A New Measurement Standard for the Characterization of Automotive Fuel Sprays

Anand H. Gandhi*  
Ford Motor Company

Scott E. Parrish  
General Motors Corporation

Joseph S. Shakal  
TSI Incorporated

David L. Harrington  
General Motors Corp (Retired)

Lee E. Markle  
Delphi Corporation

Hamid Sayar  
Continental Corporation

David L.S. Hung  
Visteon Corporation

Jason L. Kramer  
Robert Bosch LLC

Steven D. Cummings  
Chrysler LLC

Mark A. Meinhart  
Ford Motor Company

Abstract

A completely new set of standards for spray measurement and characterization has been developed over the past five years by the SAE Gasoline Fuel Injection Standards Committee (GFISC). The objective of this paper is to share this development with the spray community. The standardized protocols are compiled in SAE J2715, which is a comprehensive document addressing the characterization of fuel sprays from automotive gasoline fuel injectors. This technical standard includes detailed procedures for the configuration, measurement, data reduction and reporting of a wide range of spray parameters, including drop size distribution, mass distribution, cone angle, spray angle, bend angle and spray-tip penetration. Separate sections of test procedures are provided for both low-pressure injectors (under 1.0 MPa fluid pressure) and high-pressure injectors (1.0 to 20.0+ MPa fluid pressure). All of the standardized tests are fully detailed, including phase-Doppler interferometry, laser diffraction, digital imaging and high-resolution patternation.

The overall goal of the SAE GFISC committee in developing this document was to provide and promote the standardization of fuel spray measurement within the worldwide automotive community. This has become an increasingly important consideration as gasoline direct (in-cylinder) injection has emerged as the future combustion strategy of choice, and as engine emission requirements have become more stringent. The lack of such a spray measurement standard within the automotive industry over the past two decades has led to individual injector manufacturers and end-users necessarily developing their own in-house procedures for measuring and reporting each spray parameter. This has resulted in a wide range of test protocols, test conditions, test fluid types and data reduction algorithms, which has made it quite difficult for one spray laboratory to verify the reported results of another. Although the measurement procedures in J2715 were developed for the pulsed gasoline sprays from automotive fuel injectors, many of the test protocols may be employed for other applications, such as for steady sprays or for sprays using fluids other than gasoline. Additionally, SAE J2715 may be considered as a template for other spray standards.

A comprehensive round-robin test program was developed and is currently being conducted at six major automotive spray laboratories around the world. A representative set of injector and driver hardware is being circulated for testing using both the SAE J2715 and the in-house test procedures of each laboratory. The resultant data will be utilized to quantify the advantages provided by this spray standard.

*Corresponding author: 2400 Village Road  • Dearborn, MI 48124  • Phone/ Fax 313/337-4070  • agandhi1@ford.com
Introduction to Automotive Fuel Spray Characterization

The measurement and characterization of fuel sprays from automotive fuel injectors have been of increasing interest and importance for the past 25 years. It began with the first large-scale introduction of Port Fuel Injection (PFI) in the mid-1980s. With the low-pressure, port fuel injector, metered fuel is introduced into each engine intake runner individually by means of a brief injection event during each engine cycle. Early dynamometer tests indicated that numerous engine performance and emission parameters were significantly influenced by both the cone angle of the spray plume and its direction relative to the back face of the intake valve. The combination of these two geometric parameters was denoted as spray "targeting" among fuel systems engineers, and it soon emerged as a prime consideration in selecting an injector design for minimizing unburned hydrocarbon emissions. The need of engine designers for an advance selection and knowledge of targeting resulted in injector manufacturers developing portfolios of port fuel injectors, with each unit having a different angle and direction for the spray cone. The later introduction of engine designs having two intake valves per cylinder, in turn, to "dual spray" injectors, making the spray geometry even more critical, and introducing additional spray geometric parameters such as the spray separation angle. A backlit image of a representative spray from such an injector is shown on the left-hand side of Fig. 1.

In order for injector manufacturers to develop and categorize the tip designs of their products, certain geometric parameters of the resultant fuel spray had to be measured. It was also observed early on in the development of gasoline PFI technology that the finer the degree of atomization, the better the transient and cold operation of the engine. When the need for a spray-drop-size distribution was added to the requirement for an accurate representation of the cone angle, cone bend angle and separation angle, the first simple automotive spray characterization was born. The need was a practical one, with the resultant numerical values for the characterization parameters becoming necessary marketing classifications that were nearly as important as the flow rate to the end user. Injector manufacturers developed portfolios of injectors having a specific static flow rate, but that could be optionally obtained in increments of the cone angle, such as 9°, 12°, 15° or 18°. Engine designers used the measured virtual cone angle and the indicated direction of the spray axis to ensure that during engine operation the back of the intake valve was impacted, but that the port wall surfaces were not.

The later introduction of the KIVA computer code and the first CFD combustion analyses for automotive combustion systems greatly increased the need for more comprehensive spray characterization measurements. The latest significant increase in the importance of gasoline fuel spray characterization came with the introduction of high-pressure gasoline direct injection (G-DI), and with the inherent need for CFD combustion modeling as a key to the development of such engines. With this technology, knowledge of the delivered drop size distribution of the G-DI fuel spray is critical, as is the spray penetration rate and the angular extent of the spray envelope. A backlit image of the spray from a representative G-DI injector is shown on the right-hand side of Fig. 1. The advanced computer analysis methods require numerous inputs for proper spray modeling in order to tune the adjustable code parameters, and, in addition, the injector manufacturers required accurate spray data to develop, categorize and market their hardware. Unfortunately, there was no comprehensive spray measurement standard that specified definitions, equipment, test fluids, test procedures and data-reduction and reporting requirements. Each injector manufacturer, end user, university research group and private research laboratory independently developed their own test procedures over the years, with the result being that no laboratory could rigorously check the reported spray characterization results of any other laboratory.

Scope and Purpose

The purpose of the main standards development project that is being reported here was to develop a comprehensive standard for the complete characterization of the fuel sprays from all automotive
gasoline fuel injectors. The scope of this new SAE J2715 Standard [1] encompasses both the PFI and G-DI classes of injectors, and specifies in detail the associated configurations, test conditions, measurement protocols, data-reduction methods and reporting procedures. SAE J2715 is intended to be used with two other key SAE J-documents: SAE J1832 [2] and SAE J2713, which is currently being completed. These additional SAE J-documents address the non-spray performance metrics of PFI and G-DI injectors, respectively.

The purpose of this particular paper is to convey to the worldwide spray community that such a spray characterization standard has been developed for the automotive industry, and to provide an overview of the spray measurement categories that are incorporated within the document. This may provide a valuable resource tool for other industries that have specific spray characterization requirements, and will hopefully assist those industries in developing their own spray measurement standards by providing a comprehensive starting template.

Key Variables in the Characterization of Fuel Sprays

Whether the injection of fuel from an automotive fuel injector takes place in an intake manifold (as with a PFI configuration) or into an engine cylinder (as with a G-DI configuration), the injection event is very brief, normally lasting only 1 to 18 milliseconds. As illustrated in Fig. 2 for a direct-injection configuration, the fuel spray may be observed by means of a stroboscope to have a number of prominent features that appear during this brief interval. These observable features generally apply to both G-DI and PFI fuel sprays, and include a main spray portion and a wetted footprint geometry if an impacting surface is present. In addition, other features that are generally categorized as non-desirable may be present. These include such observable features as a separate sac spray, with one or more distinct spray fingers, after-injection sprays and unatomized fuel ligaments. Whether or not any of the latter set of features is present depends upon the injector design.

It should be emphasized that, except for the angular extent of the main spray plume, and in some cases the wetted footprint, the majority of these observable features are not key spray characterization metrics. The important metrics that are required to characterize a fuel spray are a separate set of parameters that have been accumulated over the past two decades according to the discussion in the Introduction section, with a number of them required for spray model tuning. It should also be noted that, in the automotive community, spray characterization is somewhat distinct from injector characterization. In an injector characterization the performance parameters of interest include many non-spray metrics such as the static flow rate, the working flow range, the injector opening time and the tip leakage rate, along with many other parameters. Spray characterization deals with parameters that are directly related to the delivered fuel spray.

Many additional details of G-DI injector and spray sub-classifications are provided in reference [3]. The details of G-DI spray measurement techniques are discussed, as are the variations in the measured values of spray characterization parameters for both ambient and engine conditions. The influences of non-standard environmental conditions on the resultant G-DI fuel spray are illustrated for a number of tip designs, including the effects of large variations in fuel temperature, fuel pressure and downstream ambient pressure. A concise summary of the development and application of the SAE J2715 Standard for spray characterization is provided in reference [4]. This SAE technical paper provides insight on the alternative methods that were considered during the drafting of the document, as well as a discussion of the numerous lessons learned. A general overview of the characteristics of sprays from atomizing nozzles is provided in reference [5]. This is not restricted to the fuel sprays from automotive injectors, but applies to a wide range of atomizing nozzles, including those producing a steady (non-pulsed) spray. The emphasis in the designated chapter of the book is on the parameters that influence atomization, and upon the physics of spray formation, rather than upon the details of spray measurement procedures.
In the Introduction section it was noted that such spray parameters as the mean drop diameter, the fuel mass distribution and the PFI cone angle (or spray angle for a G-DI spray) were experimentally observed to be critical to the operation of an automotive engine. Therefore, these became key spray metrics that were critical to the selection of an injector for a given engine application. In obtaining numerical values for the key spray parameters, it has also been experimentally observed that certain measurement techniques are much more suitable for PFI sprays than for G-DI sprays, and vice versa, due to the nature of the sprays in terms of their mean drop size, vaporization rate and penetration distance. In general, the key metrics of measuring automotive gasoline fuel sprays are well established in the automotive industry. Some measurements, such as the spray-tip penetration, are considered to be macroscopic spray parameters, while others, such as the mean drop size, involve the determination of microscopic characteristics. These key metrics and their associated parameters have been grouped based on their characteristics as follows:

1. **Spray Geometric Characteristics** – the cone angle for the spray from a PFI injector, and the spray angle for the spray from a G-DI injector. Other geometric parameters of importance are associated with injectors having special features or options, such as the bent-spray injector (G-DI or PFI) and the PFI dual spray injector. The associated spray geometric parameters are the cone bend angle for a bent-spray (offset) PFI injector, and the spray bend angle for a bent-spray G-DI injector. For a PFI dual spray injector, the additional geometric parameters are the individual cone angles of the two separate plumes, as well as the separation angle between those two plumes.

2. **Fuel Mass Distribution Characteristics** – the fuel mass distribution in a specified plane that is downstream from the injector tip, plus the location of the centroid of that fuel mass relative to the injector axis. This is typically applicable only to the fuel spray from a PFI injector.

3. **Drop Size Characteristics** – the Sauter Mean Diameter (SMD) and the D_{90}, or 90% cumulative volume diameter, are statistical parameters that are indicators of the size of the ‘mean’ and the ‘largest’ drops in a spray, respectively. These two characteristic diameters are generally regarded as the most meaningful parameters derived from the measured drop-size distribution of an automotive fuel spray.

4. **Transient Spray-Tip Penetration Characteristics** – the spray tip penetration as a function of time and the penetration distance at a specified standard time into the injection event. This specified time depends upon the class of injector, with one standard penetration time specified for a G-DI injector, and another for a PFI injector.

A verification of the need for standardization in spray characterization is provided by the work in reference [6]. In this study the cone angles of three types of gasoline port fuel injectors were measured utilizing three different measuring techniques; digital image processing, shado graphy and spray patternation. It was concluded that the measured cone angle varied throughout the injection event and that the value was also dependent on the injection pressure. Further, the authors reported that the cone angle was affected considerably by the measurement technique, and also varied with the measurement location relative to the injector tip. In reference [7] the range of experimental equipment and techniques that are required for even a partial spray characterization is illustrated. A characterization of the spray from a G-DI injector was obtained using both experimental and computational techniques. The injector was of the hollow-cone, swirl type, and two different injection pressures of 5.0 and 7.0 MPa were utilized. The experimental techniques included planar Mie imaging for penetration, as well as time-averaged, phase-Doppler interferometry (PDI) for drop size and velocity. The PDI data was obtained for axial distances from the injector tip of 20 and 40 mm, and for a number of radial locations.

It is worth noting that a Standards document does not necessarily specify the very latest emerging technology and cutting-edge measurement equipment. In fact, this could be counter-productive, as very few laboratories could then utilize the required procedures or instrumentation. In the field of spray diagnostics there has certainly been a significant number of emerging technical developments in recent years that have resulted in several novel measurement tools and techniques. Such tools permit the measurement of ever more complex and detailed spray phenomena, and can provide valuable insight into the physical processes that are associated with spray formation and development. Most of these new measurement instruments were evaluated by the Standards Committee as to whether such technology would be feasible for definitive measurement as an accessible and reliable technique. For example, a number of emerging optical techniques such as optical patternation and laser-induced fluorescence were considered to be still under development. They were considered as not yet applicable for use in an industry-wide standard. However, they will be given consideration in future revisions of the spray measurement standard.
<table>
<thead>
<tr>
<th>Test Fluid</th>
<th>n-Heptane</th>
<th>n-Heptane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Temperature (°C)</td>
<td>21 ± 2</td>
<td>21 ± 2</td>
</tr>
<tr>
<td>Ambient Pressure (kPa)</td>
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<tr>
<td>Injection Period (ms)</td>
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<td>Flow Measurement</td>
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<td>To be reported in mass flow units (g/s or mg/pulse)</td>
</tr>
<tr>
<td>Injector Axis Orientation</td>
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<td>Vertical unless specified by application</td>
</tr>
<tr>
<td>Injector Electrical Connector Orientation</td>
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<td>Specified by application and to be reported</td>
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<tr>
<td>Measurement Height (mm)</td>
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<tr>
<td>Pre-conditioning or purging</td>
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<td>6000 pulses at 50 ms period</td>
</tr>
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**Table 1.** Summary of Spray Characterization Tests and Standard Test Conditions
Overview of Standard Test Procedures for Characterizing Automotive Fuel Sprays

The numerous spray characterization parameters that were discussed in the previous section may be quantified using seven of the eight standardized test procedures that are listed across the top of Table 1. This comprehensive Table summarizes not only the types of tests that are detailed for an automotive fuel spray characterization, but also lists the many standardized test conditions that are to be utilized. This encompasses the fluid type, ambient conditions, the injector driver control settings and the geometric positioning of the injector. The injector dripping test, while quite important to fuel system engineers, is not strictly a spray test, although the source of the drip is the spray (drippage is not leakage), thus it will not be discussed in this paper. The seven remaining standardized spray-test procedures may be seen to employ a total of four major measurement techniques. These are imaging, high-resolution mechanical patternation, laser diffraction and phase-Doppler interferometry (PDI). These four categories encompass the range of measurement equipment that may be employed to obtain a full characterization of an automotive fuel spray. Further, the laser diffraction and PDI instruments are not both required; either may be optionally used to conduct a full spray characterization.

<table>
<thead>
<tr>
<th>SPRAY CHARACTERIZATION PARAMETER (SAE Primary Set)</th>
<th>TYPE OF TEST PROCEDURE IN SAE J2715</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spray Angle</td>
<td>Imaging</td>
</tr>
<tr>
<td>Spray Angle</td>
<td>Imaging</td>
</tr>
<tr>
<td>Main Spray Tip Penetration</td>
<td>Imaging</td>
</tr>
<tr>
<td>Sec Spray Tip Penetration</td>
<td>Imaging</td>
</tr>
<tr>
<td>Cone Angle</td>
<td>Imaging</td>
</tr>
<tr>
<td>Separation Angle (Dual Spray Injector)</td>
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<td>Cone Bend Angle (Bent Spray Injector)</td>
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<td>Imaging</td>
</tr>
<tr>
<td>Dv10</td>
<td>Imaging</td>
</tr>
</tbody>
</table>

Table 2. Listing of Primary Spray Parameters and the Associated Spray Test Equipment

Table 2 provides a concise presentation of the relationship of the spray characterization metrics to the four major measurement types, and is complementary to Table 1. For each of the ten key spray characterization parameters that are identified and discussed in SAE J2715, Table 2 provides the measurement system or systems that are utilized, or may be optionally utilized, to obtain the data. Thus, it may be seen that the J2715 Standard specifies that high-resolution mechanical patternation be used to obtain the cone angle of a PFI injector, whereas either PDI or laser diffraction may be used to obtain the Sauter mean diameter of the fuel spray from a G-DI injector.

For the characterization of a fuel spray from a G-DI injector, only two measurement systems are required; imaging and either laser diffraction or PDI. No high-resolution patternation is necessary. Similarly, for the fuel spray from a PFI injector, only two instrument equipment systems are required; a high-resolution patternator and either a laser diffraction or a PDI system. In the new SAE J2715 standard, alternate test procedures and data reduction protocols are provided for both laser diffraction and PDI, and either may be optionally utilized depending upon the equipment present in a particular spray laboratory.

Imaging for the Determination of Key Spray Characterization Parameters

Certain geometric variables that are required for spray characterization may be obtained by imaging the overall spray geometry. The spray-tip penetration and the angular extent and bend angle of the G-DI fuel spray are three examples of macroscopic variables for which the imaging technique is best suited. The SAE Standards committee considered all of the current imaging methods, including backlighting, side-lighting, laser-light-sheet, volume illumination and optical patternation, and selected backlighting for obtaining the images. The imaging procedure is discussed in detail in the SAE J2715 document, but may be summarized by noting that a sub-microsecond flash lamp is employed, and is triggered with a specified delay from the injector driver pulse circuit. The light from the flash lamp passes through a diffuser to backlight the spray uniformly. The triggering time relative to the injection pulse is standardized at 1.50 milliseconds after the appearance of the first fuel at the injector tip. This time is independent of the opening interval of the injector, and is unaffected by any electronic driver delay time that many engine controllers use. It should be emphasized that this is for G-DI injectors only, and that the alternate technique of high-resolution mechanical patternation is specified for the sprays from PFI injectors.

As compared to a G-DI spray, the spray from a PFI injector is generally too coarse and sparse to permit accurate and repeatable determinations of the spray boundaries by means of imaging. This is evident from the representative PFI spray image that was provided in Fig. 1. Mechanical patternation is therefore utilized instead of imaging for sprays from PFI injectors. In contrast, the fuel spray from a G-DI injector is too fine for mechanical patternation, as it exhibits a reduced penetration and substantial mass loss due to...
vaporization prior to entering the collection cells. Therefore, in the standardized test procedures for automotive spray characterization, imaging is precluded for PFI fuel sprays, whereas mechanical patteration is precluded for G-DI fuel sprays. The only exception in the standard is for PFI spray-tip penetration, where imaging is employed. PFI spray-tip penetration is not nearly as important as the penetration characteristics of a G-DI spray, and is seldom required. However, for those instances for which the penetration rate of the PFI fuel spray within the intake port is required, imaging is permitted to obtain it. The digital images of the backlit spray are processed according to the thresholding procedures in the standard, and the values of the G-DI spray angle (note: not cone angle) and the G-DI spray bend angle (if any) are determined by specified equations that are applied to the processed images. This will be illustrated later in the section entitled, “Example of Standardization of Spray Test Parameters”.

**Determination of Key PFI Spray Characterization Parameters using High-Resolution Patternation**

Mechanical patteration is a methodology for determining the mass distribution within a spray. In recent years within the automotive industry, patterators of fairly high-resolution have been developed and are commonly utilized. These units have 250 to 625 discrete collection cells, and are fully automated under computer control. The high-resolution (H-R) patterator is employed to measure the time-integrated, 2-D, fuel mass distribution in a plane that is orthogonal to the injector axis. The standardized test configuration for making such a measurement is illustrated in Fig. 3. The test fluid specified is n-heptane, which is the fluid specified for all of the spray characterization tests. The standard measurement distance of 100 mm from the injector tip is also shown. The many additional details regarding the configuration, preconditioning, data acquisition and data reduction of the H-R patteration tests are provided in the SAE J2715 document.

Algorithms are utilized after the spray test to analyze the measured mass distribution among the hundreds of collection cells. The location of the center of mass is computed, as is the direction of the center of mass. The cumulative fuel mass percentage, as measured radially outward from the center of mass, is computed by applying the algorithms. The cone angle of the spray is computed from the 90% cumulative mass radius.

Therefore, the cone angle for a PFI injector is defined as the angle of a right circular cone that emanates from the injector tip and contains 90 percent of the measured (collected) fuel mass of the spray. The two main spray characterization values obtained via H-R mechanical patteration are the PFI cone angle and the PFI bend angle (spray offset angle of the spray plume), with additional parameters such as the spray separation angle being obtainable for optional PFI spray designs such as dual spray injectors.

**Laser Diffraction and Phase Doppler Interferometry for the Determination of Key Spray Characterization Parameters**

The degree of fuel atomization that is delivered by an automotive fuel injector is one of the most important considerations in spray characterization. It is arguably the most important consideration for a G-DI fuel spray, and is second only to the cone angle for a PFI fuel spray. In the J2715 Standard the atomization performance is characterized by two statistical parameters that are derived from the measured drop size distribution; the Sauter mean diameter (SMD) and the 90 percent cumulative volume diameter ($D_{v90}$). This is true for both the laser diffraction and PDI measurement techniques. It should be noted that the J2715 Standard requires that the entire distribution curve be attached to the data-reporting sheet. The SMD and $D_{v90}$ values represent two convenient numerical shorthand descriptions of aspects of the entire drop-size distribution. For automotive fuel system engineers, the
The D<sub>90</sub> value represents a convenient numerical descriptor of the largest drops within the delivered spray.

The standardized test configuration for characterizing the atomization performance of an injector by means of laser diffraction is shown in Fig. 4. The standard test procedure indicates a distance of 100 mm (shown) from the center of the laser beam to the PFI injector tip, and 50 mm (not shown) for a G-DI injector. The test fluid for all measurements is n-heptane. The details of the initial configuration of the laser diffraction test, as well as the pre-test and post-test validity checks, are provided in the SAE J2715 document.

If a particular test laboratory has a phase-Doppler interferometry system instead of a laser diffraction system, the Standard contains an accommodation for this. A complete, parallel test procedure for spray atomization characterization by means of PDI instead of laser diffraction is provided. The tests are completely different, however, with the PDI procedure being more complex and time consuming. A schematic of the 1-D PDI measurement configuration is illustrated in Fig. 5.

Using similar logic, the committee consensus on the use of both PDI and laser diffraction time-windowing was that all measurements be time-integrated. Therefore, the option for time-windowing is to be turned off, even if the PDI system has such a capability. Time-integrated measurements were specified even though an automotive fuel spray is a pulsed, highly transient event that typically occupies a duration of only milliseconds. While it is certainly true that state-of-the-art PDI and laser diffraction systems incorporate time-windowing as an option, an informed decision was made during development of the standard that this option not be used. Time-windowing does offer some additional capabilities for measurement, such as the separation of the sac spray drops and any after-injection drops from the main spray, but this must be weighed against the associated increase in test complexity. There was a committee consensus that the inclusion of time-windowing would result in a significantly more intricate test procedure, and would make it more difficult for any spray test facility to verify the reported results of any other spray laboratory.
Round-Robin Testing Overview and Status

In order to quantify the benefits provided by J2715 in laboratory-to-laboratory and test-to-test variabilities for the full range of spray characterization parameters, a comprehensive two-year, round-robin test program was developed. This blind, round-robin program is being conducted at six major spray laboratories around the world, and is 60% completed. A unique and representative set of injector and driver hardware covering all major types of automotive fuel injectors was selected, and is being circulated to each spray test laboratory. Each of the facilities will test all of the units using the J2715 test procedures, as well as their own established, in-house test procedures. The resultant values for all of the key characterization parameters will be provided to an independent monitor for statistical analysis. The results from these analyses are to be presented at a future ILASS conference.

The round-robin test is on-going; however, as an illustration of an early result from the program, a simple example of the in-house measurement of the angular extent of a G-DI fuel spray (the spray angle) will be provided. In regards to the spray angle, G-DI injectors are often classified based upon the measured value of this parameter. In fact, the spray angle is considered to be one of the most important spray parameters when a particular G-DI injector is being considered and evaluated for a specific engine application. In spite of the importance of this spray metric, it was noted early in the development stage of the J2715 Standard that each of the automotive spray laboratories had a specific, in-house, test method for the measurement of the G-DI spray angle. While it is true that almost all employ imaging tests to acquire the images from which the G-DI spray angle is computed, the similarity ends there. Significant deviations in the reported value, even for the same injector, result from the combination of variations in illumination method, test fluid, injector set point, imaging time, edge definition, number of boundary lines and the distances of those lines from the tip. The following test example will illustrate this point. In this portion of the round-robin test a G-DI injector was provided to three automotive spray laboratories, with the request that each measure the G-DI spray angle according to their own established, in-house procedures. The injector that was tested was not just similar, but was the exact injector and driver provided sequentially to each laboratory. The need for standardization is reinforced by the spray images that resulted, and which are shown in Fig. 6. These are the actual spray images from which the spray angle would eventually be computed. Due to the lack of an industry standard, each laboratory had evolved an ad hoc test protocol to conduct such tests, with no two protocols being the same among them.

Three different spray illumination methods were used at the three labs, with each being the established imaging method within that laboratory. Backlighting by means of a Nd-YAG laser was utilized at Lab A, with copper-vapor-laser backlighting used at Lab B. For Lab C, volume illumination of the entire spray by means of a strobe light was the method employed. The times at which the images were obtained during the rapid development of the spray were also different for the three labs. At Lab A and Lab B the image was taken at a time of 1.50 milliseconds after the start of injection. In Lab C a pre-specified injection pulse width was not utilized, but, instead, a floating pulse width that provided a fixed fuel mass delivery of 10.0 milligrams per injection event was used. The flash time for spray illumination was 1.00 ms after the first appearance of fuel. Further differences were noted for the test fluids, with two different test fluids utilized by the three laboratories; n-heptane for Lab A and Lab B, and Indolene for Lab C. The post-processing procedures for the image also differed considerably. In Lab A the spray boundaries are specified as being along two lines orthogonal to the injector axis at 5 mm and 15 mm from the tip, and the spray-boundary points on these two lines were used to define two lines that each formed a half-angle relative to the injector axis. In Lab C, two lines are specified that are orthogonal to the injector axis at 1 mm and 15 mm from the tip, with the four points on the spray boundary defining two lines in space. The absolute angle between these two lines is defined as the spray angle. In Lab B the spray angle is determined using an algorithm from a commercial image-processing program. This program effectively uses a line orthogonal to the injector axis at every pixel of the image to determine the left and right spray boundaries at each downstream pixel location. The angle between the two lines is the G-DI spray angle that would be reported by Lab B.
Example of Standardization of Spray Test Parameters

In the previous section the need for the standardization of all aspects of spray characterization was made apparent. The illustrative example in Fig. 6 conveys the importance of standardization in testing procedures, but also critical to complete standardization are the data reduction and reporting procedures. Once the test has been conducted according to the detailed test protocol, the data must be reduced and the specified equations and algorithms applied. One example of this may be provided by the specified standard method for obtaining the G-DI spray angle from a spray image. If the image has been obtained according to the strict protocol in the SAE J2715 spray characterization document (the images in Fig. 6 are from in-house procedures, and have not been so obtained), then the image is processed according to the data reduction procedures that are listed for that parameter. These procedures are illustrated in Fig. 7. The standardized method of obtaining the G-DI spray angle specifies a test procedure for obtaining the spray image, followed by a required method of data reduction and reporting.

A backlit image of an n-heptane spray is obtained at 1.50 millisecond after the first appearance of fuel at the tip of a G-DI injector, then specific thresholding and other image processing procedures are applied to define the left and right spray edges. As in the illustrative example depicted in Figure 7, two lines orthogonal to the injector axis at axial distances of 5 mm and 15 mm from the injector tip are used to define four points in space on those edges; two on the right edge and two on the left edge. These four points are used to define two lines that yield two half angles relative to the injector axis. The sum of the two half angles is defined in SAE J2715 as the spray angle for that G-DI injector.

Figure 6. Example of the Variation Resulting from the Use of In-House Testing Procedures – Initial Photos for the G-DI Spray Angle from Three Spray Laboratories

Figure 7. Illustration of the Calculation of the SAE J2715 Spray Angle from the Specified Digital Image of a G-DI Fuel Spray
Recommendations

While this spray characterization standard is focused on gasoline injector sprays, the rationale employed has application for all fields that utilize spray measurement. Thus, for the wide range of applications of spray measurement, such as the agricultural industry, the pharmaceutical industry and a number of additional, discreet areas of industry, the following set of recommendations apply:

1. The main standards document, SAE J2715, that is the first reference in this paper, should be reviewed for any industry that uses spray measurement. The information in J2715 will be a valuable resource as an early step in establishing a meaningful spray characterization standard within that industry.

2. Standard practices should then be developed for the spray measurements, preferably by a consensus representative committee from that industry, as has been done for the automotive industry. These documents should include the establishment of rigid definitions of industry spray terms, testing configurations, standard test conditions, detailed test procedures, data reduction methods and data reporting formats. Standard practices establish common terminology, reduce ambiguity and will enhance both the repeatability and the verifiability of spray measurements in that industry.

3. In the reporting of the results of spray characterization tests, reference should be made to the equipment used to obtain the measurements. For example, drop size measurements reported from phase-Doppler interferometry and laser diffraction instruments have no universal cross-correlation, thus the values obtained for SMD, \(D_{90}\), etc, need to reference the type of instrument used. For spray envelope boundary angles determined by means of digital imaging, the term “spray angle” should be used. Similarly, a spray envelope boundary angle determined by means of mass distribution obtained via patternation should be denoted as the “cone angle”. The terms should not be interchanged, as they represent values for different phenomena.

4. Careful consideration should be given to the physical limitations of the spray measurements being employed, and to the applicability of the technique to the spray being measured. For example, patternation may not be appropriate for fine sprays of high vaporization rate, limited penetration or high drop dispersal. Similarly, measurement techniques that employ imaging and image processing may not be appropriate for coarse or sparse sprays that do not scatter sufficient light to permit reliable identification of the spray boundaries.

Acknowledgements

The Authors would like to acknowledge the long-term support of numerous corporations that provided fuel system engineers and laser-optical engineers for the five-year duration of this project. This includes all of the corporations listed in the authors’ affiliations, plus Denso America. Also to be noted are the extensive and invaluable contributions of Min Xu, Gaetan Vich, Brad VanDerWege, William Humphrey, David Lewis, Michael Kaput and Timothy Cushing in developing the SAE J2715 Standard for spray measurement. The valuable assistance of the SAE Standards Board and its staff support, particularly Patricia Ebejer, in many meetings and Webex conferences is also recognized.

References

Additional Standard Practice Documents

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


1. ASTM E 799-03, Standard Practice for Determining Data Criteria and Processing for Liquid Drop Size Analysis
2. ASTM E 1617-97, Standard Practice for Reporting Particle Size Characterization Data, 2002
4. ISO 9276-2; Representation of results of Particle Size Analysis - Part 2: Calculation of Average Particle Sizes/Diameters and Moments from Particle Size Distributions, 2001
6. ISO 13322-1, Particle Size Analysis - Image Analysis Methods - Part 1: Static Image Analysis Methods, 2004