

 SURFACE VEHICLE RECOMMENDED PRACTICE	J2715	ISSUED MAR2007
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Gasoline Fuel Injector Spray Measurement and Characterization		

RATIONALE

The rationale for this document is that fuel spray measurement and characterization continues to become increasingly critical to the automotive industry; whereas no comprehensive, industry-wide set of measurement and reporting procedures has been available. This has led to a situation in which many spray parameters and test procedures have, of necessity, been created and utilized within individual original equipment manufacturer (OEM) companies, and even among third-party testing laboratories and universities. This non-uniformity regarding test and reporting procedures has resulted in a lack of repeatability and traceability for many claimed spray parameters. It has also made it very difficult for any laboratory to check the values of spray-characterization parameters that are reported by another laboratory. The lack of standardization has also resulted in considerable confusion and obfuscation regarding the names and definitions of spray parameters as they apply to port fuel injection and gasoline-direct injection. The current situation regarding the term "cone angle" for these two classes of injectors is a prime example.

The use of the uniform and well-defined procedures for test configuration, testing, data reduction and reporting that are contained in this document should significantly enhance the ability of one spray-test laboratory to accurately repeat and verify the results of another. The very detailed procedures and test specifications for all of the spray parameters should also serve to reduce the variation of spray parameter values that are reported, even for the same injector model. This should, in turn, reduce the overall time and overhead for obtaining a proven fuel system for an engine, as OEMs could ultimately conduct one set of spray tests per J2715 as opposed to a separate set of tests for each customer. This document should also supply the industry with a neutral, unbiased test for each defined spray parameter.

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1. SCOPE

This SAE Recommended Practice promotes uniformity in the characterization tests conducted on sprays generated by automotive fuel injectors used in both port fuel injection and gasoline-direct injection engine applications. SAE J2715 contains the detailed background, procedures and data reduction protocols for nearly all fuel spray characterization metrics that are applicable to automotive applications. It is intended to be utilized in conjunction with other SAE J documents that address injector performance metrics. These are SAE J1832 for Port Fuel Injection and the forthcoming SAE J2713 for Gasoline Direct Injectors.

1.1 Purpose

a. Standardize the use of nomenclature specifically related to gasoline fuel injector spray measurements.

b. Identify and define the key metrics that constitute the characterization of fuel sprays.

- c. Establish detailed test procedures and recommend test equipment and methods to measure and quantify these key metrics.
- d. Establish the recommended data reduction and analysis procedures.
- e. Establish the criteria for data reporting and the required accompanying information that must be supplied in order to interpret and reproduce the test results.

2. REFERENCES

The following publications form a part of this specification to the extent specified herein. Unless otherwise specified, the latest issue of SAE publications shall apply.

2.1.1 SAE Publications

Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

SAE J1832 Low Pressure Gasoline Fuel Injectors

2.2 Related Publications

The following publications are provided for information purposes and are not a required part of this document.

2.2.1 ASTM Publications

Available from ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

- | | |
|----------------------|---|
| ASTM F 328-98 | Standard Practice for Calibration of an Airborne Particle Counter Using Mono-Disperse Spherical Particles |
| ASTM E 799-03 | Standard Practice for Determining Data Criteria and Processing for Liquid Drop Size Analysis |
| ASTM E 1260-03 | Standard Test Method for Determining Liquid Drop Size Characteristics in a Spray Using Optical Non-Imaging Light-Scattering Instruments |
| ASTM E 1458-92(2001) | Standard Test Method for Calibration Verification of Laser Diffraction Particle Sizing Instruments Using Photomask Reticles |
| ASTM E 1617-97(2002) | Standard Practice for Reporting Particle Size Characterization Data |
| ASTM E 1620-97(2004) | Standard Terminology Relating to Liquid Particles and Atomization |

2.2.2 ISO Publications

Available from ANSI, 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, www.ansi.org.

- | | |
|-------------------|--|
| ISO 9276-2(2001) | Representation of results of particle size analysis—Part 2: Calculation of average particle sizes/diameters and moments from particle size distributions |
| ISO 13320-1(1999) | Particle size analysis—Laser diffraction methods—Part 1: General principles |
| ISO 13323-1(2000) | Determination of particle size distribution—Single-particle light interaction methods—Part 1: Light interaction considerations |
| ISO 13322-1(2004) | Particle size analysis—Image analysis methods—Part 1: Static image analysis methods |

3. BASIC SPRAY CHARACTERISTICS AND DEFINITIONS

3.1 Introduction to Gasoline Fuel Spray

The primary function of the gasoline fuel injector is to accurately meter the required amount of fuel. Another key function, however, is to atomize the injected liquid fuel. The transformation of the liquid stream into a myriad of small gasoline drops dramatically increases the surface area of the injected fuel, thus enhancing the rate of vaporization. The transient event that simultaneously meters and atomizes the liquid gasoline may be considered as concurrent spray formation and penetration processes that occur on the order of milliseconds. The resultant atomization is a positive factor in the port fuel injection application, but is an even more critical factor for gasoline-direct injection, due to the fact that for G-DI, the available time interval between the end of injection and ignition is very brief. The mean diameter of a representative sample of the delivered gasoline drops is a statistical metric that is a key measure of goodness of the spray delivered by a particular injector. As the mean diameter becomes smaller, the surface-to-volume ratio of the injected gasoline increases, and the vaporization rate increases substantially.

There are many spray classifications in the field of gasoline injection, but the initial, primary classification is historically based upon the application. The two major gasoline applications are port fuel injection (PFI) and gasoline, direct, in-cylinder injection (G-DI). This is illustrated in Figure 1. In general, the PFI injector application utilizes relatively low fuel pressures of less than 0.5 MPa, and achieves a mean drop diameter in the range from 50 to 200 microns in the delivered spray, depending upon the design. SAE J1832 refers to injectors with fuel pressure below 1000 kPa as low-pressure gasoline injectors. The G-DI injector, however, is required to deliver a mean drop diameter of less than 30 microns in order to sustain combustion; therefore, extensive measures such as a high fuel pressure (5.0 to 20.0 MPa) or the introduction of compressed air are generally required.

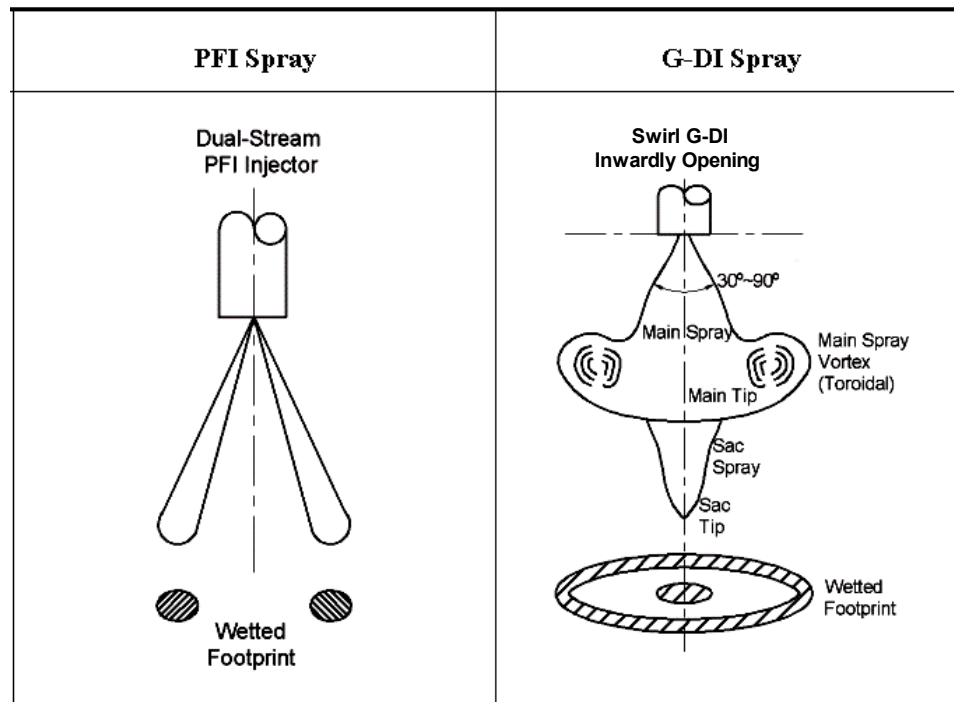


FIGURE 1 - MAJOR CLASSIFICATION OF SPRAYS FROM AUTOMOTIVE FUEL INJECTORS

Typical geometric configurations for both a PFI application and a G-DI application are illustrated in Figure 2. On the right in this illustration, α depicts the injector mounting angle relative to the engine fire deck, and β depicts the spray angle of the spray plume. In the port injector classification illustrated on the left panel in Figure 2, the fuel injector is positioned to introduce the fuel spray into the intake port upstream of the intake valve or valves. This may be anywhere within a significant range of distances from the injector tip to the rear face of the intake valve. This distance is commonly referred to as the "targeting distance", and is a key parameter in the overall design of the combustion system. The PFI injector is most commonly mounted in the intake manifold runner, which yields targeting distances of 65 to 120 mm. Some special applications such as supercharging may have the injector mounted in the cylinder head portion of the intake runner, with associated shorter targeting distances of 40 to 65 mm. This option, and the G-DI in-cylinder mounting, generally yield elevated injector operating temperatures. The timing of the port fuel injection event in the vast majority of applications occurs while the intake valve is closed, and with no mean airflow in the port. This results from the observed fact that engine-out UBHC (unburned hydrocarbon) emissions are significantly elevated if injection into the port occurs during the period when the intake valve is open. The fuel spray from the PFI injector normally requires from 4 to 9 milliseconds to traverse the targeting distance and to impact the rear face of the intake valve. This rear face is the most common "target" for the fuel spray axis, which is again due to the observed fact that the engine combustion and emission characteristics are both degraded as greater amounts of the fuel spray mass are allowed to contact the port wall.

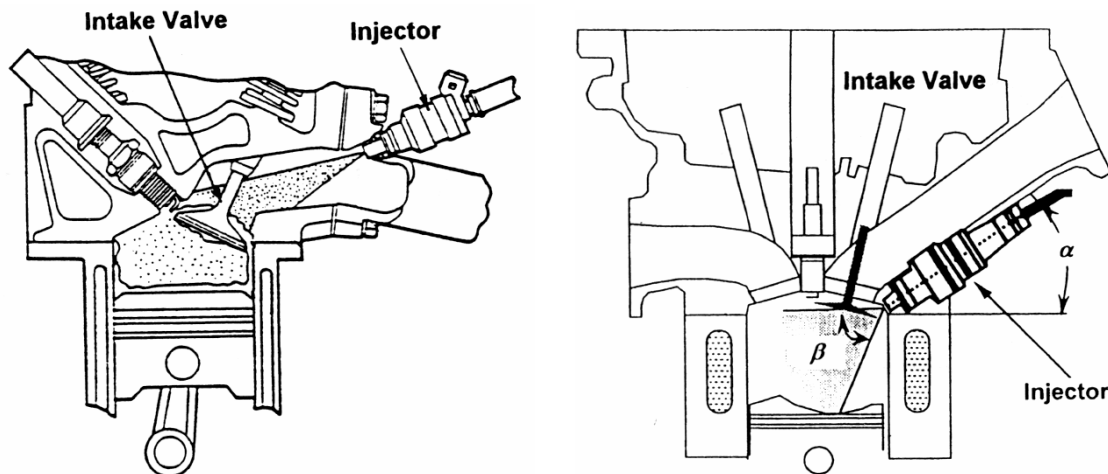


FIGURE 2 - SCHEMATIC REPRESENTATIONS OF THE PORT FUEL INJECTION AND GASOLINE-DIRECT INJECTION CLASSIFICATIONS

The G-DI injector, in contrast, introduces the fuel spray directly into the engine cylinder. This is depicted schematically in the right panel of Figure 2. As a direct consequence of the very limited time available for penetration, evaporation and mixing, the spray must, out of necessity, be significantly more brief and of a finer atomization level than that from a PFI injector. The G-DI injector may be open less than 2 milliseconds at light load operating conditions, and will normally exhibit a mean drop size that is an order of magnitude smaller than that of a PFI spray. The time scale of the spray event is quite different for the two main application classifications, with nearly all of the event time markers such as injector opening, spray formation, pulse duration, penetration, vaporization and injector closing being two to four times faster for direct injection. This is, of course, forced by the stringent timing requirements for achieving stable combustion when injecting directly into the combustion chamber. As is the case for the mounting of PFI injectors, a number of options exist for G-DI injectors. Depending upon the type of intended combustion system, the spray may be intentionally directed at the piston crown, at a special bowl in the piston crown or against or with the in-cylinder air motion.

For the transient processes of spray formation, penetration and dissipation, there are a number of key spray features that may be readily identified. These features are illustrated and identified in Figure 3. Although the spray features are illustrated schematically for a G-DI injector spray, nearly all those shown except for the toroidal vortex also exist in the port injection spray. Thus, each classification may have an early sac spray and a later main spray, and may have one or more after-injections.

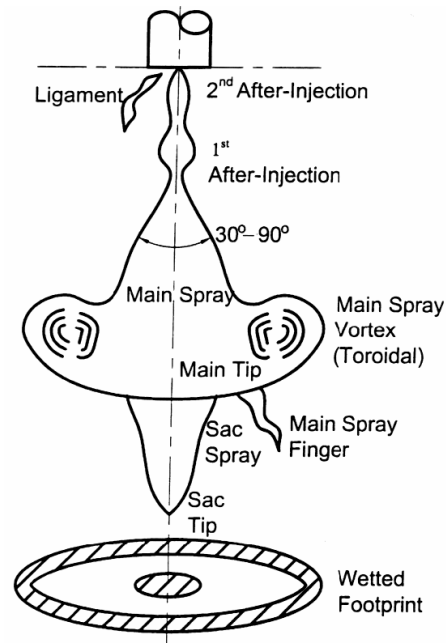


FIGURE 3 - GEOMETRIC CHARACTERISTICS OF A TRANSIENT G-DI SPRAY

This document will detail the recommended practices for obtaining numerous key metrics that quantify the spray performance parameters for both PFI and G-DI gasoline sprays. This includes recommended procedures for the imaging, measurement and reporting of important spray parameters such as penetration, drop sizes and spray cone angle. These recommended practices that have been developed by an industry-wide committee will provide both end-users and OEMs with measurement and reporting criteria that are critical for future technical developments, and that will significantly enhance the ability of the results to be verified by repeat testing in other laboratories.

3.2 Fuel Injector and Spray Classifications

The two major classifications of automotive fuel injectors are the PFI injector and the G-DI injector, as was briefly discussed in the previous section. Beyond that broad division, however, are numerous sub-categories of many common injector types that are currently in use. The second level of classification is by nozzle design, with some common representative types illustrated for gasoline-direct injection in Figure 4.

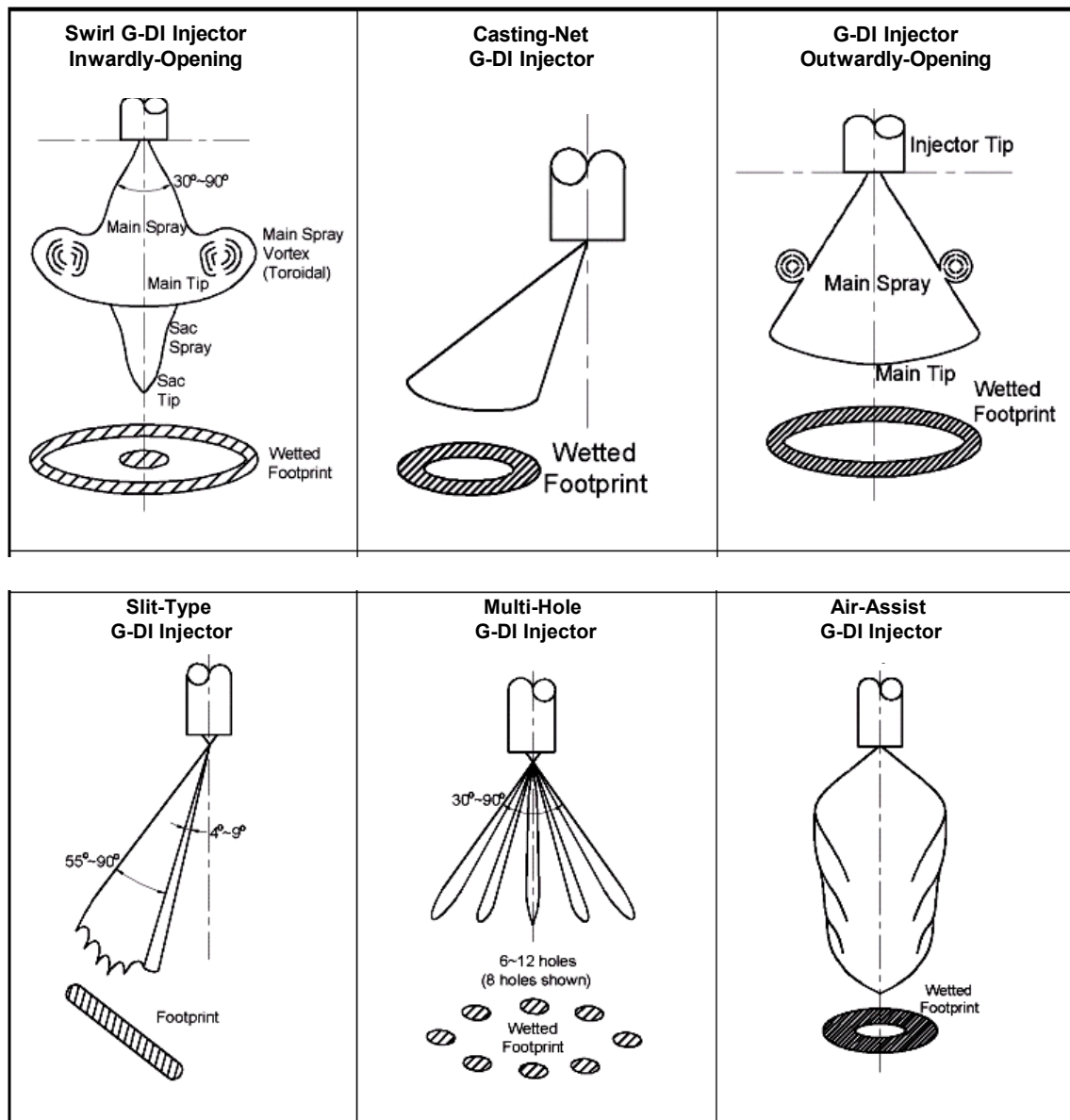


FIGURE 4 - G-DI INJECTOR SUB-CLASSIFICATION BY NOZZLE DESIGN

The design categories are quite diverse, and only the most representatives are shown here. As discussed in the next section, many of the classifications for G-DI injectors also apply to PFI injectors. This includes the multihole, the bent spray and the air-assist. There are numerous additional sub-classifications that may be used to conveniently identify types of PFI and G-DI injectors. Most of these sub-classifications apply to both overall types. These include the type of tip, which may be a pintle or an isolating director plate containing one or more delivery holes. The Casting-Net injector tip, for example, was developed to alleviate the common difficulty encountered in bending a spray, which is to normally yield a greater concentration of fuel mass toward the injector axis. By optimizing the design of the tip-cavity geometry of a G-DI injector, a more uniform distribution of fuel in the horizontal impact plane (the piston bowl floor) may be achieved, even though the spray is bent off-axis.

The injector design may also utilize a single fluid (the fuel) or may use two fluids, which are the delivered fuel and an atomization-assisting auxiliary air stream. Fuel injectors utilizing such an air stream are denoted as air-assist injectors, and may use either a steady flow or a pulsed flow of air. The normal designation for a unit that is designed to use an additional air solenoid to pulse the air is a pulsed-pressurized, air-assist injector, or PPAA. These are normally G-DI injectors, although they may be employed in a PFI configuration. The more common air-assist PFI injector has the atomizing air generated by the engine vacuum rather than from a compressed air source. Another common method of categorizing automotive fuel injectors is by the direction of opening motion of the armature and pintle. Thus, injectors may be designed to be inwardly-opening or outwardly-opening. The intended direction of the resultant fuel spray cloud yields another common differentiator among injector designs; this is the on-axis versus the off-axis, or bent spray. Throughout the remainder of this document, this type of injector design will be denoted as a bent spray. The bent spray design provides mounting options for cases where choices for injector packaging are limited, and is normally available in specified increments of the bend angle.

3.3 Measurement of Fuel Spray Characteristics

Spray testing has evolved over many decades, and improvements to equipment, methodology, and protocols are being made continuously. The recommended practices in this document establish baseline common procedures to be followed in both industry and academia. Specifically, this section contains information to allow spray testing and characterization per a standard recommended practice. The obtainable data from this characterization includes:

- a. Spray Geometry
- b. Spray Tip Penetration
- c. Fuel Mass Distribution
- d. Cone Angle (PFI)
- e. Spray Angle (G-DI)
- f. Drop Size Distribution and Characteristic Diameters (SMD, D_{v90})

The determination of the characteristics of sprays from automotive fuel injectors is a very important, but specialized, area of measurement. Specialized optical equipment and considerable care and expertise are required to obtain the key metrics for these transient fuel sprays. Parameters such as the mean drop diameter, spray-tip penetration, mass distribution and the cone angle or spray angle are critical to the selection of an injector for a given application, and the values must be determined by standardized procedures if the performance of one injector is to be meaningfully compared to the performance of another. Some measurements, such as those of spray tip penetration, involve macroscopic spray parameters, while others, such as the mean drop size, involve the determination of microscopic characteristics.

All spray measurement tools should initially undergo rigorous calibration, repeatability and reproducibility testing, and should be subjected to periodic audits to ensure proper functionality and data integrity. Even if a test facility has an established calibration and audit program using known master parts, a number of the testing procedures in this document call for the test to be conducted a minimum of three times, with the average and sample standard deviation values reported to provide an estimate of error.

Fuel sprays can be characterized using a variety of measurement techniques; however, certain techniques are more suitable for PFI sprays than for G-DI sprays, and vice versa, due to the nature of the sprays. For example, the macroscopic parameters of the direct injection spray, such as spray penetration and spray angle, can be quantified via imaging (Section 6.1). Although a single large drop scatters more light than a single small drop, it is observed that the collection of small drops in a G-DI spray scatters significantly more light than the collection of larger, but many fewer, drops in a PFI spray. This is because the highly atomized G-DI spray has many times the number of drops of a PFI spray for the same amount of total fuel mass. Therefore, the imaging of a PFI spray generally yields a poorly defined spray boundary. This leads to possible errors in the quantification of PFI spray geometry by imaging. Hence, imaging of PFI sprays is recommended in this document only for qualitative comparisons. Another example is provided by the fuel mass distribution, from which the cone angle is obtained. The mass distribution of the PFI spray, and a number of associated key spray parameters such as the cone angle and the bend angle, can be determined by using a

patternator (Section 6.2). However, the application of patternation to gasoline-direct injection fuel sprays is not recommended due to the significant percentage loss of fuel that is associated with very small drops. This is injected fuel that is never collected and measured. The drops from G-DI sprays have limited penetration and, by design, vaporize very rapidly, making patternation currently impractical. Because the cone angle is derived from the 90% point of cumulative mass distribution, and because the mass distribution in a G-DI spray cannot be reliably determined by patternation, there is no "cone angle" for a G-DI spray that corresponds to that of a PFI spray. Rather, the angular extent of a G-DI spray is described by the term "spray angle", and is determined by imaging. The terms "cone angle" and "spray angle" both represent measures of the angular extent of a spray, but that is where the similarity ends. They are respective measures of quite different quantities. In this document, the SAE J2715 Cone Angle is the 90% point on a measured curve of fuel mass distribution, and applies only to PFI fuel sprays. The spray angle is the included angle between imaged spray edges, and applies only to G-DI sprays. Unfortunately, it is fairly common to encounter the term "cone angle" in regards to the angular extent of G-DI sprays; in fact, some G-DI injectors are marketed with this as a descriptive parameter. This should be corrected, and the term "spray angle" should be used by the industry when the sprays from G-DI injectors are being characterized.

Thus, for numerous reasons that are discussed in detail in subsequent sections, imaging should not generally be applied to PFI sprays to obtain spray characterization data, and patternation should not be applied to G-DI sprays. However, the two drop-size measurement techniques discussed in this document, laser diffraction and phase-Doppler interferometry, can both be employed to measure the drop-size distribution and drop size statistics for either PFI or G-DI sprays. The following sections detail the range of spray parameters and measurement protocols that can be used to characterize the complete spectrum of automotive fuel sprays.

3.3.1 Basic Concepts in the Use of Imaging to Obtain Fuel Spray Characteristics

A brief overview and introduction to the imaging of automotive fuel sprays is provided in this section. This includes the concepts and parameters that will be measured by means of spray imaging in Section 6.1. The details of the imaging tests and the data reduction and reporting are provided there. Spray imaging of the type to be used in this recommended practice generally produces a two-dimensional static representation of a three-dimensional, time-varying spray, as depicted in Figure 5. The outline of the main spray at the time of the light-source flash may be discerned, as can the position of the leading drops in the sac spray. As fuel sprays are not generally perfectly symmetrical, it should be noted that the results obtained by imaging measurement are sensitive to the injector orientation with respect to the viewing angle. This orientation is normally quantified by the angle of the electrical connector centerline relative to the imaging camera lens axis.

There are three general classifications of imaging. The first is when a spray image is obtained by means of backlighting, as is depicted in Figure 5. In this method a very brief pulse of light that is nearly opposite to the camera lens axis creates a shadow image of the spray. This method will be employed in the testing described in Section 6.1 to obtain numerical data on fuel sprays. The second method is volume illumination, in which a steady or triggered-stroboscopic light source is used to illuminate the entire viewable spray surface. This is commonly employed for the initial examination of the macroscopic characteristics of a spray, and is recommended as a preliminary procedure for all spray testing. However, it will not be used to obtain numerical data. The third method is the light sheet, either steady or pulsed, in which a thin sheet of light, normally from a laser of some reasonable power level, is passed through a portion of the spray. The laser sheet illuminates that particular cut through the spray, revealing inner details that may not be evident with volume illumination. For dense sprays there can be significant secondary scattering of light from drops that are outside the sheet, sometimes masking the detail along the internal cut. There are numerous sub-categories of imaging that involve laser pulsing, double-pulsing, fluorescence, seeding, holography and a number of other sophisticated techniques that are not employed in this document for obtaining numerical characterization of fuel sprays. These research tools can be quite valuable in gaining a basic understanding of the physics of spray formation and development.



FIGURE 5 - TYPICAL BACK-LIT IMAGE OF A G-DI SPRAY

3.3.1.1 Spray Penetration

Figure 6 schematically depicts the basic axial penetration of the spray, which is defined in this document as the maximum distance along the injector axis between the leading edge of the spray and the tip of the injector, at a specified time after the Start of Fuel (SOF). The imaging delay time (IDT) is the time increment after SOF at which the imaging light source is energized. The standard IDT value for a gasoline direct injector spray is 1.50 ms; however, the additional values of 0.50, 1.00, 2.00 and 2.50 ms may be used for obtaining a complete penetration curve. The standard IDT value for a PFI injector spray is 5.0 ms, and the additional values of 2.0, 3.5, 6.5 and 8.0 ms may be employed to obtain a full penetration curve. A driver charge delay (DCD) increment of time is sometimes utilized in the circuitry of G-DI injector drivers to ensure that the main capacitor is fully charged before the pulse is delivered to the injector opening coil. Such delays are seldom, if ever, employed for PFI injector drivers. Typical DCD values are 0.25, 0.50 or 1.0 ms. A driver circuit having no driver charge delay has a DCD value of 0.0 ms. The leading edge of the spray at a particular instant is commonly referred to as the spray tip. In most cases the "tip" is well defined and does not shift from side to side as time progresses. For some sprays, however, such as a wide fan spray, there may be many small ripples in a generally uniform penetration all across the spray. For such cases the "tip" may move from center to left to right at three different times. The axial penetration is used in this document, even for cases where the spray plume is intentionally designed to penetrate in a direction other than along the injector axis; for example, with a dual spray PFI injector or a six-hole G-DI injector. For those cases the axial penetration will be the penetration along the plume centerline angle, reduced by the cosine of that angle.

The "injector tip", which is not to be confused with the "spray tip", is the point on the injector axis that corresponds to the lowest point on the injector body, when the body is positioned vertically with the fuel delivery direction being down. The "Right Hand Rule" will apply to the spray measurement. That is, the positive Z axis corresponds to the injector axis and the positive X axis will be oriented through the center plane of the electrical connector.

The penetration of a spray tip is, of course, a time-varying event, with the penetration increasing non-linearly with time. The spray-tip velocity slows significantly in the first two milliseconds, and over the first 50 to 70 mm, thus the curve will be concave downward. As the penetration curve is continuous, there are an infinite number of time and penetration points that describe it. The purpose of the SAE J2715 Recommended Practice for G-DI spray penetration is to determine and report one key point on that curve (at 1.50 ms after SOF), and to designate that point as the SAE J2715 Main Penetration.

For the common case of a G-DI spray there may be two SAE penetration points; one for the main spray and one for the sac spray. The second number determined will thus be designated as the SAE J2715 Sac Penetration. In many portions of the automotive industry there may be an interest in identifying the full curve of spray-tip penetration in addition to the single key point on the curve. This is analogous to having an interest in the entire drop-size distribution curve in addition to the SMD value. It is common practice to approximate the entire penetration curve with five points from images taken at five increasing times. The option to obtain additional penetration points via additional images is permitted, with a total of four additional images and points to be obtained. These would be for two earlier times; 0.5 and 1.0 ms after SOF, as well as two later points (2.0 and 2.5 ms after SOF). The two designated SAE penetration values (SAE J2715 Main Penetration and SAE J2715 Sac Penetration), however, are the values obtained at 1.50 ms after SOF.

Imaging for spray characterization is normally intended for G-DI sprays, not for PFI sprays, with the only exception being for PFI spray penetration if such a characterization point is required. Commonly there is much more interest in the penetration characteristic of G-DI sprays, but there may be special situations where PFI penetration characterization is needed. In this case the imaging procedures for penetration that are provided in Section 6.1 may be utilized, with the exception of substituting 5.0 ms for the 1.5 ms as the time after SOF to be used.

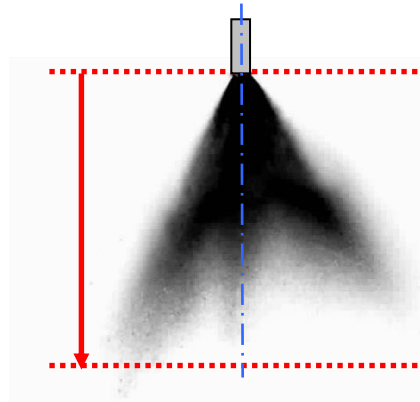


FIGURE 6 - SCHEMATIC REPRESENTATION OF AXIAL SPRAY PENETRATION

It is obvious from the laser-light-sheet spray image in Figure 7 that there may be two separate sprays that can be tracked by means of a series of images. This is, in fact, true for many, if not most, G-DI injectors, and for some PFI injectors. For PFI injectors the sac spray is generally present, but may be quite difficult to detect by imaging. The sac fuel that forms the sac spray in most G-DI injector or PFI injector designs may be considered as the small amount of residual fuel in the delivery orifices that remains downstream of the pressure sealing line after the injection event has been completed. This fuel is not at the elevated fuel pressure, but instead resides in a portion of the fuel delivery path at the lower, downstream pressure. When the next injection event occurs it must be accelerated and forced from the orifices as the first fuel to exit.

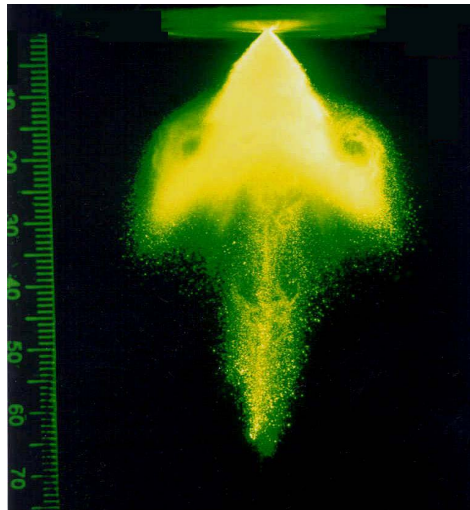


FIGURE 7 - G-DI SPRAY LIGHT-SHEET IMAGE AT 1.5ms AFTER SOF
SHOWING BOTH THE MAIN AND SAC SPRAYS

For a G-DI swirl injector that relies on a high-swirl in the tip cavity to achieve atomization, the problem is multiplied. The fuel emanating from the sac volume generally has little or no tangential velocity, and consequently does not atomize well or develop as a hollow cone. This fuel will remain in the vicinity of the injector axis, and will generally exist in the form of drops that are substantially larger than those in the main spray. Because these drops are formed earlier, exit first and have lower relative drag, the drops are found further downstream than the fully developed main spray. This leading cloud of identifiable drops, as shown in the lower portion of Figure 7, is commonly designated as the “sac spray”. The term “main spray”, is generally used to describe the bulk of the spray, minus the sac spray and any after-injections that may occur due to pintle bounce. Although not the case in the laser-light-sheet image in Figure 7, the sac spray may sometimes be difficult to image if the sac volume and number of drops are small. This difficulty is more prevalent for sprays from PFI injectors, where the mean drop size in the sac spray may be hundreds of microns, hence there are few drops to scatter adequate light for good backlit imaging. For many G-DI sprays, however, it is easily discernable (as in Figure 5), and the sac and main sprays may be advantageously treated as two different sprays with different spray-tip-penetration curves. Some injector designs, such as the outwardly-opening G-DI type, have little or no sac volume, and produce only a main spray.

The presence of a separate sac spray along with the main spray serves to emphasize a problem that has an impact on the other spray parameters such as the mean drop size. Both the laser diffraction and phase-Doppler interferometry techniques that are recommended for drop-sizing in this document are time-integrated, and measure drops over the entire injection event and, in fact, over many consecutive injection events. As is obvious from the images in Figure 5 and Figure 7, the two separate sac and main sprays will be measured as one, and the two drop-size curves will be blended into one. It is well established that sac sprays have larger drops than the main spray, thus the presence of a sac spray will increase the mean drop size that is measured. It is certainly debatable as to whether this is an error in drop-sizing, as the engine receives all of the spray in the total distribution, both sac and main. At least the reader should be cognizant of the fact that there are often two distinct sprays present during an injection event. These main and sac sprays will have different spray characteristics that will be blended in all of the recommended practice tests in this document, with the exception of those obtained by spray imaging.

3.3.1.2 Spray Angle

The spray angle is a measure of the angular extent of a G-DI fuel spray, and is determined by backlit imaging. It is defined as the angle between the spray edges at the pre-determined locations near the injector tip at a specified time after the start of fuel (SOF). This angle is denoted as θ_s , and is illustrated schematically in Figure 8. The details of how the test for spray angle is to be conducted and reported are provided in Section 6.1. It is important to note that the spray angle represented and described here differs conceptually from the cone angle of a PFI spray, which is not determined by imaging, but by a patternation test. This key point is discussed in detail in Section 3.3, and should be reviewed and understood. Imaging is applied to G-DI sprays to determine the angular extent of the spray because patternation for such sprays is not recommended. Thus, the mass distribution, which is supplied by patternation, will remain unknown for the G-DI spray. Imaging will provide only a measure of the angular extent between spray edges, not the mass distribution between them. Hence the distinctly different and non-interchangeable names; spray angle (G-DI) and cone angle (PFI). These terms describe two different metrics, and should *not* be interchanged.

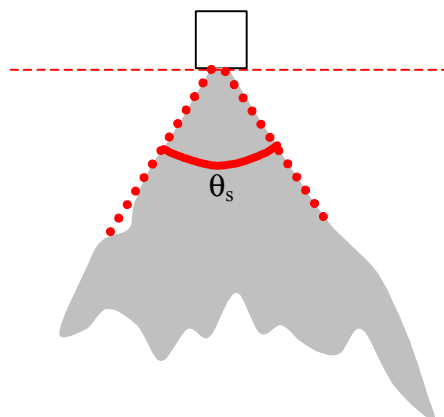


FIGURE 8 - REPRESENTATION OF THE G-DI SPRAY ANGLE

3.3.1.3 Spray Bend Angle

The Spray Bend Angle, θ_B , is normally associated with a single-plume G-DI spray and quantifies the angular deviation of the spray plume from the injector axis. In the literature, it may also be referred to as the spray offset angle, particularly for those G-DI injectors that are designed to intentionally spray off-axis. The descriptive term in this document for injector designs that produce an offset, single-plume spray is a bent-spray injector. In such units the center of the plume is designed to be at an angle to the injector axis, and such injectors are normally designed as a series to provide enhanced engine mounting options. The sprays provided by members of the design series are usually at equal increments of the Spray Bend Angle, such as at 10, 15 and 20 degrees. This type of injector tip design can indeed provide injector mounting options when there are interfering engine components. As was the case for the cone angle, it should be noted that the bend angle of a PFI injector is not measured by imaging, but is determined by means of high-resolution mechanical patternation. The proper descriptive term for this angular offset of the plume from a PFI injector is "Cone Bend Angle". Angular offsets of G-DI sprays are determined by imaging (instead of patternation), and are denoted as Spray Bend Angles instead of Cone Bend Angles.

The Spray Bend Angle is a measure of the actual angular deviation of the single-plume G-DI spray, whether the deviation is intended or not. The imaging test makes no distinction. For multi-plume sprays, such as those produced by the multi-hole G-DI injector, each plume has a separate axis that is not in alignment with the injector axis. There may be one delivery orifice, and one plume, that is on-axis, but the remainder will not be. Strictly speaking, each plume of an eight-hole G-DI injector would have a separate spray bend angle, which is why the term is not applied to such injector-tip configurations. The spray bend angle as determined in the SAE J2715 imaging test is normally determined to verify a nominal, or design-intent, spray bend angle. This actual measured value may differ from the design-intent angle. For example, a design-intent bend angle of 20.0 degrees may have an actual, measured Spray Bend Angle of 22.3 degrees. The intended nominal angle should be referred to as the design-intent bend angle. For a G-DI injector that is designed to spray on-axis, the design-intent bend angle is zero. A typical measured Spray Bend Angle for such a unit might be 1.3 degrees. As illustrated in Figure 9, the spray bend angle that will be determined by the imaging test in Section 6.1 is the angle between the bisectrix of the included angle between spray edges and the axis of the injector (dashed line), at the specified time of 1.50 ms after the SOF.

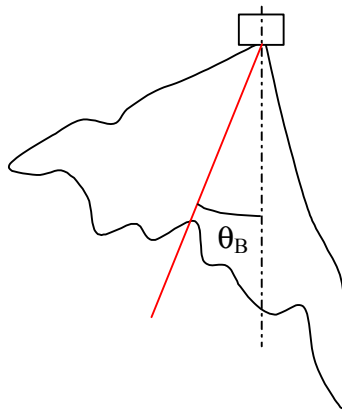


FIGURE 9 - REPRESENTATION OF THE G-DI SPRAY BEND ANGLE

3.3.2 Port Fuel Injection Spray Characteristics Obtained Using Patternation

The fuel mass distribution of the spray can be determined by collecting the liquid drops from many consecutive fuel spray pulses by means of a mechanical patternator. The original SAE eight-ring, annular patternator has been almost completely superseded by high-resolution (H-R), automated patternators having more than two-hundred individual collection cells, as opposed to eight. As is discussed in Appendix D in conjunction with drop sizing, there are many and varied spray-plume geometries that may be encountered in spray characterization work; however, there will be somewhat less variety encountered for patternation than for drop sizing, as patternation for gasoline-direct injection fuel sprays is precluded. This is discussed in detail in Section 6.2. For PFI fuel sprays, a fairly wide range of complex spray plumes may still be expected, including those from solid-cone, hollow-cone, pencil-stream, single-plume, bent-spray and dual spray injectors. Also occasionally encountered are dual spray injectors that do not produce two distinct fuel regions, as well as multi-hole injectors having multiple plumes that do not converge into either single or dual plumes. The information provided in this section should facilitate the patternation testing of the bulk of these PFI spray types, although the equations, definitions and patternation data-reduction algorithms may not be universally applicable to all possible spray-plume configurations. For example, if an injector produces four randomly-spaced islands of fuel, equations are not provided for the multiple separation angles between any two plumes, although it is not a difficult task to compute if the four centroid locations are identified. However, the proprietary data-reduction algorithms for a particular corporate patternator will likely not be programmed to yield this data from the cell fuel-mass information. This should be kept in mind if very complex spray geometries are encountered.

Equations are provided in this document for the much more common spray-plume geometries of a single, nominally-on-axis, spray plume, a dual-spray-plume geometry and a single, bent-spray-plume geometry. For these spray geometries there is normally one (or at most two) major areas of fuel concentration in the patternator, with each area having a separate location for the fuel mass centroid. As will be discussed in detail in Sections 3.3.2.2 and 6.2, these centroid locations are relative to the point of injector axis intersection with the inlet plane of the patternator, which is the origin of the patternator coordinate system.

The patternator test fixture and associated equipment are discussed in detail in Section 6.2, but there is an important point regarding fuel volume and mass that must be emphasized even within this introductory overview. In much of the patternation work encountered in the literature, the terms fuel volume and fuel mass are often used interchangeably. It may be stated in one source document that the cone angle is based upon a fuel mass measurement, while another source document may state that it is computed from a cumulative fuel volume curve. Both statements are basically true. For most high-resolution mechanical patternation measurements the parameter that is measured for each cell is fuel volume, although for earlier, low-resolution patternation the collected fuel was actually withdrawn and weighed. This is seldom, if ever, done for the hundreds of cells in high-resolution patternators. Nonetheless, it is important to state that the volume is measured, but mass is inferred. As the test fluid, n-Heptane, is treated as a pure, incompressible fluid with a constant specific gravity at the test temperature, the volume and mass differ only by that constant multiplier. There may be some direct fuel mass measurement if a fuel mass flowmeter is installed on the injector inlet to measure the amount of fuel injected during the patternation test, but even if there is no direct mass measurement (just volume), the fuel volumes are directly converted to fuel mass and, for consistency, all equations and terminology within this document refer to fuel mass. Thus, terms such as "mass-weighted" and "collected fuel mass" will be used, even though the basic patternator measurement cell is configured to transduce the volume.

3.3.2.1 Definitions of General Terms and Parameters Used in High-Resolution Patternation

Definitions for the terminology that is used in mechanical patternation are provided in this section. The following two sections contain definitions of the parameters that are associated with the testing of single-plume and dual-plume sprays, respectively. The latter are the spray plumes from a dual spray PFI injector.

- a. Spray – The total collection of atomized fuel that is produced in an individual injection event. Nearly all spray characterization techniques in this document deal with the liquid portion of the delivered fuel; however, strictly speaking, any fuel that evaporates is also part of the spray.
- b. Plume – A distinct and identifiable collection of fuel within the total spray; sometimes referred to synonymously as a spray plume. For example, an injector tip having six fuel-delivery orifices would initially have a spray consisting of six plumes. Some or all of these plumes can merge as the spray moves downstream, yielding a lesser number of plumes than were created at the tip.

- c. **Geometric configuration** – The geometric configuration of a patternator is an expression of the planar placement of the collection cells. Patternator geometries that are commonly used include the square grid, the hexagonal grid and the linear array.
- d. **Resolution** – The resolution of a patternator is an indicator of the smallest increment of distance that can be resolved. The resolution of a patternator is determined by the center to center distance between two adjacent collection cells. Typical H-R spray patternators as used in the automotive industry have resolutions on the order of 5 mm.
- e. **Splashing** – Splashing is the unintentional ejection of fuel from a patternator collection cell because of the spray interacting with liquid already present in that cell. The ejected fuel can be captured by adjacent cells; thus, splashing will result in measurement error.
- f. **Overflow** – Overflow is the unintentional spillage of fuel from a patternator collection cell that is filled beyond its capacity. The spilled fuel is captured by adjacent cells, which will result in measurement error.
- g. **Capture efficiency** – The capture efficiency is an indicator of the quality of a patternator test. Because of entrainment of the spray in recirculating air flows, evaporation, and spray rebounding from the patternator surfaces, the total mass of liquid fuel collected is less than the total fuel mass delivered by the injector for that test. The capture efficiency of patternator test is expressed as a percentage, and is defined as the mass of fuel collected by the patternator divided by the measured mass of fuel delivered by the injector, multiplied by 100%. The mass of fuel collected is normally determined from a summation of all cell collected volumes multiplied by the density of the fuel. The percentage of fuel not measured is 100% minus the capture efficiency. Typical capture efficiencies for PFI injectors using n-Heptane fuel are 90+%.
- h. **Region** – In reference to high-resolution mechanical patterning, a distinct and identifiable grouping of collection cells that contain the fuel from a spray plume that enters the patterning inlet plane. Ideally the Region would be contiguous; that is, all cells in the Region would contain some fuel; however, in some complex spray patterns the data-reduction operator may have to include multiple groupings of cells into a single Region, thus some cells in the Region would be empty. For example, if a dual-spray type of analysis is being conducted and four separate contiguous areas of fuel are noted, this would commonly be done. In this case the operator would inspect the four contiguous areas and, based upon experience, would assign two of the groupings to one Region, and the other two groupings to the second Region.
- i. **Centroid** – The centroid is the mass-weighted center of the collection of fuel in the individual cells of the patternator. The cells may contain all of the fuel collected, as for a typical single-plume spray, or may be just that group of cells in a selected, identifiable area, such as the second fuel island in a dual-spray. The coordinates of the centroid (x_c , y_c) are determined from:

$$\textbf{x-coordinate: } x_c = \frac{\int x \cdot \delta m \cdot dA}{\int \delta m \cdot dA} \quad (\text{Eq. 1})$$

$$\textbf{y-coordinate: } y_c = \frac{\int y \cdot \delta m \cdot dA}{\int \delta m \cdot dA} \quad (\text{Eq. 2})$$

Within the integrals in these equations, x and y are the coordinates of an interpolated data point. dA is the incremental area associated with each interpolated data point and δm is the interpolated mass accumulation at that data point. The integral in the denominator is the total mass collected by the patternator. In developing the data-reduction algorithms for the specific patternator geometric configuration, these integrals are normally treated as summations, and are evaluated numerically.

3.3.2.2 Definitions of Parameters for a Spray having a Single Plume

For patterning testing, the following parameters are illustrated and defined in association with the characterization of spray geometric parameters for a single-plume spray:

Figure 10 contains a schematic representation of a typical single-plume pattern collected using a high-resolution patternator. The gradations of gray in the Region of fuel collection are simple representations of different areas of fuel concentration. The collection cells in the central areas of a single-plume spray normally contain more fuel than cells further from the center. The injector axis (z-axis) is normally configured to pass orthogonally through the center of the patternator. Moreover, the centerline of the electrical connector of the injector is set at a specific orientation with respect to the patternator coordinate system, and is normally in alignment with the positive X axis, but may be oriented in any specified position as defined by the application.

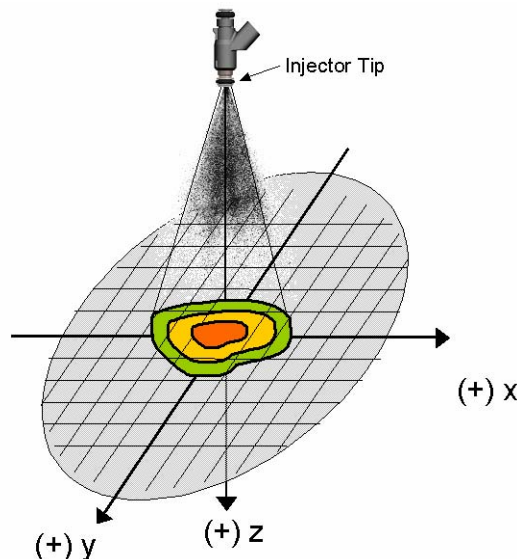


FIGURE 10 - REPRESENTATION OF A SINGLE-PLUME SPRAY PATTERN
AS DETERMINED BY A HIGH-RESOLUTION PATTERNATOR

3.3.2.2.1 Bent Spray

Figure 11 illustrates the comparison between a “bent spray” and an “on-axis” spray. The bent spray is shown schematically in the right side of Figure 11, and may be compared to the more common on-axis spray plume on the left side. The term “bent spray” is industry terminology for the spray plume produced by an injector that is specifically designed to have the spray centerline at an angle to the injector mounting axis. That resultant angle will be defined in this section, and is here designated as the Cone Bend Angle, which implies the mass-weighted mean angle of bend of the fitted right-circular cone that models the spray.

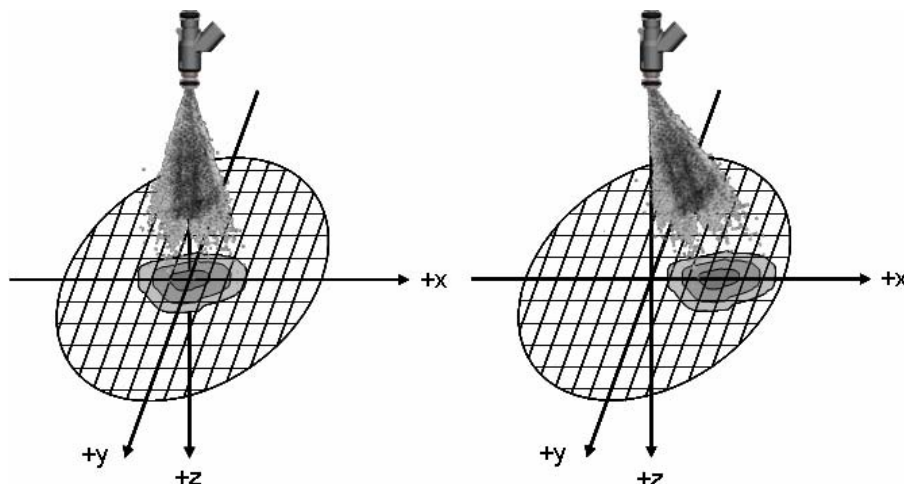


FIGURE 11 - SINGLE-PLUME SPRAY – COMPARISON OF ON-AXIS SPRAY AND BENT SPRAY

3.3.2.2.2 Spray Region Centroid

The spray plume will have a center of mass that is denoted as the centroid. The position of the spray region centroid will, in general, not correspond exactly with the injector axis, even for a spray that is designed to be on-axis. It will certainly not be centered for a bent spray that is designed to provide a spray that is at an angle to the injector axis. Figure 12 illustrates a general spray boundary on the patternator, which is denoted as the Spray Region. In this region are the X and Y coordinates of the spray region centroid, which is the mass-weighted center of the fuel collection pattern. The three shades of gray that are depicted within the fuel collection pattern constitute a simple representation of gradations in the amount of fuel mass collected. More fuel mass in a cell is represented by a darker gray. The centroid of the Spray Region containing collected fuel is normally determined by data reduction algorithms that first smooth and interpolate the raw data from the collection cells. This effectively provides a virtual set of collection cells that number three to seven times greater than the actual number used.

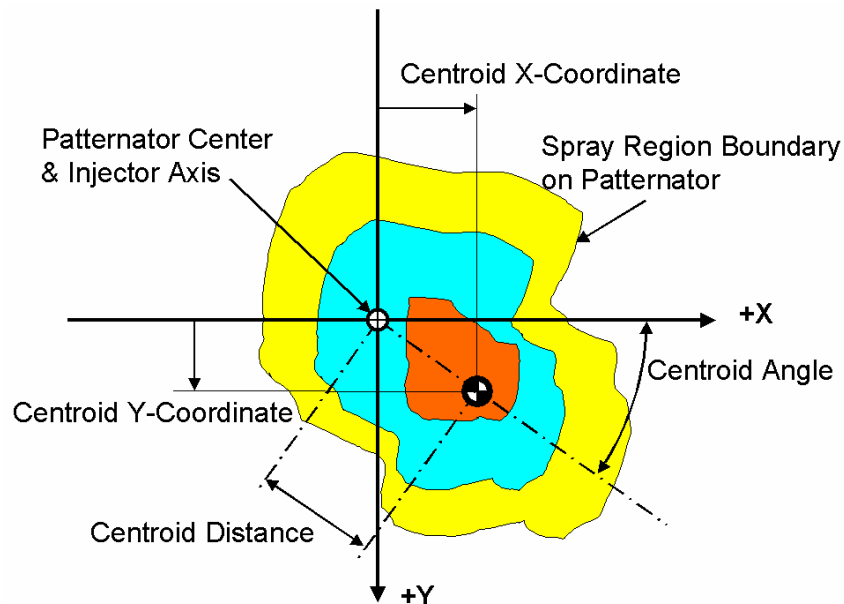


FIGURE 12 - NOMENCLATURE FOR CENTROID COORDINATES, DISTANCE AND ANGLE

3.3.2.2.3 Distance to Spray Region Centroid

The distance from the injector axis to the spray region centroid is also shown in Figure 12. This is the distance, as measured in the inlet plane of the patternator, from the injector axis to the Spray Region Centroid. Note that the injector axis is normally positioned during the test setup to pass through the patternator center, which is the origin of the patternator coordinate system.

3.3.2.2.4 Spray Centroid Region Angle

Figure 12 also depicts the Spray Region Centroid angle, which is defined as the angle between two lines in the inlet plane of the patternator; the first being the line corresponding to the positive X axis and the second being the line connecting the patternator center and the Spray Region Centroid.

3.3.2.2.5 Cone Bend Angle

This is defined as the angle between two lines; the first being the line representing the positive Z axis (the injector and patternator axis), and the second being the line connecting the injector tip and the Spray Region Centroid. As is illustrated in Figure 13, there is a key right triangle consisting of three sides, each representing a parameter. These are the Test Vertical Distance, the Distance to the Spray Region Centroid and the Slant Distance. The angle between the Test-Vertical-Distance line and the Slant-Distance line in the Figure is denoted as the measured Cone Bend Angle. The Slant Distance is not considered as a spray geometric variable to be reported, but is a useful intermediate parameter.

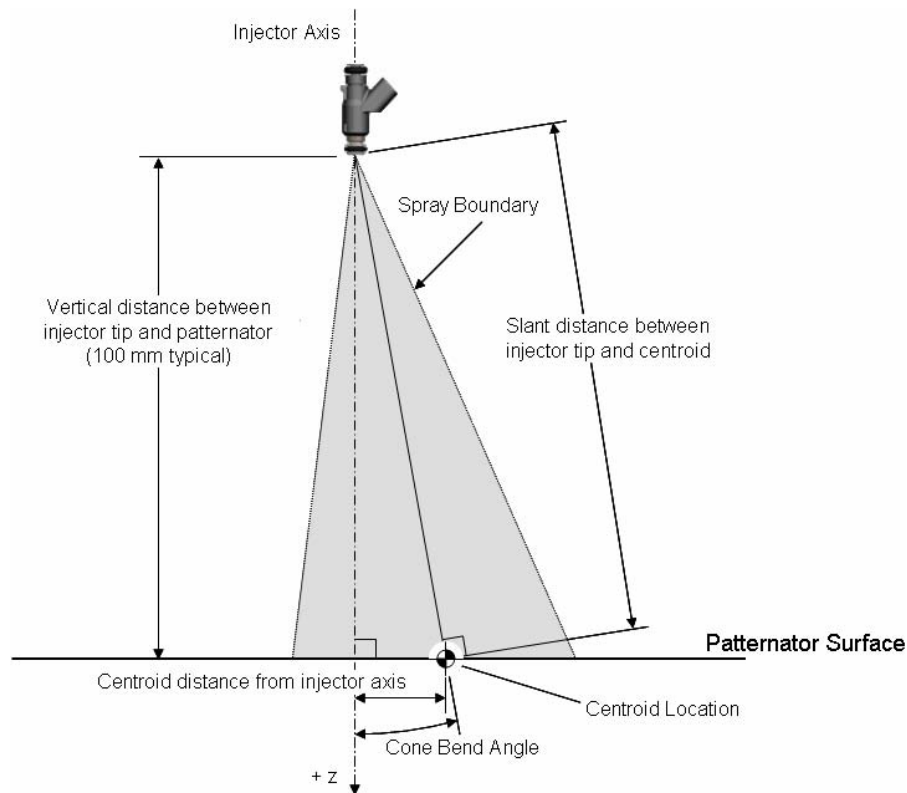


FIGURE 13 - NOMENCLATURE FOR SPRAY WITH A CONE BEND ANGLE

3.3.2.2.6 Mass Percentage Circle

The Mass Percentage Circle is defined as the circle in the patternator-inlet plane that is centered on the Spray Region Centroid point and that includes a specified percentage of the total mass collected in that Region. The initial requirement for computing the Mass Percentage Circle is that a particular percentage (such as 90%) of the total fuel collected be specified. Two such arbitrary percentages, 50% and 90%, are used in Figure 14 to illustrate two Mass Percentage Circles. Whatever percentage is specified will be used multiple times in the data reduction, thus the Mass Percentage Circle, and eventually the cone angle, will depend upon the initial choice. If, for example, 90% is chosen, the Mass Percentage Circle, or, more specifically, the radius that defines that circle, is computed to include 90% of the total mass collected. The Mass Percentage Circle Radius may be obtained directly from the raw cell data, but it should be noted that it is commonly obtained by automated algorithms that first generate a virtual set of interpolated and smoothed cell data. This is done to enhance the resolution well beyond the 250+ cells in the patternator.

3.3.2.2.7 Cone Angle

The spray plume geometry of the spray from the fuel injector is approximated by a right-circular cone emanating from the injector tip. The injector tip is the point on the injector axis at the lowest point of the injector body. This is not necessarily the point where fuel first exits the injector, practically if the injector has protective end cavity in the region. The Cone Angle is defined as the included angle of the right-circular cone with the vertex at the injector tip, and having the radius of the computed Mass Percentage Circle at the patternator inlet plane.

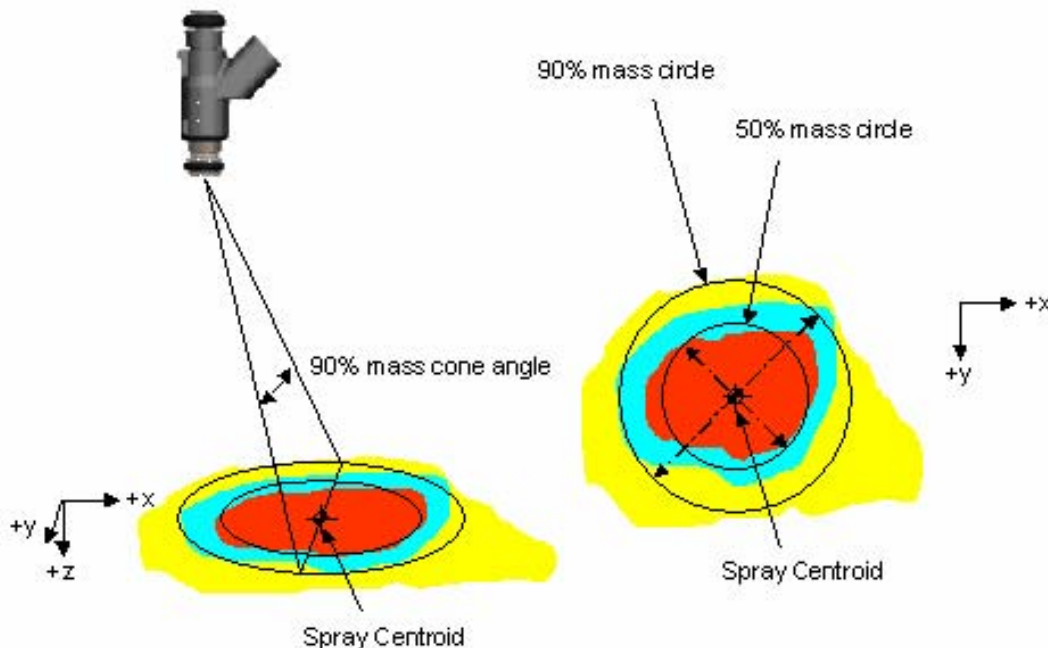


FIGURE 14 - ILLUSTRATION OF MASS PERCENTAGE CIRCLE AND CONE ANGLE FOR 50% AND 90% COLLECTED MASS – SINGLE PLUME BENT BY 15 DEGREES

It is important to note that these concepts are precise for on-axis sprays, but become approximations of increasing error as the spray becomes more bent. This is because a spray cone that is bent does not produce a circular region (footprint) in the plane of the patternator inlet, even if the originating spray is a perfect right-circular cone. If the envelope of the originating spray itself deviates significantly from a right-circular cone, then the resulting error in Cone Angle can be even larger. The region of collected fuel is approximately elliptical for a right-circular, conical plume that is bent, and it exhibits more and more eccentricity as the Cone Bend Angle increases. It is approximately elliptical because there are only a finite number of collection cells. This is analogous to taking a picture of a perfect ellipse with a digital camera having only 256 pixels. All currently known algorithms that are used for high-resolution patternators fit a circle to the spray region (footprint), but do not fit more complex mathematical shapes to the measured pattern. Therefore, in spite of the fact that the spray footprint (Region) may be decidedly non-circular, the data-reduction algorithms still fit circles to the Spray Region to include varying percentages of the total collected mass. Although the Spray Region Centroid and the Cone Bend Angle will be correct, the Mass Percentage Circle and the resultant Cone Angle will have a small inherent error (overprediction) that increases with Cone Bend Angle. The indicated radius of the Mass Percentage Circle and the resultant Cone Angle will be slightly larger than if the same plume were directed vertically downward. It is not the purpose of this document to reconstruct and increase the complexity of all of the existing algorithms that are used to reduce patternator data, but instead, to acquaint the reader with the fact that some moderate overprediction errors in indicated cone angle may result for sprays of large Cone Bend Angle.

3.3.2.3 Definitions of Parameters for the Two Plumes from a Dual Spray Injector

For patternation testing, the following parameters are illustrated and defined in association with the characterization of spray geometric parameters for the two plumes from a dual spray injector:

Figure 15 shows a schematic representation of a typical pattern for a PFI spray having two identifiably distinct spray plumes. The class of injectors that deliver such a spray of two plumes is traditionally referred to as "dual spray injectors". According to the definitions provided in Section 3.3.2.1, this class of injector should be denoted as "dual-plume injectors"; however, the very common and accepted industry terminology of "dual spray injectors" will be used in this document. It should be understood in the definitions that the term "dual spray injector" implies a PFI unit having a spray that is designed to deliver two distinct plumes at the distance of the test. It may have more plumes than two at distances less than 100 mm, but they will merge and produce two identifiable regions of fuel mass collection at the patternation test distance. However, as discussed in Appendix D, it is possible to have a very complex spray pattern that is not immediately evident as either a single-plume or a dual-plume spray.

Assuming the more common case of two main fuel areas from a standard dual spray injector, there will be two fuel collection regions as depicted in Figure 15. These regions result from, and correspond to, Spray Plume 1 and Spray Plume 2. Spray Region 1 will be the closest region counterclockwise from the electrical connector, looking down on the injector from the end opposite the tip, whereas Region 2 will be the closest region clockwise from the connector. Each of these fuel collection regions will yield a separate Spray Region Centroid location, a separate direction in space relative to the injector axis and a separate Cone Angle. There is also an additional parameter that is not present for an injector having a single spray plume, which is the Separation Angle between the two centroids. As was the case for a spray having a single plume, the injector axis (z-axis) is orthogonal to the inlet plane of the patternator, and is normally positioned to pass through the center of the patternator. Similarly, the centerline of the electrical connector of the injector is normally set to align with the positive X axis of the patternator, but may be placed in any orientation required by the application as long as it is clearly noted on the data reporting sheet.

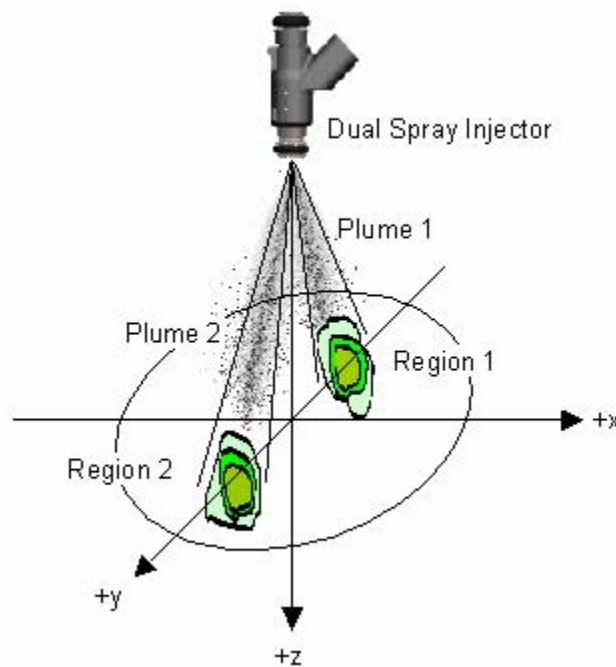


FIGURE 15 - DUAL-SPRAY PATTERN DETERMINED BY A HIGH RESOLUTION PATTERNATOR

There is an additional type of dual-plume pattern that is on the borderline between a complex spray pattern and a conventional spray pattern. This is the pattern from a bent dual spray injector, which is still somewhat uncommon, but which is increasing annually in percentage of applications. For this type of injector the two spray plumes are each at a compound angle in space relative to the injector axis. All of the parameters that describe the spray from a conventional dual spray injector may be obtained for the spray from a bent dual spray injector; however, the components of the compound angles for each plume are not included in this document. A consensus on the naming, data reduction and reporting practices for these complex parameters is still being developed. For patternation testing of this type of injector, the injector axis may be placed in an eccentric (offset) location for dual spray injectors that have significant X-axis components of the spray regions. This can result from an injector design in which the two spray plumes are not designed to be centered on the Y axis (see Figure 15), but are both "bent" at a designed bend angle. For this type of injector the two spray regions can be displaced quite far from both the X axis and the Y axis, and may overspray some patternators. An eccentric location of the injector axis mounting (normally offset in the -X direction) may be required for this type of application in order to prevent fuel from overspraying the patternator boundary. It is permissible to offset the injector axis as long as this is clearly noted on the data reporting sheet.

The following parameters are used to characterize the spray from a dual spray injector, with "1" and "2" referring to the individual spray plume regions that result in two distinct regions of fuel collection in the patternator:

3.3.2.3.1 Mass Percentages for Each Region

This is the percent of the total collected fuel mass that is contained in each of the two Spray Regions. The sum of the fuel in the two regions must equal the total mass of fuel collected in the test; that is, each individual fuel cell must be designated prior to data reduction as being in either Spray Region 1 or Spray Region 2. As is noted in Appendix D on Complex Spray Patterns, this can be a difficult task for some cases.

3.3.2.3.2 Distance to Spray Region Centroid for Each Region

This is the distance from the injector axis to the Spray Region Centroid (1 or 2). There are two values for a dual spray injector: 1 and 2. They are the mass-weighted centers of the respective fuel-collection areas, and are normally determined by means of algorithms that are associated with each patternator design. If an offset of the injector axis of a bent dual spray injector in the -X direction is used to alleviate overspraying, the offset distance must be added to the X distance of each Spray Region Centroid.

3.3.2.3.3 Separation Angle

For a dual spray injector, the Separation Angle is defined as the absolute angle in space between the two lines from the injector tip to the two Spray Region Centroids. This is illustrated in Figure 16, which also depicts the individual Cone Angles of each spray plume. The Separation Angle is obtained by means of a trigonometric equation using the Vertical Test Distance and the X-Y patternator coordinates of the two Spray Region Centroids. The coordinates are to be adjusted for the injector offset distance if offset is employed to alleviate overspraying. Although the simple example in Figure 16 shows the two Spray Region Centroids as being perfectly positioned on the Y axis, it is important to note that this is not the case in most tests. In many cases the three points consisting of the two centroids and the injector axis point (the patternator origin if the injector is not offset) will not necessarily lie on a perfect straight line for any type of dual spray injector, thus the total separation angle will not be the simple sum of the individual Cone Bend Angles. In fact, it is somewhat infrequent that a dual spray injector will produce plumes with two centroids that lie exactly on the Y axis. In more cases than not, there will be some deviation, thus there will be an X-axis component to each Spray Region Centroid.

3.3.2.3.4 Mass Percentage Circle and Mass Percentage Circle Radius for Each Region

As shown in Figure 16, the Mass Percentage Circle for each region is defined in a manner similar to that for a spray having a single plume, except that there are two Regions and two Mass Percentage Circle Radii for each specified fuel mass percentage. It is defined as the circle (1 or 2) that is centered on the Spray Region Centroid location (1 or 2), and that includes a specified percentage of the total fuel mass collected in that region (1 or 2). Each Mass Percentage Circle is defined by the radius of the circle. This radius (in mm) will be the numerical value that is used as the key parameter in the computation of the associated Cone Angle.

3.3.2.3.5 Cone Angle for Each Region

The Cone Angle that is associated with each spray region is also defined in a manner similar to that for a spray having a single plume, except that there are two Cone Angles for each specified fuel mass percentage, one for each Region created by a spray plume. The cone angles represent the included angles of respective right-circular cones that emanate from the injector tip, with each having the respective radius of the corresponding mass percentage circle at the patternator inlet. As dual spray injectors produce plumes that are significantly inclined to the patternator inlet plane, the inherent errors that are discussed in the previous section 3.3.2.2.7 regarding fitting a circle to an elliptical or other non-circular footprint region apply.

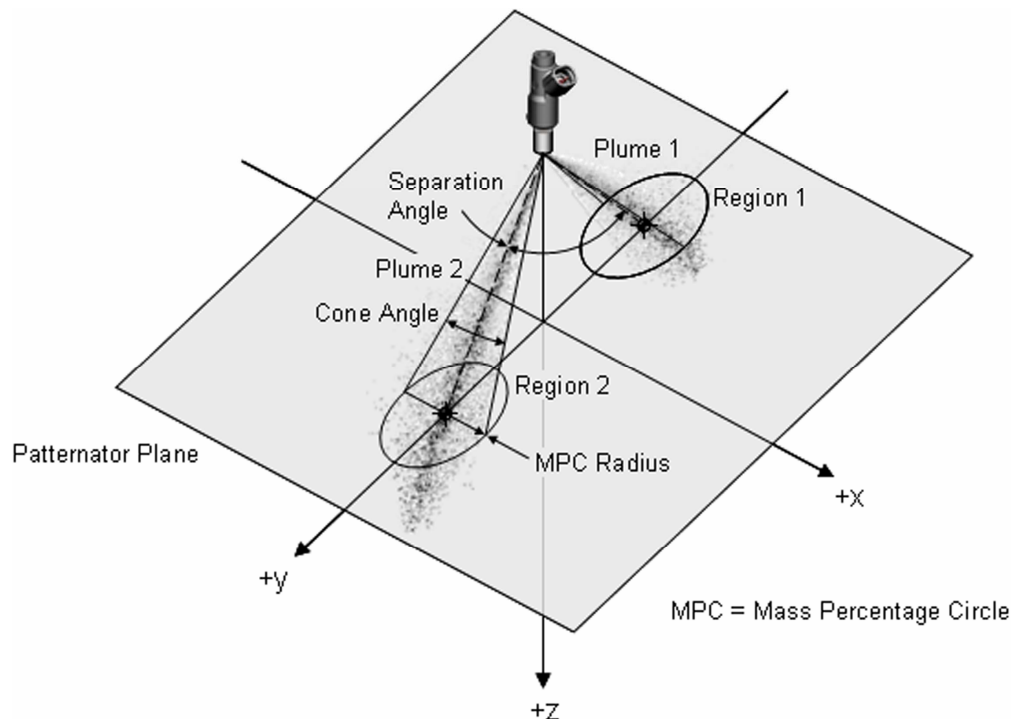


FIGURE 16 - REPRESENTATION OF THE SEPARATION ANGLE AND THE CONE ANGLES IN A DUAL-SPRAY CALCULATION

3.3.3 Fuel Spray Characteristics Obtained Using Drop Sizing

The size of the resultant fuel drops is important for both PFI and G-DI applications because of the substantial influence on engine exhaust emissions and driveability. No automotive fuel injector spray contains drops of a single drop size. Rather, gasoline fuel injector sprays can contain drops ranging in diameter from a few micrometers to half a millimeter or so. Typically, fuel sprays for gasoline-direct injection rarely contain drops larger than 80 microns in diameter, while sprays for PFI injection may contain a large fraction of the liquid mass in drops larger than 120 microns. Measurement of injector spray drop size, by any technique, reveals that sprays have a drop size distribution. Two common ways to represent the spray drop size distributions are first, to represent the frequency or numbers of drops of a specific range of diameters using a histogram or curve, and second, to plot the integral of the frequency curve to obtain a cumulative mass distribution. In regard to whether it is fundamentally a cumulative volume or cumulative mass distribution, they are equivalent for n-Heptane. (See Section 3.3.2 for the discussion.) Since it is often difficult and time consuming to compare complete drop-size distribution curves, drop size statistics derived from these two methods of representing spray drop size distributions are widely used in the industry for specifying and comparing gasoline injector sprays. The statistics serve as a convenient shorthand description of the full distribution.

3.3.3.1 D_{v90}

The D_{v90} is a drop diameter value that is a statistical indicator of the largest drops present in the spray. That is, 90% of the spray liquid volume (and mass) is contained within drops that have a diameter less than or equal to D_{v90} .

3.3.3.2 D_{v50}

The D_{v50} is a drop diameter value that is a statistical indicator of the median drop size. Half the spray volume (and mass) is contained in smaller drops and half contained in larger drops. D_{v50} may also be denoted in the literature as the MMD (Mass Median Diameter) or VMD (Volume Median Diameter).

3.3.3.3 Sauter Mean Diameter (SMD)

In addition to the D_{V50} and D_{V90} , a mean diameter statistic commonly known as the Sauter Mean Diameter (SMD) is also used to describe the representative mean drop size diameter. In the literature, it may also be denoted as D_{32} , which is the shorthand notation for the third moment of the distribution (total drop volume) divided by the second moment (total drop area). This mathematical descriptor is a mean diameter which is defined as:

$$SMD = \frac{\sum_{i=1}^M N_i D_i^3}{\sum_{i=1}^M N_i D_i^2} \quad (\text{Eq. 3})$$

where N is the number of drops in each size bin, and M is the number of bins. In other words, it is the diameter of a representative drop that has the same ratio of the volume to the surface area as that of the entire spray. This diameter is particularly useful for spray combustion computation and measurement. For this reason, the SMD has become one of the most important parameters of spray characterization.

3.4 List of Abbreviations

- a. CFD Computational Fluid Dynamics
- b. CCW Counter-Clockwise
- c. CW Clockwise
- d. DCD Driver Charge Delay
- e. ECU Engine Control Unit
- f. G-DI Gasoline-Direct Injection
- g. IDT Imaging Delay Time
- h. IPW Injection Pulse Width
- i. H-R High-Resolution
- j. LPW Logic Pulse Width
- k. mg Milligram
- l. mm Millimeter
- m. MMD Mass Median Diameter
- n. MPC Mass Percentage Circle
- o. ms Millisecond
- p. OEM Original Equipment Manufacturer
- q. PDI Phase-Doppler Interferometry
- r. PFI Port Fuel Injection

- s. PPAA Pulse-Pressurized, Air-Assist
- t. SMD Sauter Mean Diameter
- u. SOF Start of Fuel
- v. SOI Start of Injection
- w. TTL Transistor-Transistor Logic
- x. UBHC Unburn Hydrocarbons
- y. VMD Volume Mean Diameter

3.5 Nomenclature

This nomenclature section was developed to provide a common understanding and usage of the technical terms useful in fuel injection systems for spark ignition engines. Specific nomenclature related to fuel spray characteristics, measurements and reporting procedures can also be found in the individual sections.

3.5.1 Air-Assisted Fuel Injection

A fuel injection system where pressurized auxiliary air is mixed with the metered fuel to aid in vaporization and/or transport of the fuel. See also Vacuum Air-Assisted Fuel Injection.

3.5.2 Dual Spray PFI Injector

A PFI fuel injector that is designed to provide two distinct spray plumes; normally intended for an engine having two intake valves per cylinder.

3.5.3 Electronic Fuel Injection

A general term referring to any fuel injection system in which fuel metering is controlled electronically. The quantity of fuel delivered is scheduled by an engine control unit (ECU). The electronic signal to the injector is based on information received from several sensors that monitor the operating conditions of the engine.

3.5.4 Fuel Injection

A general term referring to any type of system in which fuel is injected into the engine, as opposed to being primarily drawn in by sub-atmospheric pressure. Fuel delivery may be mechanically or electronically controlled.

3.5.5 Fuel Injector

An electromagnetic or mechanical device used to meter and/or deliver pressurized fuel, directly at the point of injection.

3.5.6 Fuel-Injector Driver

An electronic circuit that converts the fuel control signal from the ECU into the proper voltage and current signal required. The two commonly used drivers in the industry are a peak-hold driver that is used with low resistance injectors and an "on-off" (saturated-switch) driver that is used with high impedance injectors. For PFI systems, the saturated-switch driver has become the most common driver type, whereas G-DI systems generally employ some form of peak and hold.

3.5.7 Gasoline-Direct Injection

A fuel delivery system in which the injector is located in the engine cylinder head, and in which the fuel spray is injected directly into the engine combustion chamber.

3.5.8 Injection Pulse Width (IPW)

The increment of time (ms) that the injectors are commanded to deliver fuel during an injection period. This injection pulse width does NOT include any charge delay that is used to provide a final peaking charge to the main capacitor in the circuitry of a G-DI injector driver. (Refer to Appendix F for more information.)

3.5.9 Logic Pulse Width (LPW)

The increment of time (ms), provided to the injector driver circuit by the ECU, that determines the time that the injectors are commanded to be energized during an injection period. This logic pulse width may include a driver charge delay that is used to provide a final peaking charge to the main capacitor in the circuitry of a G-DI injector driver. (Refer to Appendix F for more information.)

3.5.10 Port Fuel Injection

A fuel delivery system in which the injector is located in the intake manifold, or in the intake port close to the intake valve. The fuel spray is injected into the intake port upstream of the intake valve. The spray is normally directed ("targeted") at the back of the intake valve.

3.5.11 Sequential Fuel Injection

A multi-point fuel delivery technique in which each injector is individually energized and timed relative to its cylinder event. Fuel is delivered to each cylinder once per two crankshaft revolutions in four-cycle engines and once per crankshaft revolution in two-cycle engines.

3.5.12 Single Spray PFI Injector

A PFI fuel injector that develops one distinct spray plume at the design working distance.

3.5.13 Vacuum Air-Assisted Fuel Injection

A PFI fuel injection system in which auxiliary air is drawn into the delivered fuel by means of the pressure differential caused by the intake manifold vacuum. This air is mixed with the metered fuel to aid in the atomization and vaporization of the fuel. See also Air-Assisted Fuel Injection.

4. STANDARD TEST CONDITIONS

Unless otherwise specified, the following test conditions are to be utilized:

4.1 Ambient Condition

The testing should be performed at an absolute ambient pressure in the range from 100 kPa $\pm$ 5 kPa and at an ambient temperature of 21 °C $\pm$ 2.0 °C.

4.2 Test Fluid

n-Heptane is recommended for the measurement of injector spray characteristics. (See Appendix G)

4.3 Fluid Pressure

The differential pressure (which corresponds to the fuel inlet gauge pressure for testing at room ambient pressure) across the injector. This pressure level will be determined by the application, and is to be maintained to within $\pm$ 1% of this value throughout the test. It should be specified in SI units (kPa or MPa) and measured at the injector fuel inlet.

4.4 Fluid Temperature

The fluid temperature should be measured as close to the injector fuel inlet as possible and stabilized at 21 °C $\pm$ 2.0 °C.

4.5 Injector Temperature

The initial injector body temperature should be stabilized at an ambient temperature $21\text{ }^{\circ}\text{C} \pm 2.0\text{ }^{\circ}\text{C}$ prior to preconditioning and testing.

4.6 Injection Period (P)

The time elapsed between the beginning of one commanded injection pulse to the beginning of the next pulse shall be $50\text{ ms} \pm 0.01\text{ ms}$, unless otherwise specified.

4.7 Injection Pulse Width (IPW)

The increment of time (ms) that the injectors are commanded to deliver fuel during each injection period shall be 1.5 ms for direct injection applications and 5.0 ms for port fuel injection applications. The injection pulse width is to be maintained within $\pm 0.01\text{ ms}$.

4.8 Injector Driver

The driver type is to be determined by application, and is to be of instrument grade quality. The voltage supplied to the driver shall be specified by the application and maintained within $\pm 0.05\text{ V DC}$. The driver type and any unique operating characteristics, such as a driver charge delay time, shall be recorded on the injector performance data sheet.

4.9 Injector Polarity

The design injector electrical polarity is determined by the application, and should be maintained constant throughout all testing.

4.10 Test Apparatus

The fixture used to supply the injector with fuel may vary depending on the particular injector application and spray characterization parameter being evaluated (refer to Section 5 for more details).

4.10.1 Instruments

The test instruments should be calibrated and stabilized per manufacturers' recommendations.

4.10.2 Injector Position

The injector should be mounted vertically unless otherwise designated in a specific test procedure. The injector fuel drippage test is one exception to this.

4.10.3 Preconditioning

Purge injectors and test apparatus with test fluid to remove all air, vapors, and shipping fluids. Flow injectors for 2000 pulses at IPW, as defined in 4.7, and at 50 ms P, as defined in 4.6. Do not reuse the purged fluid in any spray characterization tests.

4.10.4 Flow Measurement

Flow rate may be measured by either volume or mass flow; however, volume measurements should be converted to mass. Data should be reported in mass flow units (g/s or mg/pulse), and all pertinent information shall be recorded (number of pulses, fuel mass, etc.). Prior to flow measurement, the injector should be preconditioned. The injector flow curve is not considered a spray parameter, and the PFI metering flow curve is discussed in J1832. Some tests in this document, such as patternation, utilize flow measurement as an option to ascertain the total injected amount of fuel flow during the test.

4.11 Summary of Standard Test Conditions

The summary of standard test conditions is provided in Table 1. Any deviations from the recommended test conditions described in Table 1 must be recorded and clearly noted on the application data reporting sheet.

TABLE 1 - SUMMARY OF STANDARD TEST CONDITIONS

	Port Fuel Injection					Gasoline-Direct Injection		
	Qualitative Imaging	Patternation	Laser Diffraction	Phase Doppler Interferometry	Dripage Test	Imaging	Laser Diffraction	Phase Doppler Interferometry
Test Fluid	n-Heptane					n-Heptane		
Ambient Temperature (°C)	21 ± 2					21 ± 2		
Ambient Pressure (kPa)	100 ± 5					100 ± 5		
Fluid Temperature (°C)	21 ± 2					21 ± 2		
Initial Injector Temperature (°C)	21 ± 2					21 ± 2		
Fluid Pressure (kPa or MPa)	Specified by application to within ± 1%					Specified by application to within ± 1%		
Injection Pulse Width (ms)	5 ± 0.01					1.5 ± 0.01		
Injection Period (ms)	1000 ± 0.1	50 ± 0.01				1000 ± 0.1	50 ± 0.01	
Flow Measurement	To be reported in mass flow units (g/s or mg/pulse)					To be reported in mass flow units (g/s or mg/pulse)		
Injector Axis Orientation	Vertical unless specified by application				45 ± 1 degrees from vertical	Vertical unless specified by application		
Injector Electrical Connector Orientation	Specified by application and to be reported					Specified by application and to be reported		
Measurement Height (mm)	N/A	100			N/A	N/A	50	
Axial Field of View (mm)	100	N/A				100	N/A	
Pre-conditioning or purging	2000 pulses at 50 ms period				6000 pulses at 50 ms period	2000 pulses at 50 ms period		

5. TEST EQUIPMENT AND ENVIRONMENT

The purpose of this section is to provide basic information on test equipment used in measuring spray characteristics according to the specifications described in Sections 4 and 6. Recommendations are given for the design of the test flow head (fluid pressure) and hydraulic circuit, instrumentation resolution, and driver board connections.

The test equipment must be capable of precisely testing various electronic injector designs. The equipment and installations must be in compliance with all applicable fire and safety codes and regulations, and must be capable of safely purging fuel drops from previous injection events away from the test chambers.

5.1 Fuel Pressurization System

A number of fuel pressurization systems may be required for spray testing, depending upon the type of injector that is being evaluated. The testing of single fluid and air-assist G-DI injectors and PFI injectors will require a wide range of supply pressures. All fuel pressurization systems should be capable of operating with n-Heptane. Figure 17 and Figure 18 illustrate the two options available for fuel pressurization systems commonly used for the spray testing of PFI and G-DI injectors.

5.1.1 Port Fuel Injection System

For the spray testing protocols, the required injector inlet pressure for PFI injectors may be obtained by a fuel pump/regulator/heat exchange system, or alternatively, by a nitrogen-pressurized bladder accumulator system. Each PFI injector system should be capable of delivering a maximum of 10 g/s of the test fluid to the inlet of the injector at a regulated maximum pressure of 1 MPa. Additionally, the test fluid temperature should be maintained to $21\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$. The injector inlet pressure shall be maintained to the design pressure ± 1 percent.

5.1.2 Direct Injection System

For the spray testing protocols, the required injector inlet pressure for G-DI injectors may be obtained by a fuel pump/regulator/heat exchange system, or, alternatively, by a nitrogen-pressurized bladder accumulator system. Either G-DI injector system should be capable of delivering a maximum of 20 g/s of the test fluid to the inlet of the injector at a regulated maximum pressure of 20 MPa. For a pump system, if the design pressure of the injector and pump that are being utilized is significantly less than 20 MPa, the maximum pump pressure of the test system should be noted on the data sheet. Additionally, the test fluid temperature should be maintained to $21\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$. A pump system shall also incorporate an air-dampened accumulator to minimize the effects of pump pressure pulsations. The injector inlet pressure shall be maintained to the design pressure ± 1 percent.

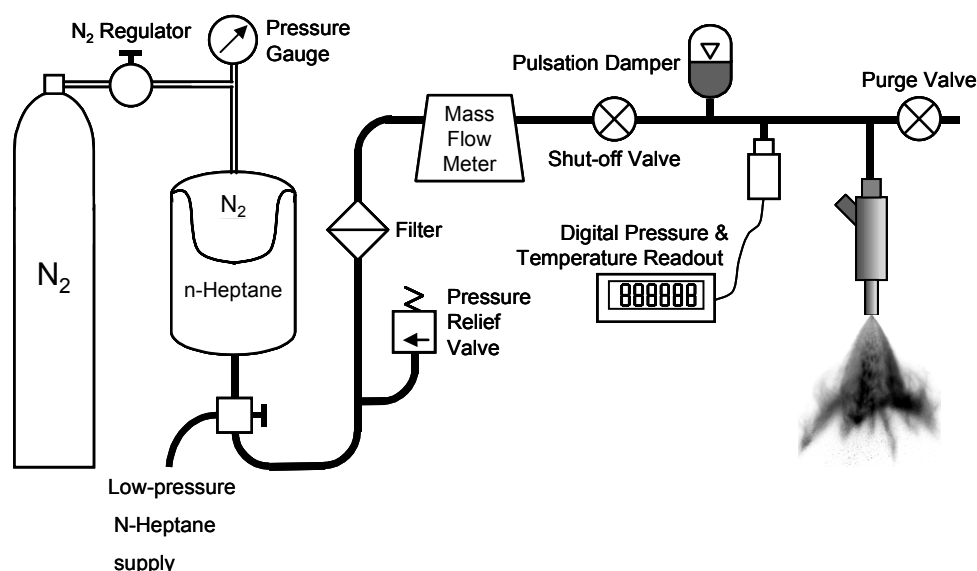


FIGURE 17 - SCHEMATIC OF FUEL PRESSURIZATION SYSTEM USING A BLADDER ACCUMULATOR

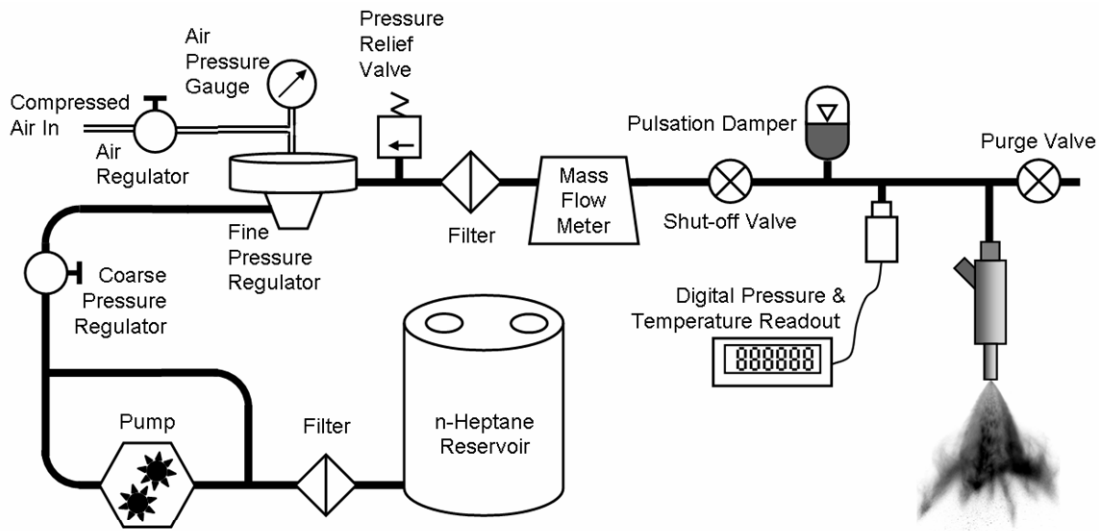


FIGURE 18 - SCHEMATIC OF A FUEL PRESSURIZATION SYSTEM USING A RECIRCULATING FUEL PUMP SYSTEM

5.2 Electrical System

The wiring diagram for the injector, injector driver, and power supply is shown in Figure 19. To accommodate the different injector drivers used in the automotive industry, it is recommended that the test stand be equipped with an interchangeable (plug-in) type driver board. It should be noted that some G-DI injectors use specialized, proprietary drivers which may activate the injector by the leading edge of a square wave logic pulse signal. The facility should be capable of incorporating these options.

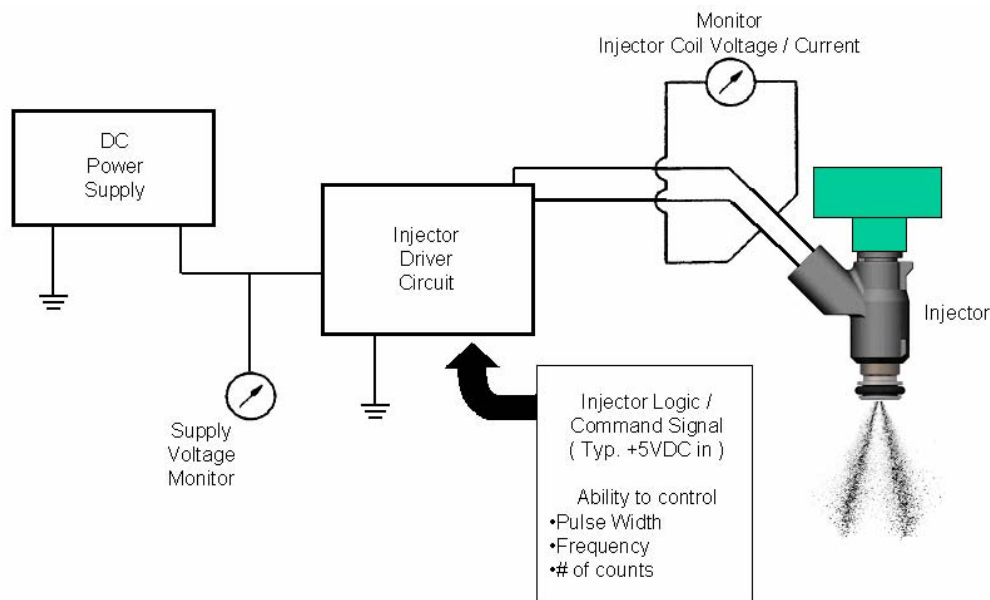


FIGURE 19 - ELECTRICAL WIRING DIAGRAM FOR FUEL INJECTOR TESTING

5.3 Ambient Pressure

The ambient pressure for all spray characterization tests in this document is normally one atmosphere (room conditions). The normal daily variations in room barometric pressure for any testing laboratory with an elevation of less than 350 meters are acceptable. This is equivalent to the range from 95 kPa to 105 kPa that is listed in 4.11. The actual ambient pressure at the time of the test is to be recorded on the appropriate data reporting sheet. Although not required in any test in this document, the characterization of a spray for an ambient pressure significantly higher than the normal atmospheric pressure requires the use of an enclosed optical pressure chamber. Such a chamber may also be used for tests at normal room pressure conditions. To prevent the accumulation of fuel drops in such a chamber, a long injection period, typically between 1 s and 2 s, is necessary. As discussed in the next section, the scavenging airflow used to evacuate the fuel from prior injections in the chamber is to be maintained as low as possible to avoid excessive distortion of the spray.

5.4 Establishment of a Purge Flow for Spray Testing

In many of the tests that are associated with the characterization of fuel sprays, repetitive injections are utilized. For measurements such as drop sizing or spray penetration, residual drops from the previous injection may be present during the current injection event being measured, particularly if there is no purging airflow to conduct them away. For injection into a quiescent ambient, the near field that is downstream of the injector tip will normally contain drops from the previous one, or even two, injection events. This is more pronounced for G-DI sprays than for PFI sprays because the smaller drops in the distribution rapidly attain terminal velocity, and will remain in the vicinity of a subsequent spray plume until they evaporate. Even if drop evaporation is completed prior to the start of the injection event being measured, fuel vapor will be present in concentrated pockets within the test region. This can result in laser beam steering, which can adversely affect imaging, laser diffraction and interferometric measurements.

As illustrated in Figure 20, some degree of purging air or nitrogen flow is required for any spray measurement protocol in which the injector is pulsed repetitively. Drop sizing typically requires a higher purge rate than imaging. For imaging tests in particular, the injector may have to be run at a significantly longer period (P), allowing for a reduced purge flow. This period can correspond to an injection frequency as low as 1 Hz. The two main considerations are, first, to provide a safe working environment, and second, to permit a valid measurement with minimal influence of prior spray events.

A uniform, low velocity, flow field is a necessity, with the primary parameter being the mean axial velocity of this purging stream. The goal is to convect the residual drops and fuel vapor out of the test volume during the dwell period between consecutive injection events, and to achieve this without adversely influencing the spray parameters. The purge stream for room bench testing is normally generated by creating a slight, fixed vacuum downstream of a honeycomb flow straightener, thus establishing a purge flow of air in the vicinity of the injector. In an enclosed optical spray chamber the purge medium may be nitrogen instead of air. The mean purge velocity required should be no more than necessary, but is typically in the range of 1.0 to 2.0 meter per second for PFI sprays, and 1.3 to 2.6 meter per second for gasoline G-DI sprays. At 2.0 meter per second, for example, the purge air will move 100 mm downstream during 50 milliseconds between injections (2.0 mm per millisecond), thus convecting the vapor and drops from the test region. As a check on the adequacy of the purge velocity, it should be gradually increased from zero while injecting at 20 Hz, with the spray being illuminated by a strobe with a flash delay of 30 ms. The lighting orientation should be selected to provide backlighting. The purge flow velocity should be increased until the observed spray position is downstream from the measurement volume.

If a PDI drop-sizing system is available, a superior method of establishing the minimum purge velocity may be invoked. With the PDI measurement location positioned at the point of interest, for example 100 mm from the tip for a PFI spray, the drop velocity arrival pulse is displayed on a monitor. At a near-zero purge velocity, many residual, low-velocity drops will be measured and displayed in the time period from zero until the arrival of the first, high-velocity drops from the injection event. The purge flow velocity may be gradually increased until these residual drops are eliminated from the display.