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VIEWS ON THE STRUCTURE OF TRANSIENT DIESEL SPRAYS

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There has been tremendous change over the last few decades in the operating conditions of diesel fuel injection systems and engines, and in the diagnostic tools and numerical models available to evaluate them. Improvements in the diagnostic techniques coinciding with changes in diesel injector technology have brought about an entirely different view of the breakup of liquid in current diesel sprays. A detailed examination of the history and current understanding of the structure of the dense core region in transient diesel sprays is presented.

Diagnostic methods are reviewed, and the appropriate uses are discussed. Of the techniques currently available, tomography is the most appropriate for determining the structure of the dense core region. Conductivity is not recommended. Line-of-sight techniques are recommended only for studying the periphery of the spray. Due to its greater contrast, high-intensity Mie scattering is preferred over line-of-sight methods for liquid spray penetration distance measurements. Advances in phase-Doppler interferometry are required to provide drop size and velocity measurements in the near-nozzle region.

A review of the spray structure and breakup mechanisms is presented. The structure of the spray has been shown to be completely atomized at or near the nozzle tip, with nozzle cavitation and turbulence instabilities as the dominant breakup mechanisms. Buckling may be responsible for breakup during the very early phase of injection. Aerodynamic shear may cause some secondary atomization, but its role in breakup is far less significant than previously thought. Cavitation affects jet breakup through the bursting and collapsing vapor cavities, thus contributing to the disintegration of liquid, resulting in a mixture of bubbles and liquid occupying most of the cross-sectional area, and through increasing the turbulence intensity, thus contributing to the instability of the liquid jet. The turbulence instability, along with pressure fluctuations in the nozzle, cause variation in the exit velocity of the droplets, resulting in temporal and spatial clustering of the droplets in the plume.

The results of recent research on the liquid spray penetration distance and drop size have been summarized. For liquid spray penetration distance, the orifice diameter is the dominant injection parameter, and ambient density is the dominant engine parameter, although ambient temperature is also significant. Fuel properties have been shown to have an effect on the liquid spray penetration distance, but further research is required to draw significant conclusions. For drop size, injection pressure and orifice diameter are the known dominant parameters.

The evidence for complete atomization of diesel sprays near the nozzle has come from a variety of sources, including tomographic imaging of the internal structure, microphotography of the near-nozzle region, diffraction droplet sizes that are greater on the periphery than the centerline, infrared multiwavelength extinction droplet sizing, and internal flow studies.

INTRODUCTION

Diesel engines are the most efficient prime movers for road transportation in widespread use today, offering unparalleled fuel economy and minimized CO_2 emissions. Present diesel engines produce dramatically lower particulate and NO_x emissions than do those

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of only two decades ago. Despite this, there is continuing pressure by regulators around the world to make further substantial reductions in particulate and NO_x emissions while maintaining the fuel economy and CO_2 emissions advantages for light- and heavy-duty diesel engines. This widespread interest in reducing diesel exhaust emissions has prompted increasing research work targeting an improved understanding of the diesel ignition, combustion and pollutant formation processes.

The mixing of the evaporating fuel spray with air plays a pivotal role in ignition and combustion processes in diesel engines. The temporal and spatial variations in the fuel/air mixing process control the ignition and the nature and progress of combustion [1]. This turbulent mixing event is in turn highly dependent on the atomization and vaporization characteristics of the intermittent fuel spray, the characteristics of the charge motion in the combustion chamber, and, to a certain extent, the combustion chamber geometry. The relative influences of these individual effects are not understood in detail, and knowledge of their variation as a function of engine operating conditions is inadequate [2]. Nonetheless, a widely subscribed view is that the characteristics of the diesel spray have a major role in controlling the significant events in diesel combustion. For this reason, a basic understanding of the transient diesel spray structure is essential for a reasonable description of the diesel combustion process [3, 4]. There has been a lack of knowledge regarding the mechanics of transient spray formation and the influence of the operating and design parameters. As a result, optimizing diesel engine performance and reducing pollutant emissions has been achieved by using lengthy iterative testing and development procedures. Recently, these have been ameliorated somewhat by adopting design-of-experiments statistical methods [5]. Multidimensional numerical codes are increasingly being applied as a design tool to reduce this development effort. These codes require a detailed physical understanding of the internal structure, breakup mechanisms, and droplet dynamics in diesel sprays. It appears that with improved experimental diagnostics and changes in the fuel injection technology for modern engines, a reasonable understanding of current diesel sprays has emerged [6]. The rapidly growing view being embraced by the spray research community, supported by many recent experiments, is that the direct injection diesel spray is fully atomized as it exits the nozzle [7, 8] or very near the nozzle [9–11], and these views are being adopted in current models [12, 13].

BACKGROUND

Evolution of Diesel Fuel Injection Research

There has been tremendous change over the last few decades in the operating conditions of diesel fuel injection systems and engines, and in the diagnostic tools and numerical models available to evaluate them. Injection pressures have increased by an order of magnitude since the early 1970s and there has been a steady decrease in the mean droplet size, as shown in Fig. 1. The engines have evolved, from indirect injection (IDI) to direct injection (DI), from inline pumps to unit injectors to common rail injectors, incorporating turbocharging and, in the near future, exhaust-gas recirculation. In addition to the increased injection pressures and high-pressure fuel delivery systems, the advent of electronic controls has provided the opportunity for split injection, multiple injections, and rate shaping [5, 14], and variable-orifice nozzles [15]. In addition, the number [16] and angle [17] of holes is being optimized. Unfortunately, much of this research tends to

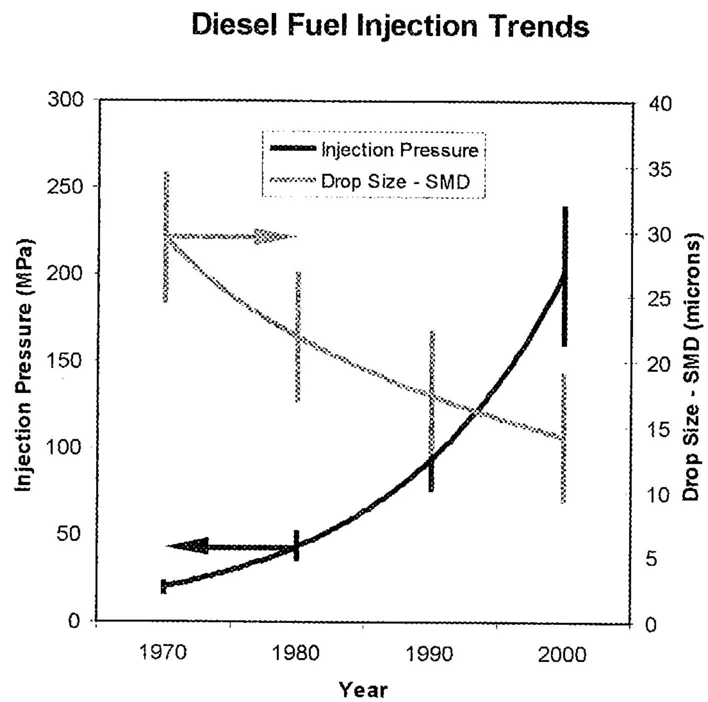

Fig. 1 The rapid change in diesel engine technology has resulted in dramatically higher injection pressures, and a related decrease in the mean droplet diameters. The bars represent the range found in commercially available diesel engines.

be engine- or injector-specific, and cannot be extrapolated to produce universal optimization strategies.

There is now recognition that nozzle pressure fluctuations have a significant effect on diesel sprays [9]. A new understanding of the role of cavitation in spray breakup [18] has resulted in increased interest in the internal geometry [15] and surface finish of atomizers and the corresponding impact on internal flows.

The impact of diagnostics of sprays [19] in general, and the impact of modeling [20, 21] of diesel sprays specifically, have provided tremendous gains in our understanding and knowledge of the physical processes governing the atomization of diesel fuel. Awareness that the penetration of the liquid phase of the diesel spray is much shorter than previously thought has led to a radically new concept of diesel combustion [22] that is gaining acceptance among the diesel combustion community. The increased knowledge of the physical processes of diesel atomization has led to improvement in the application of diesel fuel injection technology, such that particulate matter and NO_x emission levels have been dramatically lowered.

Structure

The importance of the internal structure in general, and the nature of the dense core region in particular, has been recognized for a long time. The geometry and the dynamics of the core are a result of the jet breakup process, which controls the initial droplet size distribution and velocity [23]. The breakup of the diesel fuel sprays and the following spray formation have been one of the most debated issues in diesel combustion. Due to the very high optical density of these sprays, the internal features, especially those near the nozzle exit, have been considered in the past to be nonvisible [23]. Nonoptical techniques have been performed under conditions far from those of an evaporating diesel spray, forcing inferred conclusions. Thus the experimental efforts to elucidate the breakup mechanism and the internal structure of the diesel sprays have been confronted with difficult challenges. In the past, this dense core region was thought to have consisted of an intact liquid core.

A widely accepted view was that the jet breakup was not complete near the injector nozzle tip and an intact liquid core existed, extending beyond more than 100 nozzle diameters downstream. This view was based primarily on extrapolation of the information obtained from pressure-atomized steady liquid sprays at low injection pressures into ambient or low-pressure conditions. In steady pressure-atomized sprays, the dense spray region consists of an intact liquid core (similar to the potential core of a single-phase turbulent jet) surrounded by a dispersed-flow region that begins at the injector exit [24, 25]. The atomization progresses by primary breakup forming droplets through stripping from boundary layers on the liquid core surface followed by a secondary breakup of ligaments and large drops. In analogy with this picture of the steady spray atomization mechanism, the highly transient and intermittent diesel sprays at high injection pressures into diesel conditions were thought to have a similar breakup mechanism. Although the presence of an intact liquid core in unperturbed intermittent diesel sprays has never been observed directly, formulations and correlations to describe the intact core length (or breakup length) have been reported (see, for example, [26–28]). These correlations were widely used by the modeling community for lack of a better numerical formulation.

The presence of an intact liquid core has also been inferred from data representing spray tip penetration as a function of time [27, 29, 30]. These data indicated that the jet is divided into two regions, showing that the tip of the fuel plume moves at an almost constant velocity during the initial portion of the injection period, followed by a sharp transition to decelerating motion. The transition was interpreted to be that from an intact liquid core to an atomized spray. However, it has been shown that the measured spray tip velocity data do not support the sharp transition to indicate the sudden change from an intact liquid core to an atomized spray [4]. Furthermore, it has been demonstrated that the transition is not abrupt, and is simply a consequence of the spray gradually evolving from a primarily liquid fuel mass to a primarily gas (fuel vapor and entrained air) mass [31].

MEASUREMENT METHODS

As our understanding of the nature of diesel sprays has evolved over the past decades, it has become apparent that the limitations of the earlier experimental techniques produced some unfortunate misinterpretations of the results available. However, it must be recognized that the nature of the diesel sprays themselves has also evolved over time, and that what may have been correct for a lower injection pressure, larger orifice diameter injector of yesteryear has simply changed with advancing technology. This points to the need to be clear and specific about the range of conditions for which results apply, as there are many parameters that can affect the properties of a diesel spray.

Experiments (and model calculations) need to be carefully designed and documented, with a clear set of objectives, and a path to achieve those objectives without confounding influences or assumptions. Any assumptions that are made need to be properly addressed and accounted for. We now have improved knowledge and control of actual injection and ambient conditions. The instrumentation has improved greatly, with better temporal and spatial response to monitor and analyze injection conditions, and the ability to make nonintrusive measurements. As a result, the most beneficial knowledge about diesel sprays is to be gained from performing experiments under well-controlled engine-like conditions reflecting the actual transient nature of diesel sprays, with appropriate temperatures, densities, and fuels.

The advent of lasers has given rise to an abundance of optical techniques for characterizing sprays. Due to the very dense structure of diesel sprays, light is strongly attenuated throughout most of the spray plume, creating impediments for the optical techniques. The limitations and advantages of various optical techniques as well as alternatives, such as the conductivity technique, are discussed below.

Conductivity

Some of the earliest insights to the structure of dense diesel sprays were direct measurements of the breakup length by using the conductivity technique in continuous diesel sprays [23, 29, 32–34]. Conductivity is based on the measurement of the electric impedance between the nozzle and a fine wire net detector, located downstream in the spray, for continuity. Diesel fuel does not provide sufficient conductivity, so substitute simulants are used in its place. Although the relevance of these measurements made in continuous sprays to intermittent and highly transient diesel sprays is now debatable, diesel spray submodels based on the long breakup length measured with conductivity have provided reasonable predictions of spray penetration in numerical diesel combustion simulations [35].

More recently, Yule and Salters [36, 37] studied the structure of unsteady diesel-like sprays with a refined conductivity probe. The structure they inferred from the conductivity measurements suggests a poorly atomized liquid core region containing voids and consisting of sheets and ligaments that are connected back to the nozzle. The breakup length was reported to be of the order of 100 nozzle diameters at engine conditions for gas density, and it increased with an increase in liquid viscosity and reduction of gas density [38]. Only 1% of the injected liquid was incompletely atomized 100 nozzle diameters downstream, and the proportion is not linear with distance, as most of the fluid is atomized very near the nozzle. The breakup lengths inferred from conductivity measurements agree with the published correlations for moderate liquid viscosities [38]. As the conductivity experiments have approached diesel-like conditions, the results have become similar to those obtained with other techniques under more realistic conditions, in that most of the liquid is atomized near the nozzle exit. Much of the discrepancy between the conclusions from the conductivity experiments and the view that DI diesel sprays are fully atomized near the nozzle exit may be attributed to the substantially different conditions under which the conductivity experiments were performed.

Shadowgraph/Schlieren

Other early reports on the structure of diesel sprays are based on observations made with some of the earliest available optical diagnostics, direct photography and shadowgraphy, which produce line-of-sight path integrated images [32, 33]. Due to the high obscuration by these sprays, it is now recognized that it is difficult to obtain sufficient information related to the internal structure of full-cone transient diesel sprays from such images.

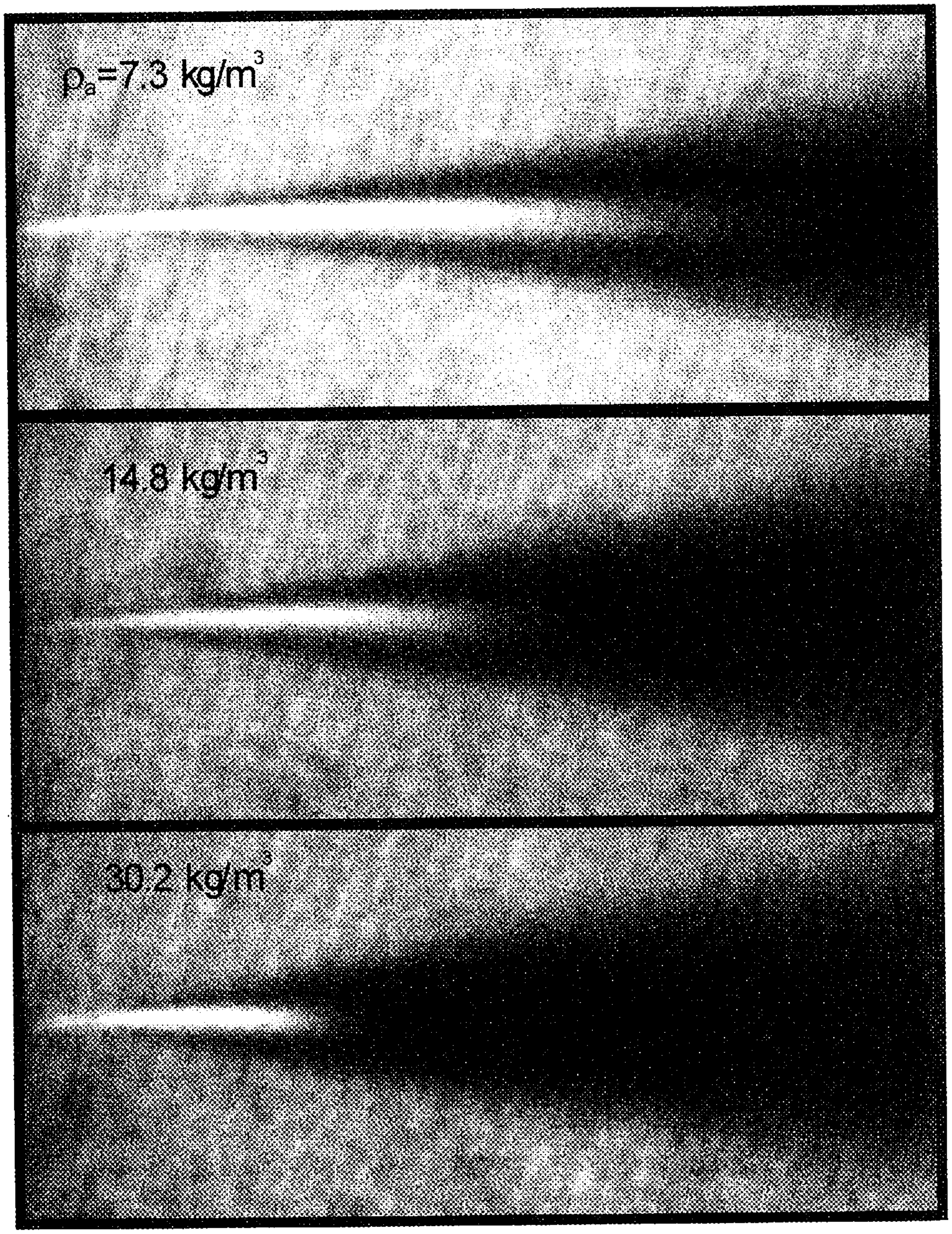

Fig. 2 Time–averaged Mie scattering light images of diesel plume superimposed on time–averaged schlieren images, identifying the vapor-phase spreading angle with the dark region. (From [40].)

Using the shadowgraph method, Ishikawa and Murakami report an entangled ligament structure in the core of a spray passing through a skimmer [39]. However, this also was a line-of-sight technique, which inherently images the whole spray field, not just the core, and could only result in nearly complete obscuration due to path length attenuation. Even with a slit width (and thus a path length) of only 1 mm, it would be impossible to distinguish between tightly packed droplets, ligaments, or an intact liquid core in a dense spray due to obscuration with this method. Direct uncompromised observation of the dense core region is not possible with a line-of-sight technique. Interpretation of such images must be performed with due caution.

Recently, schlieren has returned to favor, not to image the structure of the liquid phase of the spray, but to identify the outer boundary of the vapor phase under realistic engine conditions [7, 40], as shown in Fig. 2. It has been found that the fuel vapor propagates with the same velocity as the initial droplets, due to efficient transfer of momentum, and that the liquid penetration depth is only one-third of the final vapor penetration depth under specific engine conditions [7], where the piston bowl wall limits the vapor penetration. In an unconfined environment, the vapor will continue to penetrate, whereas the liquid penetration will remain constant for fixed conditions [40].

Mie Scattering

The imaging of scattering from sprays has primarily been performed in one of two ways: illumination of the full volume of the spray, or planar sheet illumination for tomographic imaging. Volume imaging of Mie scattering is currently routinely applied to identify the extent of the liquid-phase penetration of diesel sprays, for both single injection images [41] and multipulse averages [40], as illustrated in Fig. 2. Side-illuminated volume imaging is more effective, especially for determining liquid spray penetration distance, than back-illuminated volume imaging because it has better contrast. However, it is the use of tomographic imaging that first identified the extant nature of the structure of the dense core region in high-pressure transient diesel sprays [42]. Researchers have adopted the view that tomographic methods provide the most detail about structure in dense sprays, if prudently applied under well-controlled conditions [43].

For tomographic imaging in a multiple-scattering environment, noise is generated by near-forward rescattering of the light that has side-scattered off droplets in the plane of the laser sheet. This noise is analogous to the signal that is analyzed to determine size in diffraction instruments. Initial experiments with a skimmer to minimize the effects of multiple scattering indicated the optical configuration required for successful imaging of the dense core region without a skimmer [42]. Subsequent experiments [4] involved the imaging of the unperturbed structure of the dense core region of a full-cone intermittent diesel spray on photographic film at high resolution with weak laser excitation, as shown in Fig. 3, and the simultaneous measurement of laser sheet transmission along the centerline of the spray. Application of advanced image processing techniques eliminated the relatively minor multiple scattering present in the images, as shown in Fig. 4. The measurements showed that the dense core region is fragmented very near to the nozzle exit, about 25–30 nozzle diameters downstream and perhaps much closer. Farther downstream from this location, the transmission measurements and simultaneous tomographic images revealed that the structure has an intermittent appearance with pockets of dense spray separated by relatively void regions. The images displayed a highly atomized spray structure beyond 50

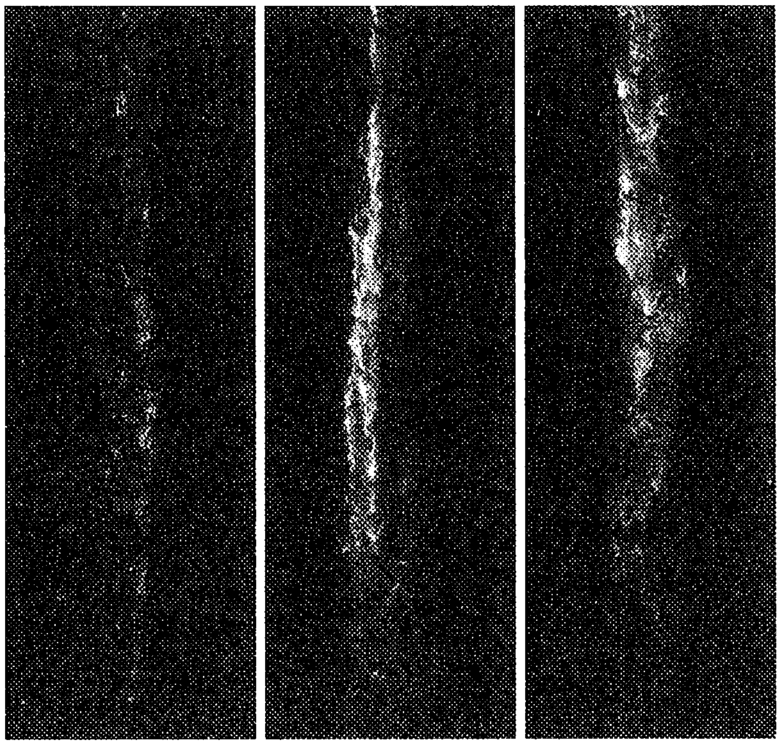

Fig. 3 Tomographic imaging based on low-intensity Mie scattering of the dense core region of a diesel spray injecting into atmospheric conditions. (From [4].)

nozzle diameters downstream, with no indication of an intact liquid core for the range of injection pressures studied.

Other issues for tomographic imaging in a multiple-scattering environment are the effects of forward scattering in a dense spray on the laser sheet. The forward scattering results in a broadening of the illuminated region, and attenuation of the illuminating intensity, as the laser sheet traverses the spray. These effects must be considered when interpreting the results of Mie scattering images.

Mie scattering measurements have been somewhat quantified with the application of ensemble scattering polarization ratio (ESPR) to diesel sprays [44, 45], in order to determine spatially resolved droplet size, and number, surface, and mass densities. However, it is recognized that reliable quantification of the technique is limited to the peripheral regions of the spray [45].

Visualization of the relative locations of the liquid and vapor phases has been performed with dual-intensity Mie scattering [46]. As noted above, the liquid phase is best imaged with Mie scattering from weak laser excitation. However, a high-boiling-point tracer is added to the diesel fuel, so that the vapor phase contains microdroplets of the tracer after the diesel fuel has evaporated. This region is then illuminated with much stronger laser excitation so that the scattering from the tracer droplets in regions downstream from the liquid phase may

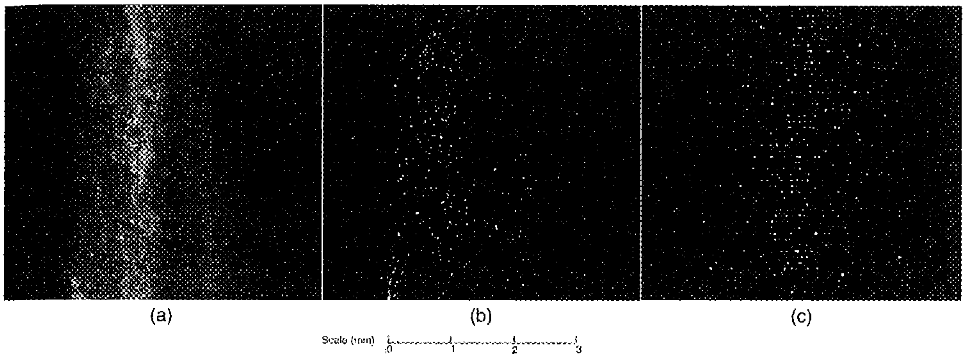

Fig. 4 *(a)* Enlargement from the center of Fig. 3; *(b)* Image processing to remove noise due to multiple scattering; *(c)* Results of KIVA3 simulation for the same region. (From [4].)

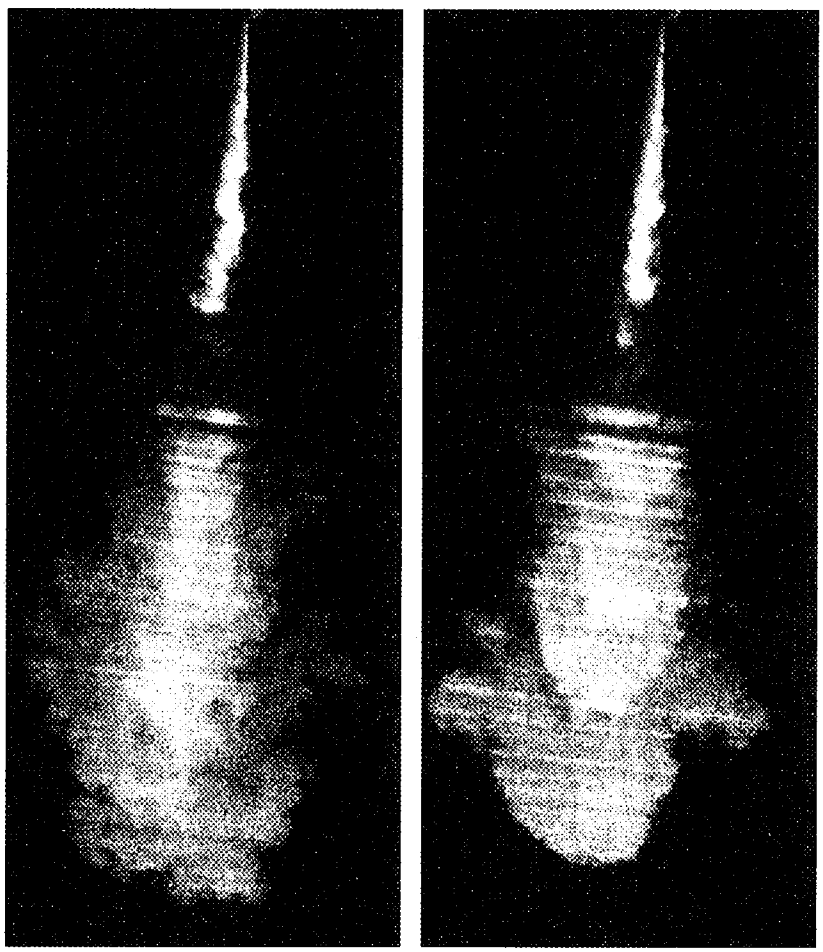

Fig. 5 Dual-intensity Mie scattering to visualize liquid and vapor phases simultaneously. Weak laser excitation is used in the top portion of the image to visualize the liquid phase; strong laser excitation is used in the lower portion of the image to visualize scattering from tracer droplets in the vapor phase. (From [46].)

be recorded, as shown in Fig. 5. This technique has recently been extended to obtain a quantitative measure of the fuel concentration in the vapor phase [47].

Although the Mie scattering methods discussed above rely on pulsed lasers, direct photography of scattering from diesel sprays without a laser source continues to be applied effectively to establish the gross features of the spray plume [14].

Laser-Induced Fluorescence/Exciplex

Laser-induced exciplex fluorescence was developed by Melton and Verdieck specifically for visualizing the vapor and liquid phases of fuel sprays [48]. Semiquantitative information about the fuel jet, such as relative gas and liquid concentrations, is available with exciplex fluorescence [41, 45]. Exciplex fluorescence also provides the relative locations of the liquid and vapor phases, as shown in Fig. 6. The exciplex results have shown that increased injection pressure and reduced orifice diameter reduce the liquid spray penetration distance of the fuel and improve the mixing of the vapor phase [41]. Exciplex fluorescence has also been applied to perform two-dimensional measurements of the liquid-phase temperature field in engine-like conditions [49]. This could prove valuable in evaluating heat transfer to droplets and their subsequent evaporation rates, mixing, and ignition.

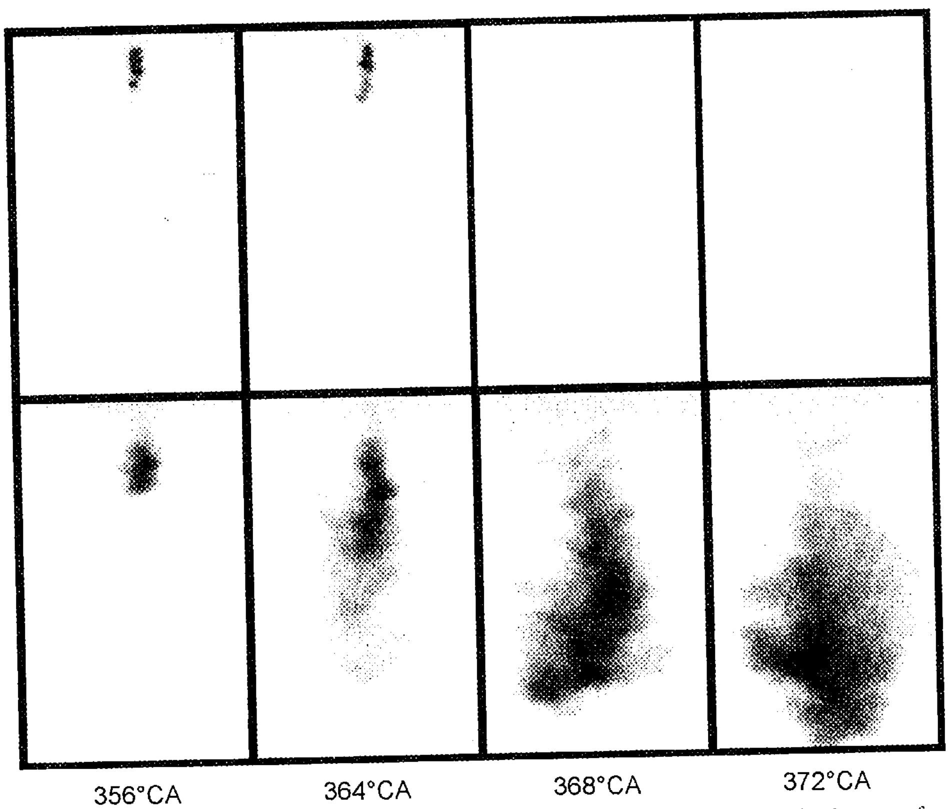

Fig. 6 Images of the liquid phase (upper row) and of the vapor phase (bottom row) of a diesel spray at four time intervals after the start of injection using the laser-induced exciplex fluorescence technique. (From [41].)

Laser-induced fluorescence (LIF) has been applied to perform mass (or volume) distribution measurements in patternation applications [50]. LIF has also been applied in moderately dense sprays in combination with Mie scattering to perform two-dimensional measurements of Sauter mean diameter (SMD) [51]. The application of this combined technique to highly attenuating dense diesel sprays remains to be demonstrated. Since LIF produces a signal that is proportional to volume, and is not morphology dependent, as Mie scattering is, it should prove to be superior to Mie scattering tomography for determining the structure of the dense core region. However, this also remains to be demonstrated.

With appropriate calibration and accounting for the effect of temperature on the measured intensity, LIF has been demonstrated as a quantitative technique to determine the fuel vapor concentration in evaporating diesel sprays [52].

Laser Diffraction/Phase-Doppler Interferometry

Diffraction-based instruments have proved useful for drop size measurements in dense sprays, although they are limited to nonevaporating conditions due to beam-steering sensitivity [19]. Assuming axisymmetry, radially resolved measurements can be obtained from the line-of-sight measurements through an Abel-type inversion. To remove the bias in the measured drop sizes for dense sprays, reducing the beam size and applying a correction scheme is effective [53].

The dominant drop size measuring technique in use today is the phase-Doppler interferometer (PDI) [19], which is a single-particle counting technique that also measures droplet velocity. However, application of PDI to the dense core region in diesel sprays has eluded its grasp. The fundamental limitation of PDI is that there can only be one particle in the measurement volume at any given time. Thus measurements in diesel sprays are limited to the periphery, and the leading and trailing edges on centerline, as little data is acquired during the bulk of the spray process due to the high number density of droplets [54]. A recent approach successfully applied in dense rocket sprays holds promise for making PDI measurements in diesel sprays [55]. Fundamentally, it involves the use of a much smaller probe volume, thus reducing the likelihood of multiple particles in the probe volume at one time. Furthermore, measurements made with a skimmer and the small probe volume indicated promise for also making volume flux measurements in dense sprays [56].

It is anticipated that with cautious use of a skimmer and new developments in PDI measurements, researchers will soon be able to acquire drop size and velocity measurements in the dense core region of diesel sprays.

Other Current Methods

Imaging of light attenuation has been used to estimate an overall average SMD droplet size for the diesel spray plume ([17] and citations therein). This method requires significant assumptions, including negligible multiple scattering. Since this assumption is not valid for dense diesel sprays, efforts have been made to minimize the effect on measured SMD [17], and an accuracy of 8% is claimed for the method [16]. A variation of this method, based on two-wavelength extinction, requires fewer assumptions and has been shown to be less sensitive to the problems associated with making measurements in dense sprays [57]. A unique feature applied in this method was the use of infrared lasers, which suffer less attenuation than visible wavelengths in multiple-scattering dense sprays.

Interest in the structure of the spray in the near-nozzle region has led to the adoption of microphotography with pulsed laser illumination [8, 10, 11]. The high-magnification images from these studies have confirmed the finding that spray breakup commences at or very near the nozzle exit, as shown in Fig. 7.

Fractal analysis of photographic images has been applied to characterize vortices in the boundary region of diesel sprays [58]. This technique may provide evidence about the effects of turbulence, air entrainment, and momentum exchange, as the boundary of the plume appears to have a fractal nature, lending credibility to the method.

Many other methods to characterize dense sprays exist but have not seen widespread use and are too numerous to be discussed.

Skimmers in Diesel Fuel Injection. The use of a skimmer to reduce the attenuation due to multiple scattering in dense diesel sprays has been the subject of controversy for many years, as it is a semi-intrusive approach. The results presented in Ref. 42 clearly demonstrated that the use of a skimmer did not affect the core region of the diesel spray in comparison with unskimmed sprays.

Further evidence is provided here in the form of a simulation [59] performed with KIVA3 for the injection conditions present in [42]. Briefly, the TAB breakup model was used with KIVA3. The skimmer was placed 10 mm downstream of the nozzle exit, with a 1 mm slit width. The simulation was performed with a full-cone angle of 10° and a velocity of 100 m/s, with a 3 ms duration. The results shown in Fig. 8 are at 1.2 ms after the start of injec-

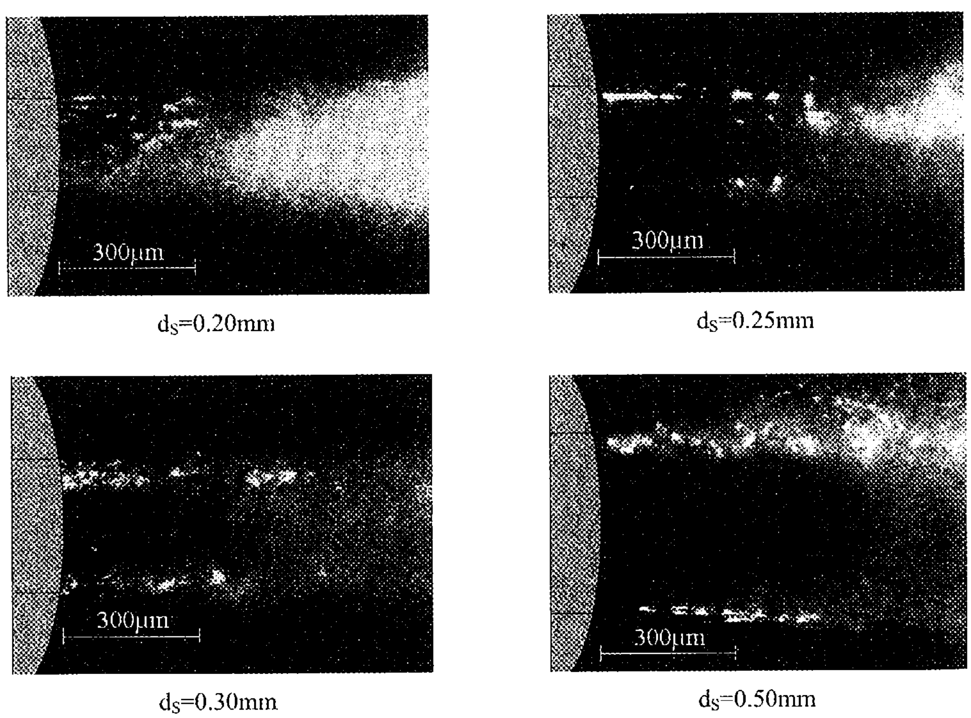

Fig. 7 Mie scattering microphotography of near-nozzle region, indicating full breakup of spray very near to the nozzle exit. (From [11].)

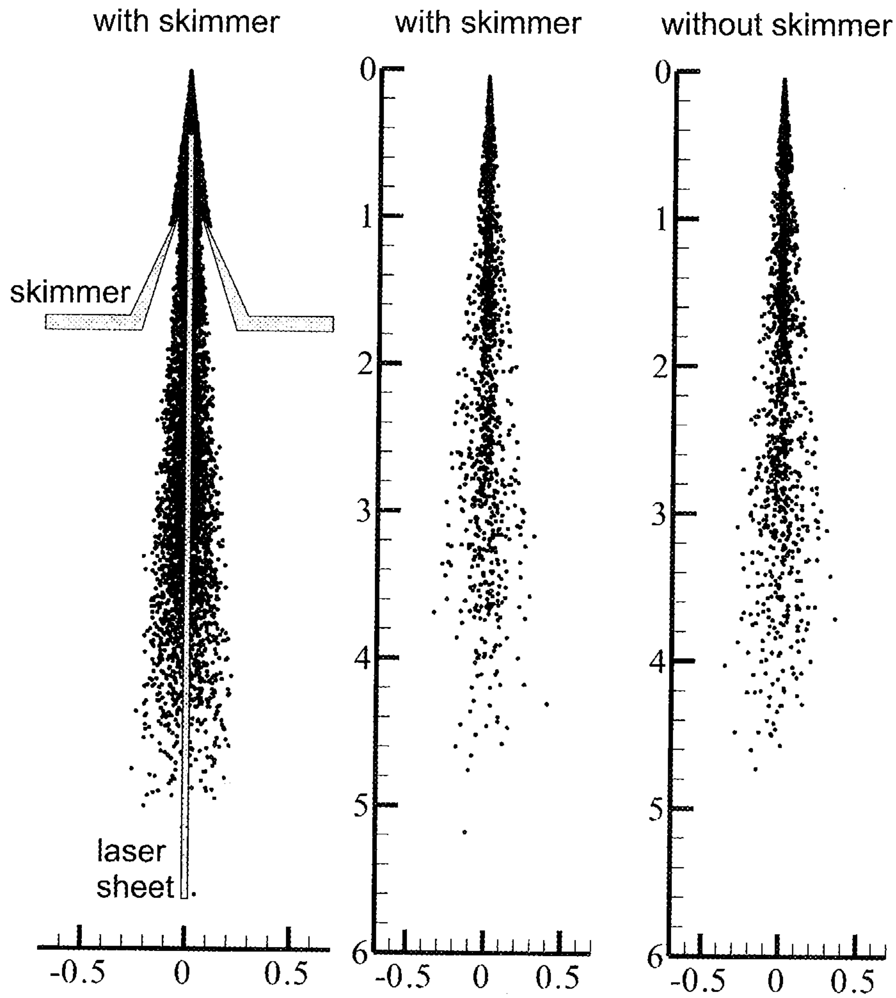

Fig. 8 KIVA3 modeling results for the skimmed (left and center) and unskimmed (right) sprays. The image at the left shows the location of the skimmer and the laser sheet. The center and right images, orthogonal to the left image, indicate the predicted droplet locations within the region illuminated by the laser sheet, showing that there is no significant difference in the spray between the skimmed and unskimmed sprays in the region of the dense core.

tion. As can be seen in Fig. 8, there is no significant difference in the model prediction for the central 0.3 mm (the region illuminated by the laser sheet in [42]) of the spray passing through a 1 mm slit as compared to one spraying into the open atmosphere. By adjusting the slit width, experimentally or numerically, one can (and should) determine the point at which the slit is having an effect on the region of the spray being studied. In spite of this, it is recommended that a skimmer be used only when absolutely necessary in order to adhere to the practice of best experimental design.

Emerging Techniques

Efforts in medical imaging to visualize structures in turbid media are leading to developments for dense sprays. Ultrafast time-gated optical imaging has been applied to observe the dense core structure of a rocket-like spray [60]. This technique is based on picosecond laser pulses and detector gating, so that ballistic and snake photons are recorded, but not the diffuse light. Ballistic photons are defined as the component of the transmitted light that is coherently scattered in the forward direction, and are the first to arrive at the detector. Snake photons are defined as those scattered slightly in the forward direction, traveling a zigzag path about the incident direction, and arrive shortly after the ballistic photons, but considerably before the diffuse photons that scatter through the medium. These ballistic/snake photons retain maximum/significant information about the interior structure of the scattering medium, respectively, and do not obey diffusion statistics. Application of image processing techniques has rendered the technique capable of generating observable images through turbid media with attenuation of the order of 10^{-10} [61]. Currently the method is limited to line-of-sight imaging, and has not yet been demonstrated in a diesel spray. The issue of multiple droplets existing along the path of the light through the spray may impair the use of this technique for detailed determination of the structure of the dense core region in diesel sprays.

Advances have been made in suppression of multiple scattering in turbid media, thus favoring single scattering, by use of cross-correlation techniques [62, 63]. These techniques take advantage of single speckle [62] or the 3-D cross-correlation function [63] to discriminate against multiple scattering in point measurements, and have been demonstrated to perform accurate particle sizing of submicron spheres in turbid media. The concept of applying cross-correlation techniques to minimize multiple scattering in two-dimensional imaging of dense sprays has not yet been developed, but holds promise for the future.

Degenerate four-wave mixing and other coherent technologies may advance the capabilities of holographic imaging to the point that it becomes a viable diagnostic for dense sprays. In observing the progress in optical diagnostics of sprays over the last two decades, further unanticipated developments for measurements in dense sprays are likely to emerge in the future.

DIESEL SPRAY STRUCTURE

The current view of breakup mechanisms and the structure of the spray from modern diesel injectors, based on recent experimental and modeling evidence, is that four mechanisms play significant roles: cavitation, turbulence-driven instability, buckling, and aerodynamic shear. These mechanisms will each be discussed in detail in the following sections. The relative contributions of each of these mechanisms and the resulting impact on the spray structure are dependent on many factors, including the transient nature of the injection process, the peak injection pressure, the pressure profile, the ambient density, the air motion and turbulence, the nozzle diameter and length, the sac volume and configuration, and the finish on internal flow passages (sharp versus rounded edges, etc.). In the literature, most of these factors are routinely reported, with the exception of details of the internal flow passages. Some of the disagreement over the breakup mechanisms may be due to unreported differences in these passages, which may, for instance, cause some injectors to have a more laminar internal flow than others. For example, nozzles for high-pressure water jet cutting are specifically designed to maintain laminar flow in the nozzle passages so that jet breakup does not occur near the nozzle exit.

The current view of the breakup and structure of DI diesel sprays is summarized below. Initially, a small quantity of poorly atomized liquid is injected. This produces a relatively large, contiguous, and low-velocity fuel mass, which is subsequently atomized by the highly disruptive cavitating flow. The cavitating flow dominates the injection period, producing small droplets until the needle closing, at which point a few relatively large drops may emerge from the injector. Recent drop size measurements indicate that the droplet size has little variation with time or with axial distance from the injector during the injection period [9]. This suggests that the fuel is completely atomized at the nozzle exit, and it also suggests that secondary atomization and coalescence due to collisions offset each other, or, more likely, occur to such a small fraction of the spray field that there is negligible impact on the drop size distribution. Due to entrainment, the relative velocity between the droplets and the air in the core of the spray is less than at the periphery, and thus droplets in the dense core region are not subjected to the levels of aerodynamic shear experienced by those at the periphery. The measurements also indicate that, if anything, the drop sizes are larger at the periphery than they are on the centerline. This suggests that secondary atomization of the peripheral droplets due to aerodynamic shear plays a minimal role in the breakup of the spray.

Spray Breakup Mechanisms

The general theory, breakup regimes, and breakup mechanisms for liquid jets have been recently reviewed [64]. As discussed in the Background section, diesel atomization was historically thought to progress by primary breakup forming droplets through stripping from boundary layers of an intact liquid core surface which extended far downstream of the nozzle, followed by a secondary breakup of ligaments and large drops. This concept is illustrated schematically in Fig. 9.

In a modification of the historical approach, the fuel jet exiting from the nozzle hole was proposed to gradually break into ligaments and sheets, connected back to the nozzle [39]. This core, consisting of ligaments and sheets, extends beyond more than 100 nozzle diameters downstream. In a slightly different concept, it was speculated that injected fuel

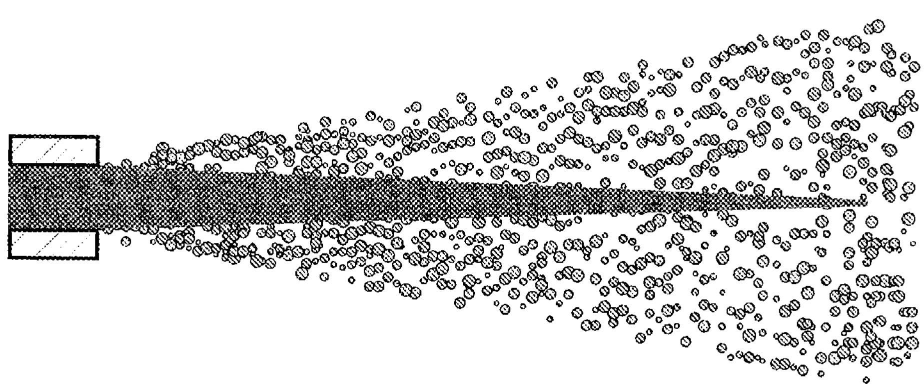

Fig. 9 Schematic view of the diesel spray with a long intact liquid core breakup length.

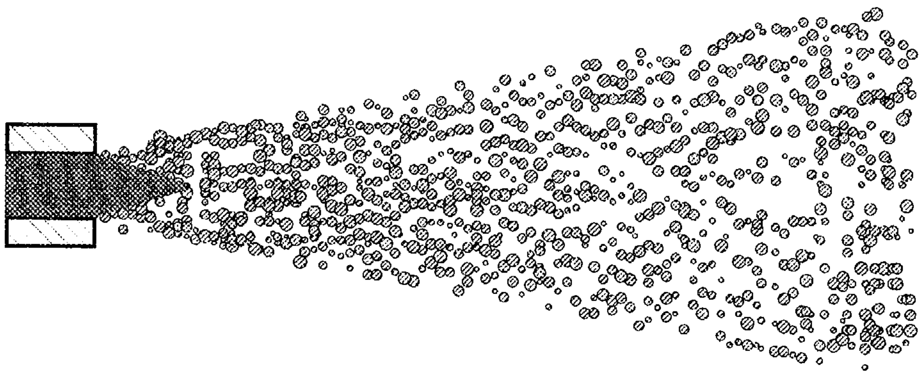

Fig. 10 Schematic view of the diesel spray with a very short breakup length.

with high momentum could break initially at the nozzle exit, and then fragments or droplets could coalesce, forming ligaments or columns of liquid during the injection period [65].

The current concept is that the liquid jet exiting from the nozzle hole atomizes completely at the exit of the nozzle or within, at most, a few nozzle diameters, as illustrated schematically in Fig. 10. This means that in full-cone unsteady diesel sprays no intact core or ligaments exist except possibly very near the nozzle. Development of this view was based on experimental data obtained on intermittent and highly transient dense diesel sprays using two-dimensional laser light scattering and transmission techniques [4, 42, 66]. It was demonstrated that the scattering is from randomly spaced point sources, which were interpreted as droplets, rather than liquid columns, ligaments, or large masses of fuel. These findings have been strongly supported by the most recent experimental work coming from different research groups. Yeh et al. [51] have inferred the spatially resolved droplet size distributions in high-injection-pressure diesel sprays by analyzing two-dimensional fluorescence and scattering images. They have not observed any evidence for the presence of an intact core or ligaments. The spray exhibited a fully atomized structure very close to the nozzle tip. Parker et al. [57] conducted droplet size measurements based on infrared multiwavelength extinction and scattering in the near field of dense diesel sprays showing a fully atomized spray with no indication of an intact liquid core or unatomized liquid. Even the very low injection pressure results of Fath et al. [11] show a possible intact core extending at most 1–3 nozzle diameters downstream from the injector, Fig. 11. Further observations indicate that typical high-pressure diesel sprays atomize directly at the nozzle exit [8, 12, 67], and there is no indication of an intact core [12, 67].

Aerodynamic Breakup. Historically, aerodynamic shear-generated disturbance of the liquid jet exiting from the nozzle orifice was considered the dominant breakup mechanism for diesel sprays, and has formed the basis for atomization in most diesel spray models [68, 69]. The aerodynamic shear at the liquid/gas-phase interface produces instabilities on the liquid surface and causes surface stripping. The instabilities can manifest in the form of Rayleigh–Taylor or Kelvin–Helmholtz disturbances, which result in aerodynamic disintegration of the liquid through wave growth mechanisms. Fundamental research performed at relatively low injection pressures and steady conditions indicated that effective atomization required a combination of cavitation and aerodynamic effects, and thus complete at-

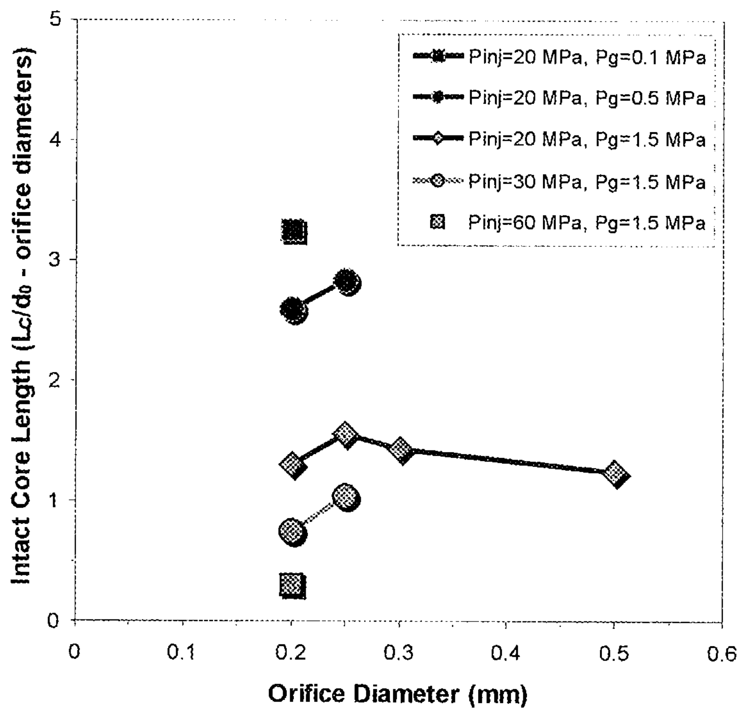

Fig. 11 Intact liquid core length (L_C) versus orifice diameter (d_0) for various injection pressures (P_{inj}) and ambient gas pressures (P_g). (Adapted from [11].)

omization requires the presence of a pressurized gas [70]. However, many results obtained at atmospheric backpressure have demonstrated that the spray is fully atomized near the nozzle [4, 42, 53]. Earlier work, also at relatively low injection pressures, concluded that cavitation alone could explain the spray breakup behavior, while aerodynamic interactions alone could not [71].

Recent evidence, presented below, suggests that aerodynamic shear is accompanied by several other breakup mechanisms. The relative importance of aerodynamic shear as a primary breakup mechanism is diminishing, and its greatest role may be in secondary atomization of the droplets. Regardless of the significance of aerodynamics on spray breakup, aerodynamics is critically important to the diesel combustion process, as the entrained air, along with the drop size and drop spacing, governs the fuel air mixing and local equivalence ratio. Further discussion of the role of air entrainment on diesel combustion can be found in Li et al. [72] and Siebers [91] (and references therein).

Buckling. Tomographic images [8, 66] have been reported showing the structure of the fuel jet in the first 50 μs after the start of injection, as shown in Fig. 12. These images show features that are consistent with a liquid jet that has buckled as a result of the ambient air resistance, but appear only during the initial stages of diesel injection, shortly after needle lift. Alternatively, the buckled appearance is also consistent with the distribution of vorticity in an unsteady spray predicted by numerical simulation employing the discrete vortex method [73], and thus may be a result of the unsteady interaction of the

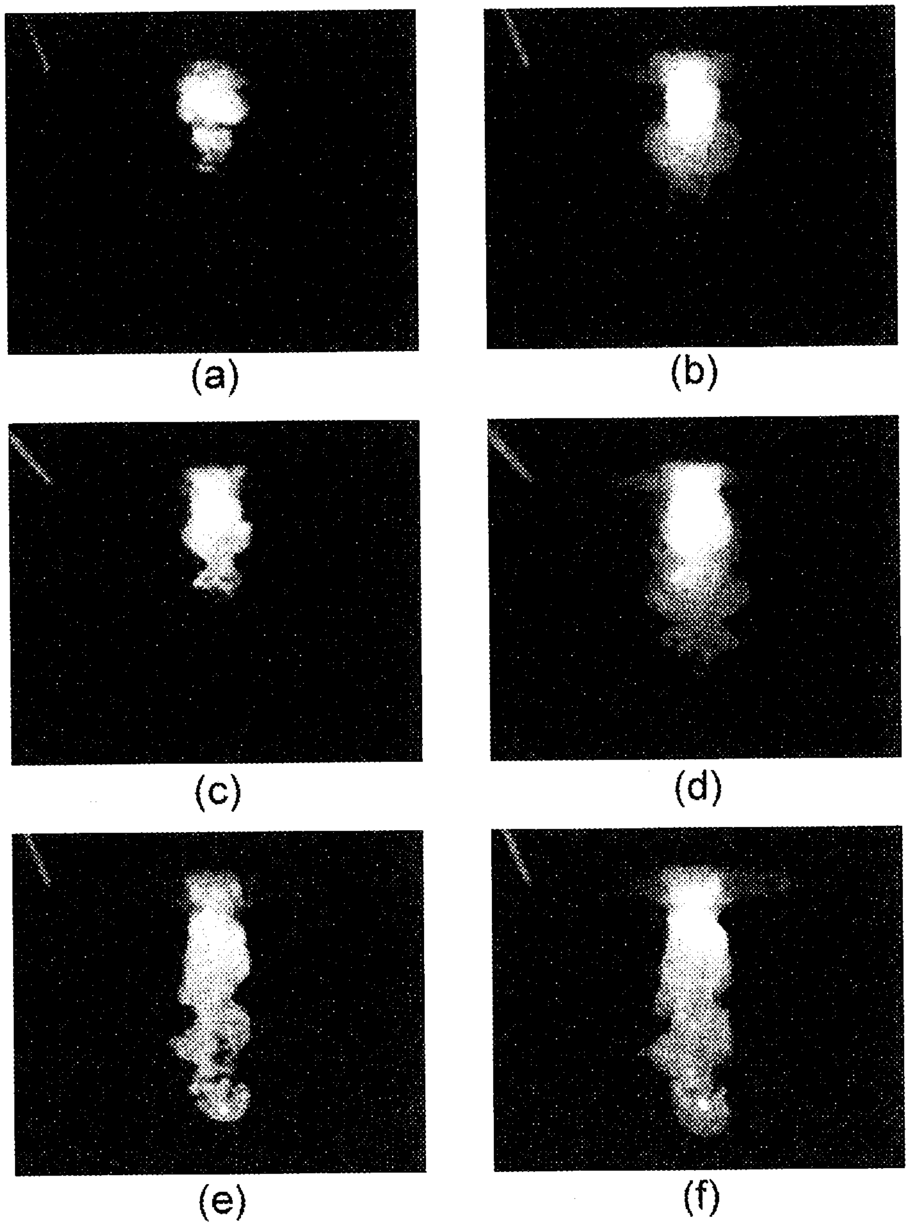

Fig. 12 Tomographic images of the structure of the liquid jet during the buckling phase of breakup, for a diesel spray injecting into atmospheric conditions. The pairs of photographs (*a* and *b*, *c* and *d*, and *e* and *f*) are from three separate injections. The time delay between the two images of each pair is 10 μs. Images *a*, *c*, and *e* were taken about 5, 10, and 30 μs after the start of injection. (From [66].)

initial liquid column with aerodynamic forces. As the buckling phase occurs only during the first 50 μs of injection, the quantity of liquid injected is relatively small. Even though this liquid is initially poorly atomized, the subsequent accelerating flow overtakes the initial fuel mass, contributing to its breakup due to collisions and through the disruption caused by the cavitating flow.

It was first speculated by Gülder [66] that buckling might make a contribution to the jet breakup in diesel sprays. Gülder and Smallwood [6] have presented a thorough description of the rationale for buckling as a breakup mechanism. In the studies related to the stability of liquid jets the initial disturbance of the flow is assumed given, and the attention is focused on the time evolution of this disturbance or deformation. Buckling in a round jet can be induced by either a flat obstacle that terminates the jet or by the ambient air that resists the jet flow [74–76]. This is analogous to the Euler instability due to buckling in thin elastic rods subjected to end compression. The repeated buckling that is induced by the aerodynamic interaction between the jet and the atmosphere appears to be favored, not inhibited, by the increase in speed [74]. Under transient circumstances, especially for a liquid jet started impulsively, instability induced by buckling will be more severe due to the acceleration of the liquid jet.

Cavitation. Cavitation of the flow through the diesel nozzle has long been considered as a possible contributor to the breakup and atomization process [77]. However, it was not until recently that several studies recognized and demonstrated the existence and the influence of nozzle hole cavitation in diesel injection systems [11, 67, 78, 79]. Although quantitative information on cavitation structure is missing [78, 80], it is recognized that cavitation has important implications for spray formation in diesel engines [18, 81]. The relative importance of the effect of cavitation as compared to aerodynamic and turbulence induced effects has not been resolved yet [11, 82], although most current research work assigns a major role to cavitation in high-pressure liquid jet breakup and atomization [78, 83]. The effect of pressure waves, generated by the implosion and explosion of cavitation bubbles in the liquid at the nozzle exit, on the process of spray breakup has been described previously [81].

He and Ruiz [78] proposed simplified expressions for predicting the critical value of the cavitation parameter at the onset of cavitation and the energy lost by the mean flow. Fig. 13 displays the regimes of cavitating and noncavitating flows through the diesel nozzle holes for a specified hole geometry [67]. The span of the error bars in Fig. 13 indicates the regime where cavitation is happening, but the vapor cavities do not survive to the exit plane of the nozzle hole. In the area above this regime, the collapse time of the vapor cavities is longer than the residence time of the liquid through the nozzle hole, and the cavities collapse outside the nozzle hole. All high-pressure injection nozzles are likely to have cavitating flows through their holes.

The influence of cavitation on jet breakup is twofold. First, the bursting and collapsing vapor cavities contribute to the disintegration of liquid masses at the exit of the nozzle hole, resulting in a mixture of bubbles and liquid occupying most of the cross-sectional area [18]. Second, cavitation increases the turbulence intensity of the flow through the nozzle hole, thus contributing to the instability of the liquid jet. It seems that no experimental data comparing the relative contributions of these two effects are available, but detailed numerical modeling efforts (similar to those described in [82, 84, 85]) may provide some qualitative answers. The nozzle discharge coefficient is known to depend more on the cavitation than on the Reynolds number, reducing gradually and asymptotically approaching a minimum with increasing cavitation number [18]. The presence of cavitation bubbles and/or flow separation (hydraulic flip) in the internal passages narrows the effective size *(vena contracta)* of these passages, thus increasing the fluid velocity and momentum, possibly creating a throt-

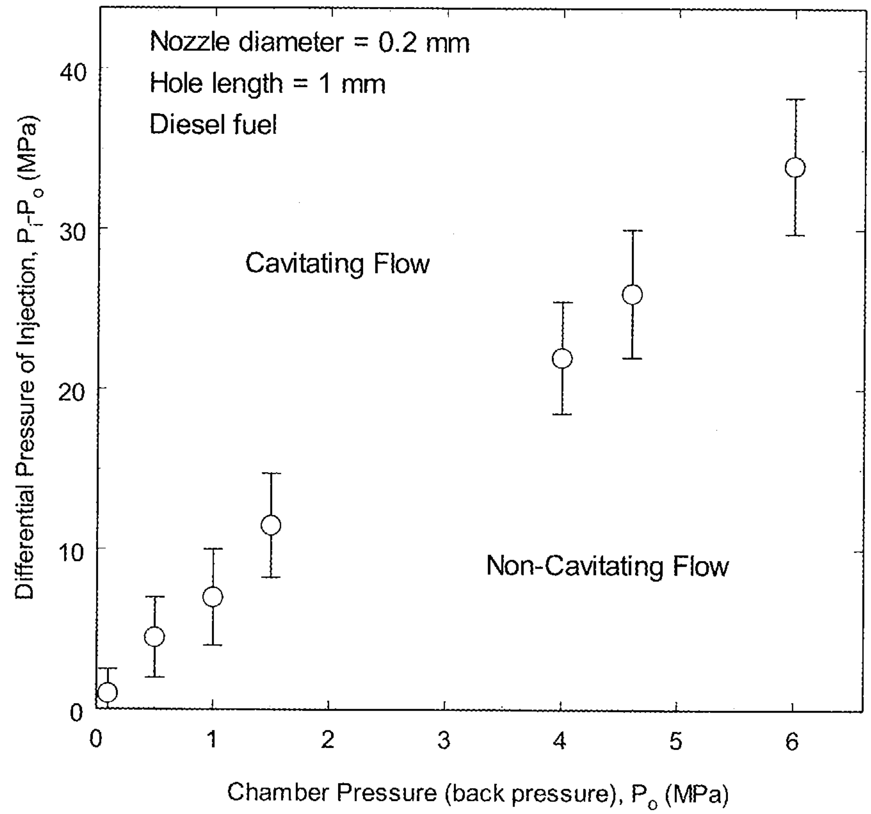

Fig. 13 Regimes of cavitating and noncavitating flows through the diesel nozzle holes for a typical hole geometry. (Adapted from [67].)

tling effect. For a steady spray this may produce unreasonable liquid velocities. However, for transient diesel sprays, the liquid is rapidly accelerating to high velocities and a steady mass flux analogy does not apply.

Instabilities. It is generally agreed that instability due to turbulence in the nozzle flow [86] is a contributing factor to jet breakup in diesel sprays. Since the jet breakup and atomization process is highly complicated and the physical description of the events are semi-qualitative at best, Huh et al. [82] argued that dimensional reasoning might provide the physical insight required for a realistic model. Their approach is to compare the order of magnitude of relevant forces acting on the fuel jet. As a result of this exercise for a typical diesel fuel jet, it was concluded that the surrounding gas inertia and liquid jet internal stress are the two dominant forces of comparable magnitude in the breakup process [82]. Based on this conclusion, they assumed that the initial perturbations on the liquid jet surface are induced by the jet internal turbulence that originates from the strong shear stress along the nozzle wall and possible cavitation effects. The exponential growth of these perturbations with time through Kelvin-Helmholtz instability leads to breakup and atomization. It was also concluded [82] that the internal turbulence is more effective in initiating surface perturbations than the wave growth mechanism.

Recognition that nozzle turbulence has been identified as a leading contributor to jet breakup is evidenced by models based on this concept [21]. In this approach, a characteristic turbulence time scale controls the breakup, and drop sizes are related to the turbulent length scales. One effect of modulation in injection pressure is to vary the velocity of fuel injection. This can produce a free internal stagnation point that moves along the spray axis, causing droplets to be ejected radially and forming mushroom-shaped parcels of fuel droplets [87]. This points to the need for detailed knowledge of the exit velocity to aid in interpretation of the dense core penetration.

The transient nature of diesel sprays has long been recognized as a contributing factor in the structure of diesel sprays [42]. Cook and Lin [88] demonstrated that nozzle pressure waveform effects have a great impact on the initial drop size distribution for moderate-pressure intermittent sprays. Temporal and spatial variation in the attenuation of light transmitted through dense sprays [4, 57], and the clustering of droplets [4, 87], are influenced by variations in the exit velocity due to nozzle pressure fluctuations. An example of simultaneous tomographic imaging and attenuation measurements illustrating these effects is shown in Fig. 14.

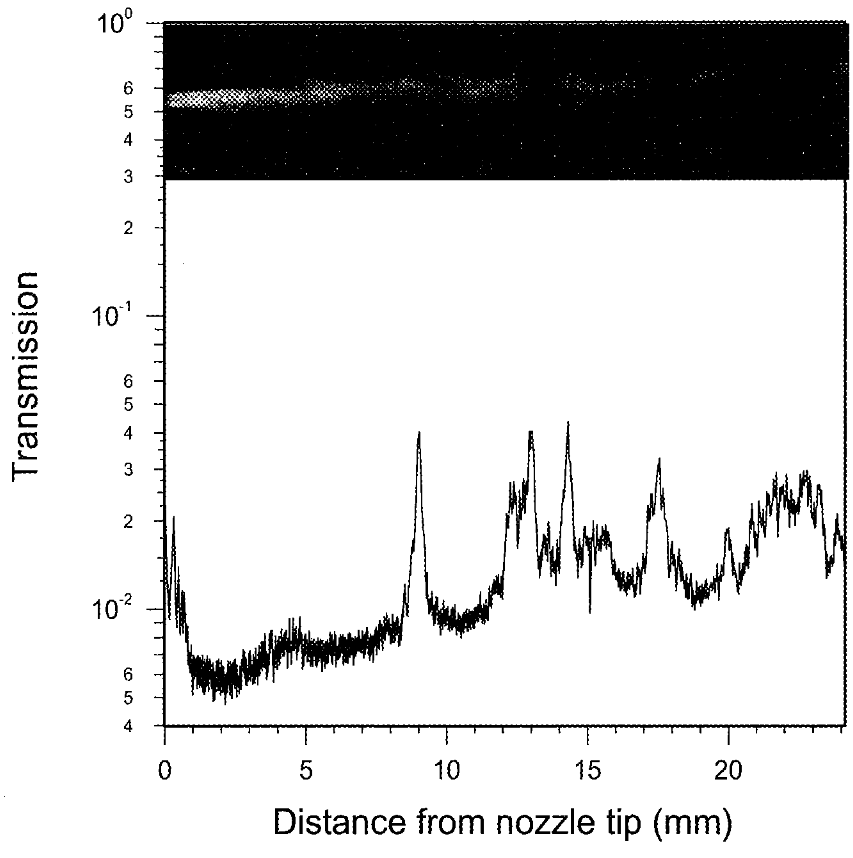

Fig. 14 Simultaneous low-intensity Mie scattering tomography and line-of-sight laser beam transmission through the spray plume, for a diesel spray injecting into atmospheric conditions. (From [4].)

Liquid Spray Penetration Distance

Liquid fuel penetration has been one of the most studied features of diesel sprays. This is because although adequate penetration is required to ensure sufficient fuel/air mixing, over-penetration can lead to wall wetting and subsequent undesirable emissions. The penetration distance is thus a significant parameter in engine design, and knowledge of the penetration distance is commonly used to evaluate the performance of multidimensional simulations of internal engine processes. As wall wetting is generally accepted as an undesirable feature in modern diesel engines with high-pressure injection systems, discussion of the structure of impinging diesel sprays is left to Senda et al. [89] (and references therein).

Much of the research to determine the liquid spray penetration distance was performed in optically accessed diesel engines or rapid compression machines, as detailed by Zhang et al. [90] (and references therein). Recently, the emphasis has switched to measurements performed in multiple-windowed combustion bombs, capable of an extensive range of ambient density and temperature conditions and gas compositions [40, 46, 49]. These bombs provide excellent optical access so that a wide range of optical diagnostics may be performed. In addition, the parameters may be varied one at a time, and they may be extrapolated beyond the conditions available with a single optical engine, so that the effects of each parameter may be ascertained independently.

Results show [40, 46, 90] that the one parameter affecting liquid spray penetration distance that can be controlled by the injector is the orifice diameter, Table 1. As the nozzle hole size decreases, the liquid spray penetration distance decreases linearly, approaching zero as the orifice approaches zero diameter, as shown in Fig. 15. The other injection parameters, the injection pressure and the aspect ratio (orifice length/diameter), have no effect on

Table 1 Parameters Affecting Liquid Spray Penetration Distance

System	Variable	Input	Effect on liquid spray penetration distance, L	Ref.
Injector	Orifice diameter	⇓	Strong decrease	90
			Linear decrease	40
			Strong decrease	46
	Injection pressure	⇑	No significant effect, time to L_{max} reduced	90
			No significant effect	40
			Weak increase	46
	Nozzle aspect ratio	⇑	No significant effect	40
Engine	Ambient density	⇑	Strong decrease	90
			Strong decrease initially, reduced sensitivity as density increases	40
			Strong decrease	46
	Ambient temperature	⇑	Strong decrease	90
			Strong decrease initially, reduced sensitivity as temperature increases	40
			Strong decrease	46
Fuel	Fuel type		Distance increases as volatility decreases	40
			Can have significant effects	46
	Fuel temperature	⇑	Linear decrease	40

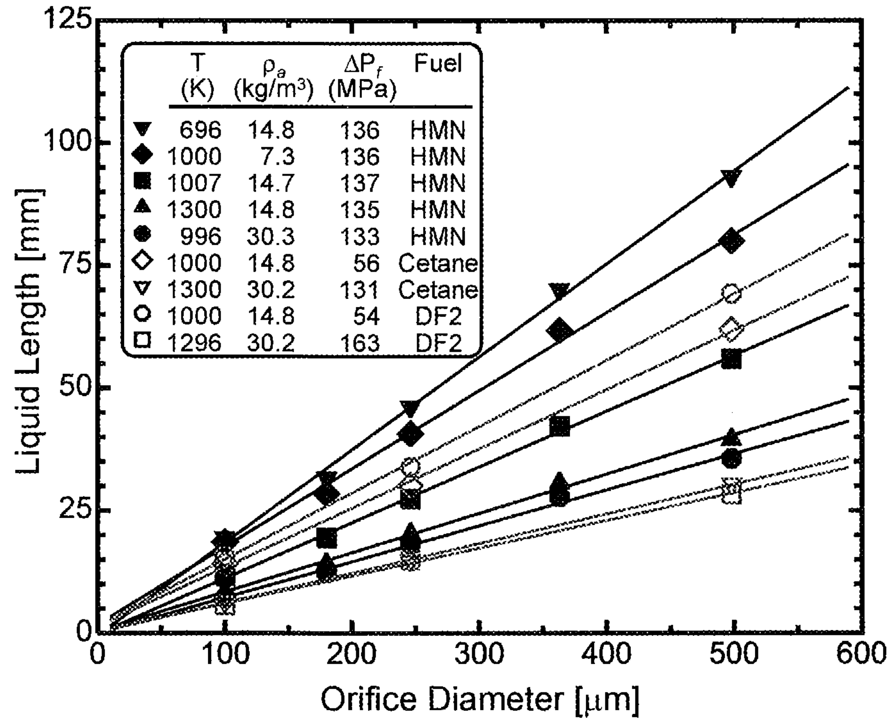

Fig. 15 Liquid spray penetration distance versus orifice diameter for various ambient gas temperatures (T), ambient densities (ρ_a), injection pressure differentials (ΔP_f), and fuels. (From [40].)

the liquid spray penetration distance over a wide range of engine-like conditions. It is important to note that higher injection pressures do result in the maximum liquid spray penetration distance being achieved more rapidly, which will affect the mixing, ignition, and combustion of the fuel. The ambient gas density and temperature, representing engine operating conditions, both cause the liquid spray penetration distance to decrease as they are increased. However, the sensitivity of the spray penetration distance to temperature and, more so, density, is diminished as they are increased. Results from Siebers [91] (and references therein) show that varying fuel composition has an effect on liquid spray penetration distance. As the fuel volatility is decreased, the liquid spray penetration distance is increased. Increasing the fuel temperature decreases the liquid spray penetration distance slightly, more significantly at lower ambient densities and temperatures.

Thus, for a given fuel and set of engine operating conditions, the only parameter (of those investigated) available to control liquid spray penetration distance is the orifice diameter. The apparent increase in liquid spray penetration distance with decreasing fuel volatility may cause wall wetting in the piston bowl, which may cause increased emissions. More comprehensive work is required to study the effect of fuel composition on liquid spray penetration distance, particularly with multicomponent diesel fuels. Furthermore, little is known about the effects of new injection strategies, such as split injection and multiple injections, on the liquid spray penetration distance.

Droplet Size

The temporal and spatial droplet size distributions in dense diesel sprays are strongly dependent on the breakup mechanism, which itself depends primarily on the diameter of the nozzle and the velocity of the jet, which in turn is a function of the transient pressure profile. As with other aspects of diesel sprays, it is difficult to make broad statements about the nature of drop size distributions due to the potential range of experimental conditions. Nevertheless, it has been shown by Su and Farrell [17] (and references therein) that both increasing the injection pressure and reducing the nozzle hole size reduce the SMD droplet size. Injection pressure has been shown to be the determining factor for final droplet size, regardless of the nozzle inlet geometry (rounded inlet versus sharp-edged inlet) [92]. Also, once the spray has developed, the mean drop size exhibits little variation over time [9, 17].

The commonly held view, based on the concept of an intact core and subsequent aerodynamic breakup, is that the larger drops are at the centerline and the smaller drops are at the diesel spray periphery. However, some of the recent experimental findings reported in the literature indicate that the reverse is true [9, 51, 73, 93], for nonevaporating sprays, as shown in Fig. 16. The mean drop sizes show a statistically significant increase as the measurement location moves from the centerline toward the spray periphery. This observation was first reported for a diesel spray injected into an atmospheric-pressure environment [94]. One explanation for this is that the large droplets are centrifuged to the periphery of the spray

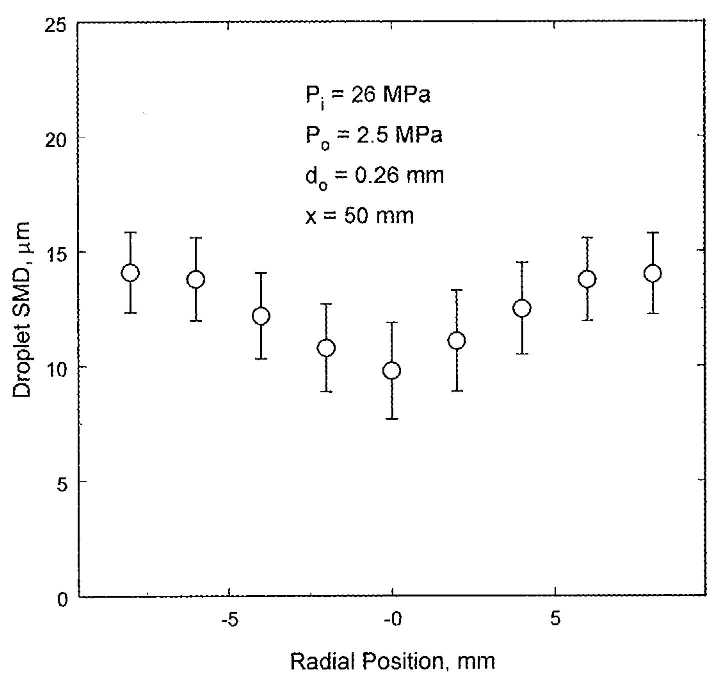

Fig. 16 Radially resolved SMD at 50 mm downstream of the nozzle tip, 1 ms after the start of injection. Experimental conditions: nozzle diameter 0.26 mm; maximum injection pressure 26 MPa; backpressure 2.5 MPa. (From [6].)

by the motion of the large-scale vortices at the tip [73]. Even though these results are for nonevaporating sprays, there is clear indication that aerodynamic breakup is not a dominant mechanism. Thus, for evaporating sprays, one would expect that the radial drop size distribution would become a balance between the nonevaporating breakup (large droplets on the periphery) and evaporation (small droplets on the periphery).

With the emergence of flow separation/cavitation as a dominant spray breakup mechanism, it is likely that the internal nozzle geometry has an impact on the droplet size similar in magnitude to the effects of the injection pressure and orifice diameter. However, details of the internal nozzle geometry are numerous, and more difficult to quantify than easily measured parameters such as the injection pressure and orifice diameter.

DISCUSSION

Advances in measurement techniques and changes in diesel engine technology have brought us to a point where it has been openly stated that in current diesel engines "the liquid fuel does not consist of a liquid core but rather of disintegrated droplets right from the very beginning of fuel injection." [7]. Although debate about the intact liquid core appears to have come to an end, there is still much to be learned about the breakup mechanisms and structure of diesel sprays, and their impact on diesel combustion. Significant research effort is being conducted to achieve greater knowledge about the structure, drop size, drop velocity, nozzle flows, and development of physics-based models. In order to maximize the benefits to the community [19], each publication must identify the limits of applicability for the results to prevent extrapolation. There are many variables in diesel fuel injection and combustion, and results often apply to a limited set of circumstances. Parameters that should routinely be reported are summarized in Table 2. Similarly, care must be taken with termi-

Table 2 Parameters of Significance to Diesel Spray Measurements

System	Parameter
Injector geometry	Orifice diameter
	Orifice length
	Orifice inlet geometry
	Number of holes
	Tip geometry (mini-sac, VCO, etc.)
Injector performance	Injection pressure profile
	Injection rate profile
	Injection duration
	Quantity/mass of fuel injected
Ambient conditions	Temperature
	Density
	Pressure
	Gas composition
Fuel properties	Temperature
	Density
	Viscosity
	Surface tension
	Composition

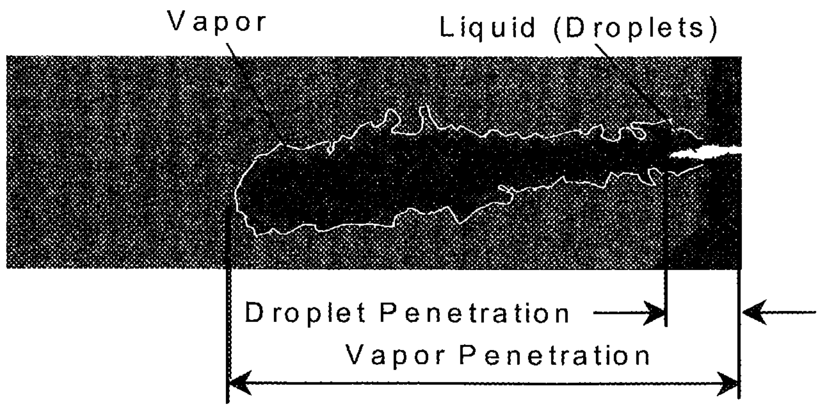

Fig. 17 Single-shot Mie scattering image of diesel plume superimposed on simultaneous schlieren image, identifying the instantaneous vapor phase penetration with the dark region. (From [7].)

nology to avoid confusion. Many definitions of the terms breakup, intact core, dense core, liquid jet, and even spray are scattered throughout the literature.

Higgins et al. [1] illustrate the need for careful consideration of experimental design, where multiple-plume spray data actually mask the pressure rise during the premixed burn phase of diesel combustion, and single-plume data provide a more realistic assessment of actual conditions. Similarly, in observing data for dense diesel sprays, one should consider the impact of making multipulse average measurements versus individual single-shot measurements. The effects of droplet clustering and local temporal and spatial variations in the spray are lost in multipulse averages, yet the subtleties and nuances of these effects may have dramatic effects on diesel combustion and emissions. An example of a single-pulse Mie/schlieren image is shown in Fig. 17, which can be contrasted with the multipulse average shown in Fig. 2.

Table 3 Suitable Applications for Imaging Diagnostics in Dense Sprays

Technique	Recommended applications[a]
Shadowgraph	Spray penetration Liquid and/or vapor cone angle
Schlieren	Liquid and/or vapor cone angle
Mie scattering (high intensity)	Spray penetration Liquid cone angle
Mie scattering (low intensity)	Internal structure
Laser-induced fluorescence	Internal structure
Exciplex fluorescence	Location of liquid and vapor phases
Ballistic/snake photon imaging Combined Mie/LIF drop sizing Other emerging techniques	Not yet recommended for diesel sprays

[a] With appropriate care to details and assumptions.

Experiments must be designed to suit the objectives of the research. Appropriate uses of some of the imaging techniques are summarized in Table 3. Care must be taken to understand the capabilities and limitations of each technique, and to address the fundamental assumptions associated with each method. Ideally, experiments should be conducted over a range of conditions that span those encountered in engines.

Modeling efforts should concentrate on providing physical submodels of the internal nozzle flow, leading to in- or near-nozzle primary breakup mechanisms. This should provide characteristic droplet size and velocity as they exit the nozzle, and place less emphasis on the secondary breakup mechanisms. In turn, the improved models should lead to more accurate predictions for fuel/air mixing, and the subsequent processes of ignition, combustion, and emissions formation. New modeling approaches, such as molecular dynamics direct numerical simulation of the atomization process [95], may prove useful in the future as knowledge of the details of the primary breakup mechanisms become available.

CONCLUSIONS

A detailed examination of the history and current understanding of the structure of the dense core region in transient diesel sprays has been presented. Improvements in the diagnostic techniques coinciding with changes in the diesel injector technology have brought about an entirely different concept of the breakup of liquid in current diesel sprays.

Diagnostic methods for dense sprays have been reviewed, and the appropriate uses of each have been discussed. Of the techniques currently available, tomography of laser-induced fluorescence or low-intensity Mie scattering are the most appropriate for determining the structure of the dense core region. Conductivity is not recommended because it requires a fluid substantially different from diesel fuel. Line-of-sight techniques are recommended only for studying the periphery of the spray, such as for determining penetration. Due to its greater contrast, high-intensity Mie scattering is preferred over line-of-sight methods for liquid spray penetration distance measurements. The most pressing need is for a capability to make drop size and velocity measurements in the near-nozzle region. Advances in phase-Doppler interferometry may provide both, and multiwavelength infrared attenuation has been shown to provide drop sizes. The careful use of a skimmer has been shown to provide reliable uncompromised results where its use is required.

A review of the spray structure and breakup mechanisms has been presented. The structure of the spray has been shown to be completely atomized at or near the nozzle tip, with nozzle cavitation and turbulence-driven instabilities as the dominant breakup mechanisms. Buckling may be responsible for breakup during the very early phase of injection. Aerodynamic shear may cause some secondary atomization, but its role in breakup is far less significant than previously thought. The influence of cavitation on jet breakup is twofold. First, the bursting and collapsing vapor cavities contribute to the disintegration of liquid masses at the exit of the nozzle hole, resulting in a mixture of bubbles and liquid occupying most of the cross-sectional area. Second, cavitation increases the turbulence intensity of the flow through the nozzle hole, thus contributing to the instability of the liquid jet. The instability, along with pressure fluctuations in the nozzle, cause variation in the exit velocity of the droplets, resulting in temporal and spatial clustering of the droplets in the plume.

The results of recent research on the liquid spray penetration distance and drop size have been summarized. For liquid spray penetration distance, the orifice diameter is the dominant injection parameter, and ambient density is the dominant engine parameter, although ambient temperature is also significant. Fuel properties have been shown to have an effect on the liquid spray penetration distance, but further research is required to draw significant conclusions. For drop size, the injection pressure and orifice diameter are the known dominant parameters.

The evidence for complete atomization of diesel sprays near the nozzle has come from a variety of sources, including tomographic imaging of the internal structure, microphotography of the near-nozzle region, diffraction droplet sizes that are greater on the periphery than the centerline, infrared multiwavelength extinction droplet sizing, and internal flow studies.

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