore the ignition delay could be read directly from captured videos. In order to reduce error, the final ignition delay of each fuel under each investigated condition is the average of five consecutive runs of experiments with same experimental setting, and standard derivation is calculated to evaluate result fluctuation, as show in Table 6.2.4. Simply seen from the ignition delay result, for all fuels and all ambient temperatures, the ignition delay could reach more than 12 ms at 650 K condition, which is much longer than the 0.3 ms injection duration that employed in this study. Therefore, combustion in this study is more like fuel and oxygen premixed combustion with fuel auto-ignition when the ambient temperature is relatively low. The free and random fuel spread after the end of injection may be the key reason for the randomly distributed auto-ignition location and the uncertain flame shape. Even for 950 K ambient temperature condition the shortest ignition delay among five fuels is still more than 0.7 ms, almost double of the injection duration. However, the ignition delay at this condition reduces to a great degree compared with the 650
K condition. As a result, much fewer time is left for fuel spread and evaporation at a higher ambient temperature condition, which could lead to weaker fuel and air mixing before the occurrence of auto-ignition. And this helps explain why flames generally move left to injector nozzle and becomes elliptical with increasing ambient temperature. At last, no obvious spray diffusion combustion is observed even for the 950 K ambient temperature condition. Comparison of auto-ignition flame images of all five fuels under 650 K and 950 K conditions are presented in Figure 6.2.4 and Figure 6.2.5. It is found that flame characteristics discussed above could also be found for all other four fuels in this study. Flames at both 650 K and 950 K of five fuels share almost the same flame structures

6.2.2.2 Ignition delay

As mentioned in last section, the ignition delay is defined as the time interval between the start of the injection trigger and the occurrence of auto-ignition. In this study, an outwardly opening piezoelectric hollow cone injector is used for all auto-ignition experiments. This type of injector has a very good repeatability for different fuels. At a certain injection pressure, the volume of injected fuel in a single injection could be considered as constant. Evaluated from fuel density, fuel quantities of gasoline, gasoline surrogate, LN, PRF65 and PRF95 are 10 mg, 9.85 mg, 8.69mg, 9.13mg and 9.20 mg, respectively. Based on spray G condition, the ambient gas density is 3.5kg/m³ and the oxygen concentration before fuel injection is 21% by volume. Therefore the fuel/air mass ratio could be estimated as 0.003 (fuel lean condition) for the current experiment conditions.

It has been discussed that a considerable ignition delay is noticed for all five fuels under the investigated ambient conditions, results have been shown in Table 6.2.4. A plot of ignition
delay to ambient temperature is presented in Figure 6.2.6. In general, a longer ignition delay is found under a lower ambient temperature condition. This is expected, as higher temperature contributes a lot to fuel evaporations and could offer more energy to trigger fuel auto-ignition. However, an obvious transition point is observed at around 750 K for all selected fuels. When the ambient temperature is lower than 750K, the ignition delay drops rapidly with increasing temperature, while the ignition delay dropping rate becomes much smaller once the ambient temperature exceeds 750 K. Furthermore, for LN, gasoline, and gasoline surrogate, the ignition delay curves intersect at almost the same point around 750 K. Comparing the ignition delay among five investigated fuels, PRF95 always has the longest ignition delay and LN has the shortest ignition delay when the ambient temperature is lower than 750 K. Gasoline surrogate has slight shorter ignition delay than neat gasoline, and the ignition delay of PRF65 is short than PRF95. However, when the ambient temperature is higher than 750 K, a distinct phenomenon is observed. Though that PRF95 still has the longest ignition delay, the ignition delay of all five fuels are quite close. No clear trend of ignition delay is found within this ambient temperature range.

This may indicate that fuel ignition delay characteristics are closely related to differences on fuel properties when the ambient temperature is lower than 750 K in this study. Two main parameters, fuel octane number (ON) and fuel boiling point or boiling point range, could help explain this phenomenon. The anti-knock index (AKI) is a common measurement of fuel octane number which is defined as the average of motor research number (MON) and research octane number (RON) of a fuel. A higher AKI indicates a stronger resistance of a fuel for auto-ignition. According to Table 6.2.3, LN has the lowest AKI, while the AKI of PRF95 is the highest. Gasoline and gasoline surrogate has close AKIs which are lower than PRF95.
but much higher than LN. Overall, the magnitude of AKI of five fuels has a very good consistence with the ignition delay at low temperatures (650 K and 725K) except for PRF65. PRF65 has an AKI of 65, but its ignition delay is even longer than gasoline and gasoline surrogate. This may be caused by a higher boiling point of PRFs compared with gasoline and gasoline surrogate. PRF65 and PRF95 are mixtures of iso-octane and n-heptane, both have a boiling point around 99°C. Gasoline and gasoline surrogate has boiling points range from 64°C to around to 162 °C. In this study, fuel is heated up to 90°C before the injection. At this temperature the evaporation rate of gasoline and gasoline surrogate is much higher than PRF65, and this could lead to a much better fuel/air mixing status for gasoline and gasoline surrogate than PRF65. As a result, shorter ignition delays were observed for gasoline and gasoline surrogate than PRF65. Furthermore, LN has the lowest boiling points among five fuels, and this contributes to reduce the ignition delay at low temperature conditions. When the temperature is higher than 750 K, the high ambient temperature is believed to be a dominant parameter that promotes fuel auto-ignition. Therefore close ignition delays are found for all five fuels.

6.2.2.3 Fuel spray characterization before ignition.

Macroscopic spray features of each fuel before auto-ignition were studied to help understand the auto-ignition process and the variation on ignition delay of different fuels. Generally, fuel spray angle and fuel front penetration length could be used to evaluate physical fuel spray characteristics and injector repeatability. Therefore time averaged fuel spray angle, spray front penetration length and spray penetration velocity were calculated and discussed in this study. Fuel spray angle is defined as the average angle between two spray edges at pre-
determined locations near the injector tip at a specified time after the start of fuel (SOF) [63]. In this study, the effective locations is selected from the nozzle tip to spray front. Spray front penetration length is defined as the average distance between the entire spray front and the exit plane. Spray penetration velocity is calculated based on spray front penetration length results. In order to calculate spray angle and spray front penetration length, spray edges and spray front are detected and marked with colored lines using a Matlab code developed in-house with the same threshold for all transient images in each single injection. In this study, the injection duration of experiments is set as 0.3 ms. In experiments, one injection ends at around 430 μs after the start of injection trigger (ASOIT) due to the delay caused by opening and closing injector nozzle. To ensure result consistency, ambient conditions were kept all the same with fuel auto-ignition experiments. In other words, spray images that captured in this part of experiments exactly represent spray development before the occurrence of fuel auto-ignition under investigated ambient conditions. Since spray liquid signal becomes negligible right after the end of injection, spray angle and spray front penetration length calculation were limited from the injection signal trigger to the end of fuel injection. A set of spray images of PRF65 under different ambient temperatures are selected as example, as shown in Figure 6.2.7.

For each image, two spray edges and spray front were marked red, blue and green, respectively. In this study, the ambient temperature ranges from 650 K to 950 K with a constant in-chamber gas density of 3.5 kg/m³. Evaluated by the ideal gas law, the ambient pressures at 650 K, 725 K, 800 K, 875 K and 950 K are around 7 bar, 7.75 bar, 8.5 bar, 9.25 bar and 10 bar, respectively. It has been discussed in [51] that a higher ambient pressure lead to a shorter spray penetration length and stronger edge vortex at downstream under the same ambient temperature. In this study, it turns out that the spray under different ambient temperature
conditions has almost the same structure and development for the same fuel. Downstream vortexes have close locations for all the investigated conditions. The only obvious difference might be the decreasing liquid signal with increasing ambient temperature caused by the increasing fuel evaporation rate. This indicates that ambient gas density might be the dominant factor that impacts spray structure. In addition, comparison of five fuels on spray structure at 650 K and 950 K is show in Figure 6.2.8 and Figure 6.2.9. It is seen that differences on fuel spray structure and development among all investigated fuels are quite similar.

6.2.2.4 Time-averaged spray angle

The time-averaged spray angle of each fuel was calculated to analyze in this section. In this study, the time interval from the start of the injection trigger to the end of the injection was used to do spray angle time-average calculation. The time-averaged spray angle of each fuel under each ambient condition is presented in Figure 6.2.10. It is found that, for each fuel the time averaged spray angle decreases with increasing ambient temperature, which is believed caused by faster fuel evaporation rate under a higher ambient temperature environment and/or the higher ambient pressure conditions. Comparing the time-averaged spray angle among the five selected fuels, PRF65 and PRF95 always have larger spray angles than the other three fuels for all investigated ambient conditions, but no obvious trend for five fuels within the investigated ambient temperature range, as show in Figure 6.2.11. Meanwhile, it should be noted that the time-averaged spray angle among different fuels is quite small. All time averaged spray angle results are around 100º, and the maximum difference is less than 3º.
6.2.2.5 Transient spray penetration length and front penetration velocity

Spray front penetration length of five fuels under different ambient temperatures were calculated and shown in Figure 6.2.12. For each fuel, a higher ambient temperature leads to a shorter penetration length during the entire injection process, and the penetration difference at difference ambient temperature is increasing with time. Two reasons may account for this phenomenon. Firstly, as mentioned above, spray at a higher ambient temperature encounters a higher back pressure. A higher ambient pressure generates faster momentum exchange, which could lead to a larger drag force experienced by the moving spray droplets. As a result the spray penetration is more prohibited with increasing ambient temperature. Secondly, a higher back pressure reduces the pressure difference between the common rail system (100 bar injection pressure in this study) and the in-chamber environment. Based on Bernoulli’s equation, the flow exit velocity is proportional to the root square of pressure difference. Therefore the flow exit velocity at a higher temperature is lower than the velocity at a lower temperature, which also affects the spray penetration length. However, it should be noted that even the tendency of spray front penetration length at different ambient temperatures is clear and consistent for all five fuels, the absolute variation on penetration length at different ambient temperature is quite small. In order to better understand the effect of fuel properties on spray characteristics, the spray penetration length was compared among five investigated fuels, as shown in Figure 6.2.13. It turns out that five fuels have quite similar spray penetration length for the entire injection process at each ambient condition. No clear correlation is found on spray penetration length among selected fuels. Similar time-averaged spray angle and spray front penetration length results of different fuels may indicate that the effect of fuel properties is not dominant on spray structure and development in this study.
The time-averaged spray penetration velocity was calculated based on the spray penetration length results, as presented in Figure 6.2.14. Similar to the time-averaged spray angle result, a lower time-averaged spray penetration velocity is observed at a higher ambient temperature for all the five fuels. However, the effect of the ambient temperature is different for different fuels. For example, the penetration velocity of PRF95 drops slower when the ambient temperature is lower than 750 K but faster when the ambient temperature is higher than 750 K while LN, on the contrary, has a faster velocity dropping rate when the ambient temperature is lower than 750 K. Comparing the time-averaged spray penetration velocity among five selected fuels, no certain pattern or trend is found under a certain ambient temperature.

6.2.3 Summary

1. Fuel auto-ignition was observed with noticeable ignition delay for five investigated fuels under all selected experiment conditions. Locations of the occurrence of auto-ignitions are randomly distributed in combustion chamber. Occasionally, more than one auto-ignition events could take place in one experiment.

2. For all experiments, ignition delay is always much longer than fuel injection duration. For each fuel, a longer ignition delay is found under a lower ambient temperature condition. The ignition delay drops rapidly with increasing temperature when the ambient temperature is lower than 750K, but the ignition delay dropping rate becomes much smaller once the ambient temperature exceeds 750 K.

3. When ambient temperature is lower than 750 K, PRF95 always has the longest ignition delay and LN has the shortest ignition delay. Gasoline surrogate has slightly shorter
ignition delay than neat gasoline, and the ignition delay of PRF65 is shorter than PRF95. Ignition delay of five fuels are quite close when the ambient temperature exceeds 750 K.

4. Five fuels have similar spray front penetration length development and close spray angles before the occurrence of auto-ignition under all investigated conditions.
6.2.4 Tables and Figures

Table 6.2.1 Gas compositions before and after the premixed combustion

<table>
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<th>NO.</th>
<th>Status</th>
<th>C\textsubscript{2}H\textsubscript{2} (V%)</th>
<th>\textsubscript{O} (V%)</th>
<th>\textsubscript{CO} \textsubscript{2} (V%)</th>
<th>\textsubscript{H} \textsubscript{2}O (V%)</th>
<th>\textsubscript{N} \textsubscript{2} (V%)</th>
<th>MW (g/mol)</th>
<th>Density (kg/m\textsuperscript{3})</th>
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<td>Before premixed combustion</td>
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<td>0</td>
<td>51.1</td>
<td>28.6</td>
<td>3.5</td>
</tr>
<tr>
<td>2</td>
<td>After premixed combustion</td>
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<td>21</td>
<td>9.8</td>
<td>4.9</td>
<td>64.3</td>
<td>29.9</td>
<td>3.5</td>
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Table 6.2.2. Gasoline surrogate composition

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<th>Species</th>
<th>Wt (%)</th>
<th>mol (%)</th>
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<tr>
<td>Toluene</td>
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<td>N-heptane</td>
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<td>Iso-octane</td>
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<td>Cyclopentane</td>
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<td>0.173523</td>
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<td>1,2,4-trimethylbenzene</td>
<td>0.21978</td>
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<td>Ethanol</td>
<td>0.087912</td>
<td>0.176038</td>
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</table>

Table 6.2.3 Selected fuel properties of investigated fuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Density (gm/liter at 25°C)</th>
<th>Boiling Point (°C)</th>
<th>RON</th>
<th>MON</th>
<th>AKI</th>
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</thead>
<tbody>
<tr>
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<td>654</td>
<td>50-73</td>
<td>65</td>
<td>63</td>
<td>64</td>
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<tr>
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<td>755</td>
<td>64-162</td>
<td>91</td>
<td>83</td>
<td>87</td>
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<td>Gasoline Surrogate</td>
<td>743</td>
<td>73-140</td>
<td>91</td>
<td>83</td>
<td>87</td>
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<tr>
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<td>687</td>
<td>-</td>
<td>65</td>
<td>65</td>
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<tr>
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<td>692</td>
<td>-</td>
<td>95</td>
<td>95</td>
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<tr>
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<td>100</td>
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<tr>
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<td>679</td>
<td>98</td>
<td>0</td>
<td>0</td>
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Table 6.2.4 Ignition delay of gasoline, gasoline surrogate, LN, PRF65 and PRF95 at different ambient temperatures

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Ignition delay (ms)</th>
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</thead>
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<tr>
<td></td>
<td>650</td>
</tr>
<tr>
<td>Gasoline</td>
<td>7.104</td>
</tr>
<tr>
<td>Gasoline Surrogate</td>
<td>5.763</td>
</tr>
<tr>
<td>LN</td>
<td>4.831</td>
</tr>
<tr>
<td>PRF65</td>
<td>10.063</td>
</tr>
<tr>
<td>PRF95</td>
<td>12.265</td>
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</table>
Figure 6.2.1. Experimental system: 1. fuel injector, 2. exhaust line, 3. chamber body, 4. quartz window, 5. plug/window retainer, 6. pressure transducer, 7. intake line, 8. metal plug, 9. spark plug, 10. Combustion chamber, 11. high speed camera

Figure 6.2.2. Locations of injector, pressure transducer and chamber view boundary
Figure 6.2.3. Auto-ignition images of PRF65 under different ambient temperatures
Figure 6.2.4. Comparison of auto-ignition images of five fuels under 650 K ambient temperature condition
Figure 6.2.5. Comparison of auto-ignition images of five fuels under 950 K ambient temperature condition
**Figure 6.2.6.** Ignition delay development of five investigated fuels
Figure 6.2.7. PRF65 spray images before ignition: (a) 650 K (b) 725 K (c) 800 K (d) 875 K (e) 950 K
Figure 6.2.8. Comparison of fuel spray before auto-ignition of five fuels at 650 K
Figure 6.2.9 Comparison of fuel spray before auto-ignition of five fuels at 950 K
Figure 6.2.10 Time averaged spray angle of five fuels under different ambient temperatures

Figure 6.2.11 Comparison of time averaged spray angle among five fuels under different ambient temperatures
Figure 6.2.12 Spray front penetration length of five fuels under different ambient temperatures.
Figure 6.2.13. Comparison of spray front penetration length among five fuels at: (a) 650 K, (b) 950K
Figure 6.2.14. Comparison of spray front penetration velocity among five fuels different temperatures
6.3 Auto-ignition of light naphtha under diesel engine environment

6.3.1 Diagnostics and Measurements

Experiments were conducted in a constant volume combustion chamber (CVCC) system with six ports under selected ambient conditions. Transient fuel combustion images were captured by using a high-speed camera (Phantom V4.3 from Vision Research Inc.). The frame rate was set at 5,500 frames per second (fps) with a resolution of 600 X 200 pixels for spray structure analysis. Camera was triggered simultaneously with fuel injection by the same pulse delay generator. In order to implement two-color measurement, a 550 nm and a 650 nm band pass filter with 10 mm width were used to capture desired emissions at selected wavelength. Meanwhile, camera exposure time, aperture and other parameters were set all appropriately.

In this study, light naphtha (LN) is selected to investigate gasoline-like fuel auto-ignition under conventional diesel-engine environment. LN is a kind of fuel with less processed refinery stream in the gasoline boiling and carbon number range. Normally LN consists molecules with 5-6 carbon atoms. LN used in this study was obtained from Saudi Aramco, with an AKI value of 61. For all experiments, fuel injection pressure difference (pressure difference between fuel and environment in chamber) was maintained at 100 bar. Fuel injection duration was set as 1.4 ms, thus fuel mass per injection was around 50 mg. In order to evaluate effect of ambient oxygen concentration and ambient temperature on LN auto-ignition characteristics, five different ambient oxygen concentrations (10%, 12%, 15%, 18% and 21%) and three ambient temperature conditions (800K, 1000K and 1200K) were selected and investigated. Environment gas density was controlled at 15 kg/m$^3$. 


The simulated diesel engine combustion environment was generated by a premixed combustion of acetylene prior to fuel spray combustion. Three different gases, acetylene, O2/N2 (50%/50%) and dry air were selected to formulate proper mixtures to obtain the desired ambient temperature and ambient oxygen concentration. Premixed reactants were ignited by a spark plug. Compositions of premixed mixture are listed in Table 6.3.1. To eliminate possible disturb of water that generated by the premixed combustion, the whole combustion chamber was heated up to 393 K through all experiments. Two-color pyrometry was employed in this study to calculate flame temperature and KL factor distribution. Principles and implementations of two-color pyrometry has been introduced in Chapter 2.

6.3.2 Results and Discussions

In this section, LN auto-ignition under selected ambient conditions were discussed first. Five oxygen concentrations and three ambient temperatures were investigated to evaluate effect of ambient conditions on LN auto-ignition characteristics. Transient flame temperature and KL factor distribution under different ambient conditions were calculated and analyzed based on two-color measurement. Average flame temperature and average KL factor at selected time steps were calculated to evaluate temperature and KL factor development during fuel combustion. In addition, flame accumulated KL factor under different ambient conditions were also calculated to estimate soot particle volume and density.

6.3.2.1 Flame transient temperature and KL distribution

In order to investigate LN auto-ignition characteristics under conventional diesel engine environment, the gas density in chamber was set as 15 kg/m³ for all experiment. Generally, convention diesel engine ambient environment for diesel compression ignition is
considered as 1000 K temperature with 21% oxygen concentration. Ambient temperature and ambient oxygen concentration both influence fuel auto-ignition greatly in engines, therefore 800 K and 1000 K ambient temperature conditions, and 10%, 12%, 15% and 18% oxygen concentration conditions were also selected in this study. It is observed that LN spray auto-ignition could take place for all investigated ambient conditions. However, LN auto-ignition is distinct in several aspects when compared with conventional diesel spray combustion. Firstly, fuel injection duration applied in this study is 1.4 ms with around 50 mg fuel mass per injection. In this study, fuel injection ends at around 1.9 ms due to some delay caused by the opening and close of injection nozzle. Evaluate from the radiation at 550 nm and 650 nm, it is found that LN auto-ignition occurs at almost the end of fuel injection. No clear spray combustion could be observed for all investigated ambient conditions. Second, seen from combustion images, slow flame spread process is noticeable in this study. This will be discussed in the following section.

6.3.2.1.1 Low oxygen concentration conditions

Transient flame temperature and KL factor distributions under 800 K and 10% oxygen concentration condition are shown in Figure 6.3.1 (a) and (b). At this condition, fuel combustion process could last for more than 30 ms. Therefore one of every ten figures with a time interval of 2.091 ms was selected to illustrate LN fuel combustion development in this section and all following sections. It should be noted first that fuel injector is located at the right side of the chamber, and spray spreads from right to left. Seen from Figure 6.3.1, fuel auto-ignition appears at a location that close to injector nozzle. The whole combustion and flame spread process is slow since flame is still visible at 21 ms after the start of the injection
trigger (ASOIT), an obvious flame spread process from the right side to left until the end of fuel combustion is noticed at this condition. As we discussed in previous chapters, spray of an outwardly opening piezoelectric fuel injector has a hollow structure when the ambient pressure is higher than atmosphere. At 800K and 10% oxygen concentration condition, fuel auto-ignition delay is relative long and flame no longer maintains a hollow-cone shape. Instead, flame occupies more than half of the chamber and has no certain structure. Flame temperature at this condition ranges from 1500K to 1800K. Areas with higher flame temperature are located at the flame center, and this high temperature area moves to left side with the spread of flame. At each time step, flame periphery always has lower temperature. Flame KL factor distribution at 800K and 10% oxygen concentration is shown in Figure 6.3.1 (b). Ten images at same time steps in Figure 6.3.1 (a) are selected. It is found that most parts of flame have very low value of KL factor. High KL factor areas are observed at flame edges for first five images. However, after 10.651 ms ASOIT, high KL factor areas gradually moves inward with time. At 21.101 ms ASOIT high KL factor areas are almost located in the middle of the flame. Compare the temperature distribution and locations of high KL factor areas, it is noted that high KL factor areas is closely related to temperature gradient. High KL factor areas mostly are located in an area where flame temperature variation is high. Specifically, at 800K and 10% oxygen concentration condition, high KL factor is observed at the area where flame temperature drops from 1800K to 1500K rapidly.

Flame temperature and KL factor distribution at 1000K and 10% oxygen concentration is presented in Figure 6.3.2 (a) and (b). Ten images were selected to illustrate flame development at this condition. Comparing with flame at 800K and 10% oxygen concentration condition, flame auto-ignition is still found at a place close to injector nozzle. However, several
differences on flame development and flame temperature distributions could be concluded. First, flame temperature ranges from 1500K to around 2000K, which is higher than flame at 800K and 10% oxygen concentration condition. Before 10.651 ms ASOIT, high temperature areas still are located at inner side of the flame, and flame periphery also has lower temperature than flame center. After 10.651 ms ASOIT high temperature generally moves to downstream of the flame, while low temperature area is still found at flame upstream. Second, fuel combustion process becomes faster at 1000 K. Flame is almost extinct at 21.101 ms ASOIT, and flame area is much smaller at this time step if compared with flame at 800K temperature conditions. KL factor distribution is shown in Figure 6.3.2 (b). Compared with 800K and 10% oxygen concentration condition, KL factor at 1000K condition is negligible before 10.651ms ASOIT. Only several tiny areas located at flame downstream edge are found with noticeable high KL factor. After 10.651 ms ASOIT, high KL factor area increases with time, and locations of high KL factor areas are observed at flame upstream. This observation is consistent with conclusion of KL factor distribution at last section. For the first five images, areas that with rapid temperature variation are mostly seen at downstream. While for last five images, flame upstream has more obvious temperature drop from around 1800K to 1500 K. These locations are consistent with high KL factor regions. Flame temperature and KL factor distributions at 1200K and 10% oxygen concentration are shown in Figure 6.3.3 (a) and (b). Both flame temperature distribution development and KL factor distribution development are quite similar as flames at 1000K and 10% oxygen concentration condition. Differences are found at flame temperature range and fuel combustion rate. The highest flame temperature at 1200K and 10% oxygen concentration reaches 2100K, which is higher than flames at a lower ambient temperature. Flame disappears
at around 18.802 ms ASOIT. This timing is the earliest under selected ambient temperature conditions with 10% oxygen concentration. In addition, flame begins to split at around 14.622 ms ASOIT until the end of the combustion, but flame at downstream still has higher temperature than flame at upstream under this condition.

### 6.3.2.1.2 Conventional diesel engine environment

Conventional diesel engine environment for diesel-like fuel compression ignition is considered as 1000K ambient temperature, 21% ambient oxygen concentration and 15 kg/m3 gas density. This experimental condition is also selected for LN auto-ignition experiments. LN flame temperature and KL factor distribution results at different timings are presented in Figure 6.3.4 (a) and (b). Under this condition, flame peak temperature reaches more than 2300K, and flame temperature of most parts are higher than 2000K before 8.651 ms ASOIT. Meanwhile, inner side of flame has higher temperature than flame periphery, and the lowest flame temperature is found at flame upstream. After 8.651 ms ASOIT, flame temperature decreases until the end of fuel combustion. Compared with the 1000K and 10% oxygen concentration condition, spray under this condition has much higher combustion rate. Flame begins to shrink at 8,651 ms ASOIT, and extinct at 12.741 ms ASOIT. Besides this, flame under this condition could only spread to 55 mm horizontally from the injector nozzle on the wall of the chamber at right side, while flame at 10% oxygen concentration with the same ambient temperature reaches more than 85 mm. Moreover, a confined hollow-cone shape of flame could be observed at the first three images. Phenomena mentioned above are believed to be caused by the faster fuel combustion rate under this ambient condition. A faster fuel combustion rate leaves shorter time for fuel spray to spread, and also leads to a faster flame...
spread rate. Both of them shortens the flame spread areas. KL factor distributions at 1000K and 21% oxygen concentration are presented in Figure 6.3.4 (b). KL factor results at 1000K and 21% oxygen concentration condition is consistent with the flame at 1000K and 10% oxygen concentration. KL factor on the whole flame could be negligible until 10.651 ms ASOIT. Only a few discrete areas are found with high KL factor by the end of combustion. In addition, flame temperatures at areas that have high KL factor are lower than 1800K. Combine with the conclusion of KL factor distribution in previous sections that high KL factors appear at an area with rapid temperature drop within 1500K to 1800K, it may indicate soot is more likely to exist at an environment with temperature lower than 1800K.

6.3.2.1.3 Effect of ambient oxygen concentration and temperature

In this study, five ambient oxygen concentration conditions ranges from 10% to 21% were selected to explore the effect of oxygen concentration on flame temperature and KL factor distribution. Results of flames at 1000K ambient temperature with different oxygen concentrations are illustrated in Figure 6.3.5 (a) – (e). Several flame temperature development tendency could be concluded. Firstly, a higher flame peak temperature could be found at a high oxygen concentration condition for all investigated experiment conditions. For example, peak flame temperature at 21%, 15% and 10% oxygen concentrations are around 2300K, 2100K and 2000K, respectively. Second, higher flame temperature areas are mostly located at inner side of the flame until the end of fuel combustion. By the end of fuel combustion, flame downstream generally has higher temperature than flame upstream. It should be noted that the timing of the end of fuel combustion varies at different oxygen concentrations. At 10% oxygen concentration combustion lasts more than 21 ms, but at 21% oxygen concentration condition this period reduces to less than 13 ms. This indicates that a higher oxygen concentration could accelerate fuel combustion rate at selected ambient temperature range. At last, a more confined flame structure could be observed under a higher oxygen concentration condition. At 6.741 ms ASOIT, flame
structures at 10%, 12% and 15% oxygen concentrations are irregular. For 18% and 21% oxygen concentration conditions, flames gradually present an oval shape. KL factor distributions at 1000K with different oxygen concentrations are presented in Figure 6.3.6. Flames at different oxygen concentrations have quite similar KL factor distributions and developments. KL factor are maintained at low level for the whole flame until the end of combustion. By the end of combustion, high KL factors could be noticed once flame begins to shrink and extinct. Most high value KL factors are located at the region that has rapid temperature drop with temperature lower than 1800K. Extra flame temperature and KL factor distribution results are shown in Figure 6.3.7 – 6.3.17.

6.3.2.2 Time resolved results

6.3.2.2.1 Averaged flame temperature

In order to evaluate the effect of ambient temperature conditions on flame temperature development, average flame temperature at each time step is calculated for all selected ambient conditions. The average flame temperature at a time step is defined as the accumulated temperature over the flame area. Results of average flame temperature at each oxygen concentration with different ambient temperatures are presented in Figure 6.3.18. Developments of average flame temperature are quite similar. For each experiment condition, the average flame temperature first increases monotonically for the first half of combustion process, then decreases until the end of combustion. Differences are found with average temperature value at each time step, the timing for each flame to reach temperature peak, and temperature drop rate. In the temperature monotonically increasing period, a higher ambient temperature results in a higher average flame temperature at the same time step. However, average flame temperature drops faster for flames at a higher ambient temperature than a lower ambient temperature condition. Moreover, flame at a higher ambient temperature reaches the
peak average temperature earlier. This might be caused by the faster fuel combustion rate at a higher ambient temperature condition. Comparison of average flame temperatures at different ambient temperature conditions are shown in Figure 6.3.19. Oxygen concentration has similar effect as ambient temperature. At each ambient temperature, a higher ambient oxygen concentration leads to a higher flame average temperature at the same time step during the monotonically increasing stage, and a faster temperature drop rate after the temperature peak. Meanwhile, flame at a higher oxygen concentration reaches the peak flame average temperature earlier.

6.3.2.2 Averaged KL factor

Average KL factor at each ambient condition is calculated to evaluate the soot density during the combustion process. Comparisons of average KL factor development at different ambient temperature for each oxygen concentration are shown in Figure 6.3.20. In general, a M shape development pattern is noticed for flames at each ambient condition. At the beginning of fuel combustion, average KL factor is relatively high for all flames. Then the average KL factor continuing decreasing until the half stage of the whole combustion. In the second half stage of combustion, KL factor first increase rapidly and then drop to around zero by the end of combustion. For each oxygen concentration, the effect of ambient temperature on average KL factor is different in different time period. For the first half of combustion process, a higher average KL factor is observed under a lower ambient temperature condition for each selected time step. However, for the second half of combustion process, a higher ambient temperature on the contrary leads to a higher average KL factor. Comparison of average KL factor at different oxygen concentration for each ambient temperature is illustrated in Figure 6.3.21. The effect of ambient oxygen concentration on average KL factor development is similar as
the effect of ambient temperature. The two-stage effect of ambient oxygen concentration is still observed for all investigated ambient temperatures. A higher ambient oxygen concentration results in a lower average KL factor for the first stage of fuel combustion, while a lower ambient oxygen concentration leads to a lower average KL factor in the second stage. However, it should be noted that ambient oxygen concentration has little effect on average KL factor peak. For each ambient temperature condition, the highest average KL factor value are close under different ambient oxygen concentrations. For each ambient temperature, flame under a higher ambient oxygen concentration reaches the peak value earlier than flames under a lower ambient oxygen concentration.

6.3.2.3 Accumulated KL factors

In order to evaluate over soot formation during the combustion process, accumulated KL factors are calculated for each ambient condition. Accumulated KL factor is defined as the sum of KL factors of the whole flame at each time step. In general, accumulated could be regarded as an indicator of amount of soot formation during the combustion. Results of accumulated KL factor at different ambient temperatures under each oxygen concentration are shown in Figure 6.3.22. It is seen that the M pattern development is only found with flames at 800K ambient temperature and 10% or 12% ambient oxygen concentration. For flames at other experiment conditions, the accumulated KL factors are all first increasing and then decreasing until the end of combustion. Flames at 800K ambient temperature always has the highest accumulated KL factor for all selected ambient oxygen concentration conditions. Lowest accumulated KL factors are observed with flames at 1000K ambient temperature when the ambient oxygen concentration is 10% or 12%. However, when the oxygen concentration is
higher than 12%, flames at 1200K then have the lowest accumulated KL factor for all selected time steps.

Comparison of accumulated KL factor development at different oxygen concentration for each ambient temperature is presented in Figure 6.3.23. The effect of ambient oxygen concentration on accumulated KL factor is consistent at different ambient temperature conditions. A lower oxygen concentration always results in a higher accumulated KL factor for most part of the combustion process. Meanwhile, it is noticed that at 1000K ambient temperature, accumulated KL factor at different oxygen concentration are quite close, especially before 10 ms ASOI. However, for 800K and 1200K ambient temperature conditions, accumulated KL factors of flames at 10% and 12% ambient oxygen concentrations are much higher than flames under an ambient oxygen concentration that is higher than 12%. This may indicates that a lower oxygen concentration could promote soot formation, and this promotion is more significant at 800K and 1200K.

6.3.3 Summary

In this study, two-color measurement was conducted for LN auto-ignition experiments under different ambient conditions. Both conventional diesel engine environment and low temperature low oxygen concentration environment were investigated. Major conclusions are summarized as follows:

1. LN auto-ignition is observed at all selected experiment conditions. Ether a higher ambient temperature or a higher oxygen concentration could accelerate fuel combustion rate. In general, LN flame temperature ranges from 1500K to 2400K under selected experiment
conditions. A higher flame temperature peak could be observed at a higher ambient temperature or a higher ambient oxygen concentration condition.

2. For each ambient condition, high flame temperature areas are found at flame center or flame downstream during most parts of combustion, and high temperature areas gradually moves downstream with flame. Flame upstream always has lower temperature than other flame regions.

3. LN flames have low KL factor values for all selected experiment conditions. High KL factors are observed at flame periphery where the flame temperature is lower than 1800K and has strong temperature variation. Locations of high KL factor areas are discrete.

4. For each experiment condition, average flame temperature first increases then decreases with time. Flame at a higher ambient temperature or a higher ambient oxygen concentration has higher average flame temperature during the increasing stage. After the temperature peak, average flame temperature at a higher ambient temperature or a higher ambient oxygen concentration drops faster.

5. Average KL factor have a M shape development pattern in this study. A higher ambient oxygen concentration or a higher ambient temperature results in a lower average KL factor for the first half combustion process, while a lower ambient oxygen centration or a lower ambient temperature leads to a lower average KL factor in the second stage.

6. Flames at 800K ambient temperature always have the highest accumulated KL factor. Lowest accumulated KL factors are found with flames at 1000K ambient temperature when the ambient oxygen concentration is 10% or 12%. When the oxygen concentration is higher than 12%, flames at 1200K then have the lowest accumulated KL factor for all selected time steps.
### 6.3.4 Tables and Figures

Table 6.3.1 Composition of the premixed combustion reactants

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<tr>
<th>NO.</th>
<th>Fuel</th>
<th>Ambient Oxygen (V%)</th>
<th>C$_2$H$_2$ (V%)</th>
<th>O$_2$/N$_2$ (V%)</th>
<th>Air (V%)</th>
<th>MW (g/mol)</th>
<th>Density (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LN</td>
<td>10%</td>
<td>4.85</td>
<td>8.63</td>
<td>81.82</td>
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<tr>
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</tr>
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<td>49.46</td>
<td>29.21</td>
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</tr>
</tbody>
</table>
Figure 6.3.1 Flame temperature and KL factor distribution at 10% and 800K condition.
Figure 6.3.2 Flame temperature and KL factor distribution at 10% and 1000K condition

(a) Flame temperature distribution at 10% 1000K

(b) KL factor distribution at 10% 1000K
Figure 6.3.3 Flame temperature and KL factor distribution at 10% and 1200K condition

(a) Flame temperature distribution at 10% 1200K

(b) KL factor distribution at 10% 1200K
Figure 6.3.4 Flame temperature and KL factor distribution at 21% and 1000K condition
Figure 6.3.5 Comparison of flame temperature distributions at 1000K with different ambient oxygen concentrations

(a) Temperature distribution at 1000K and 10% oxygen concentration

(b) Temperature distribution at 1000K and 12% oxygen concentration

(c) Temperature distribution at 1000K and 15% oxygen concentration

(d) Temperature distribution at 1000K and 18% oxygen concentration

(e) Temperature distribution at 1000K and 21% oxygen concentration
Figure 6.3.6 Comparison of flame KL factor distributions at 1000K with different ambient oxygen concentrations

(a) KL factor distribution at 1000K and 10% oxygen concentration

(b) KL factor distribution at 1000K and 12% oxygen concentration

(c) KL factor distribution at 1000K and 15% oxygen concentration

(d) KL factor distribution at 1000K and 18% oxygen concentration

(e) KL factor distribution at 1000K and 21% oxygen concentration
Figure 6.3.7 Flame temperature and KL factor distribution at 12% and 800K condition

(a) Flame temperature distribution at 12% 800K

(b) KL factor distribution at 12% 800K
Figure 6.3.8 Flame temperature and KL factor distribution at 12% and 1000K condition

(a) Flame temperature distribution at 12% 1000K

(b) KL factor distribution at 12% 1000K
Figure 6.3.9 Flame temperature and KL factor distribution at 12% and 1200K condition
Figure 6.3.10 Flame temperature and KL factor distribution at 15% and 800K condition
Figure 6.3.11 Flame temperature and KL factor distribution at 15% and 1000K condition

(a) Flame temperature distribution at 15% 1000K
(b) KL factor distribution at 15% 1000K

Figure 6.3.12 Flame temperature and KL factor distribution at 15% and 1200K condition

(a) Flame temperature distribution at 15% 1200K
(b) KL factor distribution at 15% 1200K

Figure 6.3.12 Flame temperature and KL factor distribution at 15% and 1200K condition
Figure 6.3.13 Flame temperature and KL factor distribution at 18% and 800K condition

(a) Flame temperature distribution at 18% 800K
(b) KL factor distribution at 18% 800K

Figure 6.3.14 Flame temperature and KL factor distribution at 18% and 1000K condition

(a) Flame temperature distribution at 18% 1000K
(b) KL factor distribution at 18% 1000K

Figure 6.3.15 Flame temperature and KL factor distribution at 18% and 1200K condition

(a) Flame temperature distribution at 18% 1200K
(b) KL factor distribution at 18% 1200K
Figure 6.3.16 Flame temperature and KL factor distribution at 21% and 800K condition

(a) Flame temperature distribution at 21% 800K
(b) KL factor distribution at 21% 800K

Figure 6.3.17 Flame temperature and KL factor distribution at 21% and 1200K condition

(a) Flame temperature distribution at 21% 1200K
(b) KL factor distribution at 21% 1200K

Figure 6.3.18 Flame temperature and KL factor distribution at 21% and 1200K condition
Figure 6.3.18 Comparison of flame average temperature at different ambient oxygen concentrations
Figure 6.3.19 Comparison of flame average temperature at different ambient temperatures.
Figure 6.3.20 Comparison of flame average KL factor at different ambient oxygen concentrations
Figure 6.3.21 Comparison of flame average KL factor at different ambient temperatures
Figure 6.3.22 Comparison of flame accumulated KL factor at different ambient oxygen concentrations
Figure 6.3.23 Comparison of flame accumulated KL factor at different ambient temperatures
7. Conclusion

7.1 Conclusion

In this study, experimental study of spray characteristics and fuel auto-ignition properties from an outwardly opening piezoelectric gasoline direct injection fuel injector were conducted in an optically accessible constant volume combustion chamber (CVCC) experiment system.

The study of fuel sprays of light naphtha (LN), primary reference fuel (PRF) and E10 gasoline under different ambient pressures shows that clear filamentary hollow-cone spray structures could be observed for all selected fuels at atmospheric condition. Toroidal recirculation vortex is noticed at the spray downstream, and a higher ambient pressure leads to a stronger vortex close to the exit plane. Spray structures of three fuels are consistent at the same ambient condition. Vortexes appear at almost the same location for each fuel. This indicates that the spray structure has little dependence on the fuel properties. The spray front penetration length and penetration velocity reduce considerably with increasing ambient pressure for all the fuels. A velocity peak right after the end of the injection is observed, which is believed to be caused by the shutting off of the injector pintle at the end of the injection. After the peak, the spray penetration velocity decreases. The spray front fluctuation shows two distinct stages during spray penetration process. In Stage one spray front fluctuation of each fuel is close for all ambient pressures. During Stage two, spray front fluctuation increases rapidly to a certain level and then becomes stable. A higher ambient pressure generally leads to weaker spray front fluctuations when the ambient pressure is higher than 1 bar.

Distinct spray structure is noticed when the ambient pressure is extended to a lower range (0.01 bar to 0.1 bar). While the original hollow-cone structure is still observable, spray deforms from a hollow-cone structure to a blurred diamond shape with a long tail at spray
downstream. Liquid signals at the tail part are much weaker than the original hollow-cone shape part. Within this pressure range, a higher ambient pressure leads to a shorter tail. Spray penetration length is greatly enlarged due to the deformation on spray structure. Spray under a lower ambient pressure penetrates much longer at the same time step. Fuel injection pressure and fuel injection duration has little effect on spray front penetration length development. Specially, the highest spray front penetration velocity at 0.01 bar exceeds local sound speed. Spray structure, spray penetration length and spray penetration velocity are mainly dominated by ambient pressure conditions in this study.

Auto-ignition of gasoline fuels, including light naphtha, primary references fuels, gasoline and gasoline surrogate, are studied under different ambient conditions. At spray G condition, all investigated fuels could be successfully auto-ignited under each selected experiment condition. Locations of the occurrence of auto-ignitions are randomly distributed in combustion chamber. Ignition delays are considerable for all fuels. For each fuel, the ignition delay drops rapidly with increasing temperature when the ambient temperature is lower than 750K, but the ignition delay dropping rate becomes much smaller once the ambient temperature exceeds 750 K.

Auto-ignition of light naphtha is further studied under diesel engine environment. Two-color pyrometry is employed to analyze flame temperature distribution and KL factor distribution. Five different ambient oxygen concentrations and three ambient temperatures are investigated. It is found that temperature of LN flames range from 1500K to 2400K under selected experiment conditions. Ether a higher ambient temperature or a higher oxygen concentration could accelerate fuel combustion rate. For each ambient condition, high temperature areas are found at flame center or flame downstream, and high temperature areas gradually moves
downstream with flame. Flame upstream always has lower temperature than other flame regions. In general, LN flames have low KL factors for all selected experiment conditions. High KL factors are observed at flame periphery where flame temperature is lower than 1800K and has rapid temperature variation. Locations of high KL factor areas are discrete. In addition, flames at 800K ambient temperature always has the highest accumulated KL factors. The lowest accumulated KL factors are observed at 1000K ambient temperature condition when the ambient oxygen concentration is 10% or 12%. When the oxygen concentration is higher than 12%, flames at 1200K ambient temperature have the lowest accumulated KL factor.

7.2 Future work

By summarizing the current work, the following aspects are worthy of further investigation according to the author’s understanding.

Investigation of the effect of spray characteristic from a piezo-electric fuel injector on fuel auto-ignition is needed. Fuel evaporation rate and droplet size are critical to auto-ignitions of gasoline fuels. Due to the differences of fuel properties, spray structure parameters (spray angle, spray front penetration length .etc.) from the same fuel injector differs. The variation on spray characteristic may lead to different auto-ignition delay, flame temperature distribution or soot emission.

Further study on the distinct spray structure from a piezo-electric fuel injector under low ambient pressure condition are necessary. Currently, most work on fuel injection under superheated conditions are done with single-hole or multi-hole injectors. As the hollow-cone piezo-electric fuel injector is more widely used, investigation of fuel injection under superheated condition with piezo-electric injector is worthy further work.
Application of gasoline fuels in diesel compression engines is also interesting. Difficulties on ignition timing manipulation of diesel are always limiting the emission control for diesel engines. Gasoline fuels has higher resistance to auto-ignition, which leads to longer ignition delay. This property offers the potential to reduce engine emissions and increase combustion efficiency of gasoline fuels.
REFERENCES


