**Investigation of the Effects of
Fuel Injection Nozzle Parameters
on
Ignition Delay and Cetane Number**

by

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Abstract

The work undertaken aims to determine the effects of fuel injection nozzle parameters on the ignition delay and cetane number as measured using ASTM test method D6890. To determine the effects of fuel injection nozzles on the ignition delay and cetane number, a test plan was developed employing the use of several experimental apparatus. A sample of 15 delay pintle type nozzles and a single typical diesel fuel were chosen for the study.

Each of the 15 nozzles was used to test CF12, a diesel reference fuel, according to ASTM D6890 using an Ignition Quality Tester (IQTTM) available from Advanced Engine Technology (AET). An optical spray pattern test rig was developed to analyze the spray pattern of the test nozzles. Internal geometry for each of the nozzles was then characterized in terms of choked flow rates according to ISO 4010 test methods using two test rigs that were designed and developed specifically for this task. Finally, accessible nozzle geometry was measured directly with the aid of a profile projector. All the obtained spray and geometry characteristics of each of the 15 nozzles were then compared to their corresponding ignition delay and cetane number values for examination and discussion.

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“ ... He who taught the use of the Pen, taught man that which he knew not.”

- The Noble Qur'an {96:04-05}

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Nomenclature

$\bar{h}$	Average convection heat transfer coefficient	
σ	Standard deviation	
A_s	Surface area	
API	American Petroleum Institute Specific Gravity	[°API]
DCN	Derived Cetane Number	[CN]
ID	Ignition Delay	[ms]
n	Number of readings	
q	Heat transfer rate	
T_∞	Combustion air temperature	
T_s	Surface temperature of fuel droplet	
x	Deviation of reading from estimated correct value	

Chapter 1

Introduction

The combustion of sprays of liquid fuels is of considerable technological importance to a variety of applications ranging from diesel engines to rocket motors. First introduced in the 1880's [1], spray combustion remains the major way of burning liquid fuels today.

A critical component in obtaining successful combustion of liquid fuels is the fuel injection nozzle. These nozzles are generally designed with two primary functions. First, they atomize or finely divide the metered fuel to promote ignition and combustion. The atomization or disintegration of the liquid fuel by the nozzle produces a spray of small droplets in order to increase the surface area resulting in a significant enhancement to the heat and mass transfer rates. Second, they distribute the fuel spray through the combustion chamber to mix with the air to obtain a combustible mixture. Given the key functions that the nozzle carries out, it is easily deduced that nozzle parameters such as its physical dimensions, and spray pattern produced could play a major role in the combustion quality of a given fuel.

In the diesel engine industry, a desirable combustion quality of fuels is easy auto-ignition under compression. A well established and regulated rating for this quality is the Cetane Rating. A high cetane number (CN) indicates a high performance diesel fuel that

auto-ignites faster and easier, while a low CN indicates a lower performance diesel fuel that auto-ignites slower and is harder to ignite. The cetane number for a fixed compression ratio is a function of the ignition delay of the fuel. A more thorough discussion of the cetane number and the ignition delay is given in Section 2.1.

The purpose of this research was to try to identify the effects of various nozzle parameters on the ignition delay and the cetane number. In the following sections, the overall scope of the research undertaken is presented and the objectives and tasks of the work carried out are outlined.

1.1 Motivation

Since the 1940's [2] the cetane number has been used to characterize the ignition quality of commercially available diesel fuels. The CN is a regulated diesel fuel specification and is used by the petroleum and automotive industries, and regulatory bodies to ensure diesel fuels produced are able to ignite as completely as possible in the allotted time. For the engine manufacturer, the CN becomes a key parameter when considering engine performance in terms of fuel efficiency, engine durability, and exhaust emissions.

One of the standard tests for determining the CN is an ASTM standard, test method D6890 (see Section 2.1). This test method relies on measuring the ignition delay of a specimen of fuel which has been injected into a heated, temperature-controlled constant-volume chamber [3]. Presently, most of the world's major oil companies have acquired technology that conforms to D6890 to test their fuels [4] in the form of the Ignition Quality Tester (IQTTM) available from Advanced Engine Technology Inc. (AET). The test method specifies a particular nozzle type built to a specific standard (ISO 4010) to be used. However, research and development efforts by AET have demonstrated that different fuel injection

nozzles built to the same design and standards can have a significant impact in the variability of results, suggesting that small differences in nozzle parameters, such as physical dimensions and spray pattern, can have an effect on the ignition delay measurement.

Understanding the effects of fuel injection nozzles on ignition delay and the CN will lead to a more accurate determination of the ignition quality for diesel fuels. Refineries frequently employ a buffer of CNs (using cetane improvers and additives) to ensure they are meeting the legislated minimum for a particular fuel product within the accuracy of their CN measurement. This CN buffer is known in the oil industry as “cetane giveaway”. An improvement in the accuracy of determining the CN would lead to an overall improvement of fuel quality control, as well as an overall reduction in production costs by reducing the “cetane giveaway”.

1.2 Objectives and Tasks

The objective of the research undertaken was to determine the effects of the fuel injection nozzle on the ignition delay and cetane number as measured using ASTM test method D6890 (using an IQTTM), and to determine the key parameters of the nozzle that affect the ignition delay.

Nozzles are responsible for atomization of the fuel and distributing the fuel inside the combustion chamber. Therefore, to identify key parameters of the nozzle used in the IQTTM, the physical dimensions that drive the atomization process needed to be investigated, as well as the distribution pattern that the nozzle produces. In Chapter 3, the test plan along with the experimental apparatus used to carry out these tasks is presented. The following chapter will present the necessary topic background, as well as a review of the pertinent literature.

Chapter 2

Background and Literature Review

In this chapter, the cetane number and ignition delay are presented in detail. The relationship between the two is defined, and several methods of measurement are explained. A summary of nozzle testing techniques developed is also presented, along with a literature review of studies concerning fuel injection nozzles and their effects on combustion characteristics.

2.1 Cetane Number and Ignition Delay – Measurement Methods

Combustion does not commence at the instant of fuel injection into a combustion chamber, but only after a small amount of the injected fuel has been raised to the temperature of self ignition. This delay period from the beginning of injection to the initiation of ignition is defined as the ignition delay, and is in the order of milliseconds. The ignition delay period itself, can be divided into two separate periods, a physical and a chemical delay period. The physical delay period is the time required for the atomization, heating, vaporization and mixing of the fuel with air before ignition takes place. Proceeding, or

even overlapping the physical delay is the chemical delay, which is the time required by pre-flame reactions to reach flame conditions, reactions proceeding so slowly that no effect is discernible [5].

In the diesel engine industry, ignition delay is very important. If a fuel has an ignition delay that is too long, the bulk of the charge in the cylinder tends to fire simultaneously, causing violent combustion. With a short delay, ignition is initiated at several points, and the flame subsequently spreads progressively throughout the charge [6]. However, the injection into the cylinder has to be timed appropriately for the ignition delay of the fuel being used, otherwise excessive vibrations, and low fuel efficiency may occur. This has led to the development of the Cetane Scale. A high cetane number indicates a high performance diesel fuel that auto-ignites faster, while a low CN indicates a lower performance diesel fuel that auto-ignites slower.

2.1.1 Standard Methods

First introduced in 1941 [2] in ASTM test method D613, the Cetane Scale is an arbitrary scale from 0 to 100. N-cetane, a hydrocarbon fuel, ignites very easily under compression and was therefore assigned a CN of 100. Alpha-methylnaphthalene (AMN), another hydrocarbon fuel, is very hard to ignite and was therefore assigned a CN of 0. The CN of a fuel sample is then determined as the percent volume of n-cetane in AMN, that provides the same ignition delay of the fuel sample at a given compression ratio. A special engine is used to determine this volume percent of cetane (i.e., the CN), known as the Cooperative Fuel Research (CFR) engine [2]. The CFR engine, is a single-cylinder diesel engine, with a variable compression ratio. The fuel sample to be tested is used in the test cylinder and the compression ratio is adjusted until a standard ignition delay period in terms of crankshaft angle (13 degrees) is reached [2]. Using the same compression ratio, various

volumetric mixtures of n-cetane and AMN are used until the standard ignition delay value is attained again. The CN of the fuel sample tested is then equal to the percent volume of cetane in the n-cetane/AMN mixture that yielded the same standard ignition delay period with the same compression ratio. In 1962, a change was made from AMN to heptamethylnonane (HMN) to utilize a material of better storage stability and availability. HMN was determined to have CN of 15 using blends of n-cetane and AMN [2].

While the CFR engine using ASTM D613 method is currently the primary standard in determining CN of fuels, there is another method that has recently been developed. A combustion-based analytical method, initially developed by the Southwest Research Institute (SwRI)[7], has been further developed by Advanced Engine Technology (AET) [8]. A small fuel sample is injected into a constant-volume combustion chamber that is pre-charged with air and heated by electrical heaters. The ignition delay of several single injections of the fuel sample is then measured and averaged. The ignition delay is defined as the time delay between start of injection (initial nozzle needle lift) and the start of ignition (start of increase in combustion chamber pressure). This is measured by a proximity sensor that detects the initial needle lift, and a pressure transducer detecting the combustion pressure rise [8]. Once the ignition delay (ID) is determined in ms, it can be converted to a derived cetane number (DCN) using the following correlation [3],

$$DCN = 83.99(ID - 1.512)^{(-0.658)} + 3.547 \quad (2.1)$$

In 2004, this method was made a standard ASTM test method under the designation D6890 [3]. A testing apparatus conforming to ASTM D6890 is available from AET in the form of the Ignition Quality Tester (IQTTM). The IQTTM was used as part of the experimental apparatus in the research undertaken, and will be presented in more detail in Chapter 3.

2.1.2 Alternate Methods

The cetane number of different fuels (assuming the same injection and combustion conditions) is ultimately a function of molecular properties of the fuel. Numerous attempts have been made to correlate the CN with various physical and chemical attributes of the diesel fuel. These include correlations based on either bulk properties such as *API* gravity, boiling points, and aniline points [9], or based on molecular composition, measured by gas chromatography [10] or inferred from different spectroscopic methods such as Fourier transform infrared spectroscopy, and nuclear magnetic resonance [11].

Several of these correlations have enjoyed enviable success in determining the CN of various diesel fuels and their blends. One in particular developed by the Institute of Petroleum [12], is used extensively in the petroleum industry and is referred to as the Cetane Index. However, these correlations are based on empirical data from commonly used fuels at the time of development, and with the push towards low sulfur diesel fuels and the addition of cetane improvers to fuels, the results of such equations are becoming progressively less satisfactory. Thus, they need constant updating, or risk being not applicable to new future fuels being developed.

Some research has been done to try to determine the the ignition delay of a fuel numerically [13] instead of experimentally in a combustion chamber. However, no further development has been done to correlate numerical ignition delay values to the CN.

2.2 Fuel Injection Nozzle Testing

Fuel injection nozzles being a very critical component of spray combustion systems are frequently tested to ensure they conform to certain standards. This has led to the development of several testing methods to characterize key nozzle parameters such as the

spray pattern produced by the nozzle, and the critical physical geometries responsible for the atomization of the fuel and the injection rate.

2.2.1 Spray Pattern Analysis

The spatial distribution of drops in sprays is critical to the performance of many atomization systems, including diesel engine injectors, gas turbine injectors, spray coating systems, and furnace burners. An approach to obtain reliable pattern information from laser light sheet imaging was developed at Queen's University and the Royal Military College [14]. This technology is now available as the Optical Spray Pattern Analyzer (OSPA) from Nexum Instrumentation.

The technique uses an array of laser diodes to produce a planar region of illumination, as shown in Figure 2.1. Objects crossing this region of illumination scatter light in different

Figure 2.1: Planar region of illumination produced by laser array [15]

directions through refraction and reflection. The scattered light is then captured and recorded by a high-speed CCD camera [14].

This system is used to capture images of the spray pattern of a nozzle as illustrated in Figure 2.2. Post processing of the signal corrects for illumination non-uniformities that exist within the planar region of illumination, as well as for the skewness of the image due to the position of the camera [14]. The resulting image is a true representation of the spray pattern, and quantitative data of the spray such as the average diameter, circumferential distribution, and radial distribution can be obtained.

Figure 2.2: Capturing of nozzle spray pattern [15]

2.2.2 Nozzle Geometry Analysis

Nozzle geometry is a critical factor in determining the level of atomization of the fuel spray, the spray shape, and the injection rate. It is therefore important to be able to characterize the key nozzle parameters that drive those properties.

Many dimensions of the nozzle are easily accessible and can be directly measured on a profile projector. This was done in the research undertaken and is presented in Chapter 3. However, internal nozzle dimensions such as the pintle clearance, or the clearance between the needle and the barrel are so small and inaccessible that they can only be measured indirectly.

A particular standard test method (ISO 4010) [16] developed for a nozzle design known as a delay pintle type nozzle, employs choked gas flow to quantify small clearances that are inaccessible for direct measurement. Once gas flow is choked at a constant upstream stagnation pressure, it becomes a direct function of the minimum cross sectional area. ISO 4010 specifies two test methods for delay pintle type nozzles. One for quantifying clearance at the pintle and the other for quantifying clearance at the needle guide. The ISO standard specifies a particular range of flow values that must be achieved by the test nozzle in order for it to be classified as an ISO 4010 nozzle. The standard also specifies needle dimensions that can be measured directly on a profile projector.

The nozzles used in the IQTTM, and specified in ASTM D6890 are specified as ISO 4010 nozzles [3]. The test methods specified in ISO 4010 were used in the experimental apparatus of the research undertaken, which is discussed in detail in Chapter 3.

2.3 Fuel Injection Nozzles and Ignition Delay

The self-ignition process of diesel fuels is influenced by many parameters which are partially interrelated. There is a limited amount of work in the literature that has sought to narrow down the effects of the fuel injection systems on ignition delay. Several studies can be found where the effects of the fuel injection system on overall combustion characteristics such as NO_x emissions, soot-formation, and flame structure were investigated [17; 18], but not specifically on ignition delay.

Of the limited amount of work relating to ignition delay, one particular study has investigated the effects of varying nozzle orifice diameter on ignition delay [19]. In this study, a high-pressure chamber at pressures up to 60 bar and temperatures up to 600°C was used as a combustion chamber for injected fuel. The ignition was detected by a photomultiplier, where start of ignition was indicated by a steep increase of the photomultiplier signal. The needle lift signal of the injection nozzle was also measured, and thus the ignition delay was calculated as the time between the start of the needle lift and the first light signal. Bosch type one-hole injection nozzles with orifice diameters ranging from 0.30 to 0.20 mm (0.30, 0.27, 0.25, 0.20 mm) were tested. The study shows that in their results, the ignition delay for high-pressure injections through a single hole nozzle of small diameter was longer than in the case of the low-pressure injection through a single hole nozzle of large diameter [19]. The authors attributed the longer ignition delay in the smaller hole nozzle to a drop of local mixture temperature caused by the more rapid vaporization resulting from finer atomization.

Another study [20] compared the ignition delay between a two-stage and a single-stage injection diesel spray using a high-speed video system in a constant-volume combustion chamber. The results showed that the ignition delay of a two-stage injection spray was shorter than that of a single-stage injection spray. The authors attributed this to the enhancement of the mixing effect between fuel and surrounding air caused by the two-stage injection.

To date, no studies have been found in the literature that explicitly address the effects of the nozzle spray pattern on the ignition delay or cetane number. Although several studies have been carried out on spray characteristics of nozzles, there do not appear to be any results published in the open literature with specific references to the spray pattern and ignition delay or cetane number.

Chapter 3

Test Plan and Experimental Apparatus

To determine the effects of fuel injection nozzles on the ignition delay and cetane number, a test plan was developed employing the use of several experimental apparatus. A sample of 15 delay pintle type nozzles and a single typical diesel fuel were chosen for the study.

Each of the 15 nozzles was used to test CF12, a diesel reference fuel, according to ASTM D6890 using an Ignition Quality Tester (IQTTM) available from Advanced Engine Technology (AET). Each one of the nozzles was placed in the same IQTTM unit, and the same fuel from the same source was tested. This ensured to a reasonable degree that any fluctuation of the ignition delay and cetane number was a function of the nozzle. Once completed, a data set of ignition delay and cetane values was obtained for CF12 for each corresponding test nozzle.

The spray pattern for each of the nozzles was analyzed using the developed optical spray test rig. Internal geometry for each of the nozzles was then characterized in terms of flow rates according to an ISO test method [16] using two test rigs that were designed

and developed specifically for this task. Finally, accessible nozzle geometry was measured directly with the aid of a profile projector. All the obtained spray and geometry characteristics of each of the 15 nozzles were then compared to their corresponding ignition delay and cetane number values for examination and discussion. This is presented in Chapter 4. The delay pintle type nozzle and its injection properties are presented in detail in the following section, followed by a detailed presentation of each of the experimental apparatus used.

3.1 Test Nozzles – Delay Pintle Type

ASTM D6890 specifies a delay pintle type nozzle [3] to be used in the test method. Therefore, the test nozzles had to be of the delay pintle type shown in Figure 3.1.

Figure 3.1: Delay pintle type nozzle

To accentuate the effect of the nozzle on the ignition delay, the test nozzles were chosen from several manufactures or from different batches. The idea was, nozzles, even though of the same design, being from different manufactures or from different assembly lines, would have slightly different characteristics that would show up in our measurements of the ignition delay and cetane number. The 15 test nozzles are identified in Table 3.1. All 15 nozzles were thoroughly cleaned before and after each of the tests to avoid contamination of the nozzles. The cleaning procedure is outlined in Appendix A.

Table 3.1: Fifteen test nozzles from 3 different manufacturers

Nozzle ID
Sun 1
Sun 32
Sun 63
Sun 65
Sun 66
Sun 68
Sun 69
Zexel 9
Zexel 15
Zexel 22
Zexel 35
Zexel 70
Zexel 71
Zexel 76
CAV 14

The delay pintle type nozzle is designed in such a way that at beginning of injection the initial rate of injection is slow. The fuel enters the nozzle from three holes in the barrel and sits in a sac at the bottom of the nozzle. The valve at the bottom of the nozzle formed by the needle and the barrel is kept shut typically by spring pressure pushing the needle against the barrel. Once the fuel pressure increases (from the injection pump), and overcomes the spring pressure, the fuel pushes on the needle and is sprayed through the

clearance between the barrel orifice and the needle pintle known as the pintle clearance. The rate of injection is controlled by the minimum cross sectional area that the fuel encounters as it flows through the valve. The needle typically lifts to a maximum of about 0.8 mm. As the needle lifts, the minimum cross sectional area changes as illustrated in Figure 3.2, effectively controlling the injection rate.

Figure 3.2: Minimum nozzle pintle clearance varying with lift — (a) no lift, closed position (b) beginning of lift to 0.45 mm, flow controlled by *AA* surfaces (c) 0.45 to 0.65 mm, flow controlled by *BB* surfaces (d) 0.65 to end of lift, flow controlled by *CC* surfaces

Figure 3.3 shows a typical variation of the throat clearance as the needle lifts. From the figure, the delaying effect from 0 to 0.45 mm is clearly visible. This pintle clearance along with the needle clearance slightly vary from nozzle to nozzle due to manufacturing differences. This variation was characterized for all 15 test nozzles using the apparatus described in Sections 3.4, and 3.5.

Figure 3.3: Typical variation of the throat clearance in a delay pintle type nozzle

3.2 Ignition Quality Tester

The ignition quality tester (IQTTM) available from Advanced Engine Technology (AET) shown in Figure 3.4, is an automated experimental apparatus for measuring ignition quality of diesel fuels using ASTM test method D6890 [21]. The IQTTM as per ASTM D6890 test method, measures the ignition delay of a fuel sample, utilizing a constant-volume combustion chamber with direct fuel injection into heated, pressurized air.

The IQTTM injects a small fuel sample into a constant-volume combustion chamber that is pre-charged with air and heated by electrical heaters. Fifteen pre-injections are carried out to prepare the injection system, followed by 32 injections. The ignition delay of the 32 injections of the fuel sample is measured and averaged. The ignition delay is defined as the time delay between start of injection (initial nozzle needle lift) and the

start of ignition (start of increase in combustion chamber pressure). This is measured by a proximity sensor that detects the initial needle lift, and a pressure transducer detecting the combustion pressure rise [8]. Once the averaged ignition delay is determined, the IQTTM converts it to a derived cetane number (DCN) as per the ASTM test method using equation 2.1.

Figure 3.4: The ignition quality tester (IQTTM) [21]

The ASTM test method covers the ignition delay range from 3.3 to 6.4 ms (60 to 33 DCN). The repeatability of the test method for the DCN is the same throughout the covered DCN range, and is equal to 0.76 DCN. For the ignition delay range of 3.3 to 6.4 ms, the repeatability varies accordingly from 0.059 to 0.175 ms [3]. A detailed schematic of the IQTTM is given in Figure 3.5.

Figure 3.5: Ignition quality tester schematic, courtesy of AET

All 15 test nozzles were used one at a time in one IQTTM machine to test one fuel (CF12 with an established ignition delay of 3.472 ms and DCN of 57.5) according to ASTM D6890. This resulted in 15 ignition delay and DCN values corresponding to each of the 15 test nozzles.

3.3 Optical Spray Pattern Test Rig

To determine the effects of spray pattern on ignition delay and cetane number, an optical spray pattern test rig was developed. The test rig was comprised of the IQTTM fuel injection system and data acquisition system, and the Optical Spray Pattern Analyzer from Nexum. The opening spring pressure was kept the same as in the IQTTM for all the nozzles at 3000 psi. A schematic of the test rig is shown in Figure 3.6.

Figure 3.6: Optical spray pattern test rig schematic

The OSPA system uses an array of laser diodes to produce a planar region of illumination. Spray droplets crossing this region of illumination scatter light in different directions through refraction and reflection. The scattered light is then captured and recorded by a high-speed CCD camera at a rate of one frame every 2 ms with a temporal resolution of 0.18 ms, and a spatial resolution of 320 by 320 pixels. The laser sheet was placed 46 mm from the nozzle, and injection was done horizontally as was the case in the IQTTM. This is illustrated in Figure 3.7.

Figure 3.7: Optical spray pattern test rig — horizontal injection, 46 mm from test nozzle

The images were corrected through the OSPA system for illumination non-uniformities, and the skewness of the image due to the angled position of the camera. Essentially, this setup produced planar images of the spray pattern of the nozzle that would have occurred inside the combustion chamber of the IQTTM, with the exception that injections were done in free quiescent air, instead of inside the IQTTM combustion chamber. A spray collection system, consisting of a large plastic collector, connected to a vacuum pump was placed sufficiently downstream of the spray (so as to not disturb the spray behaviour) to collect the diesel fuel after injection.

The main injection event typically lasted for just over 2 ms. This presented a challenge since the camera was capable of only 1 frame every 2 ms, which would have allowed for a possibility of only one frame inside the main injection event. To add to this, the OSPA system does not allow for direct control of the CCD camera. The camera is constantly running, taking a frame every 2 ms with no way to synchronize to the injection event. To overcome this, a test procedure was developed to test each nozzle that would allow for several frames of the main injection event to be captured along with the time in the injection event (zero being start of injection event) corresponding to each frame.

To accomplish this, each of the 15 nozzles were tested using the same fuel (CF12), and 5 injections were done using each nozzle. The camera was constantly running during all 5 injections, which resulted in frames falling randomly inside the main injection event. By repeating the test with each nozzle 5 times, at least 5 frames within the main injection event were captured. To determine the temporal location of each captured frame relative to the start of injection event, two signals from the OSPA system were routed to the IQTTM data acquisition (DAQ) system. The two signals were the CCD camera on/off signal indicating when the frames were being taken in time, and an average signal of the 16 laser detectors indicating when the spray contacts the laser sheet. By combining these two signals with the needle lift sensor signal of the IQTTM fuel injection system, the temporal location of the captured frame could be determined. This is illustrated in Figures 3.8, and 3.9.

Each test nozzle was tested in this manner, resulting in at least 5 captured frames within the main injection event with temporal location information allowing for comparison of the spray pattern among all of the 15 test nozzles. To determine the repeatability of the test rig, it was necessary to obtain images for the same nozzle during the same time within the injection event. This was achieved by repeated testing of a nozzle until two frames were obtained that fell at the same time (or very close) on the injection event. The images were then visually compared, and were found to be fairly close. This repeatability study was done using two test nozzles and is included in Appendix B.

Figure 3.8: The time difference between the start of needle lift and first laser contact, is the time it takes for the first nozzle spray drops to reach the laser sheet

Figure 3.9: By knowing the time delay for the spray, the camera frame can be corrected back by that delay to give us the temporal location on the needle lift of the captured spray

3.4 Pintle Clearance Air Flow Test Rig

An important nozzle parameter in terms of combustion performance, is the clearance between barrel orifice and the needle protrusion known as the pintle clearance. To characterize this clearance for the 15 test nozzles, a test rig was designed conforming to ISO 4010 Test Method 1 [16]. A schematic of the developed test rig is given in Figure 3.10.

The test method employs ambient air flow driven by a vacuum pump using pressures sufficiently below ambient pressure so as to choke the flow (sonic velocity reached) in the effective cross section and at the outlet of the nozzle. Once the flow is choked, the flow rate becomes proportional to the effective cross-section of the nozzle [16].

Figure 3.10: Pintle clearance air flow test rig schematic

The needle lift can then be varied and flow rate readings can be taken corresponding to each lift value. This results in a flow vs. lift curve representative of the throat area variation as needle lift varies. Since the flow rate is proportional to the pintle clearance, the resulting curve is very similar to Figure 3.3.

The test rig developed adheres to the ISO 4010 test method. A nozzle holder was designed that would allow for varying the needle lift of the test nozzle. Detailed drawings of the design are provided in Appendix C along with a list of main parts and components of the test rig. The needle lift was measured using a high accuracy Mitutoyo Model 543-262 dial gauge indicator. A vacuum pump was used to provide up to 0.96 bar below ambient vacuum pressure, which was measured using a manufacturer calibrated Cole-Parmer Model 68075 vacuum pressure transducer. A Brooks Model 5850S thermal mass flowmeter was used to measure the flow rate. The flowmeter was manufacturer calibrated for air at ambient conditions, and outputs a volume flow rate reading standardized to calibration

conditions density. The manufacturer calibration data is reproduced in Appendix E.1. A PC using a 12 bit ComputerBoards Inc. CIO-DAS16/Jr ISA interface data acquisition card was used for data collection. The data acquisition system was shared with the Needle Clearance Nitrogen Flow Test Rig. Details and wiring schematic of the data acquisition system developed are included in Appendix D.

To ensure that the flow was indeed choked at the nozzle outlet, all piping was chosen such that the nozzle outlet geometry was the smallest throat area that was encountered by the flow. The test method specifies a minimum pressure of 0.8 bar below ambient downstream of the nozzle to achieve choked flow. Compressible flow theory states that once sonic velocity is established in the nozzle throat, decreases in the downstream pressure will have no influence on the nozzle inlet flow [22]. To ensure that the flow was in fact choked, the pressure downstream was decreased from an initial 0.8 bar below ambient to 0.96 below ambient with no resulting change in flow rate, suggesting that the flow was indeed choked at the throat.

All 15 test nozzles were tested in the test rig. Flow rate measurements were taken at 0.05 mm increments of needle lift, resulting in a flow rate vs. needle lift curve for each of the 15 test nozzles. The testing procedure that was developed and used for each test nozzle is given in Appendix F. A repeatability study was also conducted to determine the precision of the test rig, and is included in Appendix E.2.

3.5 Needle Clearance Nitrogen Flow Test Rig

The clearance between the needle and the barrel was quantified in terms of nitrogen flow rate for each of the 15 test nozzles. ISO 4010 Test Method 2 [16], is a standard test method for such measurement. A test rig was designed conforming to this standard, and a schematic of the developed test rig is given in Figure 3.11.

Figure 3.11: Needle clearance nitrogen flow test rig schematic

The test method employs nitrogen pressurized at 20 bar to be forced through the clearance between the barrel and the needle exiting to ambient air. The significant drop from 20 bar to atmospheric pressure leads to sonic flow conditions with the flow rate becoming a direct function of the needle clearance [16]. The test rig developed adheres to the ISO 4010 test method. A nozzle holder was designed that would allow for the nitrogen to flow through the needle clearance of the test nozzle. Detailed drawings of the design are provided in Appendix C along with a list of main parts and components of the test rig.

An ASCO Model 40 manufacturer calibrated pressure transducer was used to ensure the nitrogen pressure was at the required 20 bar. A Cole-Parmer Model FMA1710 thermal mass flowmeter was used to measure the flow rate. The flowmeter was manufacturer calibrated for air at ambient conditions, and outputs a volume flow rate reading standardized to calibration conditions density. The manufacturer calibration data is given in Appendix G.1. A PC using a 12 bit ComputerBoards Inc. CIO-DAS16/Jr ISA interface data acquisition card was used for data collection. The data acquisition system was shared with the Pintle Clearance Air Flow Test Rig. Details and wiring schematic of the data acquisition system developed are included in Appendix D.

All 15 test nozzles were tested in the test rig. The testing procedure that was developed and used for each test nozzle is given in Appendix H. A repeatability study was also conducted to determine the precision of the test rig, and is included in Appendix G.2.

3.6 Profile Projector

A Mitutoyo profile projector Model PJ-300 was used to take key measurements of nozzle needles for each of the 15 test nozzles. X and Y measurements, as well as angle measurements were made on the profile projector at 50 times magnification. Figure 3.12 shows the profile of a nozzle needle in position for measurement.

Figure 3.12: Needle profile shadow on the profile projector

The key dimensions measured are identified in Figure 3.13, and were measured to an accuracy of 0.01 mm, and 0.25° [23] using the profile projector.

Figure 3.13: Key nozzle needle dimensions measured, reference values shown (mm)

Chapter 4

Results and Discussion

By using the experimental apparatus described in Chapter 3, data was collected for all 15 test nozzles. For each of the nozzles, ignition delay and cetane number values were obtained using CF12 as fuel, along with nozzle spray images, internal geometry flow data, and needle profile dimensions. The complete data set is given in Appendix I.

The ignition delay and cetane number values found for each of the nozzles using ASTM D6890 test method are summarized in Figure 4.1. By comparing the nozzle spray and geometry data to the corresponding nozzle ignition delay data, the effects of the various nozzle parameters on ignition delay and cetane number were investigated. The results along with a discussion of the findings are presented in the following sections.

Figure 4.1: Ignition delay and cetane number values for all 15 test nozzles

4.1 Effects of Spray Pattern

The optical spray pattern test rig resulted in several spray images being captured corresponding to a particular time in the injection event for each of the test nozzles. The same fuel was used for all the nozzles along with the same injection pump to ensure that any changes in spray pattern were a sole function of the test nozzle. The complete set of images captured is given in Appendix I.2.

By comparing spray images of test nozzles that have different ignition delay values, the effects of spray pattern on ignition delay can be investigated. Test nozzle Sun 65 has an ignition delay value of 3.355 ms and a cetane number (CN) of 59.7, while at the other end test nozzle Sun 63 has an ignition delay of 3.512 ms and a CN of 56.8. Given that Sun 65 and Sun 63 are on either end of the obtained ignition delay range of values, any captured effect of the spray pattern on ignition delay would be most visible between these two nozzles. However, a direct comparison of spray images from Sun 65 and Sun 63 corresponding to the same time intervals in the injection event shows little or no difference in the spray pattern as illustrated in Figure 4.2.

On the other hand, Sun 68 with an ignition delay of 3.429 ms and a CN of 58.3, and Sun 1 with an ignition delay of 3.443 ms and a CN of 58.0, are very close in terms of their ignition delay values. Yet, when comparing their spray images corresponding to similar times in the injection event, it is evident that there is a large difference in the spray pattern. The Sun 68 pattern is small and focused, while that of Sun 1 is larger and scattered as shown in Figure 4.3.

Figure 4.2: Comparison of spray pattern images at similar time intervals between Sun 65, 3.355 ms ignition delay and Sun 63, 3.512 ms ignition delay

Figure 4.3: Comparison of spray pattern images at similar time intervals between Sun 68, 3.429 ms ignition delay and Sun 1, 3.443 ms ignition delay

Further qualitative visual inspection of the captured images appeared to yield no connection between the spray pattern and ignition delay, and quantitative comparison of the images between the nozzles was not warranted. However, by examining the entire data set for all the images obtained, a typical evolution of the spray pattern across the main injection event can be estimated. This is illustrated in Figure 4.4. This spray behaviour appears to be typical of all the nozzles regardless of their ignition delay or cetane number values.

Nozzle spray pattern has been determined to have an effect on emissions in several studies [24; 25]. However it does not appear to have any noticeable effect on the ignition delay and the cetane number.

Figure 4.4: Typical spray pattern evolution of test nozzles

4.2 Effects of Internal Nozzle Geometry

Using the Pintle Clearance Air Flow Test Rig and the Needle Clearance Nitrogen Flow Test Rig, employing ISO 4010 test methods, the internal geometry of the 15 test nozzles was determined in terms of choked volume flow rate.

The air flow rig resulted in several flow values corresponding to different lift points as shown in Figure 4.5, with the choked volume flow rate being directly proportional to the pintle clearance at each of the lift values for each of the test nozzles. Similarly, the nitrogen flow rig resulted in an average choked volume flow rate directly related to the clearance between the needle and the barrel for each of the test nozzles. The complete set of flow data is presented in Appendix I.3.

Figure 4.5: Typical data curve produced from the pintle clearance air flow test rig

By comparing the different flow rate vs. needle lift curves for test nozzles with large differences in their ignition delay and cetane number values, the effects of the nozzle pintle clearance on ignition delay and the cetane number can be investigated. Figure 4.6 shows several curves for nozzles spanning the entire ignition delay and cetane number range of values. At needle lifts 0.0 to 0.65 mm, there does not appear to be any correlation between the pintle clearance (in terms of flow rate) and the ignition delay. However, at needle lifts over 0.65 mm, there appears to be a clear trend as illustrated in Figure 4.7.

Figure 4.6: Pintle clearance data for nozzles spanning the ignition delay range of values

Figure 4.7 shows that at high needle lift values (0.70 mm and higher), as the pintle clearance increases (higher flow rate values), the ignition delay decreases.

Figure 4.7: Effects of pintle clearance on ignition delay and cetane number

The pintle clearance is the annular orifice area between the needle and the barrel as shown in Figure 3.2. As the fuel is forced through the annular orifice under pressure, an unstable jet is formed, which disintegrates as it leaves the nozzle and comes into contact with the air in the combustion chamber [26]. This disintegration of the unstable jet results in the atomization of the fuel into small droplets, where the droplet size is primarily influenced by the nozzle orifice area for a given injection pump. The smaller the orifice area, the higher the injection pressure will be, and the smaller the droplet size [27].

The ignition delay is divided into two separate periods, a physical and a chemical delay period. The physical delay period being the time required for the atomization, heating, vaporization and mixing of the fuel with air before ignition takes place, and the chemical

delay period being the time required by pre-flame reactions to reach flame conditions. The rate of heating and vaporization is driven by the rate of heat transfer to the atomized fuel, which is a direct function of the surface area as shown by this simple convective heat transfer equation [28],

$$q = \bar{h}A_s(T_s - T_\infty) \quad (4.1)$$

Finer atomization will result in a larger surface area and therefore faster vaporization, reducing the physical delay period of the ignition delay. However, a more rapid vaporization will result in a reduction of the local temperature leading to a decrease in the pre-flame reaction rates. Reaction rates are an exponential function of temperature [29], and thus a nozzle that results in slightly lower local temperatures (due to finer atomization and rapid vaporization) can have a substantially longer chemical delay period leading to a longer overall ignition delay. Figure 4.7 suggests that nozzles with smaller orifice areas will lead to longer ignition delays, which could be explained by the latter. Similar trends were obtained by [19], where their results showed the ignition delay for high-pressure injections through a single hole nozzle of small diameter was longer than in the case of the low-pressure injection through a single hole nozzle of large diameter. The authors attributed this to a drop of local mixture temperature caused by the more rapid vaporization due to finer atomization in the smaller diameter nozzle.

The ignition delay is driven by the first initial amount of injected fuel, and not the entire amount of the fuel from the complete injection event [6]. Figure 4.8 shows how the initial period of a typical injection event encounters high needle lift values, which could explain the apparent dependence of ignition delay on the nozzle pintle clearance at the higher needle lifts, and not so much at lower needle lifts.

Figure 4.8: Initial injection period of a typical injection event

The needle clearance, is the clearance between the barrel and the needle. If this clearance is too tight, the nozzle could jam, on the other hand, if the clearance is too large, excessive leaking from the nozzle fuel sac through the needle clearance can occur. To examine the effects of the needle clearance on ignition delay, the choked nitrogen flow rate was plotted against the ignition delay values for all 15 test nozzles. However, as seen in Figure 4.9, there does not appear to be any clear trend in the data.

Figure 4.9: Needle clearance effect on ignition delay

ASTM D6890 test method specifies a mass calibration with each new nozzle. As this was the case for the tests carried out, it is likely the variation in needle clearance and therefore fuel leakage was compensated for by the mass calibration of each nozzle. Thus, no clear effect of the nozzle needle clearance on the ignition delay was found.

4.3 Effects of Nozzle Needle Geometry

With the aid of a profile projector, the key dimensions shown in Figure 3.13 were measured for all 15 test nozzles. The obtained needle dimensions for all 15 test nozzles are given in Appendix I.4. Comparison of all key needle dimensions yielded no clear correlations to ignition delay as shown for the cone angle (dimension F) in Figure 4.10 .

Figure 4.10: Cone angle (dimension F) effect on ignition delay

These key needle dimensions are primarily responsible for the injection spray pattern. Therefore, not finding any strong effects of the needle dimensions on ignition delay is consistent with our previous results regarding the spray pattern in section 4.1.

Chapter 5

Conclusions and Recommendations

The effects of fuel injection nozzle parameters on ignition delay and the cetane number has been investigated. The results of the investigation have shown that nozzle spray pattern does not appear to have any effect on the ignition delay and cetane number. Similarly, needle dimensions that drive the nozzle spray pattern do not appear to have any effect on the ignition delay and cetane number.

Nozzle pintle clearance was found to have a strong effect on ignition delay and cetane number, with ignition delay decreasing as the pintle clearance increases. On the other hand, nozzle needle clearance had no clear effect on the ignition delay and the cetane number.

To further the research, the following items may be recommended for future work,

- A similar numerical investigation can be pursued to complement the experimental work undertaken
- To build on this investigation, the effects of nozzle deposits on the various nozzle parameters could be investigated
- A better understanding of the ignition process within the IQTTM by use of an optically accessible combustion chamber can be developed

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Appendix A

Nozzle Cleaning Procedure

This cleaning procedure was carried out on each test nozzle prior to testing in any of the experimental apparatus.

The cleaning procedure employs an ultrasonic cleaner,

1. Remove nozzle from its storage case
2. Separate the needle from the barrel
3. Place the needle and the barrel in a 250 mL glass beaker filled with a clean solution of Varsol
4. Place the beaker in a water bath inside an ultrasonic cleaner for 15 minutes
5. Remove the barrel and needle from the beaker and rinse with Alcohol
6. Blow dry the needle and the barrel using clean compressed air, or a blow dryer
7. Place the needle back inside the barrel
8. Return the nozzle to its storage case

Appendix B

Optical Spray Pattern Test Rig Repeatability

By repeated testing of a nozzle, two frames were obtained that fell at the same time, or very close on the injection event. Two such images were obtained for three of the test nozzles. They are presented in Figures B.1, B.2, and B.3. From visual comparison of the two images for all three nozzles, the level of precision of the spray test rig can be assessed.

Figure B.1: Spray test rig repeatability – comparable images for test nozzle Sun 1

Figure B.2: Spray test rig repeatability – comparable images for test nozzle Zexel 9

Figure B.3: Spray test rig repeatability – comparable images for test nozzle Sun 68

Appendix C

Air and Nitrogen Flow Test Rigs – Design

The Pintle Clearance Air flow Test Rig, and the Needle Clearance Nitrogen Flow Test Rig, were both assembled on the same test bench shown in Figure C.1. Stainless steel, $\frac{1}{4}$ " tubing, and Swagelok compression fittings were used to connect the components. Design drawings of the nozzle holders for each test rig are provided in the following sections.

Figure C.1: Air and nitrogen flow test rigs – shared test bench

C.1 Air Flow Test Rig Drawings

Drawings for the air flow test rig nozzle holder are summarized in Table C.1. Design drawings have been reduced to 75% of original size and are presented in Figures C.2 to C.9.

Table C.1: Air flow test rig nozzle holder design drawings

DWG #	Title
A-1A	Nozzle Holder Assembly
A-2A	Collet Assembly
A-3P	Nozzle Body
A-4P	Lift Adjuster
A-5P	Collet Tube
A-6P	Lift Stopper
A-7P	Collet Sleeve

Figure C.2: Air test rig design drawings - Nozzle Holder Assembly Sh. 1 of 2

Figure C.3: Air test rig design drawings - Nozzle Holder Assembly Sh. 2 of 2

Figure C.4: Air test rig design drawings - Collet Assembly

Figure C.5: Air test rig design drawings - Nozzle Body

Figure C.6: Air test rig design drawings - Lift Adjuster

Figure C.7: Air test rig design drawings - Collet Tube

Figure C.8: Air test rig design drawings - Lift Stopper

Figure C.9: Air test rig design drawings - Collet Sleeve

C.2 Nitrogen Flow Test Rig Drawings

Drawings for the nitrogen flow test rig nozzle holder are summarized in Table C.2. Design drawings have been reduced to 75% of original size and are presented in Figures C.10 to C.13.

Table C.2: Nitrogen flow test rig nozzle holder design drawings

DWG #	Title
N-1A	Nozzle Holder Assembly
N-2P	Top Cap
N-1X	Fixture Block

Figure C.10: Nitrogen test rig design drawings - Nozzle Holder Assembly Sh. 1 of 2

Figure C.11: Nitrogen test rig design drawings - Nozzle Holder Assembly Sh. 2 of 2

Figure C.12: Nitrogen test rig design drawings - Top Cap

Figure C.13: Nitrogen test rig design drawings - Fixture Block

Appendix D

Air and Nitrogen Flow Test Rigs – DAQ System

A data acquisition (DAQ) system was developed to be shared by the air and nitrogen flow test rig. The system employed a 12 bit ISA interface DAQ card, and a Pentium-III PC. The software was written in Visual Basic 6.0 and was contributed by Aaron Wilcox of Advanced Engine Technology. Table D.1 provides a list of the main components of the DAQ system, including the sensors. Wiring schematic is given in Figure D.1

Table D.1: Air and nitrogen flow test rig shared DAQ system main components

Component	Model
Data acquisition system card, 12-bit ISA interface	CIO-DAS16/Jr
Thermocouple signal conditioner	5B04
Two thermocouples	Type J
Air thermal mass flowmeter	Brooks 5850S
Air vacuum pressure transducer	Cole-Parmer 68075
Nitrogen thermal mass flowmeter	Cole-Parmer FMA1710
Nitrogen pressure transducer	ASCO 40
24V DC powers supply	CUI T815
24V DC to 5V DC voltage regulator	LM7805C
DAQ system wiring cabinet	Aluminium chassis BPA-1597

Figure D.1: Air and nitrogen flow test rig shared DAQ system wiring schematic

Appendix E

Air Flow Test Rig Calibration

In this appendix, the manufacturer calibration data of the Brooks Model 5850S flowmeter is presented. A repeatability study of the entire test rig was conducted to determine the rig's precision, and is also presented in this appendix.

E.1 Air Flowmetre Calibration

The Brooks thermal mass flowmeter was manufacturer calibrated for air, at 21.1°C and 1013.25 mbar using calibration equipment traceable to the national standard [30]. The calibration data is provided in Table E.1.

Table E.1: Air flowmeter calibration data [30]

Nominal Flow (L/min)	Actual Flow (L/min)	Error (% of flow rate)
1.50	1.5024	0.16
2.50	2.5035	0.14
3.75	3.7612	0.30
5.00	5.0088	0.18

E.2 Air Flow Test Rig Repeatability

A delay pintle type nozzle, designated as Delphi 4-031 calibration nozzle, was used to conduct a repeatability study of the Pintle Clearance Air Flow Test Rig. The variation in the test rig's measurements was assumed to be of normal distribution. Since the correct flow rates at the different lift values for the nozzle were not known, it was estimated using a simple numerical average [31]. The calibration nozzle was repeatedly tested in the test rig 25 times as per the testing procedure in Appendix F. The standard deviation was then calculated using the following equation [31],

$$\sigma = \sqrt{\frac{\sum x^2}{(n-1)}} \quad (\text{E.1})$$

The results of the study are illustrated in Figure E.1, and summarized in Tables E.2 and E.3.

Figure E.1: Pintle clearance air test rig repeatability with one standard deviation

Table E.2: Pintle clearance air test rig standard deviation

Needle Lift (mm)	Estimated Actual Flow (L/min)	σ (L/min)
0.00	0.00	0.000000
0.05	0.15	0.006091
0.10	0.16	0.006096
0.15	0.18	0.006264
0.20	0.20	0.007862
0.25	0.21	0.005986
0.30	0.23	0.008104
0.35	0.26	0.008885
0.40	0.33	0.016134
0.45	0.89	0.123532
0.50	1.79	0.121634
0.55	2.61	0.137098
0.60	3.47	0.122985
0.65	3.95	0.100850
0.70	3.89	0.091542
0.75	3.72	0.097938

Table E.3: Pintle clearance air test rig standard deviation – end of lift, and maximum flow test points

Test Point	Estimated Actual Value	Standard Deviation
End of lift location	0.79 mm	0.006904 mm
End of lift flow	3.62 mL/min	0.069590 mL/min
Maximum flow location	0.66 mm	0.006000 mm
Maximum flow	3.96 mL/min	0.093348 mL/min

Appendix F

Air Flow Test Rig Testing Procedure

The following testing procedure was followed for each test nozzle tested in the Pintle Clearance Air Flow Test Rig. Each of the nozzles was cleaned as per Appendix A.

All steps are to be performed while wearing safety glasses and rubber gloves in a clean dust free environment to ensure the safety of the operator and to avoid contamination of the test nozzles,

1. Take out the test nozzle from storage
2. Remove the two blue plugs from the air circuit
3. Record the Nozzle Type and Nozzle ID on the data sheet
4. Carefully insert the nozzle into the retaining hex nut
5. Insert the lift stopper on top of the nozzle inside the retaining hex nut, and hand tighten to the nozzle body
6. Using adequate force, insert the barrel (now attached to the nozzle body) into the yellow tubing of the air circuit

7. Fasten the nozzle body to the mounting bracket using the two nuts and screws
8. Fasten the steel tubing connecting the flowmeter to the nozzle body using the appropriate wrenches
9. Ensure the lift adjuster is all the way to the bottom (i.e. at the zero lift position).
DO NOT TIGHTEN OR TORQUE
10. Tighten the twist handle at the top using the appropriate wrenches
11. Roll down the top nut until it reaches the lift adjuster surface. DO NOT TIGHTEN OR TORQUE. Simply thread it down until it reaches the top surface of the lift adjuster
12. Place the dial gauge just touching and perpendicular to the top surface of the lift adjuster, and magnetize it to the metal plate behind the mounting bracket
13. Turn on the gauge and zero it
14. Launch the FIE software from the desktop by double clicking the shortcut icon
15. Open the green valve on the air circuit
16. Fully open the metering valve
17. Turn the pump on
18. Fully close the metering valve
19. Wait until the pressure goes over 0.8 bar, and the flow reading stabilizes, then ensure the flow reading is 0.00 L/min on the monitor. Record this on the data sheet at the lift value of 0.00 mm
20. Record the temperature on the data sheet

21. Twist the lift adjuster to attain a needle life of 0.05 mm on the lift gauge
22. Once the flow reading stabilizes, record the value on the data sheet at the corresponding lift value
23. Repeat steps 21 to 22 for lift increments of 0.05 mm all the way until the end of lift point is reached. Record all the flow readings at the corresponding lifts, and also the end of lift point and its corresponding flow reading on the data sheet. This end of lift point will be when the lift adjuster can no longer twist (usually around 0.78 to 0.81 depending on the test nozzle). BE CAREFUL NOT TO FORCE THE LIFT ADJUSTER PAST THE END OF LIFT POINT
24. By varying the lift on the needle using the lift adjuster, find the maximum flow lift point and record the lift value and its corresponding flow rate on the data sheet (this point is usually around 0.64 to 0.66 mm depending on the test nozzle)
25. Return the lift adjuster to the zero lift position
26. Turn off the green valve
27. Shut down the pump
28. Turn off the dial gauge, remove it, and magnetize it to the left rail on the side of the bench
29. Untie the steel tubing connecting the flowmeter to the nozzle body
30. Untie the twist handle on the nozzle body to release the nozzle needle
31. Untie the screws and nuts fastening the nozzle body to the bracket
32. Remove the nozzle body by pulling the nozzle body to the right side causing the nozzle barrel to slip out of the yellow tubing

33. Untie the retaining hex nut on the nozzle body and remove the nozzle and lift stopper
34. Carefully return the nozzle to storage
35. Place the disassembled nozzle holder on a clean paper towel on the bench to be ready for use
36. To test another nozzle, repeat steps 1 to 35

Appendix G

Nitrogen Flow Test Rig Calibration

The manufacturer calibration data of the Cole-Parmer Model FMA1710 flowmeter is presented. A repeatability study of the entire test rig was conducted to determine the rig's precision, and is also presented in this appendix.

G.1 Nitrogen Flowmetre Calibration

The Cole-Parmer thermal mass flowmeter was manufacturer calibrated for nitrogen, at 21.1 °C and 14.7 psi(a) using calibration equipment traceable to NIST test #18010C [32]. The calibration data is provided in Table G.1.

Table G.1: Nitrogen flowmeter calibration data [32]

Nominal Flow (mL/min)	Actual Flow (mL/min)	Deviation (% of F.S.)
0	0	0.0
50	50	0.0
100	100	0.0
150	150	0.0
200	200	0.0

G.2 Nitrogen Flow Test Rig Repeatability

A delay pintle type nozzle, designated as Delphi 4-031 calibration nozzle, was used to conduct a repeatability study of the Needle Clearance Nitrogen Flow Test Rig. The variation in the test rig's measurements was assumed to be of normal distribution. Since the correct flow rate of the nozzle was not known, it was estimated using a simple numerical average [31]. The calibration nozzle was repeatedly tested in the test rig 25 times as per the testing procedure in Appendix H. The standard deviation was then calculated using equation E.1. The estimated actual flow was found to be 127.92 mL/min with a standard deviation of 6.14 mL/min, or 4.80 %.

Appendix H

Nitrogen Flow Test Rig Testing Procedure

The following testing procedure was followed for each test nozzle tested in the Needle Clearance Nitrogen Flow Test Rig. Each of the nozzles was cleaned as per Appendix A.

All steps are to be performed while wearing safety glasses and rubber gloves in a clean dust free environment to ensure the safety of the operator and to avoid contamination of the test nozzles,

1. Ensure the nitrogen tank valve is closed
2. Ensure that the green and black valves on the nitrogen circuit are in the closed position
3. Remove the retaining hex nut at the end of the nozzle body on the nitrogen flow circuit using a torque wrench if necessary, and place on a clean paper towel on the aluminum surface on the bench
4. Take out the test nozzle from storage

5. Carefully insert the nozzle inside the retaining hex nut, and hand tighten to the nozzle body
6. Carefully torque the retaining hex nut using a torque wrench to 50 ft-lbs
7. Launch the FIE software from the desktop by double clicking the shortcut icon
8. Slowly open the nitrogen tank valve fully
9. Adjust the 2nd pressure regulator until the nitrogen pressure sensor reads 20 bar on the software window on the monitor
10. Place the black valve in the flowmeter position (i.e. arrow pointing towards the flowmeter line)
11. Slowly open the green valve
12. Re-adjust the 2nd pressure regulator until the nitrogen pressure sensor reads 20 bar on the software window on the monitor
13. Record the flow reading once it stabilizes on the data sheet (approximately after 5 minutes)
14. Return the green and black valves on the nitrogen circuit to the closed position
15. Vent the nitrogen in the circuit by placing the black valve in the vented position, and then return it to the closed position
16. Close the nitrogen tank valve fully
17. Remove the retaining hex nut containing the nozzle from the nozzle body using a torque wrench.

18. Repeat steps 5 to 17 twice more rotating the nozzle needle with respect to the nozzle barrel by approximately 120 degrees between each repetition. Once done, place the nozzle back into storage, and hand tighten the retaining hex nut to the nozzle body
19. To test another nozzle, repeat steps 1 to 18

Appendix I

Experimental Data

In this appendix all experimental data collected for all 15 test nozzles is presented. Ignition delay and cetane number values along with spray pattern data, internal geometry flow data, and needle profile data are presented in the following sections.

I.1 Ignition Delay Data

Ignition delay and cetane number (CN) values for all 15 test nozzles are presented in Table I.1. All values were obtained using ASTM D6890 test method employing an IQTTM with CF12 as the fuel.

Table I.1: Ignition delay and CN values for all 15 test nozzles

Test Nozzle	Ignition Delay (ms)	Cetane Number
Zexel 9	3.473	57.5
Zexel 15	3.477	57.4
Sun 1	3.443	58.0
Sun 32	3.561	55.9
Zexel 76	3.517	56.7
Zexel 22	3.585	55.5
Zexel 35	3.472	57.5
Sun 63	3.512	56.8
Sun 65	3.355	59.7
Sun 66	3.516	56.7
CAV 14	3.540	56.3
Zexel 70	3.582	55.6
Zexel 71	3.425	58.4
Sun 68	3.429	58.3
Sun 69	3.544	56.2

I.2 Spray Pattern Data

The captured spray images for each of the 15 test nozzles using the Optical Spray Pattern Test Rig are presented in Figures I.1 to I.15 in order of increasing ignition delay values. Each spray image corresponds to a particular time in the test nozzle's injection event. All spray images are to the same scale.

Figure I.1: Sun 65 captured spray images, 3.355 ms ignition delay

Figure I.2: Zexel 71 captured spray images, 3.425 ms ignition delay

Figure I.3: Sun 68 captured spray images, 3.429 ms ignition delay

Figure I.4: Sun 1 captured spray images, 3.443 ms ignition delay

Figure I.5: Zexel 35 captured spray images, 3.472 ms ignition delay

Figure I.6: Zexel 9 captured spray images, 3.473 ms ignition delay

Figure I.7: Zexel 15 captured spray images, 3.477 ms ignition delay

Figure I.8: Sun 63 captured spray images, 3.512 ms ignition delay

(a) 0.22 - 0.40 ms

(b) 1.32 - 1.50 ms

(c) 1.34 - 1.52 ms

(d) 1.40 - 1.58 ms

(e) 1.48 - 1.66 ms

(f) 2.22 - 2.40 ms

Figure I.9: Sun 66 captured spray images, 3.516 ms ignition delay

Figure I.10: Zexel 76 captured spray images, 3.517 ms ignition delay

Figure I.11: CAV 14 captured spray images, 3.540 ms ignition delay

Figure I.12: Sun 69 captured spray images, 3.544 ms ignition delay

Figure I.13: Sun 32 captured spray images, 3.561 ms ignition delay

Figure I.14: Zexel 70 captured spray images, 3.582 ms ignition delay

Figure I.15: Zexel 22 captured spray images, 3.585 ms ignition delay

I.3 Internal Geometry Flow Data

Flow data for the 15 test nozzles gathered using the Pintle Clearance Air Flow Test Rig, and the Needle Clearance Nitrogen Flow Test Rig are given in Tables I.2 and I.3 respectively.

Table I.2: Pintle clearance air flow test rig data for all 15 test nozzles

(a) Flow values at corresponding needle lifts

		Volume Flow Rate (L/min)				
		Zexel 9	Zexel 15	Sun 1	Sun 32	Zexel 76
Needle Lift (mm)	0.00	0.00	0.00	0.00	0.00	0.00
	0.05	0.12	0.09	0.14	0.15	0.13
	0.10	0.14	0.11	0.16	0.17	0.15
	0.15	0.15	0.13	0.19	0.19	0.18
	0.20	0.17	0.14	0.20	0.22	0.19
	0.25	0.20	0.16	0.23	0.24	0.22
	0.30	0.23	0.19	0.25	0.26	0.24
	0.35	0.27	0.22	0.28	0.30	0.27
	0.40	0.35	0.27	0.33	0.36	0.32
	0.45	0.70	0.55	0.49	0.83	0.43
	0.50	1.60	1.40	1.23	1.70	1.23
	0.55	2.42	2.27	2.18	2.57	2.03
	0.60	3.24	3.09	3.00	3.34	3.01
	0.65	3.78	3.78	3.71	3.76	3.66
	0.70	3.84	3.85	3.79	3.74	3.72
	0.75	3.69	3.70	3.64	3.59	3.58
	0.80	3.59	3.49	3.43	-	-
		Zexel 22	Zexel 35	Sun 63	Sun 65	Sun 66
Needle Lift (mm)	0.00	0.00	0.00	0.00	0.00	0.00
	0.05	0.11	0.12	0.14	0.12	0.10
	0.10	0.13	0.14	0.15	0.14	0.11
	0.15	0.15	0.16	0.17	0.15	0.12
	0.20	0.17	0.19	0.19	0.17	0.14
	0.25	0.19	0.21	0.21	0.19	0.16
	0.30	0.23	0.23	0.23	0.21	0.19
	0.35	0.28	0.27	0.27	0.25	0.22
	0.40	0.37	0.32	0.39	0.33	0.33
	0.45	0.93	0.58	0.99	0.89	0.89
	0.50	1.72	1.44	1.90	1.65	1.78
	0.55	2.65	2.28	2.78	2.69	2.70
	0.60	3.49	3.12	3.62	3.51	3.48
	0.65	3.81	3.75	4.00	4.00	3.97
	0.70	3.71	3.76	3.91	3.94	3.93
	0.75	3.53	3.62	3.75	3.81	3.78
	0.80	-	-	-	3.64	-

Needle Lift (mm)		CAV 14	Zexel 70	Zexel 71	Sun 68	Sun 69
	0.00	0.00	0.00	0.00	0.00	0.00
	0.05	0.16	0.14	0.14	0.09	0.15
	0.10	0.18	0.16	0.15	0.11	0.19
	0.15	0.20	0.18	0.16	0.12	0.20
	0.20	0.21	0.20	0.18	0.13	0.22
	0.25	0.24	0.22	0.20	0.14	0.24
	0.30	0.27	0.25	0.22	0.16	0.26
	0.35	0.30	0.28	0.26	0.19	0.30
	0.40	0.38	0.35	0.31	0.25	0.35
	0.45	0.93	0.61	0.48	0.72	0.66
	0.50	1.71	1.51	1.39	1.60	1.52
	0.55	2.52	2.35	2.35	2.51	2.35
	0.60	3.41	3.29	3.18	3.36	3.32
	0.65	3.87	3.84	3.77	3.79	3.77
	0.70	3.89	3.78	3.77	3.75	3.80
	0.75	3.76	3.60	3.59	3.60	3.66
	0.80	-	-	3.41	3.43	3.46

(b) Max flow and end of lift points

	Zexel 9	Zexel 15	Sun 1	Sun 32	Zexel 76
Max Flow Lift (mm)	0.68	0.70	0.69	0.66	0.69
Max Flow (L/min)	3.89	3.85	3.80	3.80	3.74
End of Lift (mm)	0.80	0.81	0.81	0.79	0.79
End of Lift Flow (L/min)	3.59	3.49	3.34	3.45	3.46
	Zexel 22	Zexel 35	Sun 63	Sun 65	Sun 66
Max Flow Lift (mm)	0.65	0.67	0.65	0.66	0.67
Max Flow (L/min)	3.81	3.80	4.00	4.02	3.98
End of Lift (mm)	0.78	0.79	0.79	0.80	0.79
End of Lift Flow (L/min)	3.48	3.50	3.63	3.64	3.62
	CAV 14	Zexel 70	Zexel 71	Sun 68	Sun 69
Max Flow Lift (mm)	0.67	0.67	0.67	0.67	0.69
Max Flow (L/min)	3.93	3.87	3.80	3.80	3.81
End of Lift (mm)	0.78	0.79	0.80	0.80	0.80
End of Lift Flow (L/min)	3.70	3.50	3.41	3.43	3.46

Table I.3: Needle clearance nitrogen flow test rig data for all 15 test nozzles

	Zexel 9	Zexel 15	Sun 1	Sun 32	Zexel 76
Average Flow (mL/min)	125	109	44	69	98
	Zexel 22	Zexel 35	Sun 63	Sun 65	Sun 66
Average Flow (mL/min)	95	125	76	64	80
	CAV 14	Zexel 70	Zexel 71	Sun 68	Sun 69
Average Flow (mL/min)	47	144	176	51	88

I.4 Needle Profile Data

Needle dimensions for all 15 test nozzles are given in Table I.4. Refer to Figure 3.13 for the dimension letters.

Table I.4: Needle profile dimensions for all 15 test nozzles

		Dimension Value (mm)				
		Zexel 9	Zexel 15	Sun 1	Sun 32	Zexel 76
Dimension Letter	A	0.73	0.77	0.77	0.74	0.80
	B	1.00	0.99	0.99	0.99	0.99
	C	0.20	0.23	0.22	0.22	0.24
	D	0.81	0.83	0.74	0.65	0.76
	E	0.85	0.87	0.84	0.83	0.86
	F (deg.)	18.00	18.25	17.25	17.00	17.50
	G	0.61	0.63	0.60	0.66	0.62
	H	0.98	0.98	1.03	1.02	0.98
	I	1.64	1.63	1.63	1.65	1.60
	J	2.49	2.51	2.54	2.51	2.51
	K (deg.)	60.30	59.50	60.25	60.80	60.00
	L (deg.)	82.00	83.50	85.00	80.75	86.00
		Zexel 22	Zexel 35	Sun 63	Sun 65	Sun 66
Dimension Letter	A	0.75	0.75	0.71	0.71	0.67
	B	0.99	1.00	1.00	1.02	0.99
	C	0.20	0.22	0.24	0.24	0.23
	D	0.81	0.79	0.76	0.76	0.76
	E	0.86	0.89	0.83	0.85	0.89
	F (deg.)	18.00	17.50	18.00	19.00	18.00
	G	0.64	0.62	0.60	0.62	0.60
	H	1.02	0.99	1.07	1.06	1.05
	I	1.65	1.63	1.69	1.70	1.73
	J	2.51	2.49	2.54	2.53	2.53
	K (deg.)	59.75	60.00	60.50	60.75	60.75
	L (deg.)	88.50	85.50	87.00	86.25	85.25

		CAV 14	Zexel 70	Zexel 71	Sun 68	Sun 69
Dimension Letter	A	0.77	0.72	0.74	0.72	0.74
	B	0.99	0.99	1.00	0.99	1.00
	C	0.20	0.19	0.23	0.23	0.23
	D	0.81	0.81	0.77	0.76	0.75
	E	0.86	0.86	0.86	0.83	0.83
	F (deg.)	17.00	17.50	18.00	18.00	17.50
	G	0.61	0.62	0.63	0.61	0.60
	H	0.94	1.00	1.02	1.05	1.02
	I	1.59	1.65	1.65	1.68	1.65
	J	2.49	2.49	2.49	2.53	2.54
	K (deg.)	60.75	60.00	60.00	60.00	60.50
	L (deg.)	86.00	84.50	85.50	85.50	85.50