EFFECTS OF FUEL ETHANOL CONTENT AND INJECTOR TEMPERATURE ON THE SPRAY CHARACTERISTICS OF GASOLINE DIRECT-INJECTION ATOMIZERS

by

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Abstract

Recently, the Energy Policy Act of 2005 was passed into U.S. Law. This, comprehensive energy legislation includes, for the first time in U.S. history, a national renewable fuels standard (RFS). The RFS legislates, with immediate effect, a significant increase in renewable fuel usage over a six-year period starting at 4 billion gallons in 2006 and increasing to 7.5 billion gallons in 2012. In practice, these legal requirements are most likely to be met by the increased use Biodiesel fuels and, most significantly, of ethanol as an additive to conventional gasoline.

It is well known that the addition of ethanol (C\textsubscript{2}H\textsubscript{5}OH) to gasoline, which is itself a multi-component hydrocarbon blend, can significantly change the distillation characteristics of the fuel. In a fully warm, port-fuel-injected (PFI) engine, the change in fuel properties may not be significant. However, it is to be expected that the next generation of gasoline engines will use direct-injection fuelling strategies. The potential advantages of direct-injection spark-ignition (DISI) engine systems are substantial. However, the limited time available for fuel preparation in DISI systems suggests that the technology may be more sensitive to fuel properties than previous generation injection technologies.

This study investigates the changes in DISI fuel spray structure induced by the addition of ethanol, in varying amounts, to a base fuel of fixed composition, a process typically known as 'splash blending'. Five fuels of different ethanol content were injected into atmosphere at an injection pressure of 10.0 MPa through two prototype DISI fuel injectors (one single hole and one multi-hole design). The fuels were: a 5-component model fuel, comprised of isopentane, iso-octane, n-octane, n-decane and dodecane, simulated E5 (5% ethanol 95% model fuel), simulated E10 (10% ethanol 90% model fuel), simulated E22 (22% ethanol, 78% model fuel), E80 (80% ethanol, 20% model fuel) and finally pure ethanol. The effect of each fuel on the global characteristics of the spray was examined at four different temperatures (20, 40, 60 and 80 degrees Celsius) using Mie-Scattering, Schlieren and Shadowgraphy imaging techniques.

Different stages of the spray development were identified. In accordance with the literature, increasing the fuel temperature was seen to increase the spray penetration while
narrowing the spray structure for all fuels. At low fuel temperatures, the impact of fuel composition was negligible. The results showed the effect of fuel composition on the spray structure to be most evident in intermediate temperatures. Further increasing the fuel temperature caused spray collapse for all fuel compositions. Evidence of flash boiling was observed at high fuel temperatures. The ethanol content of fuel blends was not found to be proportional to the changes in spray structure. Finally, observations showed the sprays exhibited the highest level of shot-to-shot variability in the case of intermediate fuel temperatures. Sprays from the swirl-type injector were found to be more consistent than those of multi-hole injectors.
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Chapter 1

Gasoline, Reformulated Gasoline, and Oxygenated Fuels

The following chapter aims to provide a brief introduction to motor gasoline, Reformulated Gasoline (RFG), Oxygenates and finally Ethanol. In particular, Ethanol-gasoline blends are considered as an alternative fuel and will be discussed in detail.

1.1 Introduction

Motor gasoline is the most important oil product both regarding its volume of production and its role in day-to-day life. However, burning gasoline has been identified as a major source of pollution in urban areas. Up until 1989, most attempts at pollution control were focused on reducing tailpipe and evaporative emissions by engine and vehicle modification [Marshall and Owen, 1995]. At this time, new engine technologies had reached the point at which fuel modification was deemed necessary for the further reduction of emissions. It was then that RFG was introduced to the market. Initially oxygenate compounds were used in RFG as an octane booster – thus, allowing the removal of harmful lead from the fuel. Since the initial introduction of oxygenates to gasoline, various compounds have been employed as gasoline additives. Over time, some oxygenate compounds – such as MTBE – have, themselves, been found to be detrimental to the environment and have been prohibited from use. Other compounds, such as ethanol, have found increased use and, during the past decade, ethanol blended with conventional gasoline has been increasingly proposed as an alternative fuel. Presently, ethanol, and bio-ethanol (extracted from bio-sources) in particular, is receiving increased attention due to both its cleaner combustion characteristics and its renewable potential.

1.2 Gasoline

Gasoline is a complex hydrocarbon mixture of over five hundred components plus a small amount of Sulfur and Nitrogen compounds, whose quantities typically depend on the crude oil quality that is used in the refinery. Gasoline is primarily used in Internal
Combustion (IC) engines as fuel. The physical properties of gasoline are defined based on a variety of national or international standards and specifications such as British Standards (BS) adopted in the UK, the Deutsche Institut für Normung (DIN) standards used in Germany, and the Comité Européen de Normalization (CEN) standard that has been widely adopted within the remainder of the European Union.

The properties of gasoline are controlled through different standardized test methods that are defined through organizations such as the American Society for Testing and Materials (ASTM), the International Standard Organization (ISO), and other international bodies. However, although both the physical properties and chemical composition of the fuel are tightly controlled under standard test conditions, in reality, the physical properties of the fuel will vary – depending on ambient conditions such as pressure, humidity and temperature.

The experimental work that follows later in this thesis will focus upon the affects of adding ethanol to a base gasoline with respect to the spray characteristics of two automotive fuel injectors intended for use in gasoline direct injection (GDI) engines. The addition of ethanol to gasoline is known to change, in some cases quite significantly, the fundamental properties of the fuel blend. The following subsections of this chapter will consider some of the most important of these fuel properties with respect to spark-ignition (SI) engine operation.

1.2.1 Octane number

Octane rating is one of the most important characteristics of any fuel intended for use in an SI engine. It is a measure of a fuel’s auto-ignition resistance (or anti-knock property). Knocking occurs in an SI engine when the air-fuel mixture auto-ignites in front of the approaching flame-front. Knock is then an uncontrolled combustion reaction that can result in extremely high in-cylinder pressures that can damage engine components.

The octane rating of a fuel is defined through the octane number, which is measured relative to the auto-ignition characteristics of iso-octane (octane number 100) and n-heptane (octane number 0) blends. For instance, a fuel with an octane number of 92 is classified as having the same knock resistance characteristics as a blend of 92% iso-octane and 8% heptane. The Octane number is determined under laboratory conditions...
and may be stated as either a Research Octane Number (RON) or Motor Octane Number (MON). RON is determined by running the fuel through a single-cylinder test engine with variable compression ratio and comparing the results with those of Iso-octane/heptanes mixtures under fixed engine conditions. MON indicates how the fuel might behave under actual load; it is determined using a similar test engine to that used to determine RON but with more variable conditions such as preheated fuel, higher engine speed and variable ignition timing. While RON is referenced to lower speed performance, MON shows the fuel anti-knock resistance in higher speed/load conditions. The difference between these two numbers often called fuel sensitivity.

Pump octane number may be specified in various ways – depending on fuel grades and country standards. Table 1.1 shows a summary of the minimum octane number requirement for some regions. [Marshall and Owen 1995].

Table 1.1: Minimum octane levels for Europe and the USA [Marshall and Owen, 1995]

<table>
<thead>
<tr>
<th>Gasoline grade</th>
<th>RON(min.)</th>
<th>MON(min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular</td>
<td>90-92</td>
<td>80-83</td>
</tr>
<tr>
<td>Premium</td>
<td>95</td>
<td>85</td>
</tr>
<tr>
<td>Super</td>
<td>97-98</td>
<td>87-88</td>
</tr>
<tr>
<td>Regular</td>
<td>90-92</td>
<td>82</td>
</tr>
<tr>
<td>Premium</td>
<td>97-98</td>
<td>86-88</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gasoline grade</th>
<th>(RON+MON)/2 (min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaded Gasoline</td>
<td>88</td>
</tr>
<tr>
<td>Unleaded Gasoline</td>
<td>87</td>
</tr>
<tr>
<td>Unleaded Gasoline</td>
<td>89</td>
</tr>
<tr>
<td>Unleaded Gasoline</td>
<td>91</td>
</tr>
</tbody>
</table>

1.2.2 Volatility

Volatility describes the ability of a chemical compound to evaporate. Given that liquid hydrocarbon fuels will only combust in vapor form, and then only when sufficiently well mixed with an oxidizer, the volatility of a gasoline blend can be expected to have a significant impact on the performance and drivability of an SI engine (drivability describes how an engine starts, warm up and runs). Low volatility fuel blends
can cause difficulty in starting from cold, and poor engine performance during warm-up and acceleration. However, high volatility blends may lead to excessive fuel vaporization within the fuel system that can decrease the fuel flow to the engine – a phenomenon commonly known as “Vapor Lock”. Avoiding these two extremes is important for the optimum performance of the engine; typically, this is achieved by specifying the volatility of the fuel to suit local meteorological and geographical conditions.

There are three measures that are commonly used to characterize the volatility of a gasoline blend; the distillation curve, the Reid Vapor Pressure (RVP), and the Vapor/Liquid ratio. Each of these measures is described briefly below:

**Distillation profile:**

Typically, gasoline boils over a range of temperatures from 30° C (Initial Boiling Point – IBP) up to 205° C (Final Boiling Point – FBP). The distillation characteristics of multi-component petroleum product fuels such as gasoline are determined by the ASTM D86 test at atmospheric pressure. Figure 1.1, below, shows the distillation profile of a typical commercial gasoline calculated through the MATLAB code developed for this research based on ASTM D86.

![Distillation profile](image)

**Figure 1.1:** Calculated Distillation curve for a typical full boiling range gasoline
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The ASTM D86 curve can be divided into three regions each of which may be correlated to some specific performance of the gasoline engine [Chevron, 2004]. Region A is the region in which 0-20% of fuel evaporates: this is often referred to as the ‘front-end’ of the fuel blend. Region B, the so-called ‘mid-range’ of the fuel is the region in which 20-90% of fuel evaporates. Region C, the region in which 90-100% fuel evaporates, is typically known as the ‘tail-end’ of the blend. These three regions are often represented in the literature by three discrete temperatures $T_{10}, T_{50}$ and $T_{90}$—that is to say, the temperature at which 10, 50, and 90% of the fuel is evaporated according to the ASTM D86 test method.

With regard to the influence of distillation properties on vehicle performance, according to one fuel company [Chevron, 2004], the front-end of a multi-component fuel, identified by $T_{10}$, affects both cold starting and hot starting. The mid-range of the fuel, identified by $T_{50}$, influences both warm-up and fully-warm running, fuel economy, power and acceleration, and the ‘tail-end’ of the blend, identified by $T_{90}$, significantly affects fuel economy after engine warm-up, fuel dilution of crankcase oil and Volatile Organic Compound (VOC) exhaust emissions.

Reid Vapor Pressure (RVP):

Reid Vapor Pressure is measure of a multi-component fuel’s front-end volatility measured using the ASTM D323 test method. A higher RVP indicates a higher amount of low-temperature vaporization and thus, relatively shows a higher front-end volatility.

Table 1.2: Reid Vapor Pressure (RVP) of various fuels and fuel components [Tshietya et al., 1991].

<table>
<thead>
<tr>
<th>FUEL</th>
<th>RVP (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol</td>
<td>31.7</td>
</tr>
<tr>
<td>Ethanol</td>
<td>15.9</td>
</tr>
<tr>
<td>MTBE</td>
<td>53.8</td>
</tr>
<tr>
<td>ETBE</td>
<td>30.3</td>
</tr>
<tr>
<td>Gasoline</td>
<td>55.1 - 103.4</td>
</tr>
<tr>
<td>Diesel</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Table 1.2 shows RVP for some conventional hydrocarbon fuel blends and some common fuel additives including Methyl Tert-Butyl Ether (MTBE) and Ethyl Tertiary
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Butyl Ether (ETBE). Both MTBE and ETBE have been used in motor gasoline as an oxygenate and will be discussed further in a later section of this work.

Vapor-Liquid Ratio:

The Vapor-Liquid ratio (V/L) of a multi component fuel refers to the volume of vapor formed at atmospheric pressure from a given volume of gasoline at a specified test temperature. The V/L ratio is considered to be indicative of a fuel’s tendency to vapor lock [Chevron, 2004].

1.3 Air pollution from the combustion of gasoline

Air pollution is a broad term applied to chemical, physical and biological agents that accumulate in the atmosphere and alter its characteristics. Air pollution is known to be a major cause of death and respiratory disease around the world. Although there are many concerns about stationary sources of air pollution such as factories and power generation plants, mobile sources of pollution (mainly automobiles) are believed to be the greatest contributor to air pollution in urban areas. Hydrocarbon emissions, from the distribution of gasoline and its usage in vehicles (products of combustion), are responsible for almost 40 percent of the 10 million tones of man made VOCs emitted into the air of Western Europe annually [Marshall and Owen, 1995]. Of this 40%, 25% is emitted from vehicle exhausts, 10% from evaporation of gasoline and 5% from the distribution process (3% in the refinery to service station and 2% from the refueling of vehicles). The remainder of this section of the thesis will consider the combustion related emissions from gasoline engines.

Vehicle emissions can be regarded as either engine-out emissions, considered immediately after the exhaust gases leave the engine, or as tailpipe emissions, considered as the exhaust gases exit the vehicle and enter the surrounding atmosphere. The discussion here is based on engine out emission. Engine-out emissions are then the products of combustion that are primarily dependent on the nature of the combustion process.

In the complete (ideal) combustion of a hydrocarbon compound with oxygen, the products of combustion will be water and carbon dioxide (CO₂). However, in the case of
a real IC engine, the oxygen required for combustion is obtained from air and the fuel typically contains some additional (non-hydrocarbon) components such as sulfur. Ideal combustion assumes stoichiometric quantities of air and fuel. In a practical combustion engine however, providing a proper mixture of air and fuel under all operating conditions is a difficult task and in many cases cannot be achieved. Accordingly, the combustion of real hydrocarbon fuels in an IC engine can, depending on operating condition, lead to the production of a significant number of toxic pollutant species. The following subsections of this work will briefly consider the five major (regulated) emissions groups (oxides of nitrogen, carbon monoxide, unburned hydrocarbons, particulate matter, and volatile organic compounds), some minor emissions species, and one non-regulated emission that is of significant interest (carbon dioxide).

Oxides of nitrogen (NOx)

Atmospheric nitrogen may be oxidized during the combustion process to produce various oxides of nitrogen (NOx). The main cause of NOx formation in IC engines is high combustion temperature. NOx emissions have many direct health risk effects and are a contributing factor in the formation of photochemical smog. Mobile sources (IC engines) are though to be responsible for more than half of the NOx emission in United States [Environmental Protection Agency (EPA), 1999].

Carbon monoxide (CO)

Carbon monoxide (CO) is, principally, a product of incomplete combustion. Although CO may also be produced by dissociation, it is mainly formed where there is not enough oxygen to oxidize all of the fuel in the combustion chamber. Carbon monoxide is a highly toxic gas that has a serious impact on both healthy people and those who suffer from heart and respiratory diseases. Mobile sources are responsible for 95% of CO emissions in the U.S [Environmental Protection Agency (EPA), 1999].

Hydrocarbons (HC)

Incomplete combustion may also cause some hydrocarbon molecules (especially those of higher molecular weight) to escape the combustion process and remain unburned. HC emissions are a precursor to ground-level ozone and contribute to smog
formation. Ozone is generated through a chemical reaction between NOx and HC in presence of sunlight. [Environmental Protection Agency (EPA), 1999]

**Particulate matter (PM)**

Particulate Matter [Environmental Protection Agency (EPA), 1999] is a term used to describe solid or liquid particles in the air. Although PM emissions more often considered in relation to CI engines rather than SI engines, the particulate emissions of SI engines are also of concern due to their smaller size and their ability to reach to deepest regions of the lung.

**Volatile organic compounds (VOCs)**

Volatile organic compounds (VOC) are carbon-containing gases and vapors such as gasoline fumes and solvents (excluding carbon dioxide, carbon monoxide and methane) such as benzene, dichloromethane. They are suspected to have a direct effect on human health. More reactive VOCs also join in photochemical reactions with nitrogen oxides (NOx) in the atmosphere to form ground-level ozone. Finally, they are also contribute to secondary formation of Particulate Matter.

**Other toxic emissions**

The presence of non-hydrocarbon compounds – such as sulfur – in gasoline can lead to the production of lesser amounts of non-regulated, but equally undesirable, exhaust emissions from IC engines. The presence of sulfur leads to the production of various sulfur oxides, which contribute to the problem of acid rain.

Although the level of pollutant production varies across different engine technologies and is dependent on many variables such as ignition timing, load and speed, the significance of proper mixture preparation in SI engines should be noted. As described in the subsections above, NOx emissions are a strong function of temperature and thus are a function of mixture strength; CO emissions are highly dependent on the local Air/Fuel Ratio (AFR), as are the emissions of unburned hydrocarbons. Similarly, particulate matter is typically formed in locally rich regions of the in-cylinder charge.
Figure 1.2, below, shows the relationship between air-fuel ratio and engine out emissions in a typical spark-ignited IC engine.

![Graph showing relationship between air-fuel ratio and engine out emissions](image)

**Figure 1.2**: Relationship between air/fuel ratio and engine out emissions for a typical SI engine [Howard et al, 1997]

**Carbon dioxide (CO₂)**

In addition to those pollutant emissions resulting from the non-ideal combustion of gasoline, recent concerns regarding global climate change have focused much attention on the production of carbon dioxide. Although carbon dioxide is not classified as a toxic gas, it is a known Greenhouse Gas (GHG) and is widely held to be the main contributor to so-called ‘global warming’. This presents a significant challenge to the engine designer as carbon dioxide is a fundamental combustion product of hydrocarbon fuels. The only way to reduce the carbon dioxide emissions of a given IC engine is to increase engine’s
efficiency (thereby, reducing the fuel consumption of the engine) or to use an alternative fuel with a reduced carbon content.

1.4 Reformulated Gasoline (RFG)

The U.S. Federal Reformulated Gasoline Program was introduced 1995 in an attempt to reduce air pollution in large urban areas. Reformulated gasoline (RFG) is specifically blended to burn cleaner and reduces smog-forming and toxic pollutants from internal combustion engines. The federal standards require RFG to have the following properties:

- Low RVP to minimize evaporative emissions
- A low light Olefins content to reduce the level of these photo-chemically active materials in evaporative emissions.
- A low aromatic content: to reduce emissions of benzene (a known carcinogen) and other toxic exhaust emissions.
- A low level of sulfur to prevent the formation of acid rain and the deactivation of the exhaust catalyst.
- A low $T_{90}$ temperature to reduce HC emissions from heavy hydrocarbons.
- The inclusion of certain additives to maintain the fuel system in a clean condition from deposits.
- A minimum oxygenate content to promote complete combustion (and thus minimize CO and HC emissions) and to enable the gasoline to meet the octane specifications.

Note that although some consideration has been given to specifying that a minimum percentage of the oxygenate compounds contained in RFG should be from renewable sources, the RFG regulations do not specify which oxygenate compounds should be used. The following section of this chapter will consider the history of oxygenated gasoline in more detail. Alternative oxygenate compounds will also be discussed.
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1.5 Oxygenated fuels

The initial development of oxygenated gasoline occurred largely by chance following the widespread introduction of the three-way catalytic converter into the automotive market. It was found that the catalyst materials were rapidly poisoned by tetraethyl lead – which at that time was used as an octane enhancer in gasoline. Accordingly, the automotive industry was forced to investigate alternative methods to boost the octane rating of gasoline. Oxygenate compounds such as MTBE and ETBE, which have significant octane enhancing properties, were widely adopted as fuel additives at this time.

Oxygenate compounds are so called due to presence of oxygen in their molecular structure. The main characteristic of oxygenate addition is an increase in oxygen content of gasoline blend. Depending on the base gasoline and blending additives, the properties of oxygenated gasoline vary significantly. Typically, oxygenates can be categorized into two classes of organic compounds: alcohol and ethers. In alcohols, a hydrocarbon group and a hydrogen atom are bonded to an oxygen atom: R-O-H, where “R” represents the hydrocarbon group. In Ethers, two hydrocarbon groups bonded to an oxygen atom: R-O-R. Oxygenate compounds that have been introduced to the market as a fuel or fuel component include methanol, ethanol, t-butyl alcohol (TBA), Isopropyl alcohol (IPA), isobutyl alcohol (IBA), t-amyl methyl ether (TAME), methyl t-butyl ether (MTBE), ethyl t-butyl ether (ETBE), and Disopropyl Ether (DIPE) [Marshall and Owen, 1995].

The additional fuel oxygen content due to the presence of oxygenate compounds effectively leans the Air Fuel Ratio (AFR) of the combustion reaction. Thus, unless the fuel system is adjusted to compensate for the oxygen content of the fuel, the reaction is effectively shifted to the right in Figure 1.2. Accordingly, emissions of CO and HC are reduced [National Science and Technology Council, 1997] Initial studies, performed shortly after the first introduction of RFG, showed that oxygenated fuels could reduce CO exhaust emissions from about 2 to 10% per wt % oxygen. For most vehicles, the reductions are about 3 to 6%. However, the effect on newer vehicles was found to be less due to their already improved combustion efficiency [National Science and Technology Council, 1997].
1.6 2005 U.S. Energy Bill

Based on national RFG standards, commercial gasoline must contain a minimum of 2% oxygen content by weight in the fuel. Until recently, this requirement has generally been met by blending MTBE in the fuel. However, recent concerns regarding groundwater pollution and the, largely unproven, negative health impacts of MTBE have led to the banning of MTBE in many states and the search for a more ‘environmentally sound’ oxygenate for commercial gasoline.

Coincident with the banning of MTBE, the most recent U.S. Energy regulation, the Energy Policy Act of 2005, has for the first time in U.S. history, set a Renewable Fuel Standard (RFS). The RFS requires a significant increase in the amount of renewable fuel sold in the U.S. – beginning with 4.0 billion gallon per year usage requirement in 2006 and escalating to 7.5 million gallons per year by 2012. Although it is anticipated that some of this requirement will partially met by bio-diesel, it is widely believed that the major part of the RFS requirements will be met by blending ethanol with gasoline, either in low volume fractions as an oxygenate or in high volume fractions as a primary fuel. Note that the new energy bill also provides tax incentives and grants to promote ethanol production from bio-sources, further increasing the likelihood of its widespread adoption as a transport fuel.

1.7 Ethanol blended fuels

The case for ethanol-blended fuels has been argued for many years; in fact, the widespread use of low content alcohol-blended gasoline was initially proposed in 1970s in response to the first Middle East oil crisis. Proponents of ethanol as a transportation fuel claim a number of significant economic and environmental benefits including:

- Blending locally-produced ethanol with gasoline can reduce the current dependency on petroleum imports
- Ethanol can be mixed easily with gasoline either in the pump station or in refineries.
- Ethanol blended fuels are able to use the existing gasoline infrastructure.
- Ethanol may be used as an oxygenates in gasoline.
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- Ethanol, or ethanol-blended fuels, provides a viable means of reducing GHG emissions over the full fuel cycle.

- The widespread adoption of ethanol as a fuel or fuel additive would create a significant number of new jobs in the agriculture sector.

The latter point is interesting. Presently, the majority of bio-ethanol (ethanol from natural sources) is produced from sugar cane (Brazil) and corn (USA). However, in recent years there has been considerable debate regarding the sustainability of bio-ethanol produced from corn in the U.S. Some researchers have argued that the energy balance for the production of bio-ethanol from corn is negative [Shapouri et al, 2004]. Although this debate is ongoing, recent advances in production methods – in particular the development of lingo-cellulostic processes for ethanol production – have increased yields and ethanol is increasingly considered to be a sustainable source of energy. [Tsitateya et al., 1991],[Shapouri et al., 2004],[Renewable Fuel Association (RFA,2005],[Egebäck et al, 2005],[Worth, 2005].

Adding ethanol to a base fuel such as gasoline has a considerable effect on the physical properties of the blend that, in turn, can affect vehicle emissions (both tailpipe and evaporative), fuel economy, drivability, power output and component durability. The extent of these effects depends not only on the ethanol content of the fuel but also on the engine in which the fuel is used. With respect to the properties of gasoline described in §1.2, the addition of ethanol is known to be highly beneficial with regard to increasing the octane number of the blend. This, therefore, will not be considered further. However, the addition of ethanol to gasoline has a serious impact on the fuel volatility as will be discussed in the following subsection.

1.7.1 Volatility of ethanol/gasoline blends

Two measures are used to characterize the volatility of gasoline/ethanol blends.

Distillation Profile:

Unlike gasoline, neat alcohols including ethanol have a single boiling point. Moreover, alcohol/gasoline blends do not obey Raoult’s law – demonstrating very non-ideal properties: Hence, standard volatility measurements are often not well suited to compare gasoline to alcohol blends. With respect to the properties of gasoline described
in §1.2, the addition of ethanol to gasoline substantially changes the distillation properties of the blend. Distillation curves of ethanol blended fuels show a significant "alcohol-flat" in the front-end and, depending on alcohol content, the mid-range of the fuel see figure 1.3).

![Properties of Ethanol Gasoline Blends](image)

**Figure 1.3:** Typical distillation curves for ethanol blended gasoline [Worth, 2005]

**Reid Vapor Pressure:**

The effect of ethanol addition to the RVP of a base gasoline varies depending on the relative quantities of the ethanol and gasoline in the final blend. As described in §1.2, the RVP is effectively a measure of a blend’s front-end volatility. Accordingly RVP often correlates well with the $T_{10}$ of a blend. With respect to ethanol blended gasoline, figure 1.4, overleaf, shows the variation of gasoline’s $T_{10}$, $T_{50}$ and $T_{90}$ distillation temperatures with increasing ethanol content between 0% and 40% by volume. Note the minor depression of $T_{10}$ between zero and approximately 15% ethanol and the significant change in $T_{50}$ between 10% and 20% alcohol content.
Figure 1.4: Variation of characteristic distillation temperature with increasing ethanol content for ethanol-gasoline blends [Guerrieri et al., 1995]

Figure 1.5 shows experimental measurements of RVP for ethanol-gasoline blends of varying ethanol content [Orbital Engine Company, 2002]. It can be seen that blending a low amount of ethanol (5-25%) into gasoline causes an increase in RVP (in comparison with either gasoline or neat ethanol) that can be interpreted as an increase in front-end volatility. However, as the percentage of ethanol content increases beyond 25% by volume, the RVP of the blend starts to decrease. For ethanol-gasoline blends with an alcohol content of between 30-45% the RVP becomes equivalent to that of the base gasoline [Orbital engine company, 2002]. Further increases in ethanol content decrease the RVP of the blend towards that of neat ethanol.

Figure 1.5: Variation of Reid Vapor Pressure with increasing ethanol content for ethanol-gasoline blends (two lines indicate two different experimental results)[Orbital engine company, 2005]
1.8 **Air pollution from the combustion of ethanol/gasoline blends**

As mentioned previously in §1.5, the addition of ethanol to gasoline increases the oxygen content of fuel, effectively leaning the combustion process. Typically, this results in a reduction of CO and HC emissions and an increase in NOx emissions as shown in figure 1.6, below. Note that the increase in NOx emissions shown in the figure are primarily attributed to enleanment of the mixture for the same mass air/fuel ratio by adding Ethanol [Guerrieri *et al.*, 1995]

![Figure 1.6: Average percentage change in vehicle emissions from base levels](image)

The use of ethanol does, however, increase the engine-out emissions of a number of minor pollutant species – in particular, aldehydes (which show a linear increase with increasing alcohol content up to 20% by volume). Note that, Figure 1.6 associated to a test were done on six vehicles (built 1990-1995) equipped by electronic fuel injection. However, regarding recent improvement in engine design as well as emission controlling system, some changes might be expected in the affect of ethanol addition to vehicle emissions.

1.8.1 **Fuel economy and greenhouse gas emissions**

Since alcohols in general, have a lower energy content than gasoline (approximately 21.4 MJ/Liter for ethanol c.f. approximately 35MJ/Liter for gasoline),
adding ethanol to the blend will cause a decrease in the power output from a given engine [Egebäck et al., 2005]. In fact, Kortum et al. [Orbital Engine Company, 2002] showed the energy content of ethanol blended fuel to be directly proportional to ethanol content for the range of fuel blends tested. A corresponding reduction in fuel economy is also expected. Table 1.3 shows the theoretical reduction in fuel economy caused by increasing the volume of ethanol in the ethanol-gasoline blend and Table 1.4 shows the results of physical testing performed by Guerrieri et al. (1995 and 2002), and Kortum et al., 2002.

Table 1.3: Theoretically expected effects of ethanol addition to gasoline on fuel energy content - adapted from [Orbital Engine Company, 2002]

<table>
<thead>
<tr>
<th>Ethanol Content (%)</th>
<th>Energy from ethanol (K Joule/Liter)</th>
<th>Energy from gasoline (K Joule/Liter)</th>
<th>Energy of 1 gal of Blend (K Joule/Liter)</th>
<th>Fuel Economy change gasoline (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.7</td>
<td>996</td>
<td>23,641</td>
<td>25,708</td>
<td>-1.7</td>
</tr>
<tr>
<td>7.7</td>
<td>1,404</td>
<td>24,145</td>
<td>25,550</td>
<td>-2.3</td>
</tr>
<tr>
<td>10.0</td>
<td>1,824</td>
<td>23,544</td>
<td>25,386</td>
<td>-3.0</td>
</tr>
<tr>
<td>20.0</td>
<td>3,648</td>
<td>20,928</td>
<td>24,576</td>
<td>-6.1</td>
</tr>
</tbody>
</table>

Table 1.4: Heat of combustion and Fuel economy for various Ethanol blends – adapted from [Orbital Engine Company, 2002]

<table>
<thead>
<tr>
<th>Ethanol Percentage (%)</th>
<th>Average Heat of Combustion (K Joule/Liter)</th>
<th>Change in Heat of Combustion (%)</th>
<th>Average Fuel Economy (Liter/100Km)</th>
<th>Change in Fuel Economy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>27699</td>
<td>-</td>
<td>10.69</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>26844</td>
<td>-3.10</td>
<td>11.06</td>
<td>-3.41</td>
</tr>
<tr>
<td>12</td>
<td>26617</td>
<td>-3.91</td>
<td>11.24</td>
<td>-4.90</td>
</tr>
<tr>
<td>14</td>
<td>26466</td>
<td>-4.45</td>
<td>11.25</td>
<td>-5.00</td>
</tr>
<tr>
<td>17</td>
<td>26265</td>
<td>-5.18</td>
<td>11.40</td>
<td>-6.23</td>
</tr>
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<td>20</td>
<td>25999</td>
<td>-6.14</td>
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<td>-6.91</td>
</tr>
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</tr>
<tr>
<td>35</td>
<td>24610</td>
<td>-11.15</td>
<td>12.01</td>
<td>-11.05</td>
</tr>
<tr>
<td>40</td>
<td>24974</td>
<td></td>
<td>15.03</td>
<td></td>
</tr>
</tbody>
</table>

With respect to the emissions of CO₂ from engines using ethanol-gasoline blends, studies suggest that, with a small increase in ethanol content (10-17% by volume) there is
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an almost negligible increase in CO₂ emissions (less than 0.5%), at 20% ethanol content, the CO₂ emissions would be the same as the base gasoline, and between 25-40% ethanol the CO₂ emissions decrease by 1.5 % reduction. For blends containing higher levels of ethanol such as in E85, CO₂ emissions can decrease by up to 40-50% [Orbital Engine Company, 2002]. However, to measure the ultimate effect of ethanol fuel on CO₂ emissions would require a full life cycle analysis of the fuel that includes the production and end use to ascertain overall benefits.

1.9 Conclusions

This chapter has considered the adoption of ethanol-gasoline fuel blends for automotive applications. It has been shown that the addition of ethanol to commercial gasoline has a significant impact the distillation properties of the fuel. The nature and extent of the changes to the fuel’s distillation characteristics brought about by the addition of ethanol are sufficient enough to suggest that the mixture formation process in an SI engine could be affected. In this regard, it is reasonable to believe that combustion system design and the choice of fuel delivery system may be particularly significant. Accordingly, the next chapter of this thesis will consider current trends in SI engine combustion system design and will consider the possible consequences of using ethanol-blended gasoline in direct-injection spark-ignition (DISI) engines.
Chapter 2

Gasoline Injection Systems

The previous chapter of this work considered the role of fuel composition and the effect of adding ethanol to gasoline. This chapter will consider Direct Injection Spark Ignition (DISI) engines and their main differences with conventional Multi-Port Fuel Injection (MPFI) engines. Due to the high sensitivity of the DISI engines to mixture preparation and regarding the purpose of this study, the main focus of this chapter will be the injection system itself.

2.1 Introduction

An ever increasing demand for automobiles with higher standard requirements regarding performance, emissions and fuel consumption poses a substantial challenge to today's automotive industry. Manufacturers have been forced to seek new technologies and solutions to meet the increasingly stringent standards required by lawmakers and the general public alike. The difficulty of the task facing the industry can be observed through the rapidly changing regulations for fuel economy or pollutant emissions. Standards such as CAFE (Corporate Average Fuel Economy), SULEF (Super Ultra-Low Emissions Vehicles), and various European Union norms such as EU3, EU4, EU5 are regularly reviewed and revised, often posing serious technical challenges in the process.

Traditionally, spark ignition (SI) engines have been the dominant engine technology for passenger vehicles. SI engines typically offer a higher performance at full load and a better transient response than their compression ignition (CI) engine counterparts. However, CI engines show superiority in regard to efficiency and fuel economy due to their higher compression ratio and unthrottled operation at part load. In light of these characteristics the automotive industry are increasingly making efforts to develop Direct-Injection Spark-Ignition (DISI) combustion engines, also known as Gasoline Direct Injection (GDI) engines. The DISI engine combines the best features of both the SI engine and the CI engine. It has the potential to operate with a fuel economy equal or better than a CI engine while maintaining the operating advantages of the SI
Chapter 2: Gasoline Injection Systems

2.2 Fuel injection systems for spark ignition (SI) engines

There are many logical criteria by which to classify SI engines. One of these classifications is based on their type of fuel metering and delivery system. Almost all gasoline passenger cars sold in the U.S.A. since 1990 and Canada have been equipped with Electronic Fuel Injection (EFI) systems and many different EFI variants have been developed. Historically, the first EFI systems introduced to the market were positioned at the throttle body where previously a carburetor had been sited. However, the site of fuel injection has shifted progressively closer to the cylinders over time in an effort to provide improved transient response and control of air-fuel ratio. Presently, the most widely adopted EFI arrangement is the Multi-point Port Fuel Injection (MPFI) system.

2.2.1 Multi-point Port fuel injection (MPFI)

MPFI systems utilize one fuel injector per cylinder. The injector is mounted in the intake manifold, close to the cylinder head and, typically, fuel is injected onto the back of a closed intake valve. A throttle is used to regulate air flow into the engine and fuel injection event controlled separately through an Electronic Control Unit (ECU). After hitting the hot surface of intake valve, the injected fuel evaporates and mixes with the air coming through the manifold. The resultant air-fuel mixture being ingested into the cylinder when the intake valve opens.

When the engine is warm, MPFI systems function well and are largely insensitive to fuel composition. However, during cranking or cold start a liquid fuel film forms on the surface of the intake valves and intake port walls that can be drawn into the engine. This issue, coupled with the poor vaporization of fuel from the cold surfaces, can cause failed or partial combustion events (with associated high HC emissions) to occur during the first 4-10 cycles of cold start [Zhao et al., 2002]. Fuel retained in the intake manifold during warm-up also affects the in-cylinder air-fuel ratio and transient response.

Although the issues mentioned above have serious implications for SI engine emissions during cold-start and warm-up, perhaps the most significant feature of MPFI
Chapter 2: Gasoline Injection Systems

systems is that load control is still achieved through the use of a throttle upstream of the cylinder. It is well known that the use of a throttle detrimentally affects the part-load efficiency of the SI engine. However, in order to move to throttle-free operation it is necessary to consider a completely different approach to fuelling.

2.2.2 Direct-injection

In DISI engines, instead of controlling load by throttling, load control is achieved by regulating the quantity of fuel injected per cycle (as per the CI engine). The injector is placed in the cylinder head and fuel is injected directly into the combustion chamber. At part-load a stratified charge approach is employed. As the fuel is injected inside the cylinder, a rich combustible cloud is formed around the spark plug, surrounded by a thermally insulated layer composed of air and residual gas. The power output is then proportional to the amount of injected fuel. This operation not only increases thermodynamic efficiency by lessening heat loss through the walls but also because of unthrottled operation the pumping loss is reduced [Leonhard, 2003].

Although, maximum part-load fuel economy is achieved through stratified charge approach, DISI engines commonly utilize homogeneous charge approach to provide maximum power at full load. Additional modes such as rich homogenous charge are also used for the transition between different load conditions [Hennessey, 2001, Lee & Nishida, 2003]. This wide range of operating modes places severe demands on the fuel injection system as described below:

Stratified Charge:

In Stratified Charge mode, the fuel injection event occurs near the end of compression stroke with the intention of forming a super-lean stratified mixture with an ignitable core at the spark-plug. Since fuel injection occurs close to top-dead-centre (TDC) in the compression stroke the injector is required to operate against a high ambient backpressure and at relatively high temperature. The available time of injection is significantly short – less than 0.5 milliseconds at idle (which is approximately one fifth of the available time in MPFI engines). Furthermore, since the injected fuel will not ignite
as a liquid, the injector must deliver a well-atomized spray to promote rapid evaporation and air-fuel mixing; at the same time, the spray must remain concentrated within the cylinder to maintain charge stratification.

**Homogeneous Charge:**

During heavy load or high-speed operation condition, in which higher power output is necessary, a greater mass of flammable mixture is needed. In this case, fuel injection occurs during the intake stroke or early in the compression stroke. In this case, fuel is injected into a relatively cool low pressure environment with the intention of forming a homogeneous charge. Again the time available for mixture preparation is short due to the higher engine speed and increased fuel mass injected. Thus, the injector is again required to produce a well atomized spray; however, in contrast to the stratified charge case, a high level of dispersion is required.

Early direct injection offers thermodynamic advantages in comparison with conventional MPFI engines. Due to cooling of the induced charge by evaporating fuel spray, the charge density increases and more power may generated – typically, around 5% increase in full load power is observed [Hennessey, 2001]. The charge cooling also reduces the tendency of the engine to knock; thus, DISI engines are able to run higher compression ratios (increasing thermal efficiency) than their MPFI counterparts. Note that this increased compression ratio may also result in higher emissions of HC however.

### 2.3 Direct-injection vs. port-injection

There are both many potential advantages and numerous technical challenges associated with the use of DISI combustion systems. §2.3.1 below presents a brief summary of the potential advantages of direct injection combustion systems in comparison with a present generation MPFI system.
2.3.1 Advantages of direct fuel injection

It is claimed that DISI engines have the potential to achieve a 25% improvement in fuel economy compared with their MPFI counterparts [Zhao et al., 2002]. Many factors contribute to this feature including; (i) reduced pumping and heat losses due to Wide Open Throttle (WOT) operation during stratified charge operation; (ii) higher compression ratios leading to increased cycle efficiency; (iii) higher volumetric efficiencies due to charge cooling [Shelby et al., 1998, VanDerWege et al., 1998], (iv) the ability to cut-off fuelling during deceleration operation and finally, (vii) a reduced requirement for enrichment during acceleration [Zhao et al., 2002].

As described in an earlier section of this chapter, there are also performance benefits associated with the use of direct-injection fuel systems. DISI engines can extract more power per unit of displacement because of their higher volumetric efficiency and also WOT operation. The performance may increase by 5 to 10% in part load condition [Hennessey, 2001; Shelby et al., 1998 and VanDerWege & Hochgreb, 2000]. Since the fuel is injected directly into the cylinder there can be no fuel ‘hang-up’ in the intake manifold. Thus, DISI engines offer the potential for better transient response with more precise control over AFR ratio.

With regard to engine emissions, it is claimed that DISI engines can help reduce the emissions of unburned HC during the cold start by eliminating the formation of manifold fuel films; there is also a reduction of CO₂ emissions due to reduced fuel consumption.

2.3.2 Disadvantages of direct fuel injection

The majority of the part-load efficiency benefits that are claimed for DISI are obtained through the use of a stratified charge. Overall then, the air-fuel ratio (AFR) of the engine at part-load is lean. The conventional three way catalyst used in MPFI engines requires the use of a stoichiometric AFR and thus does not perform efficiently in stratified charge DISI combustion systems, Tailpipe emissions of NOx, in particular, are relatively high for DISI engines in both part-load and full-load conditions and highly specialized ‘lean-burn’ aftertreatment systems are required. Moreover, DISI engines can, depending on combustion system configuration, create relatively high HC emissions.
compared with a conventional MPFI engines. Some of the major contributors to HC emissions in DISI engines include (i) the incomplete combustion due to poor air-fuel mixing, (ii) bulk flame extinction due to overleaning, (iii) low in-cylinder temperatures leading to low levels of post-flame oxidation and finally, (iv) spray impingement on in-cylinder surfaces such as walls and piston [Hennessey, 2001].

Mixture preparation in DISI engine presents a particular challenge: the available time for vaporization and mixing to occur is significantly shorter in a DISI engine than in an MPFI engine. Whereas an MPFI engine may effectively use the intake manifold and intake valve as pre-vaporization chamber – fuel is often targeted at the hot surface of intake valve to aid vaporization – the DISI engine does not have this luxury. In contrast to the low temperature and pressure environment of the MPFI intake manifold, the DISI injector is required to deliver fuel into a high temperature and, often, high back-pressure environment. Thus, the DISI fuel system is necessarily considerably more complex than its MPFI equivalent, operating at substantially higher supply pressures and in a variety of modes – homogenous (full load) and stratified (part load). Mixture formation in these engines is influenced mainly by the characteristics of the fuel spray and the air-flow inside the cylinder. Although undoubtedly significant, the influence of in-cylinder flow and its interaction with the injected fuel is beyond the focus of this research project. Therefore, the following sections of this chapter will consider the fuel injection system and its influence on mixture preparation in isolation from any discussion of airflow effects.

2.4 Fuel injectors for DISI engines

Perhaps, the key component in any DISI fuel systems is the fuel injector itself (also called an atomizer) and many different injectors and injection systems have been developed for DISI engine applications in recent years. However, the most commonly adopted arrangement, by far, has been that of a high-pressure common-rail system with a single-hole pressure-swirl type injector.

In general terms, an ideal injector should have characteristics such as providing good atomization at all injection rates; high sensitivity to any variation in injection rate;
provide a stable flow; have a low power requirement; be low cost, light weight, simple to manufacture and install; be resistant to clogging by impurities and carbon buildup on the nozzle face; have a resistance against gum formation by heat soakage and ability to provide a uniform radial and circumferential fuel distribution [Lefebvre, 1989].

The DISI engine provides a substantial challenge to the injection system in general and the fuel injectors, in particular. Due to the limited time available for mixture preparation DISI injectors are expected to provide an extremely well atomized spray, in which the Sauter Mean Diameter (SMD) is less than 20μm [Zhao et al., 2002]. Moreover, a DISI injector should also have the flexibility of providing proper atomization and control in both stratified-charge and homogenous-charge operating conditions. Zhao et al [2002] contrast the performance requirements of a typical DISI injector with that of a MPFI injector. In comparison to an MPFI injector the DISI atomizer must provide:

- A significantly higher level of atomization.
- A significantly expanded dynamic range.
- The ability to conduct multiple injections within one engine cycle.
- The ability to operate at higher injector body and tip temperatures
- Smaller flow variability under larger thermal gradients
- Enhanced resistance to deposit formation
- Combustion sealing capability
- The ability to deliver a controlled spray shape under a wide range of ambient back pressure conditions.

It is well known that the spray characteristics of a DISI injector hold paramount importance in achieving the performance and emissions targets in DISI engines. The injector must be well matched to the combustion system and the combination of atomization and penetration, air entrainment and momentum distribution of the spray must be considered [Lippert et al., 2004]. Over recent years, a number of injector configurations and technologies have suggested for use in DISI engines. Table 2.1, presents a list of recently used DISI injector types and some details of their key characteristics.
Table 2.1: Some commonly used DISI injector types [Zhao et al., 2002]

<table>
<thead>
<tr>
<th>Injectors</th>
<th>Comments</th>
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| Inwardly-opening, single fluid, high pressure swirl injector | • Hollow cone spray  
• Solid-cone spray  
• Symmetric spray: spray is symmetrically distributed across the spray axis. Spray axis can be either aligned with the injector axis or offset from the injector axis |
| Outwardly-Opening, Single-Fluid, High-Pressure, Swirl Injector | • In general, it produces a hollow-cone spray without a sac spray. It is difficult to produce an offset spray from this type of injector. |
| Pulse-Pressurized, Air-Assisted Injector      | • This type of injector uses a significantly reduced fuel pressure, but requires two separate solenoids and a source of compressed air for improved spray atomization and dispersion. |
| Hole-Type Nozzle                               | • Single-hole  
• Multi-hole pattern: spray structure varies significantly with the number and arrangement of the holes. |
| Slit-Type Nozzle                               | • The geometry of the nozzle is in the form of a slit, which delivers a fuel spray in a fan shape. |

Two of the DISI injector technologies listed in Table 2.1 were employed during the experimental work described in later chapters of this thesis. Accordingly, the following two subsections of this chapter will briefly consider the design and operation of the inwardly-opening, single fluid high-pressure swirl injector and the multi-hole pattern hole-type nozzle respectively. The liquid atomization and break-up mechanisms employed by these injectors and the global characteristics of the subsequent sprays will be discussed in greater detail in Chapter 3.

2.4.1 Inwardly opening, single-fluid, high pressure swirl injector

High-pressure swirl injectors have been widely adopted and used in DISI engines due to its ability to provide a well atomized spray with relatively short penetration length at moderate injection pressure levels. Injectors of this type transform pressure into rotational movement within the injector that enhances atomization resulting in a spray with finer droplets than normal hole-type nozzles [Zhao et al., 2002, Schmitz et al., 2002, Stan, 2002]. Typically, fuel flows through a series of tangential slots into a swirl chamber upstream of the injector orifice – See Figure 2.1 (overleaf)
After gaining angular momentum, the fuel flows through a decreasing diameter orifice, which increases the swirl velocity, to a constant diameter nozzle. The centrifugal force caused by the swirling motion in the nozzle results in the formation of an annular wall film. On exiting the nozzle the same forces cause the fuel to spread out in a thin conical sheet from the orifice. The conical spray is filled by air from below. Its final shape depends on the ratio of angular and axial velocity induced to the flow through the injector.

There is typically a significant delay phase associated with the injection process – defined as the time elapsed from sending the injection command pulse until the first appearance of fuel from the nozzle. To inject the fuel as discussed earlier requires controlled movement of the injector’s needle valve. This movement, or in other words, the opening and closing response of the injector is associated both with the characteristics of the injector’s solenoid and the mechanical design of the injector. Usually, the needle both opens and closes late with respect to the timing of the control pulse. Since the delay
in Opening Time (OT) is generally less than delay in Closing Time (CT), the actual injection duration is typically longer than that commanded. For a typical inwardly opening DISI pressure swirl injector the injector delay time caused the actual injection be longer than the control pulse. Figure 2.2 illustrates the opening and closing delays of a typical DISI pressure-swirl injector with a comparison the actual needle lift and the control pulse pattern.

Figure 2.2: Comparison between control pulse and actual injection patterns [Lee & Nishida, 2003]

The spray produced by a swirl type nozzle is strongly influenced by nozzle design parameters such as swirl chamber geometry, the sharpness of the inlet to the discharge orifice and the exit radius of curvature of the discharge orifice (see Figure 2.3 - overleaf). The swirl chamber design, in particular, affects not only the spray geometry but also has a significant impact on droplet size. Furthermore, the surface quality of orifice wall is important. Imperfections in the surface finish can result in the formation of discernable liquid streams in the spray that can result in in-homogeneity of mixture.
Depending on the requirements of a particular combustion system, high-pressure swirl injectors can be designed so that they produce a spray at some offset angle from injector axis (in this case, the injector could also be called shaped-spray injector). The spray pattern of a shaped-spray can be customized to make different offset angles by altering only the geometry of orifice while the rest of the internal components remain the same. However, offsetting the spray axis in a swirl type injector will result in a change of atomization quality.

2.4.2 High-pressure hole type injector

Gasoline hole-type injectors are similar in many respects to diesel fuel injectors. The characteristics of these injectors are defined by the precise number and nature of hole used. Thus, multi-hole nozzle can produce an almost infinite number of spray patterns by utilizing various hole patterns, hole sizes and orientation.
Due to their inherent flexibility, multi hole injectors have many potentially distinctive advantages; (i) they can produce almost any spatial distribution of fuel within the spray – though few alternative arrangements have been developed so far; (ii) the spray can be offset from the main injector axis with little or no deficiency in atomization, (iii) some research suggests that multihole injectors can effectively reduce a spray’s liquid-phase penetration length while they can maintain or even increase the penetration length of the vapor phase at the same time. This feature is particularly attractive for preventing wall wetting in DISI engine, (iv) they provide effective mixing and air entrainment due to their initially separate plumes, (v) in multihole injectors, the initial sac spray that in the pressure-swirl type atomizer contains large, high velocity droplets, is usually eliminated [Lippert et al., 2004, Zhao et al., 2002].

However, there are some drawbacks associated to this type of injector. Most notably, (i) multihole injectors require a very high fuel supply pressure to provide proper atomization. Poor atomization due to low supply pressure is significant during the cranking and start-up periods leading to high HC emissions, and (ii) the overall spray is highly sensitive to the behavior of the individual spray plumes. Therefore each individual orifice must meet its desired specification all of the time in order to prevent any misdistribution of mass, momentum or penetration length that may compromise the intended design [Lippert et al., 2004].

2.5 Conclusions

This chapter has presented a brief review of gasoline fuel injection systems. The case for the direct-injection spark-ignition engine has been shown and some of the particular challenges posed by direct-injection fuelling systems have been discussed – most notably, the significant reduction in time available for evaporation and mixing to occur. Given the comparatively reduced time available for mixture preparation, it seems reasonable to believe that DISI fuel systems will be more sensitive to the effects of fuel composition (and in particular, fuel volatility) than will an MPFI system. Accordingly, the following chapter of this work will consider the spray characteristics of the two DISI injector types introduced in this chapter in greater detail. In particular, the sensitivity of these sprays to changes in ambient conditions will be examined.
Chapter 3

Characteristics of DISI engine fuel sprays

In the previous chapter, DISI engines have been introduced. It was shown that many of the advantages and disadvantages of the DISI engine are significantly dependant on fuel system performance. This chapter will consider spray formation in DISI engines in more detail.

3.1 Introduction

The air-fuel mixing process is perhaps the most critical factor determining DISI engine performance. Its starting point may be considered to be the initial fuel spray formation. Amongst other things, the characteristics of the spray dictate the speed of fuel-air mixing, the subsequent mixture distribution, and the level of in-cylinder wall-wetting. The required spray characteristics not only depend on combustion system but also depend on engine operating conditions. For instance, during homogenous charge mode (full-load condition), a well-dispersed, well-atomized homogenous fuel spray is required while a compact and stable spray structure with high repeatability is desirable in stratified charge mode (part-load) [Stan, 2002, Zhao et al., 2002, Stone, 1999, Zhao et al., 1996].

3.2 Spray formation

A spray is typically defined as “a system of drops immersed in a gaseous continuous phase” [Lefebvre, 1989]. The function of the fuel injector in a DISI engine is not only to break the liquid fuel into the small droplets, but also to disperse these drops through the cylinder in the form of a uniform spray with maximum interaction with air. Atomization occurs due to the interaction between the high-velocity liquid flow and the surrounding medium. During the first stage of the disintegration process (primary breakup) many large droplets are formed. Subsequently, these droplets may undergo secondary breakup mechanism and disintegrate to smaller drops. Therefore, the final range of droplet sizes within a spray depends on two stages of atomization. The nature of the primary atomization process will depend on the style of atomizer that is in use. The
following two subsections of this work will consider the breakup of liquid jets and sheets respectively.

### 3.2.1 Disintegration of liquid jets

An understanding of liquid jet disintegration is important for investigating hole-type injectors that are widely used in diesel engines and in some DISI engines. When a cylindrical liquid jet emerges from a nozzle, the surface of jet subjected to both cohesive and disruptive forces. These forces cause vibration and perturbations in the jet. Under favorable conditions, the vibrations are intensified resulting in the disintegration of the liquid jet into the droplets.

![Diagram of liquid jet breakup stages](image)

**Figure 3.1:** Stages of liquid jet breakup [Barnet et al., 1957]

Many factors affect the breakup mechanism that leads to liquid jet disintegration. The most important factors are the velocity profile and turbulence properties of the jet emerging from nozzle. One of the most common criterions that are used to classify jet disintegration was proposed by Ohnesorge. He used dimensionless analysis to show three different stages (refer to Figure 3.1) of jet breakup mechanism, each stage defined by the magnitudes of the Reynolds number, \( \text{Re} \) – a dimensionless number that is the ratio of inertial forces to viscous forces – and the Ohnesorge number, \( \text{Oh} \) – a dimensionless
number that relates the viscous force and surface tension force. Figure 3.1 shows these three regions by plotting log Oh versus log Re [Lefebvre, 1989, Barnett et al., 1957].

Zone (I) is the so-called Rayleigh breakup regime: in this regime, the jet velocity is low and breakup is due to the unstable growth of surface waves caused by surface tension forces on the jet. Zone (II) is known as the first wind-induced breakup regime: in this regime, the jet velocity is higher. The relative motion between jet and air reduces the wavelength of unstable waves and thereby produces forces that lead to droplet sizes of the order of the jet diameter. Zone (III) is called second wind-induced breakup regime, in this regime the jet velocity is much higher, so the relative motion between the liquid jet and the surrounding air induces unstable growth of waves with a very short wavelength. There is also another atomization regime, which occurs beyond Zone (III), in this regime the very high velocity of jet causes the outer surface of the jet to break-up at or before, the exit of the injector orifice [Barnett et al., 1957].

Atomization from hole-type DISI injectors is assumed to occur in Zone II or Zone III and, on occasion, perhaps even above Zone (III). These two regimes are the least understood of the various breakup phenomena.

3.2.2 Disintegration of liquid sheets

Some injectors are designed to form a thin conical sheet at their nozzle exit rather than a liquid jet. A conical sheet can be obtained by flowing the liquid fuel through an annular orifice with tangential velocity component resulting from passage through tangential or helical slots upstream of the nozzle. As the conical sheet emerges from the injector orifice, its initial velocity and the physical properties of the fuel as well as ambient condition will significantly influence the spray development [Lefebvre, 1989].

Based on experimental investigations of flat sheets, Fraser et al. [1962] have defined three modes of sheet disintegration; rim, wave and perforated-sheet. In the rim mode, surface tension forces acting on the sheet lead to the sheet contracting into a thick rim, which is followed by a breakup mechanism similar to that of a liquid jet. This mode of breakup usually happens when the viscosity and surface tension of liquid is high and leads to generation of large drops. However, the rim mode does not occur in conical sheets. In wave mode, a wave motion is generated on the sheet due to the effect of
aerodynamic drag. Areas of the sheet that oscillate in half or full wavelength of the wave motion are torn away to form ligaments once the oscillations reach a critical value. These ligaments rapidly contract under the action of surface tension, pinching off to form droplets in a similar manner to the break-up of a liquid jet. This is the primary break-up mechanism of a hollow-cone spray (conical sheet). Finally, in perforated-sheet mode, holes appear in the sheet due to point instabilities. Their size grows rapidly until the rims of adjacent holes coalesce to produce ligaments of irregular shape that finally break up into droplets by various sizes [Fraser et al., 1962].

3.3 Spray evaporative behavior

Once droplet has been formed within a spray, a heat-transfer process occurs that causes the droplets to be heated or cooled depending on the droplet's ambient conditions and temperature. During this time, the droplet will lose part of its mass due to vaporization and diffusion into the surrounding medium. Finally, at some point, the droplet temperature becomes steady and reaches equilibrium with the surrounding medium. The relative rates of these two simultaneous processes (heat and mass transfer) are affected by the Reynolds number of droplet, which varies due to the variation of droplet size and velocity through the droplet's lifetime. The overall rate of evaporation of liquid droplets therefore depends on the conditions of both the surrounding medium such as temperature, pressure, and transport properties of gas, and the properties of the liquid droplet such as temperature, volatility, size and velocity.

Most droplet evaporation models are based on pure fuels in which the boiling temperature is constant and the cross-sectional area of the droplet is assumed to decrease linearly through steady-state evaporation. However, gasoline and other commercial fuels are multicomponent mixtures of various hydrocarbons with various physical and chemical properties. In these fuels, evaporation is a complex process in which, individual components cannot evaporate unless they are exposed to the droplet surface. Law [1982] suggested two regimes for multicomponent droplet vaporization. In one regime, rapid vaporization in which the rate of surface regression is one or two orders of magnitude greater than the rate of liquid-phase mass diffusion. In this regime, the composition of droplets remains constant and components with different volatilities evaporate at similar
rates. The second regime is slow evaporation in which the lighter components evaporate preferentially to leave droplets with a higher percentage of heavier components.

VanDerWege et al. [2000] investigated the evaporative behavior of DISI sprays from a pressure swirl atomizer by changing the fuel temperature, ambient pressure and fuel volatility. The results of this study showed that as the evaporation rate of the fuel increased, three distinct regimes in the spray's evaporative behavior could be observed. VanBerWege defined these three regimes as (i) slow evaporation: when evaporation was slow, the spray structure was found to be governed (primarily) by the injector characteristics. The high and low volatile components were seen to behave similarly except for a small amount of vapor generated by the light end, which was drawn into the airflow surrounding the spray, (ii) non-disruptive evaporation: in this regime, there is a medium rate of evaporation caused by increasing temperature. In this situation, the light end of spray was noted to evaporate quickly but the overall shape of spray was not affected considerably, and (iii) disruptive evaporation (or flash boiling): under high temperature or low ambient pressure conditions the front-end components of the fuel were found to flash near the tip of injector causing significant disruption of spray.

3.3.1 Flash boiling effect

Generally, flash boiling occurs when a sub-cooled liquid depressurizes rapidly to a pressure sufficiently below its liquid saturation pressure as to cause almost instantaneous vaporization [Schmitz et al., 2002, Zuo et al., 2004; Kawano et al., 2004].

The Pressure-enthalpy diagram presented in Figure 3.2 (overleaf) shows qualitatively the comparison of a normal liquid fuel injection and a flash boiling injection. In the flash boiling injection, the fuel is in the liquid phase (point 1) at the start of injection. During injection, the fuel flows through the injector orifice and rapidly depressurizes to point (4). Between point (2) and (3) vapor bubbles emerge and grow to reach to equilibrium with certain fraction of vapor. Point (4) is located in the liquid-vapor zone, therefore fuel in this state exists in both form of vapor and liquid. In a conventional injection process, fuel goes from point (1') to (2') thus the fuel remains in liquid phase at all times.
Figure 3.2: Comparison of conventional and flash boiling injection [Schmitz et al., 2002]

Figure 3.3, below, shows schematically the flash boiling process of fuel in the orifice of an injector. Bubble formation starts immediately after the entrance to the orifice and is followed by bubble growth and atomization within the nozzle. When the two-phase fuel emerges from the orifice, it may either expand by flashing in a constant cone angle (first regime) or depending on the pressure ratio of chamber and injection pressure, it may flash with external expansion (second regime). Note that droplets remaining after undergoing these processes may be subjected to further flash boiling and vaporization outside of nozzle depending on the fuel composition and the amount of energy left in droplets.

Figure 3.3: Expansion of the fuel under expanded two-phase flow created by flashing within the nozzle [Schmitz et al., 2002]
Chapter 3: Characteristics of DISI Engine Fuel Sprays

As detailed in Chapter 1 of this thesis, commercial fuels such as gasoline are multi-component mixtures that contain both high and low volatility components. Studies have shown there is a clear difference between the spray structure of a multicomponent fuel and a single component fuel [Senda and Fujimoto, 2001; Schmitz et al., 2002; Kawano et al., 2002]. In the case of multicomponent fuels, the components that have a lower boiling temperature flash earlier and generate small droplets that in a hollow cone spray may follow the induced airflow into the center of the spray cone. Increasing the fuel temperature has a direct increasing effect on flash boiling tendency and consequently can have a substantial impact on the spray structure [Schmitz et al., 2002]

3.4 Spray characteristics of DISI fuel injectors

There are many ways of categorizing DISI injector. As described in Chapter 2, the classification that will be used here is based on the atomization mechanism and nozzle configuration. Similarly, there are numerous metrics by which to characterize a fuel spray. Figure 3.4, below shows some of spray characteristics and the influential factors that are used commonly by researchers.

![Spray Characteristics Diagram]

**Figure 3.4:** Some of the key DISI fuel-spray characteristics and their determinants [Zhao et al., 2002]
In this work, the defining characteristics of a spray will be considered at the macroscopic level. Thus, the relevant spray characteristics are structure and configuration along with axial and radial penetration rate. Sprays may be further characterized at a microscopic level by considering smaller features such as droplet size and momentum; clearly, the macroscopic and microscopic characteristics of a spray are highly interrelated. As may be seen from the wide variety of possible influences on spray form shown in figure 3.4, the direct mapping of any one individual spray characteristic to a single determining factor is difficult. Nevertheless, the following subsection of this work will describe both the spray characteristics of the inwardly opening, single-fluid high-pressure swirl-type injector and the reported effects of temperature, pressure, and fuel composition on those characteristics. Subsection 3.4.2 will similarly describe the performance of a typical DISI hole-type nozzle with multi-hole injection pattern.

### 3.4.1 High-pressure swirl-type injectors

As described in Chapter 2 of this work, high-pressure swirl-type injectors generate a hollow-cone spray by imparting a swirling motion to the fuel that causes the fuel to exit the nozzle as an expanding liquid sheet. A more detailed description of the characteristics of swirl-type injectors that includes the temporal evolution of the spray is provided by Lee and Nishida [2003] who define five distinct stages of spray development as shown in figure 3.5.

![Figure 3.5: Spray development stages for a high-pressure swirl-type injector that can be identified at different time after start of injection [Lee and Nishida, 2003]](image-url)
Stage I (Liquid column emerging): At the start of injection, a liquid column that includes large droplets and fuel previously trapped inside the tip of the injector, emerges first and forms pre-spray or sac spray. This column has no swirl motion and has a high axial velocity. Studies show, the SMD of this part of spray is significantly larger than the main body of spray.

Stage II (Liquid column expanding): With the progression of time the emerging liquid column expands under the action of aerodynamic forces acting at the gas/liquid interface to form a narrow jet with a characteristically high axial velocity and long penetration length.

Stage III (Liquid sheet emerging and expanding): Following the pre-spray liquid column, a liquid sheet is formed as a result of swirl motion within the emerging fuel. However, at this stage the swirl motion is still relatively weak and, thus, the early liquid sheet is often referred to as the "weak-swirl" phase of the spray.

Stage IV (Development of three types of spray): As the swirling velocity within the injector nozzle continues to increase towards its steady state value, the weak swirl phase gradually transitions to a fully developed hollow-cone spray. In this transition period it is possible to identify the three types of spray (pre-swirl, weak-swirl, and main-swirl) existing simultaneously within the overall spray structure – see figure 3,4. All of these three types of spray, the sack spray, weak swirl and the main swirl, will expand and develop further downstream to form the fully developed stage of the spray.

Stage V (Fully developed hollow-cone spray): Figure 3.6 (overleaf) shows, schematically, the structure of fully developed hollow cone spray generated by a high-pressure swirl-type injector at ambient temperature.
Different parts of spray structure are identified and described by Lee and co-workers as; (a) the spray potential core region – where the ambient condition has no considerable effect, (b) the main body of the hollow cone spray in this area, although the ambient condition may alter the spray shape, the spray shape remains constant with elapsed time, (c) the vortex ring formation region and leading edge of the main spray, and (d) the sack spray (pre-swirl) region – this region caused by the disintegration of the liquid column right after injection start. Within this definition of spray structure, regions (a) and (b) are considered to be geometric regions of the spray since it is the injector parameters that are the major contributors to the spray form rather than the aerodynamic forces acting on the spray. Conversely, in the regions (c) and (d) the dominant determining factors are the aerodynamic forces and thereby they are considered as the aerodynamic regions of the spray.

With regard to the 'hollowness' of the so-called hollow-cone main spray, the reader will note that the fully developed spray illustrated in figure 3.5 is shown to be
filled with a spray cloud or fine droplets. It is important to understand the origins of this phenomenon. Figure 3.7 shows a schematic of the fuel flow from a swirl injector nozzle.

![Diagram of airflow induced by spray motion](image)

Figure 3.7: Schematic diagram of airflow induced by spray motion [VanDerWege and Hochgreb, 2000]

As the fuel exits the nozzle, a conical liquid sheet is formed whose precise shape depends on the ratio of angular to axial velocity induced in the fuel during its passage through the injector. As the hollow cone develops, the conical shape is initially filled by air from below. As the sheet moves away from the injector nozzle it thins due to mass conservation and eventually breaks up due to aerodynamically induced instabilities. Interaction between the expanding high-velocity liquid sheet and the surrounding gas produces a low-pressure zone within the hollow-cone. This low-pressure region induces a strong flow of gas into the spray that moves radially inward at the base of spray and axially downward along the axis of the spray [VanDerWege et al., 2000]. This induced gas flow causes a toroidal vortex to form which grows and moves downstream. This vortex structure effectively separates fuel droplets by size; centrifuging out larger droplets while carrying smaller drops back around and into the spray core [Lee et al. 2003, Zhao et al., 1996, Shelby et al., 1998].
Chapter 3: Characteristics of DISI Engine Fuel Sprays

Stage VI (Post-injection spray development): Not described by Lee et al. [2003], but worthy of further comment is the behavior of the spray at the end of injection. As the injector valve is closed, the fuel flow is stopped. However, the injected fuel is still in motion. At end of injection, therefore, two counter-rotating recirculation zones that result from the vortex motion set up during the spray event are clearly evident. These counter-rotating zones cause a large amount of air to be entrained into the tail of the spray and significantly assist the air-fuel mixing process [Zhao et al., 1996]. Despite the obvious significance for mixture formation, it is interesting to note that there is relatively small body of literature focusing on this part of the spray or post-injection event.

3.4.2 Effect of fuel temperature and volatility

Numerous parameters affect spray structure: supply conditions such as the pressure, temperature, and volatility of the fuel and operating conditions such as ambient gas pressure and temperature all play some part in determining the final spray form. Many researchers have investigated these effects in many different contexts including Ozasa et al., [1998]; VanDerWege et al., [2000] and Schmitz et al., [2002] for example. In the context of the present study, the main topic of interest is the effect of fuel volatility and temperature on the structure of DISI sprays. However, volatility effects are only likely to be significant when viewed in conjunction with relatively substantial changes in fuel temperature. Thus, only the combined effects of fuel composition and temperature will be considered further.

In comparison with other types of DISI injectors, swirl-type injectors are generally believed to be more sensitive to the effects of fuel temperature/volatility. The literature shows that temperature can have a significant impact on many aspects of the spray structure [VanDerWege and Hochgreb, 2000; Zhao et al. 2002]. Typically, increases in fuel temperature or volatility are found to cause decrease the mean droplet size. Figure 3.8a (overleaf) shows the decrease of Sauter Mean Diameter (SMD) in a high-pressure DISI swirl injector spray with increasing fuel temperature for a fixed fuel composition (all other variables held constant). Similarly, Figure 3.8b (overleaf) shows the decrease in SMD associated with decreasing ambient pressure at a fixed fuel
temperature (90 °C) – this decrease in ambient pressure may also be interpreted, at least in part, as an increase in the relative volatility of the fuel.

Figure 3.8: Temperature dependencies of SMD [VanDerWege and Hochgreb, 2000]

The reduction in mean droplet size with increasing temperature and/or fuel volatility significantly affects the subsequent structure of the high-pressure swirl atomizer spray. It is well established that the expansion of the hollow spray cone causes a low pressure region to form within the core of the spray. The smaller droplets formed at higher temperatures are more readily influenced by the pressure difference across the spray sheet, hence, and are rapidly drawn into the spray core. This causes the spray structure to narrow and tends to increase the axial penetration of the spray. Figures 3.9a and 3.9b refer.

Figure 3.9: Temperature dependencies of pressure-swirl atomizers (a) spray width, (b) axial penetration [VanDerWege et al. 2000]
3.4.3 Flash boiling and its effect on pressure-swirl spray structure

Although some influence of temperature or volatility on pressure swirl is reported for fuel temperatures close to the normal boiling point of the fuel, the majority of the literature refers to the obvious effects of superheated fuels. As described in §3.3.1, liquid fuel is recognized as superheated when the fuel temperature inside the injector is higher than the boiling point of the fuel exposed to local ambient pressure. The degree of superheat is defined by the extent that the fuel temperature exceeds the boiling temperature of the fuel at the ambient pressure. When superheated fuel is injected to the surrounding gas, rapid (almost instantaneous) vaporization occurs – this process is commonly known as flash boiling.

In pressure-swirl injectors, the fuel is injected in the form of an expanding liquid sheet. When the fuel is injected as a superheated liquid, the temperature of the liquid sheet surface, which is directly exposed to the surrounding gas, immediately reduces to the boiling temperature associated with the ambient pressure while the fuel within the sheet, remains at a higher temperature than its boiling temperature at ambient pressure [Zuo et al., 2003, Nakama et al., 2003]. Hydrodynamic instabilities, induced and augmented by cavitation and bubble growth inside the sheet, cause the sheet to disintegrate rapidly. The literature suggests that size of the initial drops formed during the sheet breakup depends on the superheat degree of the fuel, with a higher degree of superheat leading to smaller drop sizes [Zuo et al., 2003].

Flash boiling has been noted to alter the structure of pressure-swirl sprays in many ways. Some of the more commonly observed phenomena are as follows: (1) Expansion of the exit cone angle. The initial spray cone angle increases with an increasing degree of fuel superheat – perhaps as the result of a positive pressure build up within the nozzle [VanDerWege et al. 2000]. (2) A significant decrease the SMD of the spray. Studies show, increasing the injected fuel temperature to flash boiling levels can cause the drop size of the spray to decrease by a factor of three [Zuo et al., 2003]. (3) A significant narrowing of the main cone angle and spray width. (4) A change from hollow-cone structure to a filled, columnar structure as the finer droplets of the flashing spray are rapidly transported into the spray core.
3.5 Spray characteristics of multi-hole injectors

As discussed in chapter 2, multi-hole nozzles are much more sensitive to the affect of fuel pressure than are pressure-swirl atomizers. Decreasing the fuel pressure below the nominal operating pressure of the injector will typically result in the generation of extremely large fuel droplets.

The number of holes and the spacing of these holes with respect to one another are important considerations in determining the expected behavior of a multi-hole nozzle. Although the spray emerges as a single plume from each hole, which is a relatively simple concept, multiple plumes from a multi-hole nozzle exhibit very complex behavior. This complexity is due to the interaction of individual plumes. These interactions are strongly influenced by nozzle design such as spray-axis spacing and individual orifice design, along with fuel properties such as temperature, volatility and pressure and ambient condition.

As the spray plumes emerge from the orifice as liquid jets, frictional effects are dominant causing the initial penetration rate to slow and the jets to disintegrate close to the nozzle. Downstream from the orifice, the inertia of the emerging jet and the further affect of frictional and aerodynamic forces on the jet cause it to widen while the penetration rate remains almost constant.

As the plume propagates further, the interaction of air and spray becomes more significant, increasing the entrainment of air into the spray plume. Due to this interaction, a toroidal vortex is formed at the lower end of the plumes. The pressure difference between spray and the surrounding air causes a distinctive airflow pattern – the entrainment airflow hitting the plume perpendicular to its original penetration direction. Figure 3.10 (overleaf) shows this process schematically while figure 3.11 (overleaf) details airflow around a multi-hole spray plume as measured by Nauwerck et al., [2005] using Phase Doppler.
Figure 3.10: Schematic of airflow around a spray plume [Nauwerck et al. 2005]

Figure 3.11: Air velocity vectors around multi-hole spray [Nauwerck et al., 2005]

Although multi-hole DISI injectors are often referred to within the literature as providing a more robust spray structure than pressure-swirl injectors, multi-hole sprays
do collapse under certain conditions. The collapse or partial collapse of multi-hole sprays is actually the process of combining the individual plumes to form a lesser number of plumes. The most influential factor governing the interaction of individual spray plumes is the angular spacing of their axes. If this spacing is larger than a certain threshold value, the plumes are not combine and collapse. However, this interaction is also dependent on individual plume cone angle and operating conditions – it may also be influenced by fuel composition and volatility. The collapse usually results in higher spray velocity, longer axial penetration and a denser, more compact spray structure.

3.5.1 Effects of fuel temperature on multi-hole injector spray characteristics

The temperature dependent behavior of multi-hole injector sprays is significantly less reported than the behavior of sprays from swirl-type DISI injectors. Generally, as the fuel temperature is increased so the fuel vaporization rate increases. In a multi-hole injector, this causes the individual plumes to become wider with less distinctive spray boundaries. If the individual plumes widen sufficiently they may blend with adjacent plumes to form what is effectively a hollow cone spray. From this point onwards the multi-hole spray behaves in a similar manner to the spray from a pressure-swirl atomizer. Toroidal vortexes form at the head of the spray and the cross sectional area of the spray decreases. Further increases in evaporation rate will cause the formation of a fully-collapsed, highly-penetrating spray similar to that obtained from a swirl-type injector. It is likely that the full collapse of the multi-hole spray is similarly related to the flash boiling of the superheated liquid fuel.

3.6 Conclusions

This chapter has presented a brief review of the spray behavior of two common DISI fuel injectors. This review will serve as a basis of comparison for the author's experimental results that will be presented in chapters 5 and 6 of this work. The temperature dependencies of both the pressure-swirl atomizer spray structures and the sprays from multi-hole injectors were described. Both spray types were shown in the literature to collapse under the influence of rapid, disruptive evaporation at high (superheated) fuel temperatures.
Chapter 4

Experiments

The three preceding chapters have examined the majority of the literature relevant to the study with the notable exception of spray visualization and measurement techniques. This chapter will describe the author's experimental apparatus, fuel modeling, visualization techniques and experimental setup and finally the measurement and processing techniques.

4.1 Introduction

The present study was designed to investigate spray characteristics of alcohol blended fuels with different content of alcohol and gasoline. Seven different fuels were used and injected through two types of injector. Furthermore, the effects of fuel temperature on spray characteristics were investigated by providing four different fuel temperatures, from 20 °C up to 80° C, associated with usual operating temperature of light duty vehicle SI engines. Three methods of spray visualization were utilized to provide information for qualitative and quantitative investigation of macroscopic spray characteristics.

The author’s experimental work was divided into four discrete phases, namely; (i) test rig preparation – including the design and fabricate of a high-pressure (< 210 bar) Fuel Pressurizing Unit (FPU), fuel injector mounting and heating system and a high-flow rate vacuum system suitable for use with flammable liquids; (ii) Fuel blends – including preparing model fuel and ethanol blended fuels accompanied by their distillation properties analysis; (iii) experimental setup and procedure – each of the three visualization method employed in the study not only required a specific optical arrangement and apparatus but also required the use of a dedicated test procedure, and (iv) data processing – including image acquisition and recording, image processing and finally measurement and analysis. The next three sections of this work will consider each of these four areas in greater detail.
Chapter 4: Experiments

4.2 Experimental apparatus

The main components of the experimental apparatus consisted of a fuel injector and driver, an injector body heating system to provide different fuel temperatures, a fuel-pressurizing unit to provide the required pressure for injection and finally a vacuum system to safely evacuate combustible mixture from the air. These system components will be briefly described in the three subsections below. Additional system components specific to any one of the three optical techniques in use will be described in the relevant subsections of §5.3.

4.2.1 Fuel injectors and injector adapter

Two types of DISI injectors were chosen that have the same nominal atomization quality while utilizing different breakup mechanisms. The first injector was a high-pressure swirl-type single-hole injector that injected fuel in the form of liquid sheet. The second fuel injector was a high-pressure multi-hole injector that injected fuel in the form of liquid jet. Both injectors were prototype units designed and manufactured by BOSCH GMBH to be used in DISI engines. Figure 4.1 shows HDEV1.2 injector, which is similar to the multi-hole injector, used in this study.

Figure 4.1: BOSCH High pressure injector HDEV12

Both injectors have the same dimensions, specifications, actuator mechanism and control/driver unit. They provide 513 gr/minute flow rate at 100 bar fuel rail pressure and form a spray with the spray axis offset by 20° - See Figure 4.2 (overleaf). Considering the angle of spray offset, the injector was designed in such a way that the fuel injected
vertically during testing. A schematic figure of injector adapter and the injector mounting is shown in Figure 4.3, below.

**Figure 4.2:** The spray axis offset of $20^\circ$ C - multihole and single hole (swirl type) injectors

**Figure 4.3:** Schematic figure of injector adapter
A developmental injector driver unit provided by Bosch was used to drive the injector solenoid. A 12V DC power supply provided the required power for driver unit and a multi-channel signal generator (BNC 5000) was used to trigger the driver and to synchronize the injector operation to other equipments such as cameras and light sources. In all of the experiments reported herein the injector was driven with a 1.5 ms pulse width and a 5 Hz frequency. A multi-channel oscilloscope was located between the pulse generator and the fuel injector equipment to provide accurate monitoring of the whole process. The following diagram Figure 4.4 shows the injector-driver electrical setup.

**Figure 4.4:** Injector driver electrical setup

### 4.2.2 Injector body/fuel heating system

To provide the various fuel temperatures required in this study, a water jacket was designed to provide a water flow around the injector adapter. Heating up or cooling down, the water flowing in water jacket channel would change the injector body temperature and subsequently the fuel temperature. The water jacket was designed in a way to provide the maximum heat transfer between water flow and the injector adapter.

Heated water was provided by a hot water bath that was connected through heat resistant hoses to the water jacket. A digital temperature gauge was used to monitor the injector temperature in addition to the hot bath temperature control. The temperature
Chapter 4: Experiments

gauge used a K type thermocouple, which placed in the hot well located in the injector adapter at a short distance from the injector body. Figure 4.5 shows the assembled injector mounting system.

![Injector system (schematic and actual setting)](image)

**Figure 4.5:** Injector system (schematic and actual setting)

### 4.2.3 Fuel Pressurizing Unit (FPU)

A Fuel Pressurizing Unit (FPU) was designed to provide high-pressure fuel to the injectors. The FPU, shown schematically in Figure 4.6 (overleaf) was adjusted to provide a 100 bar constant pressure supply during all of the experiments performed during this study. Fuel was manually charged into a diaphragm accumulator and a high-pressure nitrogen cylinder used to pressurize slowly the gas side of the accumulator. The liquid fuel passed through a pressure regulator. A fine filter (2-micron) was used to prevent injector clogging by any small particles contained within the fuels. The system was equipped with a safety relief valve to protect the injector from over-pressure while a bleed valve was positioned before the injector inlet to remove air from the system and facilitate system maintenance.
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Figure 4.6: Fuel Pressurizing Unit (FPU)-Schematic

4.3 Test Fuels

The main objective of this study was to investigate potential issues related to the use of ethanol-blended fuels in DISI engines. There are two ways of blending ethanol into gasoline; the first way is to simply add ethanol to a commercial gasoline base in a process known as *splash blending*. The second way is more complicated; the blend is formulated in such a way that the ethanol-blended fuel has the same distillation characteristics as the base commercial gasoline. This process can be done only in the refinery and each blend needs a new formulation. This method of fuel preparation is known as *refinery blending*.

4.3.1 Reference fuel

In this study, a five-component model-fuel is used to simulate the behavior of a commercial gasoline. The model fuel is then used as a base for subsequent investigations of splash blended ethanol fuel.

As described in chapter 1, gasoline is a blend of many hydrocarbon components. Its distillation curve is very broad, ranging from around 30°C up to 205°C. Therefore to
develop a realistic reference fuel, five single-component hydrocarbons (as listed in Table 4.1, below) were chosen to represent the light-end, mid-end and heavy end of gasoline. The distillation properties of the model fuel were calculated using an in-house MATLAB code which calculates the mixture properties of a non-ideal mixture using conventional vapor-liquid equilibrium algorithms.

The composition of the reference fuel was found by trial and error through running the MATLAB code multiple times with the intention of matching the known distillation properties of indolene, a commonly used gasoline substitute. The results are shown in Table 4.1.

**Table 4.1:** The Reference fuel composition (mass percentage)

<table>
<thead>
<tr>
<th>Fuel Species</th>
<th>Percentage mass</th>
<th>Boiling point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>isopentane</td>
<td>24.00%</td>
<td>27.85</td>
</tr>
<tr>
<td>Iso-Octane</td>
<td>42.10%</td>
<td>99.25</td>
</tr>
<tr>
<td>n-octane</td>
<td>18.70%</td>
<td>125.70</td>
</tr>
<tr>
<td>n-Decane</td>
<td>12.50%</td>
<td>174</td>
</tr>
<tr>
<td>dodecane</td>
<td>2.70%</td>
<td>216</td>
</tr>
<tr>
<td>Ethanol</td>
<td>0-100%</td>
<td>78.00</td>
</tr>
</tbody>
</table>

Figure 4.7 shows the distillation curve of the final reference fuel and Indolene, both calculated through the same code.
Chapter 4: Experiments

In figure 4.7, the green line presents the calculated indolene distillation curve and the red line the calculated distillation curve of the reference fuel. It can be seen that the distillation curve of the Reference fuel is well fitted to that of Indolene, therefore, it is expected that the reference fuel blend is of similar volatility to commercial gasoline. The three representative temperatures, $T_{10}$, $T_{50}$ and $T_{90}$ of Reference fuel and Indolene are shown in table 4.3. The other feature of the Reference fuel that was calculated through the same code was the compositional change of the fuel during the distillation process. Figure 4.8 shows the change of species composition by the volume fraction of the blend that is evaporated.

![Reference fuel Compositional Changes during Pseudo D86 Distillation](image)

**Figure 4.8:** The compositional change for the Reference fuel generated through MATLAB code

### 4.3.2 Ethanol blended fuels

Table 4.2 (overleaf) shows the gravimetric composition of the five fuel blends that were examined in this study. The distillation properties of each of these blends were calculated and are presented in Figure 4.9. The alcohol flat region that is described in Chapter 1 is clearly observed and expected to be the main source of difference in spray
structure. However, the non-ideal behavior of gasoline-ethanol blends may also prove to be significant.

**Table 4.2:** The composition of each blends and the component percentage (mass percentage)

<table>
<thead>
<tr>
<th>Fuel Species</th>
<th>Reference</th>
<th>E5-splash</th>
<th>E10-splash</th>
<th>E22-splash</th>
<th>E80-splash</th>
</tr>
</thead>
<tbody>
<tr>
<td>isopentane</td>
<td>24.00%</td>
<td>22.80%</td>
<td>21.62%</td>
<td>18.72%</td>
<td>4.81%</td>
</tr>
<tr>
<td>iso-Octane</td>
<td>42.10%</td>
<td>40.00%</td>
<td>37.92%</td>
<td>32.84%</td>
<td>8.43%</td>
</tr>
<tr>
<td>n-octane</td>
<td>18.70%</td>
<td>17.77%</td>
<td>16.84%</td>
<td>14.59%</td>
<td>3.74%</td>
</tr>
<tr>
<td>n-Decane</td>
<td>12.50%</td>
<td>11.88%</td>
<td>11.26%</td>
<td>9.75%</td>
<td>2.50%</td>
</tr>
<tr>
<td>dodecane</td>
<td>2.70%</td>
<td>2.57%</td>
<td>2.43%</td>
<td>2.11%</td>
<td>0.54%</td>
</tr>
<tr>
<td>Ethanol</td>
<td>0.00%</td>
<td>5.00%</td>
<td>10.00%</td>
<td>22.00%</td>
<td>80.00%</td>
</tr>
</tbody>
</table>

To get a better estimation of the difference in the volatility of these blends, Table 4.3 shows $T_{10}$, $T_{50}$ and $T_{90}$ for each of the model fuel blends under investigation. These temperatures were extracted from the distillation curves generated through the MATLAB code.

**Table 4.3:** Distillation temperatures for model fuels (extracted from the distillation curves)

<table>
<thead>
<tr>
<th>Distillation temperatures in °C</th>
<th>$T_{10}$</th>
<th>$T_{50}$</th>
<th>$T_{90}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indolene</td>
<td>63</td>
<td>108</td>
<td>160</td>
</tr>
<tr>
<td>Reference</td>
<td>66</td>
<td>112</td>
<td>161</td>
</tr>
<tr>
<td>E5-splash</td>
<td>55</td>
<td>110</td>
<td>159</td>
</tr>
<tr>
<td>E10-splash</td>
<td>55</td>
<td>109</td>
<td>157</td>
</tr>
<tr>
<td>E22-splash</td>
<td>56</td>
<td>73</td>
<td>153</td>
</tr>
<tr>
<td>E80-splash</td>
<td>70</td>
<td>77</td>
<td>78</td>
</tr>
</tbody>
</table>

It is clear that the addition of up to 22% by mass ethanol initially increases the front end volatility of the ethanol-reference fuel blends while a further increase in ethanol content over and above 22% decreases the front end volatility of the blend beyond even that of the base fuel. For the mid point volatility, adding ethanol does not change the volatility significantly until the ethanol content reaches 22% by mass, from this point onwards the mid-point volatility is dramatically increased. Note however that the E80 blend shows a decrease in mid-range volatility (or $T_{50}$) compared with the E22 case. Finally, as for tail-end volatility or $T_{90}$ adding ethanol causes a slight increase in volatility. This increase is significant only in case of E80.
Figure 4.9: The Distillation curves and Compositional change associated to each modeled fuel
Fuels: Reference, E5-splash, E10-splash, E22-splash, E80-splash
(Generated through the MATLAB code ASTM D86 Pseudo distillation curves)
4.4 Diagnostic techniques and setups

A wide variety of analysis and diagnostic techniques have been developed to investigate fuel spray characteristics. These diagnostic techniques can be broadly classified as: (i) direct diagnostic methods — where particle (droplet) characteristics (size, density, distribution, etc) are measured by direct observation of individual particles, and (ii) indirect diagnostic methods — where the concern is the inference of spray microstructure by observation of macroscopic behavior. Most of the indirect methods are based on visualization of the spray [Bailey, 1974]. Researchers select from a range of proven optical techniques (such as Mie scattering, Schlieren, Shadowgraph, and Laser Doppler methods) based on both the specific application and the nature of the information that they would like to extract from the captured images.

Mixture formation in DISI engines is a two-phase mixing process that includes both spray breakup and fuel evaporation. Mixture formation necessarily occurs within a very short time period. Non-intrusive diagnostic techniques that have high spatial and temporal resolution are necessary to investigate both phases of the mixture formation process. Spray visualization is often the initial step in spray characterization. A wide range of visualization techniques are available to the sprays researcher, each providing its own specific set of information. Three methods of spray visualization were chosen for this study; Schlieren imaging, Mie scattering imaging, and Shadowgraphy. Each of these visualization methods requires its own special arrangements and apparatus. The following three subsections of this work will describe in detail the operating principles of each of these imaging methods and the particular imaging set-up for each that was used in this work.

4.4.1 Schlieren Method

The Schlieren method is a visualization technique that allows the user to observe the variation of density in a gas. Accordingly, it is one of the widely used and effective techniques for visualization of the fuel vaporization and air-fuel mixture formation [Ozasa et al., 1998].

The Schlieren technique is based on light deflection due to variations in the refractive index of the transparent medium in which the light travels. In a transparent
medium, light propagates uniformly only if it does not encounter any inhomogeneity. Inhomogeneities are mainly caused by density variations within the medium that lead to localized changes of refractive index – the refractive index is the factor by which the phase velocity of electromagnetic radiation, such as light, is slowed when traveling through that medium, relative to its velocity in a vacuum. Therefore, when light interacts with different refractive indexes with a medium its speed varies and subsequently the light bends or deflects. In gases, the refractive index, $n$, has a simple linear relation with gas density and depends on gas composition, temperature, density and the pressure of the gas as shown in equation 4.1. Note that a similar relation exists for liquids and solids albeit in a much more complex form.

$$n-l=k\rho$$  
*Equation (4.1)*

where $n$, is refractive index, $k$ is the Gladstone-Dale coefficient and $\rho$ is the gas density.

It is known that optical inhomogeneities refract or bend light rays relative to their gradient of refractivity index in an $x, y$ plane. If the $z$-axis of a right-handed Cartesian $x,y,z$ coordinate system is taken as the “normal” direction of light ray then an $(x, y)$ pair describes the planes perpendicular to the normal $z$-direction. Hence, the light bending trajectory is shown in equations 4.2 and 4.3 [Lefebvre, 1989].

$$\frac{\partial^2 x}{\partial z^2} = \frac{1}{n} \frac{\partial n}{\partial x}$$  
*(Equation : 4.2)*

$$\frac{\partial^2 y}{\partial z^2} = \frac{1}{n} \frac{\partial n}{\partial y}$$  
*(Equation : 4.3)*

By integrating once, the components of the angular ray deflection in the $x$ and $y$ directions are shown by equations 4.4 and 4.5.

$$\varepsilon_x = \frac{1}{n} \int \frac{\partial n}{\partial x} \, dz$$  
*(Equation 4.4)*

$$\varepsilon_y = \frac{1}{n} \int \frac{\partial n}{\partial y} \, dz$$  
*(Equation 4.5)*

In two-dimensional Schlieren space with extent $L$ and surrounding medium refractive index $n_0$ the above equations will be:
Chapter 4: Experiments

\[ \varepsilon_x = \frac{L}{n_0} \frac{\partial n}{\partial x} \]  
(Equation 4.6)  
\[ \varepsilon_y = \frac{L}{n_0} \frac{\partial n}{\partial y} \]  
(Equation 4.7)

Equations 4.6 and 4.7 are the mathematical basis of the Schlieren technique. As shown, it is the gradients of refractive index, \( \partial n/\partial x \) & \( \partial n/\partial y \), that cause light bending rather than the overall refraction index.

Numerous arrangements have been proposed for viewing Schlieren objects. A simple Schlieren setup includes two lenses, a point light source, a knife-edge and a viewing screen such as camera as shown in Figure 4.10.

![Figure 4.10: Diagram of a simple Schlieren system with a point light source](Settles, 2001)

In this setup, the first lens collimates the light rays from the point source, and later on, the second lens focuses this collimated beam to a point. A knife edge is placed at the focal point of the second lens. The light rays proceed to shape an inverted image on the viewing-screen. A Schlieren object (S) bends the light rays from their original path and the deflected rays miss the focus of the optical system. The upward-deflected ray is allowed brighten a point on screen but the downward deflected ray is intercepted by the knife-edge. In this example then, phase differences causing vertical gradients in refractive index are converted to amplitude differences and thereby, become visible. However, in general, many light rays are refracted in many directions. The knife-edge in this simple setup eliminates only downwardly deflected rays. Using a circular hole on an opaque mask as a knife-edge would therefore be preferable.

In this study, a Z-type Schlieren technique based on Toepler principals is adopted, albeit with some modification. The most popular Z-type Schlieren arrangement described
in the literature is a Herschellian system that uses two oppositely tilted on-axis parabolic mirrors. A schematic diagram of this setup is presented in Figure 4.11.

![Schematic diagram of a Herschellian system using two oppositely tilted on-axis parabolic mirrors.](image)

**Figure 4.11: Z-type Schlieren arrangement [Settles, 2001]**

The main concerns with a Z-type Schlieren setup are off-axis aberrations that include coma and astigmatism. Coma occurs when the direction of light reflected from a mirror depends on the position of the point of reflection and as the result; the point focus is smeared into a region of flare with a bright core. This can be minimizing by keeping the tilt angle between the mirror and the test section small, by using long-focal-length mirrors and also tilting the two mirrors in equal angles and in opposite directions. Astigmatism is the failure to focus a point to a point caused by differences in path length along the optical centerline and the mirrors sides. Astigmatism is unavoidable in these mirror based systems, and can only be limited through the proper positioning and orientation of the knife-edge.

In the Schlieren arrangement used in the present study, due to the constraints of the optical table available, the light source and the camera were both placed to the same side of the optical test section. Figure 4.12 (overleaf) shows a schematic of the experimental Schlieren system. Light scattered from a high-intensity arc lamp was focused through a biconvex positive-converging lens with a focal length of 15 cm. A pinhole was placed at the focal point of the lens so as to form an approximate point source. Two high accuracy concave mirrors, with a focal length of 3048 mm were used to form a collimated beam through the test section and to direct the beam to the camera. Due
to the arrangement chosen for the Schlieren setup, a pinhole knife-edge rather than a normal knife-edge was used at the focal point of the second concave mirror. Schlieren images were recorded on a high-speed CMOS video camera with a 50 mm Nikon lens (1:1.2). The camera was operated with a frame rate of 20,000 fps and a spatial resolution of 160 x 272 pixels. A multi-channel oscilloscope were placed between pulse generator and both the injector driver and camera to monitor the synchronization of the injector and camera events.

Figure 4.12: Schlieren setup – Schematic
4.4.2 Mie Scattering method

Many visualization techniques are based on scattering principals. Scattering occurs when some types of radiation are redirected from their initial trajectory because of an interaction with uniformities such as particles or large molecules, in the medium in which they pass through. The amount of scattering depends on many factors including wavelength of the radiation, the abundance of uniformities and the distance that the radiation travels through medium [Hennessey, 2001]. Light scattering is particularly important, because, along with absorption properties of a given material, it determines the visible appearance of most objects.

Scattering can be in two forms, elastic and inelastic. In elastic scattering, the scattered light is at the same wavelength as the incident light. The two major forms of elastic scattering are Rayleigh scattering and Mie Scattering. Mie scattering occurs when electromagnetic (EM) radiation encounters particles that are of the same order of size as the radiation wavelength. The scattering of light by large particles regardless of wavelength may also be termed Mie scattering. Rayleigh scattering occurs when the scattering particle size is very much smaller than the incident wavelength. Where both Mie and Rayleigh processes occur simultaneously the resultant signal is dominated by the Mie scattering.

Mie scattering visualization can provide useful information concerning the mixing and interaction between air and fuel and of the macroscopic characteristics of a fuel spray. The scattered light intensity can show the presence of liquid droplets. In combination with appropriate high-speed photography techniques, significant information concerning the spatial and temporal variation of the liquid-phase of a spray can be obtained.

Often the use of Mie scattering techniques in the study of liquid sprays is associated with the use of a high-power laser light source. However, there are many cases in which the coherence of EM radiation from a laser is not necessary. Broadband light sources can yield much more information than their monochromatic counterparts. Mie-scattering imaging techniques can fail to detect some small particles, particularly those whose diameter is close to the wavelength of the light used to observe them. This potential source of error is reduced when a broadband light source is used.
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Figure 4.13 shows the Mie-scattering setup used in the present study. A 500W halogen lamp in a reflective case was used to illuminate the spray. So as to capture images with same size and location to those captured during the author’s Schlieren experiments, light scattered from the spray at a 90 degree angle was relayed to the camera using one of the concave mirrors previously used during the Schlieren work. A black sheet was placed behind the spray to avoid any background reflection in the mirror. The mirror and camera positions and the camera settings – frame rate and pixel resolution – were kept identical for the Mie-Scattering imaging compared with the previously described Schlieren experiments.

![Figure 4.13: Mie Scattering setup - Schematic](image)

4.4.3 Shadowgraphy

The third visualization technique employed in the present study was that of Shadowgraphy. Direct Shadowgraphy is one of the simplest methods of spray visualization. In fact, in its most basic form the necessary apparatus for this technique is simply a light source and viewing screen as shown in figure 4.14 (overleaf).
When there is no Schlieren object between the light source and viewing screen, the screen is uniformly lit. Where a Schlieren object does exist however, some of the light rays are refracted, bent and deflected from their original path causing a local change in the light intensity at the screen – see figure 4-15 for example (note that a collimated beam is used in this case).

With respect to figure 4.15, let us assume that the Schlieren is a spherical droplet of fuel. Light will travel slower through the liquid drop than surrounding air, so a linear wave-front passing through the droplet will become distorted – sections of the wave-front are turned towards the centerline of the drop. Subsequently, rays of light propagating normal to the wave-front are bent toward the droplet centerline as well. Therefore, the droplet acts as a positive lens, converging the light rays. Long before its focal length, the light rays encounter the screen and cast a dark circular shadow, showing the droplet boundary. Light refraction is strongest at the boundary of the drop and there is no refraction outside the droplet or at the exact center of it. Under the ideal condition...
(perfectly parallel light rays), the outer diameter of the shadow corresponds to the droplet diameter.

Although Schlieren and Shadowgraphy are based on the same principal, there are some major distinctions. The droplet mentioned in shadowgram example above is visible only, due to the gradients of refractive index that its presence causes. These gradients are equal to zero in surrounding air as well as in the center of droplet itself. Earlier, equations 4.6 and 4.7 showed that deflection angle ($\epsilon$) is proportional to refractive index gradients. In a shadowgram, it is the gradient of deflection angles ($\partial \epsilon / \partial x$ & $\partial \epsilon / \partial y$) that is observed, or in other words the second derivative or Laplacian of the refractive index: $\partial^2 n / \partial x^2$ & $\partial^2 n / \partial y^2$. In the Schlieren method, the illuminance of the image is relative to the first spatial derivative of the refractive index.

In the present study, single shot shadowgraph imaging was used to observe the spray cone structure with a significantly higher temporal and spatial resolution than was available with either of the high-speed video imaging setups described previously. The author’s shadowgram imaging apparatus consisted of a high-intensity, short-duration flash lamp (PalFlash 500) and a high-resolution 12-bit CCD camera (PCO Pixelfly VGA). Figure 4.16 shows the experimental setup.

![Figure 4.16: Shadowgraph setup](image)
A multi channel signal generator was used to send three separate trigger pulses to the injector, the CCD Camera, and finally the PalFlash. Each of these devices was found to have a specific internal delay associated with them. Besides the internal delay, most of the instruments used in this phase of the work also required time to get ready for the next operation. In the case of PalFlash this was the recharging time for the capacitors, in the case of the camera system, the read-out time for the CCD chip. Based on these characteristics and the internal delays associated with the triggering of these devices the following trigger pulse-sequence diagram was designed – see figure 4.17.

**Figure 4.17**: Pulse sequence for Shadowgraph photography

Understanding the inherent delays of the instrumentation is important in terms of characterizing the injector. By changing delay time and observing the consequent image, the start of fuel could be identified (as opposed to the start of injection, which normally refers to the sending of the initial command pulse). The comparison of spray images could then be made with respect to the start of fuelling, (X ms.ASOF).
4.5 Experimental matrices and procedures

Three spray visualization methods were used to investigate the spray characteristics of two types of injector with seven different fuels at four temperatures – a total of 168 individual tests. A test matrix was designed for each set of experiments and a specific procedure for each experiment designed and followed. The following subsections of the thesis describe each of these matrices and procedures in turn.

4.5.1 Schlieren experiments

The Schlieren test matrix is shown in Table 4.4.

Table 4.4: Schlieren photography matrix

<table>
<thead>
<tr>
<th>Test</th>
<th>Fuel</th>
<th>Injector type</th>
<th>Injector Temp (°C)</th>
<th>Number of tests</th>
<th>Number of recorded sets</th>
<th>Total sets of images</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schlieren Gasoline Single hole</td>
<td>20</td>
<td>48</td>
<td>20</td>
<td>960</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schlieren E5 splash Multihole</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schlieren E10 splash</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schlieren E22 Splash</td>
<td>80</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schlieren E80 splash</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schlieren E100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Firstly, the Schlieren imaging system was aligned and focused. Subsequently, the fuel system was charged manually with the fuel blend of interest. The fuel blend was prepared not earlier than 48 hours before the test to avoid any compositional change due to the evaporation of volatile components within fuel. After charging the accumulator and pressurizing the fuel system, tests were performed for the four different temperatures of interest in order of increasing fuel temperature. The injector was replaced after cooling down the system to 20°C from the last test temperature 80°C, the same set of test conditions repeated for the second injector.

Twenty sets of images were recorded for each test condition and each injector to minimize the potential errors caused by injection variability; each set contains 400 frames with 50 microsecond intervals.
4.5.2 Mie Scattering experiments

The Mie scattering test matrix is shown in Table 4.5. The Mie scattering test procedure was essentially identical to the procedure followed for Schlieren observation. However, in the case of the Mie scattering studies additional time had to be provided to let the test rig cool down between the recording sessions. Since the distance between the halogen lamp and the test rig was relatively small, the halogen lamp was noted to heat the injector over time, potentially leading to an unwanted increase in fuel temperature. As the result of this extended delay, this set of experiments took longer time than the Schlieren tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>Fuel type</th>
<th>Injector type</th>
<th>Injector Temp (°C)</th>
<th>Number of tests</th>
<th>Number of recorded sets</th>
<th>Total sets of images</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mie Scattering</td>
<td>Gasoline</td>
<td>Single hole</td>
<td>20</td>
<td>48</td>
<td>20</td>
<td>960</td>
</tr>
<tr>
<td>Reference</td>
<td>Fuel</td>
<td>Multihole</td>
<td></td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E5 splash</td>
<td></td>
<td></td>
<td></td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E10 splash</td>
<td></td>
<td></td>
<td></td>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E22 Splash</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E80 splash</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E100</td>
<td></td>
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</tbody>
</table>

4.5.3 Shadowgraph experiments

The shadowgraph experiments were primarily focused on the measurement of initial cone angle and the observation of detail that was unavailable from the previously recorded Schlieren and Mie Scattering images. Single images were captured at four 0.5 ms intervals after the start of fuel for all fuels and three selected fuel temperatures. Thus, images were taken at; \( t = 0.5 \) ms ASOF, a time corresponding to the end of transient phase of the spray, \( t = 1.0 \) ASOF, this time corresponds to the time that spray is fully developed, \( t = 1.5 \) ASOF, the end of injection, and \( t = 2.0 \) ms ASOF, after end of injection. In addition to these times, spray image were captured at \( t = 0.2 \) ms ASOF and \( t = 1.7 \) ms ASOF so as to gain greater understanding of the full spray event. Table 4.6 shows the shadowgraph test matrix.
Table 4.6: Shadowgraph photography matrix

<table>
<thead>
<tr>
<th>Test</th>
<th>Fuel</th>
<th>Injector type</th>
<th>Injector Temp (°C)</th>
<th>Number of tests</th>
<th>Number of recorded Images per test</th>
<th>Total sets of images</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shadowgraph</td>
<td>Reference</td>
<td>Single hole</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>1200</td>
</tr>
<tr>
<td>E5 splash</td>
<td></td>
<td>Multihole</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E10 splash</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E22 Splash</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E80 splash</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.6 Image processing

In order to effectively use the experimental images to make comparative measurements without undue subjectivity automated processing methods, tailored to each individual imaging technique, were applied to the experimental results. These processing methods, and the differences between them, are described in the following three subsections.

4.6.1 Image processing for Schlieren images

The Phantom camera software, used as the image grabber in these experiments, recorded each image set in a proprietary file format (.cin). The .cin files include the recorded frames in a sequential order— in these experiments from 0 to 500. Each frame of the .cin file was a 12-bit image of 160 pixel Width and 272 pixel Height. The image processing steps applied to each frame, which were implemented in MATLAB, are described below in the order of action.

I. **Image Conversion**: since MATLAB is unable to work with raw .cin files, all files were converted to AVI format through the phantom software. Note that this conversion results in some potential loss of information as the converted files are now 8-bit.

II. **Image Inversion**: In the Schlieren images, the spray is recorded as a dark spot in a white background. To facilitate the subsequent steps within the processing routine,
these images were inverted so the spray was shown by white spots in a dark background.

III. **Background Subtraction:** the first frame before start of injection in each image set was defined as the background image for the set. This image was subtracted from each frame within the set containing a spray image. This background correction step remove any extraneous objects and uneven light spots from the images.

IV. **Intensity Correction:** In this step initially, all pixels below a certain threshold value (determined automatically by a built-in MATLAB routine) were set to zero to eliminate background noise, subsequently the resulting pixel intensity values were integrated over the entire image. It maps the intensity value in the input grayscale image to new values in output images such that 1% of data is saturated at low and high and high intensities of input image. This increases the contrast of output image. Some other MATLAB functions were used to identify the higher and lower value (1% of higher or lower) to be used in intensity adjustment.

V. **Image Averaging:** As the final step in the initial processing of the Schlieren image sets, a mean spray image set was created by combining all 20 individual image sets. The averaging procedure produced frames in which any uniform variability of injection event was eliminated – thus, showing the injection event with minimal error due to injection variation, background noise, etc. Rather than using basic arithmetic averaging, a built-in MATLAB function that performs the addition and division in double precision and then truncates the final result was used.

### 4.6.2 Image processing for Mie scattering images

The procedure used for processing the author’s Mie Scattering images was essentially the same as that applied to the Schlieren images. However, in the Mie scattering images the spray is illuminated and is viewed as a light object in a dark background; thus, the image inversion step (step II in the Schlieren processing) was not required.
4.6.3 Image processing for shadowgraph images

The analysis of the author's shadowgraph images was not automated since the measurements taken from these images were insensitive to small variations in image intensity. In fact, no image processing was performed on these images other than small contrast/brightness modifications (performed on a case by case basis) to aid clarity.

4.7 Measurement procedures and algorithms

The last and the most important step in the analysis of the author's images was that of measurement. The axial penetration of each spray was measured from both the Schlieren images – that show both vapor and liquid phases of the spray, and the Mie Scattering images – that indicate mainly the liquid part of the spray. Measurements were taken from both individual images sets and the mean image set constructed from the full 20 images sets collected for each experimental condition. For some cases, the initial cone angle and spray width or main spray body angle were also measured in addition to penetration length. These particular measurements were taken from the author's shadowgraph images that afforded a close-up view of the injector tip region.

4.7.1 Definition and measurement of penetration length

Using the mean movie files created in image processing, another code in MATLAB was developed to measure the penetration length of spray. The spray penetration measurement was done through many steps:

- **Binarize and Thresholding**: The images then binarized based on the threshold function of MATLAB "greytresh" (based on Ostu's method on grayscale thresholding) [Ostu, 1979]. In the output binary image, the spray region is displayed as white pixels with a grayscale value of 1, and the remaining areas as black pixels with grayscale value of 0.

- **Finding spray tip**: to found the spray tip, the program searches for the white pixels (an option was included in the code to choose the number of pixels in a row to be considered as the tip) row by row, starting from bottom of the image, for each frame of the movie.
• **Recording the data:** when the spray tip was indicated, the vertical distance between the first pixel(s) as the tip of spray and the origin (upper end of image) is measured in the scale of pixels – see Figure 4.18. The distance between the related row and the upper end of the image (set to 0) and the frame number associated with, were recorded in an Excel file. This procedure was done for each frame and the final Excel file include spray tip lengths with their associated frame numbers.

![Image of penetration length measurement](Image)

**Figure 4.18:** Penetration length measurement
Scaling and Correction

- **Origin Correction:** The distances between the tip of injector and the upper end of the image, used as the origin in image processing code, were measured and subtracted from all data in the spreadsheet. This correction provided the actual penetration length of spray from the tip of injector.

- **Scaling:** before each test a calibration image was taken, which was simply done by locating a ruler on the injector axis location - see Figure 4.19. The scaling was done through Phantom software by measuring the number of pixels in 10mm on the ruler. This established the conversion factor used in the Excel file to change the penetration length from pixels to millimeters.

![Figure 4.19: Scaling (Schlieren photography)]
• **Time Correction:** There were six frames before the appearance of fuel (counted as the start of injection) which is equal to 300 micro seconds. This delay is due to injector-driver delay. However, the actual injector-driver delay can be obtained by adding the phantom camera delay to this amount.

• **Average deviation of penetration length:** In order to figure out the amount of error associated with the penetration length that measured through mean movies, the penetration length was measured for each set of images individually. The results were imported to the Excel spreadsheet and the standard deviation (Excel function STDEV was used) of the penetration length measured at each frame was calculated. The analysis of these results will be presented in the error analysis sections of Chapter 5 and 6.

The results were randomly checked by visual measurement tools available in Phantom software and showed a perfect consistency and accuracy of the information obtained. The exact same procedure was used in Mie-Scattering measurement. To measure the spray width in Shadowgraph the same procedure for scaling were followed.

### 4.7.2 Definition and measurement of spray cone angle

Cone angle measurement was made from shadowgraph images in order to provide complementary data to support the results of the author’s Mie and Schlieren data analysis. The cone angle measurements were done on the images of the spray recorded at 1.0 ms ASOF. This particular timing was selected since at this point the spray is fully developed and the cone angle is stable.

In this study, the initial cone angle, $\theta$, (sometimes called the exit cone angle) of the spray is defined as the angle included at the intersection of two lines drawn adjacent to the peripheries of the spray cone from a point 5 mm below the injector tip up towards the injector (see Figure 4.20 - overleaf). These two lines meet at a certain point, which may be inside the injector. Note that this intersection point serves as the cone angle vertex for both the initial cone angle and the main spray cone angle described in the following subsection. The process of vertex setting, as well as the scaling these images and the measurement of the included angle, was performed using routines built into the LaVision software post-processing tools. Three to five (depending on the variability in
spray shape) angular measurements were performed in each image to minimize the errors associated with the estimation of the spray boundary and cone vertex. The initial cone angle reported herein was calculated by averaging all measurements.

**Figure 4.20:** Spray initial $\theta_i$ and main $\theta_{\text{main}}$ cone angle

**Main spray cone angle**

The main spray cone angle is defined in the current work as the angle formed between two lines connecting the initial cone angle vertex to the edges of the spray at a distance of 10 mm from the tip of injector shown in Figure 4.20.

### 4.7.3 Spray probability imaging

Producing a repeatable spray structure in extreme conditions, such as those found within the cylinder of an internal combustion engine is a major concern for an injector designer. Spray variations may affect mixture formation in the engine and thereby cause
Chapter 4: Experiments

combustion instability. Hung et al. [2003] describe an imaging diagnostic technique that allows the pulse-to-pulse variability of a macroscopic spray structure to be quantified. Individual Mie scattering spray images are combined such that the intensity of each pixel within the image reflects the probability of finding liquid fuel in that particular location. In order to investigate the shot-to-shot variability within the author’s spray images a MATLAB code was used to show the probability of fuel in the manner described by Hung et al. [2003]. The resulting images were then ‘false-colored’ (See figure 4.21) to clearly show the probability of spray presence in each region. In these images, the dark red region (corresponding to a pixel intensity of 256) indicates the region of the spray in which there was a 100 % probability of finding liquid fuel. The dark blue regions (corresponding to a pixel intensity of 0) show the regions of a zero probability of finding fuel. The spectrum between these two limits shows different regions corresponding to the probability of finding fuel at that location.

Figure 4.21: An example of probability Image (Multihole injector- Mie Scattering image)
4.8 Conclusions

Various spray visualization and measurement techniques were discussed in this chapter. These techniques were used to analyze the spray, both quantitatively and qualitatively, in various conditions for two different DISI fuel injectors. The results and discussions that arise from the application of these techniques to the author's images of alcohol-blended sprays from swirl-type and multi-hole type fuel injectors are presented in Chapter 5 and Chapter 6 respectively. The results and discussions are followed by a concluding chapter; thus, completing this thesis.
Chapter 5

Result and Discussion - Swirl-type Injector

The experiments were discussed in the last chapter. In this chapter the results and discussions of the experiments related to swirl-type injector will be presented. After investigating the development of swirl-type injector spray, the effect of temperature and the ethanol content of the different fuel blends on the spray characteristics of swirl-type injector will be discussed.

5.1 Introduction

The macroscopic spray characteristics of a high-pressure single-hole swirl-type injector were investigated. The investigations were performed in order to characterize the spray formation process. The effects of fuel temperature and fuel blend ethanol content on the spray characteristics were examined.

Before getting to the results it would be useful to consider the error associated with the penetration length measurements. The sources of error in this study can be partly attributed to shortcomings in the experimental apparatus and partly to a degree of unavoidable non-repeatability that is associated with the operation of a pulsed device such as a fuel injector in a single-shot mode. However, as will be examined shortly, the spray structure is itself subject to some instability. The fuel composition was also considered as a potential source of error. It was expected that, through the course of experiment, the most volatile component of fuel would evaporate and leave the mixture. However, the consistency of data associated to Reference fuel, which contains the highest volume fraction of Iso-pentane (the most volatile component used in the blends), suggests that this potential source of error was not significant.

The standard deviation of the penetration distance from the mean penetration length was calculated for each fuel composition at the four temperatures of interest. The standard deviation of the penetration measurements provide not only the required amount
of error that should be considered when the penetration lengths are compared, but also can show the relative level of stability associated with each spray.

Based on the measured standard deviation, standard error was also calculated. However, since the amount of error was in the same order of magnitude with the marker points on the graphs, the error bars were not located in the graphs.

Figures 5.1(a) and 5.1(b) show the graphs related to the standard deviation of the spray penetration measured from the Mie Scattering images of all fuel blends with different temperatures during the time interval 0.0 to 5.0 ms ASOF.

The results indicate that, regardless of the fuel composition and temperature, the repeatability of the spray is relatively poor during the early injection period (up to 0.5 ms ASOF). This is perfectly related to transient spray phase and the instability of spray could be reasonably predicted. From 0.5 ms ASOF, the repeatability of the spray penetration is affected by changing the fuel composition and temperature. When fuel temperature is 20°C, the spray is in the most stable condition. However, even in this condition, E5 shows a higher level of variation in comparison with the other blends. However, E5 shows the highest instability at all fuel temperatures except when flash boiling happens at 80°C.

As the temperature is increased, the effect of fuel composition on spray variability increases as well as the overall spray variability associated to all blends. By further increase of fuel temperature, as the disruptive evaporation happens, although the overall variability of all fuels was increased slightly, the effect of fuel composition on spray variability decreased. A possible explanation for this phenomenon is; the disruptive evaporation regime causes the highest instability in spray in compare with slow evaporation and violent evaporation regimes.

These graphs can give a sense of the tolerance that should be considered in penetration length investigation. Referring to the graphs, the tolerance depends on the time ASOF, fuel temperature and the ethanol content. However, the minimum error associated to fully developed spray during 0.5 to 1.5 ms ASOF is about 1.5 mm while at 5.0 ms ASOF it changes from 2mm in the case of 20°C up to 3.5 mm at 60°C and even 80°C.
Figure 5.1(a): Standard deviation of spray penetration length measurements
Fuels: Reference, E5, E10, E22, E80 Fuel temperature: 20, 40°C Time: 0.05, 0.1 ms ASOF
Chapter 5: Result and Discussion - Swirl-type Injector

**Figure 5.1(b):** Standard deviation of spray penetration length measurements
Fuels: Reference, E5, E10, E22, E80 Fuel temperature: 60, 80°C time: 0.05, 0.1 ms ASOF
5.2 Baseline fuel spray

Schlieren and Mie scattering images of the reference fuel spray at 20°C fuel temperature were used to identify different stages in the spray development. These images were also used throughout this chapter as a baseline condition for comparison with sprays recorded at other fuel compositions and temperatures. Based on the experimental observations of the baseline case, the evolution of the pressure-swirl spray was categorized into three main stages; (A) the early spray formation: measured from the start of visible fuel injection (SOF) and up to 0.5 ms after SOF, (B) spray development during the injection period from 0.5 ms after SOF to the end of fuel injection (1.5 ms after the start of the commanded injection (ASOI) which is approximately equal to 1.5 ms (ASOF) - delay between the start of injection SOI and start of visible fuel injection SOF is approximately 300μs that is negligible): in this stage the fully developed spray move further downstream as fuel is added from the nozzle, and, (C) development of the spray after the end of injection (1.5 ms ASOI onwards), in this phase the spray cloud was seen to consist of both vapor and liquid. This spray cloud was followed for up to up to 20.0 ms ASOF. However, it was observed that the penetration length associated with even 5.0 ms ASOF was longer than the stroke length of most conventional gasoline engines. Accordingly, the discussion of this third stage of the spray development is restricted to the period of 1.5 – 5 ms ASOF.

It was found that dividing the spray evolution into these three stages not only helped out to understand the mechanisms involved in spray evolution in further detail, but also made it easier to investigate the effect of fuel temperature and ethanol content on the spray characteristics more accurately as will be described further in this chapter.

5.2.1 Early spray development – baseline condition.

Figure 5.2 (overleaf) shows the experimental results for the early development of the spray. Correlating these experimental results with the observation made by Lee and Nishida for a similar pressure-swirl injector [2003], the early spray development can be divided into five discrete stages. As soon as the injector valve opens, a liquid column of fuel is seen to emerge out of the injector orifice. This liquid column (variously referred to as the pre-swirl spray or sac spray within the literature) is created from the fuel that
resides inside the orifice of the injector during off period. During Stage I, there is no swirl motion and large droplets are formed and moved along the injector axis with relatively high velocity.

![Stage I: Liquid column emerging](image1)

![Stage II: Liquid column expanding](image2)

![Stage III: Liquid sheet expanding](image3)

![Stage IV: Development of three type of sprays](image4)

**Figure 5.2:** Early spray development of Swirl injector, Reference fuel at $P=100$ bar, $T=20°C$, time 0.0 to 0.5 ms ASOF

The first rows present the Schlieren images; the second rows present Mie scattering images.

During Stage II, the liquid column begins to disintegrate and, due its interaction with the air mass downstream from the injector, begins to expand. As time elapses, the flow of fuel through the swirl chamber of the injector increases due to increasing needle lift until, at Stage III, the fuel gains enough swirl motion to form a conical sheet as it emerges out of the injector. Soon after, (at Stage IV) the conical sheet expands due to both centrifugal force imparted to the fuel by the injector’s internal geometry and also the aerodynamic forces acting on the fuel. At this moment in time, three developmental stages of the spray (the pre-swirl, weak swirl and main spray stages) are closely aligned within the spray structure. These three discrete stages expand and move further...
downstream from the injector leading to the final structure of the fully developed spray described in §5.2.2.

One notable feature of the baseline results for the early spray formation is that there are distinctive differences in the spray size and shape observed between Schlieren and Mie Scattering images. These differences are readily explained by considering the fact that the Schlieren images show the vapor phase of the spray as well as the liquid phase (Mie scattering images mainly show the liquid phase of the fuel). The images shown in Figure 5.2 suggest that fuel vaporization starts immediately as the liquid fuel leaves the injector nozzle. Correlating these images with penetration length measurements suggest that the liquid spray is constantly surrounded by vapor. This phenomenon has been previously reported by many researchers [Tong et al., 2001; Kawano et al., 2002; Schmitz et al., 2002; Higgins et al, 1999]. In the author's work, it is not possible to quantitatively describe the density of liquid and vapor phase in different regions of the spray. However, a comparison of the spray's penetration length measured from the Schlieren and Mie Scattering images does provide some quantitative understanding of early spray formation. It also leads to a greater understanding of the influence of measurement technique on the experimental results.

Figure 5.3 (overleaf) shows the penetration length versus time ASOF obtained from both Schlieren images and Mie Scattering images. The first observation that can be made is that there is a longer penetration length associated to Schlieren images. It is tempting to assume that this difference could be correlated directly to vapor phase fuel present in the leading edge of the spray. However, the author does not believe this to be the case in all instances. In fact, the large difference between the penetration lengths of the early spray measured by the Schlieren method compared with the Mie scattering technique (around 10 mm at 0.5 ms ASOF) is believed to be a measurement artifact caused by the presence of the pre-swirl spray and the differing sensitivities of the measurement methods. A similar measurement artifact was also observed by VanDerWege and Hochgreb [2000]. As the spray develops, the analysis algorithm picks the pre-swirl spray mass as the tip of spray and measures the axial penetration length on that basis. In the Mie Scattering images, this pre-swirl spray becomes insignificant in comparison to the main spray at around 0.3 ms ASOF. From this time onwards in the Mie
images, the measurement technique picks the leading edge of main spray as the tip of spray. This measurement artifact was seen to occur for cold sprays and mixtures of low volatility because in these conditions the pre-swirl and main sprays are separated. In hot sprays, as will be described later in this chapter, this effect is not noticeable. Due to higher sensitivity of schlieren photography, the measurement algorithm can detect the pre-swirl spray for a longer period of time. Accordingly, the measurement artifact is seen later in the schlieren images (as will be seen in §5.2.2).

![Swirl-type Injector Early spray](Image)

**Figure 5.3:** Swirl type injector, Early spray
Reference fuel at \( p=100 \) bar and \( T=20^\circ C \)

Besides this measurement artifact, a decrease in the rate of spray penetration, which can be interpreted as a decrease in spray velocity, is observed; correlating the penetration length in Figure 5.4 with the spray images presented in Figure 5.3 clearly shows the decrease. Since the penetration length during this period is associated to the pre-swirl spray, this decrease could be attributed to the expansion and disintegration of the pre-swirl that is caused by the action of aerodynamic forces resisting the pre-swirl spray propagation.
5.2.2 Fully developed spray (0.5 ms ASOF – EOI) - baseline conditions

As described in chapter 3 of this work, Lee and Nishida [2003] identified several distinct regions within a fully developed spray structure from a pressure-swirl atomizer. The author’s experimental observations were found to be consistent with those presented by Lee and Nishida. Figure 5.4 obtained from Shadowgraph images at 1.0 ms ASOF, is typical of the author’s images of the fully developed structure.

![Figure 5.4: Swirl injector, Fully developed spray regions](image)

Reference fuel at P=100 bar, T=20°C at 1.0 ms ASOF

The labeled regions of the image correspond to the features of the fully developed spray defined by Lee and Nishida as follows:
a. **Spray potential core region**: this part of spray is bounded by the initial cone angle. The spray in this region is mainly influenced by the injector parameters and the evaporation rate is relatively low under normal injection conditions.

b. **Hollow-cone main body region**: in this region, the hollow cone structure of the spray is developed. The liquid sheet breakup mechanism converts the sheet into ligaments and droplets. Some degree of fuel evaporation occurs in parallel to the spray break-up. However, since the kinetic energy of the droplets is still high in this region, the influence of aerodynamic forces on the droplets is negligible.

c. **Vortex ring formation region and leading edge**: as the droplets get smaller, the increased influence of aerodynamic drag forces on the spray, along with the pressure difference across the spray caused by a low pressure region in the spray centre, causes a toroidal vortex to form at the leading edge of the spray. This vortex structure moves downstream along the spray axis as the spray progresses. It is interesting to note that smaller droplets are entrained into the vortex and are consequently transported into the spray core. In this region, the influence of the aerodynamic forces on the spray is significant and can be sufficient as to cause substantial narrowing of the spray (a process that is often referred to as spray collapse). However, in the baseline case of reference fuel at 20°C no collapse was observed.

d. **Pre-swirl spray region (sack spray)**: as discussed in a previous subsection, the liquid fuel trapped in injector orifice emerges from the injector without any substantial swirl motion. Being composed of large droplets and having a high axial velocity causes this part of the spray to penetrate faster and further than other regions. This is clearly observed in Figure 5.4 where the large droplets of pre-swirl spray can be seen.

Returning to the author's experimental results, Figure 5.5 shows the propagation of the fully developed spray, which was observed from approximately 0.5 ms ASOF, up to the end of injection (1.5 ms ASOF). It can be seen that, for this baseline case, the spray does not go through any significant changes in shape or structure after reaching the fully developed stage. The spray structure is simply seen to expand and move away from the injector nozzle.
Figure 5.5: Spray development of Swirl type injector during the injection event (0.5 – 1.5 ms ASOF) Reference fuel at P=100 bar, T=20°C The upper rows present the Schlieren images; the lower rows present Mie Scattering images.

Figure 5.6 shows the penetration length data for the baseline spray case taken from both the Schlieren and Mie scattering image sets. The measurement artifact described previously with respect to Mie scattering images, on this occasion, can be traced in the Schlieren images of the spray at between 0.7 and 0.8 ms ASOF (Figure 5.5 refers). This phenomenon notwithstanding, both the Schlieren and Mie Scattering data plotted in Figure 5.6 indicate that the penetration rate of the leading edge of the spray is decreasing slightly as the spray structure moves downstream from the injector. This reduction in velocity is consistent with a loss of droplet momentum due to aerodynamic drag forces and the effects of fuel vaporization. Interestingly, a comparison of the Schlieren and Mie scattering data suggests that the difference between vapor and liquid penetration lengths decreases as the elapsed time after SOF increases. One explanation of this phenomenon might be related to the slow evaporation of fuel at this 20°C baseline testing temperature. In the slow evaporation regime, it might be expected that the most...
volatile components of the fuel will evaporate during the early stages of injection. This might show up as increased penetration in the Schlieren images. In the later stages of injection the droplets would contain mainly components of relatively low volatility. This would reduce the evaporation rate of the droplets and, since the liquid core is surrounded with vapor phase (discussed in §5.2.1), the difference between the vapor phase and liquid phase of the spray would be reduced.

![Swirl-type Injector developed spray of Reference fuel](image)

**Figure 5.6:** Swirl injector developed spray penetration vs. time
Reference fuel at \( P=100 \) bar and \( T=20^\circ C \)

### 5.2.3 Post-injection spray

As the injector needle valve closes, the flow of fuel from the injector is stopped and no further momentum is imparted to the spray. However due to its existing momentum, the spray structure keeps moving downstream and, as it does so, its density decreases due to evaporation.

Figure 5.7 shows the penetration length data for the baseline spray case taken from both the Schlieren and Mie scattering image sets for the post injection period 1.5 ms up to 10.0 ms ASOF.
Figure 5.7: Swirl injector Post injection spray penetration Vs time
Reference fuel at P=100 bar and T=20°C

Figure 5.8 shows the Schlieren and Mie scattering images of the baseline spray from the end of injection up to 10 ms ASOF. Note that in later sections of this work, the time frame of 0 to 5 ms ASOF will be used for investigating different impacts on the spray. Considering the images in Figure 5.8, as the flow of fuel is stopped and the induced momentum eliminated, the front end of the spray rapidly becomes a dense cloud of decelerating fuel droplets. The images show after the end of injection, the leading edge of spray penetrates more slowly than the portion of fuel injected right before end of injection (also known as the tail of the spray). It was observed that the tail of the spray passed through the leading edge of spray propagating further downstream in a vortex like flow. Note that this behavior is consistent with the earlier observations of Kubo et al., [2001]; Kang et al., [2004]; and Williams et al., [2001]. Considering Figure 5.7 and 5.8, a reduction in spray penetration length difference associated to Schlieren and Mie Scattering is observed. Recalling that the Schlieren images detects both vapor and liquid, while Mie scattering detects primarily only liquid, this may suggest that the evaporation rate is decreased in this stage.
Figure 5.8: Spray propagation of Swirl injector after injection event
(Reference fuel at P=100 bar and T=20°C, time 0.5 to 10.0 ms ASOF)
The first rows present the Schlieren images; the second rows present Mie Scattering images
The development of the spray created by a high-pressure Swirl-type injector was investigated carefully in this section. However, the spray development process as well as spray characteristics are significantly altered by changing the ambient conditions as well as fuel properties. In the following sections the impact of fuel temperature and ethanol content on the spray characteristics will be investigated and discussed in detail.

5.3 Effect of fuel temperature on swirl injector spray characteristics

The effect of fuel temperature on the baseline spray characteristics is described with respect to the three developmental stages defined earlier in §5.2; (a) Early spray, (b) fully developed spray and (c) post injection. Since, in this section, the focus is solely on the effect of temperature without consideration of fuel volatility effects, only the images obtained from reference fuel have been used. However, it must be remembered that the effect of fuel temperature on spray characteristics is expected to be highly dependent on the properties of the fuel itself and, in particular, the distillation properties of the blend. The effect of changing the fuel blend’s ethanol content, which directly alters its volatility, on the spray characteristics of the pressure swirl atomizer is investigated both by itself and in conjunction with changing fuel temperature in §5.4 and §5.5 respectively.

5.3.1 Effect of fuel temperature on early spray – reference fuel

Figure 5.9 shows the development of the penetration length versus time for the early spray stage of the reference fuel at four different fuel temperatures as measured from the author's schlieren imaging experiments. The data shown in Figure 5.9 suggests that, in the fuel temperature range of 20 - 60°C, the impact of fuel temperature on the penetration length of the early development stage of the spray is not particularly significant. However, a noticeable difference in the early spray behavior can be observed when the fuel temperature is raised to 80°C. While increasing the fuel temperature from 20°C to 60°C causes a slight increase in penetration length, surprisingly, at 80°C, the early spray penetration is reduced in comparison with all of the other fuel temperatures under investigation.
Figure 5.9: Effect of fuel temperature on the early spray penetration Vs time
(Reference fuel at $P=100$ bar and $T=20$, $40$, $60$, $80^\circ C$)

Figure 5.10 plots the early spray penetration length vs. temperature for four different image acquisition times ($0.2$, $0.3$, $0.4$, and $0.5$ ms ASOF) to provide a better insight on this phenomenon.

Figure 5.10: Effect of fuel temperature on early spray
(Reference fuel at $P=100$ bar, $T=20$, $40$, $60$, $80^\circ C$, Time: $0.2$, $0.3$, $0.4$, $0.5$ ms ASOF)

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Figure 5.11: The Schlieren images of swirl type injector, Early spray at different fuel temperatures
(Reference fuel at P=100 bar, T=20, 40, 60, 80°C)
Considering the schlieren images presented in Figure 5.11 corresponding to this period, note that no comparative images were available at this times earlier than 0.2 ms ASOF since there is a dark region at the upper edge of the Schlieren images associated with 60 and 80°C fuel temperatures. This region, which is caused by heat flux around the water jacket close to the injector tip, masks the spray penetration period to 0.2 ms ASOF in these two cases.

Figure 5.12 shows the early spray shape to be almost the same for 20–60°C fuel temperature cases. In all three cases the images show a significant amount of pre-swirl spray. In the 80°C case however, the pre-spray penetration (and possibly the pre-spray mass) is clearly much reduced.

By correlating the data shown in Figure 5.9 and Figure 5.10 with the corresponding Schlieren images presented in Figure 5.11, it is clear that increasing the temperature causes the measured penetration length to increase in the range of 20–60°C; this increasing trend is reversed after 60°C. The observation is consistent with previous studies [VanDerWege et al., 2000; Araneo et al., 2000; Moon et al., 2005]. These studies suggest that increasing the fuel temperature enhances the atomization process and reduces droplet sizes. Referring to these studies, a possible explanation for the increased spray penetration is that the smaller droplets tend to follow the induced airflow. This phenomenon causes a greater amount of the spray momentum to be directed axially rather than radially which results in a higher axial penetration length.

With regard to the observed decrease in penetration length at times later than 0.3 ms ASOF for a fuel temperature of 80°C, this might be explained by the reduction in droplet size due to increased break-up being augmented by substantial evaporation. This would cause the pre-swirl spray to penetrate less far in case of the hot spray while in the cold spray; the larger droplets would cause further and faster penetration. Note that the observed pre-swirl spray behavior is consistent with the work of VanDerWege et al. [2000].

Figure 5.12 shows close up views of the spray from the shadowgraph imaging experiments acquired at 0.2 and 0.5 ms ASOF. Since the difference between the spray structure of the 20°C and 40°C temperature cases was found to be negligible, only images
associated with the 20, 60 and 80°C temperature cases are shown in the Figure. A slightly narrower spray can be observed at fuel temperature 80°C that is consistent with a reduction in droplet size leading to spray collapse.

![Figure 5.12: Shadowgraph images of early spray Time 0.2, 0.5 ms ASOF Reference fuel at P=100 bar, T=20, 60, 80°C](image)

From the author’s observations, the effect of temperature on early spray formation of the baseline spray can be summarized as follows: as the liquid column emerges out of the injector, increasing the temperature initially increases the penetration length. During this period, the measurement algorithm picks the pre-swirl tip to measure the penetration length in the schlieren images, while picking the main spray in Mie Scattering images after 0.3 ms ASOF (refer to Figure 5.9 and 5.10). The penetration of the pre-swirl spray increases as the temperature increases up to 60°C before decreasing at a fuel temperature of 80°C.

So far in this thesis, the effect of temperature has been considered only with respect to the early spray formation (0.0 – 0.5 ms ASOF). During this period, the effect of
temperature increase on the spray is seen to be small – the average penetration increase during this period is about 3 mm for a 40°C increase in fuel temperature. One important issue to be discussed at this point is the level of shot-to-shot variation in the penetration length measurements. The Figures presented in this section of the thesis were based on measurements performed on a mean spray movie constructed from 20 individual spray sequences. However, the measurement of each individual movie showed some cycle-to-cycle variations in the penetration length. The analysis of this shot-to-shot variability, performed using the methods initially presented by Hung and co-workers [Hung et al., 2003] was partly presented in §5.1 and will be discussed in more detail in §5.6. Note that the variation in penetration length measurement for this early spray period can be up to ±1.5 mm. accordingly, the 3 mm difference in penetration length reported above during the early spray injection period may not be counted as statistically significant.

5.3.2 Effect of fuel temperature on the fully developed spray

As discussed earlier, the fully developed stage of spray was assumed to start at 0.5 ms ASOF and to continue to the end of injection (EOI) event (1.5 ms ASOI). Figure 5.13 (overleaf) shows schlieren images of the reference fuel spray recorded during this period. It can be seen that the spray structure is not altered significantly until the fuel temperature reaches 80°C. At this temperature, spray collapse occurs earlier and closer to the tip of injector resulting in a narrower and longer penetrating spray.

The noticeable alteration of spray structure when the fuel temperature increased to a certain point has been observed in a number of previous studies [Davy et al., 2000; VanDerWege and Hochgreb, 2000; Kawano et al., 2004; Nakama et al., 2003; Moon et al., 2005]. The authors of these previous works have suggested that the early collapse of the spray is caused by flash boiling. The suggested explanation for this process is that, as flash boiling occurs, droplet sizes decrease sharply and thereby a larger number of droplets are transported by the induced airflow into the low-pressure zone of spray core. Accordingly, the hollow cone collapses and the spray is transformed to a solid cone structure. This also causes the spray to propagate further in the axial direction. The relatively compact and highly penetrating sprays that are observed in the author’s experiments at 80°C are consistent with these earlier reports.
Figure 5.13: Developed spray structure at different fuel temperature
Reference fuel at P=100 bar, T=20,40,60,80°C (Schlieren Images)
Figure 5.14 shows the effect of fuel temperature on the penetration length of the reference fuel-spray as measured from the author’s mean schlieren movies.

**Effect of Temperature on Developed Spray**

Penetration length Vs Time Reference fuel

Schlieren images at $P=100$ bars, Temp=20,40,60,80°C Time (0.5-1.5 ms ASOF)

![Graph showing the effect of temperature on spray penetration length.]

**Figure 5.14:** Effect of fuel temperature on spray penetration length of a swirl type injector

Reference fuel at $P=100$ bar, T=20, 40, 60, 80°C

(Extracted from Schlieren images)

Correlating the data shown in the Figure 5.14 with the images presented in Figure 5.13 shows that there is no obvious transition between pre-spray and main spray measurements in the 80°C case. In this case, it can be seen that the main spray overtakes the pre-spray at approximately 0.8 ms ASOF. In all of the other cases, some evidence of the pre-spray is seen ahead of the main spray until the end of injection.

As might be expected from the earlier discussion of flash boiling, the main spray penetration length is found to increase significantly when the fuel temperature reaches 80°C. However, it is worth noting that increasing the fuel temperature from 20°C to 60°C also caused a small progressive increase in penetration length. The same observation has been made in previous studies [Hentschel *et al.*, 1999; VanDerWege *et al.*, 2000; Moriyoshi *et al.*, 2000; Kubo *et al.*, 2001; Donde *et al.*, 2000]. The authors of these research works suggested that this was due to a progressively increased number of small
droplets being formed as the temperature is raised and, consequently, a progressively higher number of droplets being drawn into the spray core by the induced airflow. This is said to create a column of fine droplets that propagates along the spray axis.

Figure 5.15 shows a sequence of mean Mie scattering images of the reference fuel spray for the four fuel temperatures under investigation. It can be seen that these images, which represent the liquid phase of the spray, are consistent with those shown previously for the liquid and vapor phases (refer Figure 5.13).

Figure 5.15: Developed spray expansion for different temperatures
Reference fuel at P=100 bar and T=20, 40, 60, 80°C Time: 0.5 up to 1.5 ms ASOF
(Extracted from Mie-Scattering)
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As observed by VanDerWege in his studies of similar sprays, the rate of fuel evaporation is sufficient to disrupt the spray shape when the fuel temperature is 60°C, however, the spray was not observed to collapse severely as happened when the fuel was at a temperature of 80°C. As described in a previous chapter of this work, VanDerWege defined three evaporation regimes for hollow-cone sprays. With respect to these regimes, the author’s results suggest that the Reference fuel at 60°C can be considered as being in the disruptive evaporation regime. Whereas at a fuel temperature of 80°C the results suggest that the fuel might be entering the violent evaporation or flash boiling regime.

The spray penetration lengths extracted from these mean Mie Scattering images are presented in Figure 5.16.

![Figure 5.16: Effect of fuel temperature on spray penetration length - swirl type injector
Reference fuel at P=100 bar and T=20, 40, 60, 80°C, Time: 0.5 to 1.5 ms ASOF (Extracted from Mie Scattering)](image)

As might be expected from the similarity in the two sets of images presented in Figures 5.14 and 5.15, the data presented in Figure 5.16 is, with the exception of the measurement artifact described earlier, also similar – with the 80°C case showing a substantial increase in main spray penetration length over the 20 -60°C cases.

The initial spray cone angle and main body cone angle of the reference fuel spray at the four temperatures of interest are presented in Figure 5.17 (overleaf). These results
have been extracted from the author’s shadowgraph images. The measurements were performed at a time $t = 1.0$ ms ASOF where, based on the author’s observations and the literature, the spray structure is at its most stable.

With respect to the literature, VanDerWege and Hochgreb [2000] observed a significant ($35^\circ$) increase in initial cone angle in a similar pressure swirl injector spray subject to violent flash boiling conditions (a substantial degree of fuel superheat). In this study, the increase in initial cone angle is not more than $5^\circ$ for the reference fuel suggesting that, contrary to expectations, the violent flash boiling regime described by VanDerWege and Hochgreb has not been reached. Considering the degree of superheating of the reference fuel at $80^\circ$C, the initial boiling point of the blend at atmospheric pressure was calculated to be $28^\circ$C (related to isopentane). However, only a negligible volume of the fuel will evaporate close to this temperature. It is perhaps more appropriate to consider the fuel temperature relative to the boiling point of the dominant component of the fuel blend. As described in chapter 4, the major component within the reference fuel is iso-octane. Under standard condition, iso-octane boiling point is $68^\circ$C. Thus, the bulk of the fuel may not be substantially superheated and a higher temperature is needed to observe a considerable increase in cone angle due to flash boiling.

![Effect of Temperature on fully developed Spray of Swirl-type Injector](image)

**Figure 5.17:** Effect of fuel temperature on spray structure of a swirl type injector
Reference fuel at $P=100$ bar, $T=20, 40, 60, 80 \, ^\circ$C, times: $1.0$ ms ASOF
(Measured from Shadowgraph images)
 Whereas there is an increase of approximately 8° in the initial cone angle as the temperature is increased from 20 – 80°C, the main body cone angle (measured according to the definition given in Chapter 4) decreases by approximately 3°. Note however, that this cone angle is measured at an axial distance of 10 mm below the injector nozzle.

Details of these sprays may be seen in Figure 5.18, presenting the images obtained through Shadowgraphy with a closer look at the spray.

**Figure 5.18**: Effect of temperature on fully developed spray structure of a swirl type injector
Reference fuel at P=100 bar, T=20, 40, 60, 80°C - time: 0.5, 1.0, 1.5 ms ASOF (Shadowgraph images)

Further examination of Figure 5.18 indicates that there is a significant narrowing of the spray structure further downstream of the measurement point in the 80°C fuel
spray. As explained earlier, it is often reported that smaller droplets are generated at higher temperatures due to improved atomization and higher rates of evaporation—including the flash boiling mechanism when there is a sufficient degree of superheat. These smaller droplets tend to move into the spray core (transported by the induced airflow); therefore, as the proportion of the droplets with small size increases, the spray structure gets more compact.

So far in this work, only the effects of temperature during the injection event have been considered. Although the increase of fuel temperature has been shown to cause some narrowing of the pressure-swirl atomizer spray coupled with an increase in axial penetration, this effect is seen to be significant only if the fuel blend becomes adequately superheated as to reach the disruptive (flash boiling) evaporation regime. In the case of the reference fuel, evidence of disruptive evaporation is seen at 80°C—although the results suggest that the violent flash boiling condition reported by VanDerWege and Hochgreb [2000] has not been attained.

5.3.3 Effect of temperature on the post-injection spray structure

As shown earlier, two counter-rotating vortices propagate downstream from the injector during the post-injection period. These vortices decelerate due to air resistance as the spray propagates. Simultaneously, the evaporation process continues causing further disintegration of the spray. Figure 5.19 (overleaf) presents the images of the post-injection spray for different fuel temperatures.

It worth mentioning here that, the post-injection investigation was focused up to 5.0 ms ASOF. This time frame was chosen because the measurement after 5.0 ms ASOF becomes increasingly inaccurate due to increasing instability of the spray (explained further in §5.5). Moreover, by the time of 5.0 ms ASOF, the spray penetration length was found to be in excess of 180 mm, i.e. longer than the stroke length of most gasoline engines.

During this post-injection period the impact of spray collapse is evident. The images shown in Figure 5.19 clearly show a progressive increase in fuel penetration with increasing temperature.
Figure 5.19: Post-injection spray structure of a swirl-type injector
Reference fuel at P=100 bar, T=20, 40, 60, 80°C
(Schlieren and Mie Scattering images)

Figure 5.20 shows the effect of fuel temperature on the penetration length of the reference fuel-spray as measured from the author’s mean Schlieren and Mie scattering movies. The graphs associated to the post-injection period from 1.5 ms ASOF up to 5.0 ms ASOF.

Same with the results from observing the images presented in Figure 5.19. Investigating both Schlieren and Mie Scattering data in Figure 5.20 shows the direct relation between an increase in spray penetration with increasing the fuel temperature particularly when the fuel temperature reach to 80°C.
Effect of Temperature on Post-injection Spray
Penetration length Vs Time
Reference fuel at \( P = 100 \) bars, \( T = 20, 40, 60, 80 \) °C time (1.5-5.0 ms ASOF) extracted from Schlieren images

Effect of Fuel Temperature on Post-injection Spray
Penetration length Vs Time
Reference fuel at \( P = 100 \) bars, \( T = 20, 40, 60, 80 \) °C time (1.5-5.5 ms ASOF) extracted from Mie Scattering images

**Figure 5.20:** Effect of fuel temperature on spray penetration length of a swirl-type injector
Reference fuel at \( P = 100 \) bar, \( T = 20, 40, 60, 80^\circ C \), time 0.5 to 5.0 ms ASOF
(Extracted from Schlieren and Mie Scattering images)
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The shadowgraph images presented in Figure 5.21 were taken at 1.7 and 2.0 ms ASOF to give a better insight of the post-injection event close to the injector tip.

![Shadowgraph images showing effect of fuel temperature on post-injection spray structure of a swirl-type injector.](Image)

**Figure 5.21:** Effect of fuel temperature on post-injection spray structure of a swirl-type injector. Reference fuel at P=100 bar, T=20, 40, 60, 80°C, t: 1.5, 1.7, 2.0 ms ASOF (Shadowgraph images)

One of the important issues with DISI injectors is the residual fuel injected after the valve is (nominally) closed – most often as a result of needle bounce. In the images presented in Figure 5.21 there is some evidence of large droplets being injected after the commanded end of injection. However, further experiments using droplet sizing are needed to obtain a better insight on this phenomenon.
5.4 Effect of ethanol content on spray structure

As mentioned earlier, given the demonstrable temperature dependence of swirl-type injector spray structures it is reasonable to expect that the structure will also be affected by the composition of the injected fuel, which may be directly related to fuel volatility. In case of multicomponent blends, determining the volatility of the fuel is more difficult than for the case of a single component fuel because of the wide range of volatilities associated to the different components of the blend. Adding to this complexity, alcohols (such as ethanol) and hydrocarbons typically form highly non-ideal mixtures; thus, the mixture properties do not obey ideal multicomponent vapor-liquid equilibrium relations.

To observe any effects related solely to the physical changes in the fuel induced by the addition of ethanol, the spray structures of five different blends of ethanol and the reference fuel were investigated at a fuel temperature of 20°C – a temperature at which volatility effects were expected to be relatively unimportant. Again, the investigation is made based on three stages of spray development, early spray, developed spray and post-injection spray.

Figures 5.22(a), 5.22(b) and 5.23, respectively, present the spray penetration length versus the time elapsed (ASOF) data and their corresponding images for the different ethanol blends.

Considering penetration length measured through the author’s mean Schlieren images, no statistically significant difference is seen for the different blends. The reference fuel appears to show a slightly longer penetration while the E80 fuel penetration appears slightly shorter, the rest of the blends are too close to be distinguished. Note that the greatest difference between the maximum and minimum penetration length of the fuel blends is only 4 mm (between reference fuel and E80 around 0.25 to 0.35 ms ASOF).
Effects of ethanol content on Spray structure
Penetration length at different time ASOI for Five blended fuels
Schlieren images Temp=20°C Time (0-5.0 ms ASOF) Fuels: Reference, E5, E10, E22 and E80

Figure 5.22(a): Effect of ethanol content on spray penetration length of a swirl-type injector
P=100 bar, fuel temperature 20°C, time: 0.0 to 5.0 ms ASOF, Reference, E5, E10, E22, and E80
(Extracted from Schlieren images)
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(ii): 0.5 to 1.5 ms ASOF

![Graph showing effect of ethanol content on spray penetration length for time 0.5 to 1.5 ms ASOF.](image)

<table>
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<th>Ethanol Content</th>
<th>Penetration Length (mm)</th>
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</tr>
<tr>
<td>E5</td>
<td>30</td>
</tr>
<tr>
<td>E10</td>
<td>0.5</td>
</tr>
<tr>
<td>E22</td>
<td>1.2</td>
</tr>
<tr>
<td>E80</td>
<td>1.5</td>
</tr>
</tbody>
</table>

(iii): 1.5 to 5.0 ms ASOF

![Graph showing effect of ethanol content on spray penetration length for time 1.5 to 5.0 ms ASOF.](image)

<table>
<thead>
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<th>Ethanol Content</th>
<th>Penetration Length (mm)</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
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<td>110</td>
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<tr>
<td>E10</td>
<td>100</td>
</tr>
<tr>
<td>E22</td>
<td>90</td>
</tr>
<tr>
<td>E80</td>
<td>80</td>
</tr>
</tbody>
</table>

Figure 5.22(b): Effect of ethanol content on spray penetration length of a swirl-type injector
P=100 bar, fuel temperature 20°C, time: 0.5 to 5.0 ms ASOF, Reference, E5, E10, E22, and E80 (Extracted from Schlieren images)
Observing the Schlieren images of the spray during the early spray stage (presented in Figure 5.23), indicates that the initial spray structure at 20°C is not altered by the changing the ethanol content of the blends.

![Schlieren images](Figure 5.23: Early spray structure of swirl-type injector
Reference, E5, E10, E22, E80 at P=100 bar, T=20°C Time: 0.1, 0.3, 0.5 ms ASOF (Schlieren images)

During the early-spray period, the schlieren data shown in Figure 5.22(a) and Figure 5.22(b) indicates the penetration length of the pre-spray: to investigate the main spray penetration length of these blended fuels during early spray it is necessary to consider the penetration length measure from mean Mie-scattering images. However, as mentioned previously, even in Mie-scattering images, only after 0.3 ms ASOF can the penetration length be safely related to the main spray. The penetration length of these blends at 20°C, extracted from Mie-scattering images, is presented in Figure 5.24(a) and Figure 5.24(b).
Figure 5.24(a): Effect of ethanol content on spray penetration length – Swirl-type injector
P=100 bar and T=20°C, time: 0.0 to 5.0 ms ASOF, Fuels: Reference, E5, E10, E22, E80
(Extracted from Mie Scattering)
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(ii) 0.5 to 1.5 ms ASOF

(iii) 1.5 to 5.0 ms ASOF

Figure 5.24(b): Effect of ethanol content on spray penetration length – Swirl-type injector

P=100 bar and T=20°C, time: 0.0 to 5.0 ms ASOF, Fuels: Reference, E5, E10, E22, E80

(Extracted from Mie Scattering)
Examining the Mie-Scattering images presented in Figure 5.25 and also the related penetration length data of the early spray shows no significant difference in the spray structure for the different fuel blends. Some inconsistent and rapidly changing differences can be observed in the penetration lengths. However, within a fairly narrow band, E5 generally tends to have the highest penetration length and E22 the lowest. As mentioned earlier up to 0.3 ms ASOF, the penetration length measured in Mie-Scattering images are associated to the pre-swirl spray and only after that point they shows the penetration length of the main spray.

![Table of Fuel Blends]

**Figure 5.25**: Effect of ethanol content on early spray structure of a swirl-type injector (liquid phase). Reference, E5, E10, E22 and E80 blends at P=100 bar and T=20°C time: 0.1, 0.3 and 0.5 ms ASOF (Mie-Scattering images)

A close up view of early spray at 0.2 ms and 0.5 ms ASOF is presented in Figure 5.26 (overleaf). It can be seen that the early spray structure is remarkably consistent between blends. As a result, it may be concluded that the ethanol content of the fuel has no significant impact on the spray structure with the fuel temperature of 20°C. With
regard to possible volatility effects this is to be expected. The 20°C fuel temperature is well below the normal boiling temperature of even the lightest component of the blends (iso-pentane). Therefore, no flash boiling or even disruptive evaporation was to be expected.

![Figure 5.26: Early spray structure of swirl-type injector for different ethanol content](image)

As to the effects of ethanol content on the fully developed spray at 20 °C, Figure 5.27 shows the main spray penetration lengths and the corresponding Schlieren images. Comparing the penetration length of the different blends and correlating those experimental points with their associated images clearly shows that the ethanol content has no significant impact on the developed spray structure at 20°C fuel. The maximum difference in penetration length is about 4mm, which can not be considered to be significant. It is worth noting however that the Mie Scattering data for these fuels (presented in Figure 5.24(a) and 5.24(b) shows the E5 and E22 blends to exhibit somewhat irregular behavior. This issue will be discussed in further detail in §5.6 on error analysis.
Chapter 5: Result and Discussion - Swirl-type Injector

Effects of ethanol content on Developed spray structure
Penetration length at different time ASOF for Five blended fuels
Schlieren images at P=100 bars, Temp=20 °C time (0.5, 1.0 and 1.5 ms ASOF)
Fuels: Reference, E5, E10, E22 and E80

Figure 5.27: Effect of ethanol content on developed spray structure of swirl-type injector
Reference, E5, E10, E22 and E80 blends at P=100 bars and T=20°C time: 0.5, 1.0 and 1.5 ms ASOF
(Schlieren images)

Figure 5.28 (overleaf) shows shadowgraph images of the 20°C sprays captured 1.0 ms ASOF along with their associated initial and main spray cone angles. Although there is a slight difference correlated to ethanol content of the fuel but neither initial cone
angle nor main body cone angle, are not effected noticeably by changing the ethanol content of the fuel blends at this low temperature condition.

<table>
<thead>
<tr>
<th>Swirl-type injector, fuel temperature=20 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initia angle</td>
</tr>
<tr>
<td>Ref</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>68.55</td>
</tr>
<tr>
<td>Main angle</td>
</tr>
<tr>
<td>Ref</td>
</tr>
<tr>
<td>57.83</td>
</tr>
</tbody>
</table>

**Figure 5.28:** Effect of ethanol content on spray initial and main cone angle of swirl-type injector
Reference, E5, E10, E22 and E80 blends at P=100 bar and T=20°C time: 1.0 ms ASOF
(Shadowgraph images)

As discussed earlier, the injected fuel cloud continues propagating downstream from the injector after the injection event has ended. The spray-structure in this post-injection period is dominated by the affects of aerodynamic forces and fuel evaporation. The evaporation rate of the spray during this period depends on the composition of the fuel in the droplets as well as the level of energy within the droplets. Although the results shown in Figures 5.22(a), 5.22(b) and 5.24(a), 5.24(b) indicate that the blend volatility has no significant impact on spray development in the slow vaporization regime, it is interesting to note that there are some differences between the post-injection penetration as shown by the Mie scattering and schlieren images (refer Figure 5.29 - overleaf). The liquid phase penetration length of the E5 blend measured from the Mie-scattering images is substantially is higher than the liquid and vapor phase penetration length measured from the schlieren images which is not physically possible. This error caused by excessive temperature of test rig caused by halogen light heating and partly due to malfunctioning of thermometer.
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5.5 Combined effect of ethanol content and temperature on the spray from swirl-type injectors

The preceding sections of this chapter have shown that, for a given fuel composition, the fuel temperature has a significant impact on all stages of pressure-swirl spray development and, at a fixed temperature of 20 °C, the ethanol content of the fuel does not significantly influence the structure of the spray. To continue this investigation, this section of the thesis will present experimental results for the combined effects of fuel composition and temperature.

Figures 5.30(a), 5.30(b) show the penetration length for four different temperatures and five fuel blends measured from the author’s mean Schlieren images. Investigating these figures show only slight differences in spray penetration lengths associated to different blends particularly in fuel temperatures higher than 20 °C. However, these differences are neither significant nor proportional to ethanol content of blends. Figures 5.31(a), 5.31(b) show the corresponding data extracted from mean Mie Scattering images. Again, no distinguishable relation between ethanol content and spray penetration were found. The results suggest that, during the early spray, the penetration length is not changed significantly by altering the ethanol content of the fuel.
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Figure 5.30(a): Combined effect of ethanol content and Fuel temperature on spray penetration length

P=100 bar and T=20, 40, 60, 80°C, Time: 0.0 to 5.0 ms ASOF, Fuels: Reference, E5, E10, E22, E80
(Extracted from Schlieren images)
Figure 5.30(b): Combined effect of ethanol content and Fuel temperature on spray penetration length 
P=100 bar and T=20, 40, 60, 80°C, Time: 0.0 to 5.0 ms ASOF, Fuels: Reference, E5, E10, E22, E80 
(Extracted from Schlieren images)
Penetration length Vs Time extracted from Mie Scattering images

\( P=100 \) bars, Time (0.0 to 5.0 ms ASOF), Fuels: Reference, E5, E10, E22 and E80

(i) Fuel temperature = 20°C

(ii) Fuel temperature = 40°C

Figure 5.31(a): Combined effect of ethanol content and Fuel temperature on spray penetration length - \( P=100 \) bar and \( T=20, 40, 60, 80^\circ\text{C} \); time: 0.0 to 5.0 ms ASOF, Fuels: Reference, E5, E10, E22, E80

(Extracted from Mie Scattering)
(iii) Fuel temperature = 60°C

(iv) Fuel temperature = 80°C

**Figure 5.31(b):** Combined effect of ethanol content and Fuel temperature on spray penetration length - $P=100$ bar and $T=20, 40, 60, 80°C$; time: 0.0 to 5.0 ms ASOF, Fuels: Reference, E5, E10, E22, E80

(Extracted from Mie Scattering)
Figure 5.32: Combined effect of ethanol content and fuel temperature on spray

Penetration Vs temperature at t=0.5 ms ASOF (Schlieren and Mie Scattering)
P=100 bar and T=20, 40, 60, 80°C Fuels: Reference, E5, E10, E22, E80

Figure 5.32 presents the penetration length of five blends for different temperature at 0.5 ms ASOF i.e. the point at which the developed spray is assumed to
form. Considering Figure 5.32 in more detail, and recalling that the Schlieren data at 0.5 ms ASOF is associated with pre-swirl spray while the Mie-scattering data relates to the main spray penetration, increasing the blend’s ethanol content is shown to reduce the pre-spray penetration in comparison with the reference fuel. However, the scale of these changes is small and there is no obvious trend associated with the volume fraction of ethanol in the fuel.

Figure 5.33 (overleaf), presents shadowgraph images of the fuel sprays at 0.2 and 0.5 ms ASOF. It can be seen that all of the fuel compositions show some tendency to disruptive evaporation at 80°C and consequently present some sign of collapse. Certainly, the spray images of all cases at this higher temperature show the number of large droplets in the pre-spray to be reduced. This is in agreement with the schlieren data shown in Figure 5.32. The Mie-scattering data for the early stage of the main spray shows some indication that the blends with higher ethanol content might have a lower tendency to collapse – perhaps indicative of a larger mean droplet size within the spray. However, again the observed differences are small – of the same order as the experimental uncertainty – and hence no definitive conclusion can be made from the experimental results. At fuel temperatures of 60°C and below, there is no evidence of the spray structure being influenced by the fuel composition.

Figures 5.34(a) and 5.34(b) present, respectively, the penetration lengths (extracted from both the schlieren and the Mie imaging experiments) and the shadowgraph images associated with the fully developed stage of the spray development (1.0 to 1.5 ms ASOF). It can be seen that in the 20 °C case, when the fuel temperature is well below the boiling point of even the lightest component of the blend, the impact of ethanol content is not significant. It is interesting to note however that the schlieren data at 1.0 ms ASOF, which represents the liquid and vapor phase penetration at this does suggest some impact of fuel composition at the intermediate temperatures of 40 and 60°C. The liquid and vapor phase penetration of the E22 and E10 are similar to or greater than the reference fuel, whereas the liquid phase penetration of the similar to or less than the reference case. It is thought possible that these observations indicate increased evaporation of these fuels at these intermediate temperatures.
Figure 5.33: Early spray swirl-type injector for different ethanol content
Reference, E5, E10, E22 and E80 blends at P=100 bar and T=20, 60, 80°C time:0.2, 0.5 ms ASOF
(Shadowgraph images)
To investigate in further detail the penetration length for the 40 and 60°C cases, Figure 5.35 presents the penetration length at 1.0 and 1.5 ms ASOF.

**Figure 5.34(a):** Combined effect of ethanol content and fuel temperature on the developed spray penetration vs temperature at t=0.5, 1.0 and 1.5 ms ASOF. P=100 bar and T=20, 40, 60, 80°C Fuel: Reference, E5, E10, E22, E80
Figure 5.34(b): Combined effect of ethanol content and fuel temperature on the developed spray penetration vs temperature at t=0.5, 1.0 and 1.5 ms ASOF.

Penetration length vs fuel temperature - Mie Scattering @ 1.0 ms ASOF
P=100 bar, Temp: 20, 40, 60, 80°C Fuel: Reference, E5, E10, E22, E80

Penetration length vs fuel temperature - Mie Scattering @ 1.5 ms ASOF
P=100 bar, Temp: 20, 40, 60, 80°C Fuel: Reference, E5, E10, E22, E80
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These graphs show the effect of disruptive evaporation or spray collapse is significant only after 1.5 ms ASOF. Interestingly, the observed changes at intermediate temperatures are not directly proportional to the blended fuels’ ethanol content. For instance, E22, which has more ethanol than E5 or E10, has higher penetration length than either at 40°C while at 80°C its penetration length is less than both of them. This suggests that the disruptive evaporation is less intense for E22 case than for either the E5 or E10 cases. However, it is clearly observed at 80°C all the fuels are affected by disruptive evaporation and show a significant increase in their penetration length. The other observation that can be made here is, at a fuel temperature of 80°C the high volume of ethanol existing in E80 has evaporated soon after injection. This appears to have caused the E80 spray to undergo a rapid collapse between 1.0 and 1.5 ms ASOF. However, it can be seen that in the liquid phase, the trend is reversed (the E80 liquid phase does not penetrate significantly further as flash boiling occurred). To have a qualitative understanding of the spray structure in this period, Figure 5.35 (overleaf), presents the shadowgraph images, correlated to this moment.

Based on previous discussions, it would seem reasonable to categorize the fuel temperature of 20°C as being in the slow evaporation regime for all the blends. Increasing the fuel temperature to 60°C, there is no obvious sign of any disruptive evaporation at 1.0 ms ASOF while at 1.5 ms ASOF the spray collapse is seen — although still there is no violent evaporation of the spray. The collapse seen in all sprays at 1.5 ms ASOF, is due to the action of the pressure difference across the spray on the (presumably) smaller droplets that result from enhanced atomization and evaporation at higher temperatures. This temperature might then be categorized as being close to the limit of the disruptive evaporation regime that was described by VanDerWege and Hochgreb [1998].

A fuel temperature of 80°C is higher than the most of the fuel component boiling temperatures, which leads to violent evaporation, flash boiling, for the major part of the fuels. Accordingly, the sprays collapse much earlier and closer to the injector tip than they typically do at lower fuel temperatures. It can be seen this phenomenon happens somewhere between 1.0 and 1.5 ms ASOF, which is broad agreement with the observations of spray development made earlier in this chapter.
Figure 5.35: Developed spray structure of a swirl-type injector for different ethanol content Reference, E5, E10, E22 and E80 blends at P=100 bar and T=20, 60, 80°C time: 1.0, 1.5 ms ASOF (Shadowgraph images)
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There is a consistent change in the spray structure for the fuel temperature of 80°C. It seems reasonable to suppose that the increased penetration lengths of the developed sprays at this temperature are mainly due to spray collapse, which causes the spray momentum to be increased in the direction of the spray axis. When comparing sprays of different fuel composition at the same 80°C temperature it is interesting to note that those sprays with the maximum liquid and vapor phase penetration typically have a lower liquid phase penetration. This is consistent with the fact that those sprays that generate more vapor should be expected to consist of smaller droplets — whether through improved atomization or subsequent droplet evaporation — would therefore be expected to penetrate less far given similar initial velocity. It is also interesting to note that the changes in penetration length are again not directly proportional to the ethanol content of the fuel, this is perhaps due to the non-ideal behavior of ethanol / hydrocarbon blends. This is undoubtedly an area for further study.

Figure 5.36 presents the initial and main spray cone angles for the fully developed phase of the spray.

![Figure 5.36: Combined effect of ethanol content/fuel temperature on the developed spray structure Initial and Main spray cone angle Vs temperature at t=1.0 ms ASOF, P=100 bar and T=20,60,80°C Fuel: Reference, E5,E10,E22,E80 (Extracted from Shadowgraph Images)]
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There is no significant difference in the cone angle measurements during either the slow evaporation (20°C) or disruptive evaporation (60°C) regimes, while there is significant increase in initial cone angle and decrease in main spray angle at fuel temperature of 80°C.

It can be seen that the reference fuel has a relatively large main spray angle and a relatively small initial cone angle, while E5 has the smallest main angle and its initial cone angle is among the largest ones. However, because of subjectivity of the cone angle measurements these results are largely inconclusive.

Investigating the post-injection spray structure shows no surprising changes from what was observed during the examination of the developed spray. It can be observed that the different spray acceleration during the injection events, led to different penetration length in later stages. Again, the effect of ethanol addition during in the slow evaporation regime is minimal and no significant differences can be seen for the different blends. Differences in spray behavior of the different ethanol blended fuels are seen in the disruptive evaporation regime around 60°C before disappearing again as the fuel temperature is increased to 80°C.

Figures 5.37(a) and 5.37(b) show the post-injection penetration lengths measured through Schlieren and Mie Scattering techniques at 3.0 and 5.0 ms ASOF. A consistent increase in the penetration length is observed for higher temperature conditions. Comparing the data further, it can be seen that the impact of temperature shown in Schlieren images is again opposite to that shown in the Mie Scattering results. For instance, it can clearly seen, at 80°C, that E80 has the lowest penetration in Mie Scattering while in Schlieren it has the longest one; for E5 this trend is reversed. Again, this is thought to be related to the relative evaporation rates of the two fuel blends. A comparatively longer penetration length for a particular fuel in the Schlieren images combined with a comparatively shorter penetration length in Mie Scattering images suggests a higher evaporation rate for the fuel blend under investigation.
Figure 5.37(a): Combined effect of Ethanol content and fuel temperature on the Post-injection spray Penetration Vs temperature @ t=3.0 and 5.0 ms ASOF P=100 bar and T=20,40,60,80°C Fuels: Reference, E5,E10,E22,E80 (Extracted from Schlieren Images)
Figure 5.37(b): Combined effect of ethanol content and fuel temperature on the Post-injection spray penetration vs temperature at t=3.0 and 5.0 ms ASOF. P=100 bar and T=20,40,60,80°C Fuels: Reference, E5, E10, E22, E80 (Extracted from Mie Scattering Images)
5.6 Assessment of experimental errors

The sources of error in this study can be partly attributed to shortcomings in the experimental apparatus and partly to a degree of unavoidable non-repeatability that is associated with the operation of a pulsed device such as a fuel injector in a single-shot mode. However, as will be examined shortly, the spray structure is itself subject to some instability.

The electronic delays associated with the imaging apparatus and the injection unit were known to be potential sources of temporal error. Since these temporal errors were not attributable to one single piece of equipment and were therefore difficult to eliminate, each movie (frame set) was been investigated carefully to accurately identify the start of fuel injection. Once the start of fuel injection is marked, and knowing that each movie is of high temporal resolution due to the very short interval of frame grabbing (50 µs), the temporal errors associated with both capturing apparatus and the injection units are essentially eliminated.

Various measures have been used through the experiments to ensure the precise measurement of temperature and pressure. However, some limitations were noted; for instance, the halogen light used in the Mie Scattering experiments was found to generate a significant amount of heat. Recalling that the results in the disruptive evaporation regime were found to be highly sensitive to temperature change for both E5, and to some extent for E22, there is some concern that the experimental apparatus may have unduly influenced the results in these cases.

The injected spray is also subject to variability due; firstly, to the uncertain shot-to-shot repeatability of the injection event, and secondly, to the consistency of the spray behavior after injection. To investigate the stability of the spray structures a probability imaging technique (described in chapter 4) was employed. The resulting images show discrete regions associated to a level of probability that there is liquid fuel present at the corresponding spatial location. Figure 5.38 through 5.41 present the probability images of five blends and four fuel temperatures at six discrete times ASOF.
Figure 5.38: probability images for swirl-type injector – Mie Scattering
Fuels: Reference, E5, E10, E22, E80 Fuel temperature: 20, 40, 60, 80°C time: 0.05, 0.1 ms ASOF
Figure 5.39: probability images for swirl-type injector – Mie Scattering
Fuels: Reference, E5, E10, E22, E80 Fuel temperature: 20, 40, 60, 80°C Time: 1.5, 2.0 ms ASOF
Figure 5.40: probability images for swirl-type injector – Mie Scattering
Fuels: Reference, E5, E10, E22, E80 Fuel temperature: 20, 40, 60, 80°C Time: 3.0, 4.0 ms ASOF
Figure 5.41: probability images for swirl-type injector – Mie Scattering
Fuels: Reference, E5, E10, E22, E80 Fuel temperature: 20, 40, 60, 80°C time: 5.0, 10.0 ms ASOF
As shown in the images, there is little variability in the liquid phase distributions during the injection event itself ($t < 1.5$ ms ASOF). As the time after injection elapses, the spray cloud becomes less consistent in shape – as can be seen in the images acquired at $10.0$ ms ASOF. This is to be expected. Fuel composition and temperature may also have effect the stability of spray. Considering the images shown in Figures 5.39 through 5.42 suggest that increasing temperature may also increase instability – especially at fuel temperature of $60^\circ$C. However the qualitative investigation of these images is difficult as some subjective input is required.

5.7 Conclusion

Through this chapter the development of spray injected from a high pressure swirl type injection were investigated and the results accurately match with literature predictions. Three main stages were identified including early spray (transient), fully developed spray and post-injection spray.

The effect of temperature on the spray structure also investigated and similar behavior observed for different blends as temperature increased. Therefore, the Reference fuel was chosen as a sample to present these effects in this chapter. However, the effect of temperature, despite the same behavior, could be more or less intense by different composition. In general, increasing the temperature causes the spray condition to change from the slow evaporative regime to the disruptive evaporation and further to flash boiling. It was observed, as the spray evaporation rate increases it penetrates faster and further. Furthermore, this increase in penetration was mainly caused by the spray collapse that was directly related to the temperature. On the other hand, the pre-swirl spray behaves differently and its penetration reduced by increasing the temperature and it does not actually exist in the case of the flash boiling spray.

The effect of ethanol content was also, investigated both in isolation and also in conjunction with fuel temperature. The observations show that in slow evaporation and flash boiling sprays, the ethanol content effects is insignificant. The ethanol content alters the spray characteristics noticeably only when the spray is in the disruptive evaporation regime. This was more noticeable when fuel temperature was $60^\circ$C especially in the case of the E5 and E22 blends.
Chapter 6

Result and Discussion - Multi-hole Injector

In the last chapter, the results related to high-pressure swirl-type injector were presented and discussed. The following chapter will cover the results and discussions related to a high-pressure multi-hole injector.

6.1 Introduction

The results and discussion related to a six-hole injector are presented through this chapter. The procedure of acquiring and processing the information from experiments was largely similar to the swirl-type injector studies that were presented in the previous chapter. Again, the investigations were performed in order to identify the effects of fuel temperature and fuel ethanol content on the spray characteristics. In reading this chapter, it is important to note that the body of literature on the behavior of multi-hole injectors in DISI applications is much more limited in comparison with the number of published results concerning swirl-type injectors. Therefore, much of the discussion that is presented in this chapter refers to new or extended observations not previously reported. Note also that the error analysis associated to this set of experiments is presented in §6.6 to comply with logical structure of the chapter, however, reader might find it useful to review error analysis before going through the results and their associated discussions.

Same with chapter 5, before getting to the results it would be useful to consider the error associated with the penetration length measurements. To investigate quantitatively the spray instability and to subsequently calculate the associated errors, the spray penetration of each set of images was measured (Mie scattering data). The standard deviation of the measurements for all fuel blends with different temperature during the time period 0.0 to 5.0 ms ASOF are shown in Figure 6.1(a) and 6.1(b). Based on the measured standard deviation, standard error was also calculated. However, since the amount of error was in the same order of magnitude with the marker points on the graphs, the error bars were not located in the graphs.
Figure 6.1(a): Standard deviation of spray penetration length measurements Fuels: Reference, E5, E10, E22, E80 Fuel temperature: 20, 40°C Time: 0.0 to 5.0 ms ASOF
Figure 6.1(b): Standard deviation of spray penetration length measurements. Fuels: Reference, E5, E10, E22, E80. Fuel temperature: 20, 40, 60, 80°C. Time: 0.05, 0.1 ms ASOF.
The results indicate that there is a large amount of variability in the spray structure during the period 0.0 – 0.5 ms ASOF, regardless of the fuel composition and temperature. Recalling the results presented in chapter 5, it is shown the transient phase of multi-hole spray is much smaller than that of the swirl-type injector. From 0.5 ms ASOF onwards, the spray’s stability is altered by changing the fuel composition and temperature.

Note that the level of variability in spray penetration for the multi-hole injector is substantially different from that was observed for the swirl type injector in chapter 5. As shown in Figure 6.1(a), 6.1(b) the E5 blend exhibit the most consistent behavior at all of the temperatures under consideration. The fuel blends show varying degrees of stability at different temperatures, the behavior of all of the fuel blends being most consistent with one another at 80°C. The results for the sprays at a 60°C fuel temperature indicate that the shot-to-shot variability in the spray penetration is at its highest during the disruptive evaporation regime. Note that, considering both spray instability as well as the amount of error associated to each fuel at certain temperature and time ASOF is essential for reaching to any conclusion from earlier discussions.

6.2 The development of the multi-hole injector spray – baseline case

In general, the spray development process for the multi-hole injector is expected to be more complex in comparison with a swirl-type injector spray because there are more physical mechanisms involved in determining the spray structure. In this work, the multi-hole injector spray development process was considered in two discrete phases; the injection event and the post injection development of the fuel cloud. Spray development during the injection event (0.0 - 1.5 ms ASOF)

Figures 6.2 and 6.3 present the Schlieren and Mie Scattering images of the fuel spray associated to fuel injection period for the baseline case of the Reference fuel at a temperature of 20 °C. At the start of fuel injection, discrete cylindrical columns of fuel were noted exiting the injector. These columns were subsequently to disintegrate (through interaction with the surrounding air) forming six individual plumes.
Note that due to the viewing angle it is not possible to discern all six spray plumes in the author’s images. It is worthy of note that, unlike the swirl type sprays previously examined, there is no cluster of large droplets visible ahead of the spray plumes in the multi-hole injector sprays. This is consistent with previous observations of multi-hole injector sprays available in the literature [Lippert et al., 2004].
The author's images clearly show the individual plumes to widen as they move away from the nozzle. This is also observed by Nauwerck et al. [2005]. The explanation suggested by the authors of previous research is that the air resistance to the spray increases as the spray breaks up into smaller drop sizes. This causes a deceleration of the spray's leading edge while, upstream, the jet is still pushing. This phenomenon makes the jet wider at its front end. The widening the individual jets may significantly alter the sprays behavior if the widening of the individual plumes is sufficient as to allow two or more plumes to combine. The effects of merging plumes will be discussed in detail later in the chapter.

**Figure 6.3:** Injection event spray structure of multi-hole injector
Reference fuel at P=100 bar and T=20°C time: 0.0 to 1.5 ms ASOF - (Mie Scattering Images)
Chapter 6: Result and Discussion - Multi-hole Injector

Figure 6.4 shows the axial penetration of the baseline spray as measured from both Schlieren and Mie imaging techniques.

![Multihole Injector injection spray](image)

*Figure 6.4: Injection event spray tip penetration of multi-hole injector
Reference fuel at P=100 bar and T=20°C time: 0.0 to 1.5 ms ASOF
(Extracted from Schlieren & Mie Scattering)*

The data shows the penetration rate of the sprays to be almost linear over the approximate range of 0.0 – 0.6 ms ASOF, at this time there appears to be a distinct change in the penetration rate. The penetration rate in the period 0.5 – 1.5 ms ASOF is again linear – although the rate of penetration is reduced from that seen during the early spray penetration.

It is interesting to note that the penetration length measured from the schlieren images (representing the liquid and vapor phases of the spray) are again longer than the penetration lengths measured from the Mie images (liquid phase only). This result suggests that the leading edge of the spray structure is comprised mainly of vapor phase fuel. Figure 6.5 presents the shadowgraph images of the spray development in this period.
6.2.1 Post-Injection spray penetration (1.5 – 10.0 ms ASOF)

The penetration length of the spray for the post injection period extracted from both Schlieren and Mie Scattering is presented in Figure 6.6. The shape of the two penetration curves are consistent with one another and indicate that the vapor phase penetration and the liquid penetration follow a uniform pattern. As seen earlier in figure 6.3, the penetration length associated to the Mie scattering images is slightly lower than that found the Schlieren data. It can be seen that at later acquisition times (> 5.0 ms ASOF) the spray velocity decreases significantly. Perhaps surprisingly, by comparing the
two data sets at around 9.0 ms ASOF it is found that the penetration lengths extracted from the Schlieren and Mie Scattering are very similar. The author believes that the observed decrease in penetration length of both the liquid and the vapor phase of the spray may be caused by a reduction in the evaporation rate of the fuel with time as the fuel cloud propagates further downstream from the injector.

Figure 6.7 presents the Schlieren images of the post-injection spray / fuel cloud. The results show that, after the end of fuel injection, the tail of the spray (which still has significant injector induced momentum) penetrates rapidly in the axial direction; at some point catching the slower moving front end of the spray. This phenomenon can be explained by considering the air flow pattern in the near-nozzle region (explained in chapter 3). As reported by Nauwerck at co-workers [Nauwerck et al., 2005], an induced air flow upstream of the plumes causes the tail of the spray to penetrate axially rather than radially. The Mie-Scattering images presented in Figure 6.8 are consistent with the Schlieren images and show the same phenomena.

Another point of note that can be observed in both the Schlieren images shown in Figure 6.7 and the Mie Scattering images shown in Figure 6.8 is the unbalanced penetration of one of the plumes. The cause of this unbalanced penetration is not known.

![Multihole Injector Post-injection spray](image)

**Figure 6.6:** Post-injection spray tip penetration versus time (multi-hole injector)  
Reference fuel at P=100 bar and T=20°C time: 1.5 to 10.0 ms ASOF  
(Extracted from Schlieren & Mie Scattering)
Figure 6.7: Post-Injection spray structure of multi-hole injector
Reference fuel at P=100 bar and T=20°C time: 1.5 to 10.0 ms ASOF
(Schlieren Images)
Figure 6.8: Post-Injection spray structure of multi-hole injector
Reference fuel at P=100 bar and T=20°C time: 1.5 to 10.0 ms ASOF
(Mie Scattering Images)
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As discussed in this section, the spray development for a multi-hole injector is observed to be relatively simple for the baseline case that was considered (the author’s Reference fuel at a fuel temperature of 20°C).

6.3 The effect of temperature on the spray structure of the multi-hole injector – reference fuel

Although the spray development in the case of multi-hole injector did not show any complexities under the slow evaporation condition examined in the previous section of this work, increasing the fuel temperature was found to change the spray shape significantly, involving a number of additional mechanisms shaping the spray. Figures 6.9(a) through 6.10(b) show the penetration length data for the reference fuel at four different fuel temperatures measured from the Schlieren and Mie scattering studies, respectively.

Figures 6.9(a), 6.9(b), extracted from Schlieren images, show the penetration length curves for all of the fuels over the full time period from 0.0 to 10.0 ms ASOF. It can be seen that the spray penetration for the 80°C case, is initially lower than for the other temperatures. However at around 0.9 ms ASOF, the penetration rate for the 80°C case suddenly appears to increases – to the extent that from around 2.0 ms ASOF the penetration length of the 80°C spray exceeds that for all of the other fuels. In the 60°C fuel temperature case a similar phenomenon is observed; the penetration data suggests that there is an increase in penetration rate at around 3.0 ms ASOF. Despite its initially shorter penetration length, the penetration length of the 60°C case exceeds the penetration length associated to the fuel temperatures of 20°C and 40°C at around 5.5 ms ASOF. Subsequently, the penetration length for the 60°C case remains above those of the 20°C and 40°C cases but does not reach or exceed the penetration length associated with the 80°C fuel temperature at any time. Similar behavior is also noted for the 40°C penetration data. The penetration rate associated to this temperature increases at approximately 6.5 ms ASOF causing the penetration length of the spray to cross the curve associated to reference fuel spray penetration at 20°C.
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Effect of temperature on Multi-hole injector spray
P=100 bar Temp:20,40,60,80°C Reference fuel
(extracted from Schlieren images)

![Graph showing effect of temperature on multi-hole injector spray](image)

Figure 6.9(a): Temperature effect on Spray (multi-hole Injector) Penetration length Vs Time ASOF
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Reference fuel at P=100 bar and T=20, 40, 60, 80°C Time: 0.0 to 10.0 ms ASOF
(Extracted from Schlieren images)

(ii) 1.5 to 5.0 ms ASOF

Figure 6.9(b): Temperature effect on Spray (multi-hole Injector) Penetration length Vs Time ASOF
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Reference fuel at P=100 bar and T=20, 40, 60, 80°C Time: 0.0 to 10.0 ms ASOF (Extracted from Schlieren images)

**Effect of temperature on Multihole injector spray**
P=100 bar Temp: 20, 40, 60, 80°C Reference fuel
(extracted from Mie Scattering images)

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**Figure 6.10(a):** Temperature effect on Spray (multi-hole Injector) Penetration length Vs Time ASOF
Reference fuel at P=100 bar and T=20, 40, 60, 80°C Time: 0.0 to 10.0 ms ASOF
(Extracted from Mie scattering images)
Figure 6.10(b): Temperature effect on Spray (Multi-hole Injector) Penetration length Vs Time ASOF Reference fuel at \( P=100 \) bar and \( T=20, 40, 60, 80^\circ C \) Time: \( 0.0 \) to \( 10.0 \) ms ASOF (Extracted from Mie scattering images)
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The data extracted from Mie Scattering images also show the same behavior, albeit occurring at different times ASOF in each case. For instance, in case of curve associated to fuel temperature of 40°C, it does not pass the 20°C data until approximately 10.0 ms ASOF. Note that, although data is shown for the period 0.0 to 10.0 ASOF, the most relevant data is that obtained prior to 5.0 ms ASOF since the penetration length at this time is more than 100.0 mm – longer than the stroke length of most of gasoline engines. Figure 6.11 presents the Schlieren images for different fuel temperatures.

![Schlieren Images]

**Figure 6.11:** Effect of temperature on spray shape
Reference fuel at P=100 bar and T=20, 40, 60, 80°C, time: 0.0 to 10.0 ms ASOF (Schlieren Images)

Looking at the penetration lengths at 10.0 ms ASOF indicates that increasing the fuel temperature ultimately increases the penetration length of the sprays from a multi-
hole injector. However, this final sorting according to fuel temperature only exists after a substantial period of time has elapsed. During the injection event, and in the time period of most relevance to engine applications, this ordering does not exist and the relative penetration lengths of the fuels are changing continuously.

Correlating the data shown in figures 6.9(a) through 6.10(b) with the corresponding Schlieren and Mie-Scattering images, presented in Figure 6.11 and 6.12 (overleaf), provides some insight into the origins of this phenomenon. As the fuel temperature is increased there is clearly notable change in the structure of the sprays.

**Figure 6.12:** Effect of temperature on spray shape
Reference fuel at P=100 bar and T=20, 40, 60, 80°C time: 0.0 to 10.0 ms ASOF (Mie Scattering Images)
Figure 6.13 shows the effect of fuel temperature on the initial cone angle of the reference fuel sprays. It is seen that as fuel temperature increases so the initial overall cone angle increases. From this it may be inferred that the initial cone angle of each of the individual plumes also increases with temperature. This increase is wholly consistent with previous observations of multi-hole DISI sprays [Zhao et al., 2002]. Note that, although the increase in initial cone angle is real and substantial, the distance from the injector that is used in measuring the initial cone angle can alter the measurement value significantly.

Figure 6.13: The effect of temperature on the initial cone angle of the multi-hole injector
P=100 bar, Fuel: Reference, Time: 1.0 ms ASOF Temperature: 20, 60, 80°C
(Extracted from Shadowgraph images)

Although increasing fuel temperature is shown to increase the initial cone angle of individual plumes the physical cause of the increase is not clear. Nevertheless, this increase in initial cone angle may be an additional factor (along with the increase in drag force that was discussed earlier in this chapter) contributing to the obvious widening of
the plumes seen at higher fuel temperatures. The effect of temperature on the plume width of the reference fuel is illustrated in the lower row of shadowgraph images presented in Figure 6.14.

The widening of the individual spray plumes leads to the first mechanism that contributes towards increasing the later penetration rate of the spray. As the edges of the plumes reach each other the individual plumes combine to form a fewer number of plumes. In the multi-hole injector used in this study, six holes are aligned on a circular pattern. Therefore, when these six individual plumes combine they create what is, in effect, a hollow-cone shape spray – albeit without any swirl motion. This phenomena has been observed by a number of previous researchers [Nauwerck et al., 2005; Dahlander et al., 2006, and Zhao et al., 2002].

![Figure 6.14: Effect of temperature on plume width for Multi-hole injector spray](image)

The second mechanism contributing to the increase in spray penetration is related to the combination of the plumes. As the plumes combine to form a hollow cone structure
it is reasonable to expect that a low-pressure zone will be formed in the spray core. The resultant pressure difference across the spray walls – along with rotating airflow induced by plumes and the axial momentum of the droplets – causes the spray to collapse almost immediately. The collapse of the spray, which is clearly shown in the author's results, is visually similar to that seen when swirl-type sprays collapse, even the counter rotating vortexes are observed. The spray collapse causes a flux of fine droplets to rush through the spray core and penetrate faster than the rest of the spray. The major difference between the multi-hole and swirl type spray that has been observed in this study with respect to spray collapse is related to the timing of the event. In the case of the multi-hole injector, the author's results indicate that spray collapse can occur well after the end of injection, while in swirl type injectors the collapse of the spray structure was observed during injection. The collapse of multi-hole injector sprays has been previously reported in the literature [Nauwerck et al., 2005; Dahlander et al., 2006, and Zhao et al., 2002]. However, only Zhao [Zhao et al., 2002] describes the second mechanism of collapse as discussed in this section. The present work extends the knowledge regarding the behavior of these sprays by clearly demonstrating that as the fuel temperature increases the sprays collapse at an earlier stage and hence closer to the injector tip. The collapse of the spray results in a sudden increase in axial penetration rate. The shadowgraph images presented in Figure 6.15 shows this event during the injection period.

To summarize the effect of temperature on the spray shape and structure, correlating all the images and graphs presented in this section it can be concluded that as the fuel temperature increases the penetration length initially decreases. As shown in Figure 6.15, the penetration length associated with an 80°C fuel temperature at an acquisition time of 0.5 ms ASOF is substantially shorter than either the 20°C or 60°C cases. At later times ASOF, the two mechanisms of combination and collapse come into play. Increasing fuel temperatures cause the sprays to collapse ever earlier and closer to the tip of injector. Researchers have suggested that flash boiling of the spray is responsible for this early plume combination and therefore the subsequent collapse of spray [Schmitz & Leipertz, 2006; Dahlander et al., 2006; Nauwerck et al., 2005; Zhao et al., 2002].
Figure 6.15: Effect of temperature on spray shape
Reference fuel at $P=100$ bar and $T=20, 60, 80^\circ C$ time: 0.2, 0.5, 1.0 and 1.5 ms ASOF
(Shadowgraph Images)
The combination of the spray plumes and the subsequent collapse of the spray structures result in a sudden increase in axial penetration rate. It is interesting to note that, although the penetration of the spray cloud at 10 ms was shown to increase with increasing fuel temperature, the effects under more engine relevant conditions are less clear. If we assume a target penetration distance of 70 mm, it can be seen that the 80°C fuel spray would penetrate to this limit first. The 80°C spray would be followed by the 20°C fuel spray and subsequently by the 40 and 60°C sprays, in that order. It is interesting that for this condition, distance wise, the penetration times of both the hot and cold sprays are shorter than those of the two sprays of intermediate fuel temperature.

6.4 Effect of ethanol content on spray structure

The investigations of multi-hole fuel sprays have shown a significant impact of temperature on the spray structure and have suggested two interesting mechanisms governing spray collapse. As for the case of the swirl type spray, no major effect on spray structure is predicted when varying the fuel ethanol content at a baseline temperature of 20°C. However, although it was considered unlikely to be important in this context, there are differences between the breakup mechanisms of the two fuel injector types. Therefore, for completeness, the results for the penetration length versus time for five blends with different ethanol content at a fixed fuel temperature of 20°C are considered (Figures 6.16(a) through 6.17(b) refer). Note that the low fuel temperature is chosen to minimize any volatility effects and hence allow the investigation of the more physical effects of ethanol content on the fuel properties (surface tension, density, viscosity, etc.).

The results indicate that there is no significant effect on the spray structure that might be attributed to the ethanol content of the fuels alone. The data extracted from the Schlieren and Mie Scattering images are highly consistent with a slightly longer penetration length shown for the Schlieren measurements in comparison with the Mie Scattering data. During the injection event (0.0 to 1.5 ms ASOF), all of the penetration lengths associated with different blends increase regularly and no significant differences were observed.
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Effects of ethanol content on Multihole spray structure
Penetration length Vs Time (Schlieren images)
P=100 bars, Temp=20 °C time (0.0 to 10.0 ms ASOF) Fuels: Reference, E5, E10, E22, and E80

Figure 6.16(a): Effect of ethanol content on spray structure (Multi-hole injector) Penetration length Vs Time P=100 bar and T=20°C time:0.0 to 10.0 ms ASOF, Fuels: Reference, E5, E10, E22, E80 (Extracted from Schlieren images)
Figure 6.16(b): Effect of ethanol content on spray structure (multi-hole injector) Penetration length Vs Time P=100 bar and T=20°C time:0.0 to 10.0 ms ASOF, Fuels: Reference, E5, E10, E22, E80 (Extracted from Schlieren images)
Figure 6.17(a): Effect of ethanol content on spray structure (multi-hole injector) Penetration length Vs Time. P=100 bar and T=20°C time: 0.0 to 10.0 ms ASOF, Fuels: Reference, E5, E10, E22, E80 (Extracted from Mie Scattering images)
Figure 6.17(b): Effect of ethanol content on spray structure (multi-hole injector) Penetration length Vs Time P=100 bar and T=20°C time:0.0 to 10.0 ms ASOF, Fuels: Reference, E5, E10, E22, E80 (Extracted from Mie Scattering images)
In the immediate post-injection stage, from 1.5 to 5 ms ASOF, the penetration data associated to the Schlieren images do not show any considerable difference between fuels. However, in the graphs extracted from Mie Scattering images, E22 and E80 show a slight increase in the liquid phase penetration length, approximately 8-10 mm.

After 5 ms ASOF, there is hardly any increase in penetration length in comparison with earlier data extracted from Schlieren images. Furthermore, the experimental data points are seen to spread on the range with no specific order that can be related to the measurement technique. Therefore, no reliable information can be extracted from graphs associated to the Schlieren measurements after 5 ms ASOF. In the graphs associated to the Mie Scattering data, the difference observed in the penetration lengths of the E22 and E80 fuel blends are maintained. The other fuels do not show any considerable difference in their penetration lengths during this period.

6.5 Combined effect of ethanol content and temperature on the spray structure

As described above, the impact of reference fuel temperature on spray structure is notably more significant in comparison with the impact of ethanol content at 20°C. However, the impact of changing the volatility of the fuel blend, which results from adding varying amounts of ethanol to the base fuel, may be significant when combined with simultaneous variations in fuel temperature. It is therefore necessary to compare the spray structure of the blends at certain, fixed, temperatures in order to determine the combined effects of temperature and fuel ethanol content on the spray characteristics of the multi-hole injector. Figures 6.18(a) through 6.19(b) present the temporal variation in the penetration length of the five fuel blends under investigation (Reference fuel, E5, E10, E 22 and E80) at four different fuel temperatures (20, 40, 60, and 80°C).

Examination of the Schlieren data presented in Figure 6.18(a) and 6.18(b) suggest that, for fuel temperatures of 20°C and 40°C, the ethanol content of the fuel has no significant effect on the vapor phase penetration of the spray.
Figure 6.18(a): Combined effect of fuel temperature & ethanol content on spray structure
P=100 bar and T=20, 40, 60, 80°C time: 0.0 to 10.0 ms ASOF, Fuels: Reference, E5, E10, E22, E80
(Extracted from Schlieren images - multi-hole injector)
Figure 6.18(b): Combined effect of fuel temperature & ethanol content on spray structure
P=100 bars, T=20, 40, 60, 80°C time: 0.0 to 10.0 ms ASOF, Fuels: Reference, E5, E10, E22, E80
(Extracted from Schlieren images – multi-hole injector)
Figure 6.19(a): Combined effect of temperature & Ethanol content on spray structure
P=100 bar and T=20, 40°C time: 0.0 to 10.0 ms ASOF, Fuels: Reference, E5, E10, E22, E80
(Extracted from Mie Scattering - Multihole injector)
Figure 6.19(b): Combined effect of temperature & Ethanol content on spray structure
P=100 bar and T=60, 80°C time: 0.0 to 10.0 ms ASOF, Fuels: Reference, E5, E10, E22, E80
(Extracted from Mie Scattering - multi-hole injector)
Recalling from chapter 4, the lightest component of the fuel mixtures is isopentane, which has a normal boiling temperature of 27.85°C. When the fuel temperature is at 20°C it is therefore well below both the isopentane and normal boiling temperature of ethanol, which is 78°C. Accordingly, the rate of evaporation is expected to be too slow as to disrupt the spray structure. At fuel temperature of 40°C, although it is slightly higher than the initial boiling temperature of the fuel, it is still well below the boiling temperature of the ethanol. Therefore, a greater evaporation rate could be expected. The experimental results suggest that, for the majority of fuel blends, the increased evaporation rate at 40°C is still not sufficient as to disrupt the spray shape or penetration. Some slight indication of disruptive evaporation can be observed at this temperature for the Reference fuel and the E10 blend.

Interestingly, the results show the fuel temperature of 60°C to be the most critical temperature affecting the differential penetration of the fuel blends under investigation. This temperature is thought high enough to cause flash boiling of the higher volatility components within the fuel while also promoting a faster evaporation of the ethanol. Note however, that the non-ideal behavior of alcohols (such as ethanol) and hydrocarbon blends is likely to influence the evaporation process. Finally, as the fuel temperature reaches 80°C, the effect of ethanol content is diminished. One possible explanation for this reduction in the spray’s sensitivity to fuel composition is that the fuel temperature of 80°C is higher than the boiling temperature of a significant fraction of each blend. Therefore, violent evaporation (flash boiling) would be expected to occur early enough in each fuel blend as to cause the individual sprays to behave in a similar manner.

As for the liquid phase of the spray, the graphs presented in Figure 6.19(a) and 6.19(b) again indicate that, in agreement with the liquid and vapor phase results discussed above, ethanol content does not significantly affect the spray structures for fuel temperatures of 20°C and 40°C. An effect is seen at a fuel temperature of 60°C while again the spray penetration length at 80°C is, for the most part, unaffected by the blend composition (although the results for the E5 and E22 blends seem to indicate a shorter liquid penetration length for these two fuels). From above it can be seen that both the Mie and Schlieren results indicate that there is some effect of fuel composition on the behavior of the sprays at 60°C.
Figure 6.20(a) and 6.20(b) presents the spray behavior of the different fuel blends under investigation at this specific temperature.

**Figure 6.20(a):** Effect of ethanol content on spray structure
Temperature: 60°C, Fuel: Reference, E5, E10, E22, E80, Time: 0.0-5.0 ms ASOF
(Extracted from Schlieren and Mie Scattering images)
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Penetration length Vs Time extracted from Mie Scattering images
P=100 bars, Temp=60 °C time (0.0 to 2.5 ms ASOF) Fuels: Reference, E5, E10, E22 and E80

Penetration length Vs Time extracted from Mie Scattering images
P=100 bars, Temp=60 °C time (2.5 to 5.0 ms ASOF) Fuels: Reference, E5, E10, E22 and E80

**Figure 6.20(b):** Effect of Ethanol content on spray structure
Temperature: 60°C, Fuel: Reference, E5, E10, E22, E80 time: 0.0-5.0 ms ASOF
(Extracted from Schlieren and Mie Scattering images)
Investigating the period of 0.0 to 2.5 ms ASOF in the Schlieren data suggests that the E22 blend is the most volatile of the fuels. In the early stages of the spray development, E22 penetrates more slowly than the other fuels – as shown earlier in this chapter this behavior is well correlated to an increased level of atomization and evaporation. Later on, at approximately 1.0 ms ASOF, the spray structure collapses causing the penetration rate to increase relative to the other fuel blends. The other blends do not appear to exhibit the same trend.

Investigating Figure 6.20(a) and 6.20(b) further, the data extracted from the Mie scattering images shows the E22 blend to penetrate less than the combined vapor/liquid phase image taken from the schlieren results. This is consistent with the liquid fuel being led by the vapor phase as reported in the literature [Nauwerck et al., 2005]. More surprisingly, the E10 blend and the Reference fuel are found to penetrate further in the Schlieren data than in the Mie scattering data at 5.0 ms ASOF. This result suggests some error in the experiments that requires further examination.

Additional shadowgraph imaging experiments were performed in order to investigate the spray collapse and flash boiling of the multi-hole sprays. Figure 6.21 (overleaf) shows the shadowgraph images of Reference, E22 and E80 fuel blends for the temperature range from 60°C up to 95.5°C (the upper temperature limit of the available equipment) at 0.5 ms ASOF. Note that these three fuel blends were chosen for further study because they contain significantly different amounts of ethanol.

Careful observation of these images suggests that the E80 blend enters the disruptive evaporation regime at a temperature of approximately 64°C while the Reference fuel exhibits signs of disruptive evaporation at around 68°C. Surprisingly, the images suggest that E22 enters the disruptive regime later than two other fuels at around 72°C. The results further suggest that the violent evaporative (or flash boiling) regime starts around the same temperature for all of fuels, at approximately 90°C.
Figure 6.21: Combined effect of temperature and Ethanol content on spray structure - Multi-hole injector
P=100 bar, Temperature: 60 to 95.5°C, Fuel: Reference, E22 and E80, time: 0.5 ms ASOF (Shadowgraph images)
Figure 6.22, below, shows the combined effects of temperature and ethanol content on the initial cone angle of the multi-hole sprays.

![Graph showing combined effect of temperature and ethanol content on initial cone angle](image)

**Figure 6.22:** The combined effect of temperature & Ethanol content on spray initial cone angle

P=100 bar, Temperature:20,60,80°C Fuel: Reference, E5, E10, E22, E80 time:1.0 ASOF

(Extracted from Shadowgraph images - Multi-hole injector)

As shown in this graph, the initial angle of the spray associated with the reference fuel increases linearly with temperature. The addition of ethanol to the fuel appears to cause a steep increase in cone angle when the fuel temperature reaches to 80°C. It should be mentioned that, in the case of multi-hole injector, it was not possible to measure the
Figure 6.22, below, shows the combined effects of temperature and ethanol content on the initial cone angle of the multi-hole sprays.

As shown in this graph, the initial angle of the spray associated with the reference fuel increases linearly with temperature. The addition of ethanol to the fuel appears to cause a steep increase in cone angle when the fuel temperature reaches to 80°C. It should be mentioned that, in the case of multi-hole injector, it was not possible to measure the
included angle of the individual plumes. Moreover, the measurement of the spray angle is not an error free procedure due to the subjectivity associated with its measurement.

To summarize this section of the work, the full range of experimental results suggest that the impact of ethanol content for the multi-hole injector sprays is not significant over the slow evaporative regime (20 to 40°C), nor is it significant in the violent evaporative or flash boiling regime (minimum fuel temperature of 90°C). The impact of ethanol is discernable only at the intermediate temperatures of the disruptive regime (between 60°C up to 88°C). Note that the impact of flash boiling on these ethanol blended fuel is consistent with previous studies on multicomponent fuel presented in [Schmitz & Leipertz, 2006; Dahlander et al., 2006; Nauwerck et al., 2005]

6.6 Error analysis

The error analysis presented in this section is essentially identical in content to that presented in chapter 5. However, for the multi-hole injector considered in this chapter, the observed variability of the spray was found to differ substantially from the pressure-swirl results.

The following probability images (obtained through the same technique as described in chapter 5) show the different regions associated to the probability of liquid fuel at a particular spatial location within the image. Figures 6.23 through 6.26 presents the probability images of the five fuel blends and four fuel temperatures at certain times ASOF.

As shown in the images, the spray structure is highly consistent during the early development stage; however, as the time ASOF increases the variability in the spray becomes progressively greater (as can be seen in images associated to 10.0 ms ASOF). Note however that only measurements recorded prior to 5.0 ms ASOF will be considered further in this discussion.
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Figure 6.23: Probability images for multi-hole injector – Mie Scattering
Fuels: Reference, E5, E10, E22, E80 Fuel temperature: 20, 40, 60°C time: 0.5, 1.0 ms ASOF
Figure 6.24: Probability images for multi-hole injector – Mie Scattering
Fuels: Reference, E5, E10, E22, E80 Fuel temperature: 20, 40, 60, 80°C Time: 1.5, 2.0 ms ASOF
For this multi-hole injector, the results indicate that both fuel composition and temperature may affect the shot-to-shot variability of the spray. The images suggest that increasing temperature acts to decrease the consistency of the spray structure (particularly at a fuel temperature of 60°C).

Figure 6.25: Probability images for multi-hole injector – Mie Scattering
Fuels: Reference, E5, E10, E22, E80 Fuel temperature: 20, 40, 60, 80°C Time: 3.0, 4.0 ms ASOF
Figure 6.26: Probability images for multi-hole injector – Mie Scattering
Fuels: Reference, E5, E10, E22, E80 Fuel temperature: 20, 40, 60, 80°C Time: 5.0, 10.0 ms ASOF

6.7 Conclusions

Through this chapter the development of sprays injected from a high pressure multi-hole injector were investigated. Where such literature exists, the results are consistent with the experimental observations of other researchers in the field. Rather
than relying solely on the liquid jet disintegration mechanism, two other important mechanisms controlling the structure of these multi-hole sprays were observed - plume combination and hollow cone collapse.

The effect of temperature on the spray structure was also investigated and similar behavior was observed for different blends as temperature increased. Therefore, the Reference fuel was chosen as a sample to present these effects in this chapter. In general, increasing the temperature of the fuel was believed to progressively increase the evaporation of the fuel from a slow evaporative regime, through a disruptive evaporation and on to a flash boiling regime. It was observed that as the evaporation rate increases it cased the spray to penetrate faster and further. This increase in penetration was seen to be prompted by the collapse of the spray.

The effect of ethanol content was also investigated, both in conjunction with varying fuel temperature only by itself in isolation. The results show that the addition of ethanol to the base fuel does not significantly affect the structure of the sprays within the slow evaporation and flash boiling regimes. The ethanol content could alter the spray characteristics noticeably only when the spray was in disruptive evaporation regime. The effects of ethanol addition were most noticeable at a fuel temperature of 60°C. Finally, in this chapter, it should be noted that the observed effects of fuel ethanol content, although not negligible, were relatively small in comparison with the effects of varying fuel temperature.
Chapter 7

Conclusions and Recommendations for Future Work

This study was conducted in order to investigate the effects of fuel ethanol content and injector temperature on the spray characteristics of DISI atomizers. Five fuels of different ethanol content were injected into atmosphere at an injection pressure of 10.0 MPa through two prototype DISI fuel injectors (one single hole and one multi-hole design). The fuels were: a 5-component model fuel comprised of isopentane, iso-octane, n-octane, n-decane and dodecane, simulated E5 (5% ethanol 95% model fuel), simulated E10 (10% ethanol 90% model fuel), simulated E22 (22% ethanol, 78% model fuel), E80 (80% ethanol, 20% model fuel) and finally pure ethanol. The effect of each fuel on the global characteristics of the spray was examined at four different temperatures (20, 40, 60 and 80°C) through three different visualization techniques, Schlieren, Mie Scattering and Shadowgraph photography.

Schlieren photography was used to visualize the liquid-vapor phase mixture of the spray while the Mie Scattering photography was used to identify the liquid phase behavior. Later on, shadowgraph imaging was used to measure the initial cone angle and to examine qualitatively the structure of the injected sprays. The investigation was performed on a purpose-built experimental apparatus designed by the author and installed in the UBC Mechanical Engineering Department's Combustion Laboratory.

Various post-processing techniques were used to measure characteristic spray parameters from the acquired images. The main parameter used in this investigation was the spray penetration length. Initial cone angle measurements were performed to investigate the possible relationships between these parameters. This quantitative analysis was accompanied by a qualitative analysis that considered the temporal and spatial evolution of the spray through the full range of images obtained.
Chapter 7: Conclusions and Recommendations for Future Work

7.1 Summary and Conclusions

The spray characteristics of a swirl-type injector were investigated. The investigation was performed in the period 0.0 ms to 5.0 ms after the start of fuel (ASOF). Following the work of previous researchers, three different stages of spray development were defined; the early spray, the fully developed spray and the post-injection spray.

At the start of injection, a cluster of large droplets, often referred to as the pre-swirl spray, was noted to exit the injector with high velocity and propagate along the spray axis. Around 0.5 ms ASOF, a fully developed hollow cone shape spray was formed that continued propagating both axially and radially during the injection event. Two counter-rotating vortices were observed at the front end of the spray cone that kept moving even after the end of injection. Referring to literature, these vortices are formed by the airflow induced by a low-pressure region along the spray core. After the end of injection event (around 1.5 ms ASOF), the spray mainly followed the induced airflow while the rate of spray penetration kept decreasing.

Summarizing the key results for the pressure-swirl injector; increasing the fuel temperature did not show any significant impact on early spray formation. However, as the fuel temperature increased, the pre-swirl spray became less significant up to the point in which it was not distinguishable from the main spray at 80° C. The effect of fuel temperature on developed spray was seen to be significant only if the fuel blend became adequately superheated as to reach the disruptive (flash boiling) evaporation regime. An increased penetration length was noted at higher fuel temperatures. The results indicated that this increase was mainly caused by the collapse of the hollow cone spray structure.

With respect to the influence of changes in the fuel properties induced by the addition of ethanol to the blends, the results showed that there was no significant impact on the spray structure at 20°C. Investigations at higher fuel temperatures suggest some impact of fuel composition at the intermediate temperatures of 40 and 60°C. The observed differences in the spray behavior were small, however – of the same order as the experimental uncertainty – and therefore no definitive conclusions were drawn from the experimental results. Interestingly, the observed changes in spray structure at these
intermediate temperatures did not correlate well to the blended fuels’ ethanol content. All fuels were seen to behave similarly at 80 °C.

The average deviation of the penetration distance from the mean was calculated for each fuel composition at the four temperatures of interest. For all fuel compositions, the repeatability of the spray was relatively poor during the early injection period (up to 0.5 ms ASOF). The pressure-swirl sprays were seen to be most consistent at low fuel temperatures.

A similar set of experiments was performed on a multi-hole injector. In this case, the investigations were divided into the fuel injection phase, and the post-injection phase. Two important mechanisms controlling the structure of the multi-hole sprays were observed - plume combination and hollow cone collapse.

The effect of temperature on the multi-hole spray structure was investigated. In general, increasing the temperature of the fuel caused the spray to penetrate faster and further. The result indicates that this increase in penetration is prompted by the combination of individual plumes to form a pseudo hollow-cone spray which subsequently collapses in a similar manner to that observed in the case of the pressure swirl sprays.

The effect of blend ethanol content on the multi-hole sprays was also investigated, both in conjunction with varying fuel temperature and by itself in isolation. The results show that the addition of alcohol to the base fuel does not significantly affect the structure of the sprays within the slow evaporation and flash boiling regimes. The effects of ethanol addition are slight but noticeable at a fuel temperature of 60°C.

The results indicated that there was a large amount of variability in the multi-hole spray structure during the period 0.0 – 0.5 ms ASOF. From 0.5 ms ASOF onwards, the variability of the multi-hole injector sprays is sensitive to fuel composition and temperature. The level of shot-to-shot variability in the multi-hole injector case was significantly greater than for the pressure-swirl injector.

The two DISI injectors that were used in this research utilized different methods of atomization and, consequently, they show different behavior due to fuel temperature
and fuel composition and there can not be any direct comparison between their spray characteristics. However, the following concluding remarks can be made regarding the relative performance and sensitivities of the injectors:

- Sprays from the multi-hole injector show higher sensitivity to changes in fuel temperature, accordingly fuel composition has a stronger impact on the spray characteristics of the multi-hole injector in comparison with the swirl injector.
- The transient phase of swirl-type injector spray is larger in compare with multi-hole injector.
- The level of variability in spray penetration for the multi-hole injector is substantially greater than that observed for the pressure swirl type injector.
- The effects of ethanol content on the behavior of the sprays injected from either the pressure-swirl or multi-hole injector are slight, being obvious only at intermediate fuel temperatures (40 – 60°C)

7.2 Recommendations for Future Work

The existing combustion laboratory equipment provided the facility to investigate the macroscopic characteristics of DISI fuel sprays within a non-motored environment using simulated fuel injection strategies. The recommendations provided below will further increase the capabilities of the laboratory and provide greater understanding of the spray structure.

- It has been speculated throughout this text that many of the observed changes in spray structure result from changes to a spray’s drop size distribution. Although this is consistent with the literature, drop sizes have not been measured in this study. As a next step in this work, it is recommended that a droplet sizing be performed at various axial and radial distances from the injector tip.
- Plume combination and spray collapse have been shown to be significant mechanisms governing the penetration of multi-hole sprays. However, the spray behavior at collapse is not well captured by the existing experimental set-up. Accordingly, it is recommended that future studies employ two high-speed
cameras to investigate simultaneously both the axial and radial development of the spray. This would undoubtedly provide a better understanding of spray collapse particularly in case of multi-hole injector.

• The present studies have been performed at atmospheric pressure. However, in an engine it might be expected that the injector will operate under both sub-atmospheric and super-atmospheric conditions. It is therefore recommended that future works be performed with the injector in a pressure chamber so as to investigate the impact of backpressure on the macroscopic and microscopic spray characteristics as well as spatial and temporal evolution of the spray.

• The relationship between liquid phase and vapor phase fuel penetration is unclear. The use of diagnostic techniques, such as Laser Induced Exciplex Fluorescence (LIEF), that would allow the simultaneous imaging of both the liquid and vapor phases is recommended.

• The experimental results provide a range of data that would be useful for the validation of numerical spray predictions and the development of improved spray models. It is recommended that a numerical model of the sprays be developed as a concurrent research project with any future experimental studies.
Bibliography


inside a pressure chamber and a glass ring engine by multiple optical techniques.

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