TOPICAL REVIEW

Spray measurement technology: a review

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1. Introduction

Few areas of fluid mechanics are more challenging—or of greater practical importance—than sprays, which are encountered virtually everywhere in modern life. A short list of examples includes automobiles and aircraft (fuel injection); agriculture (pesticides and herbicides); pharmaceuticals (oral and nasal sprays); manufacturing (painting, spray drying); food processing (spray freezing); and cosmetics (hair spray, perfume). Associated with this wide range of applications is wide variation in the fluids being sprayed (e.g. non-Newtonian fluids or suspensions such as paint versus relatively volatile and low-viscosity but multi-component liquids such as fuels) and in the ambient environment (e.g. open air, nasal passages, or high-pressure, high-temperature gas in a combustion chamber). Sprays may be highly transient (e.g. durations of a few milliseconds or less in automotive fuel injection) or comparatively steady (e.g. agriculture). In many applications, the interaction of the spray with a surface is important. For example, in agriculture, pharmaceuticals and painting, the spray must deliver liquid to a surface with desired coverage, and vaporization en route to the surface must be minimized. In combustion, however, spray drop size, velocity and other characteristics must be tailored to provide the desired spray penetration and fuel-air mixing while avoiding liquid films on combustion chamber surfaces, which can cause surface deposits or undesirable exhaust emissions (soot or unburned hydrocarbons).

Precision and repeatability are essential to many spray systems and may need to be maintained over huge numbers of spray events and over many years of operation. An automobile engine, for example, can easily inject fuel ~50 million times per year. Each injection must lead to successful ignition and combustion. To steal a memorable phrase, the consequences of spray problems in combustion-driven transportation can range from nuisance (e.g. automobile-engine misfires) to catastrophe (e.g. lean flame blowout with failure to reignite in jet aircraft) [1].
Challenges to experimental characterization of sprays will be touched on in greater detail below, but for now we note a few key issues. First, sprays are intrinsically stochastic in character from their very formation since atomization results from instabilities of a liquid column or liquid sheet. Turbulence or cavitation within the injector or near the nozzle also contributes to stochastic behavior. Furthermore, sprays often induce turbulent flow or are injected into a turbulent ambient fluid. Second, physically complex phenomena are involved in atomization itself (e.g. primary atomization through liquid column or sheet instability producing ligaments and droplets); in the downstream evolution of the spray (e.g. secondary atomization, droplet collision and coalescence, gas–liquid heat and mass transfer, multicomponent-liquid vaporization); and in spray-wall interactions (e.g. droplet adhesion, rebound or breakup upon impact; liquid film formation and evaporation; atomization from pre-existing film). Third, the high droplet number density can greatly complicate experimental measurements, especially near the nozzle, leading, for example, to intense multiple scattering of light that obscures interior details [2–4].

**Predictive spray modeling** confronts these complex challenges. Not only are the key physical processes complex and difficult to model, but the experimental difficulties have led to a lack of sufficiently complete data on which to base the necessary fundamental understanding [2, 5]. Fundamental numerical simulations must deal with a dynamic range of temporal and spatial scales ~10^5. Powerful computational tools such as direct numerical simulation (DNS) [5, 6] and large-eddy simulation (LES) [5, 7] are making progress, but there remain significant issues with respect to spatial resolution, numerical stability and convergence, as well as physical issues such as the treatment of instabilities, not to mention actually verifying the accuracy of the solution [5]. Furthermore, DNS and high-resolution scientific (as opposed to engineering) LES are too demanding computationally for practical applications [5, 8]. Current spray engineering simulations mostly employ semi-empirical Reynolds-averaged Navier–Stokes (RANS) frameworks that omit details of internal flow within the atomizer and near-nozzle breakup. The resulting models have ‘constants’ that need to be “calibrated” or tuned extensively by experiment [2, 4, 5, 9, 10]. Sadly, we remain even more limited in our ability to prescribe the spray characteristics required to produce a desired end result (e.g. a given fuel–air distribution in an engine without wetting surfaces), much less to design a priori the spray equipment to achieve those characteristics [2, 9].

This review surveys needs, challenges, major trends, and progress in spray measurement technology, concentrating on developments since the publication of Bachalo’s excellent review [2] in 2000. We also examine many entry points to the vast literature through tabular summaries of key spray phenomena and associated measurement techniques. By reviewing a wide variety of techniques at a conceptual level rather than in depth, we offer an introductory guide to readers who may be new to spray research while also providing more experienced researchers to ideas from areas beyond their own spray applications. Our own research leads us to select examples primarily from high-pressure automotive fuel sprays, but the needs, trends, challenges and techniques surveyed here span a wide range of spray conditions and applications.

The paper is organized as follows. Following a brief description of the principal spray regions in section 2, section 3 surveys the more prominent measurement techniques. With this background, specific measurement needs, challenges and applicable techniques for each of the spray regions are tabulated and discussed in section 4. Section 5 offers our perspective on progress and prospects.

### 2. The principal spray regions—a quick tour

Moving from upstream to downstream, Figures 1–3 illustrate the four principal spray regions. More detailed discussion of the specific features of these figures, the associated measurement techniques, and the spray regions themselves will follow in sections 3 and 4.

Figures 1(a) and (b) show examples of high-speed imaging and quantitative measurement of the upstream internal nozzle flow region in a transparent real-scale diesel injector in which cavitation occurs, while figure 1(c) includes a shadowgraph image of the resulting optically dense near-nozzle (near-field) spray-formation region [11].

Figure 2 (left) shows a photograph of a diesel fuel spray obtained with flash-lamp (white-light) illumination, a relatively straightforward and inexpensive technique to visualize sprays and to obtain large-scale spray parameters such as the spray cone angle and the axial and radial spray penetration versus time. The labels indicate, roughly, the near-nozzle (near-field) spray-formation region and the far-field developed-spray region. Figure 2 (right), which is for a low-pressure water spray, shows the much greater near-field detail that can be resolved by suppressing multiply scattered light using a state-of-the-art technique [structured laser illumination planar imaging (SLII)] [12]; see section 4.2.4.

The highly complex spray-formation region, as in figure 2 (right), typically includes a liquid sheet or column that emerges from the nozzle and undergoes primary breakup into relatively large non-spherical flow structures (ligaments, non-spherical droplets) which subsequently undergo secondary breakup into smaller spherical droplets. Breakup occurs through a variety of instability mechanisms (e.g. surface waves, shear) and is also affected by the internal nozzle flow (e.g. cavitation as in figure 1).

The final state in many spray applications takes place in the spray-wall interaction region. As illustrated in figure 3, this interaction often forms a liquid film on the surface. Note the substantial density of the spray as it impinges on the wall in the instantaneous planar Mie-scattering image of the direct-injection gasoline spray in figure 3(a); this example is clearly not a case of isolated droplet impacts. The quantitative refractive-index-matching (RIM) images in figures 3(b) and (c) show that the liquid film in the elevated temperature and pressure of a running engine (figure 3(c)) [13] is much thinner than for injection at room temperature and atmospheric pressure (figure 3(b)).
Spray terminology in the literature is not entirely consistent. In this review, we use the terms ‘near-nozzle’, ‘near-field’ and ‘spray-formation region’ interchangeably; likewise we treat ‘far-field’ and ‘developed spray’ as synonyms. The near-field spray-formation region has often been called the dense spray, in contrast to the far-field dilute spray. Unfortunately, there is little agreement on the definition of a dense spray [4]. Operationally, whether the spray is dense or dilute depends on the quantity to be measured and the technique to be used. For example, at a considerable distance from the nozzle, a spray may be too dense optically for sharp imaging of individual droplets, whereas another technique like phase-Doppler interferometry (section 3.2) may yield droplet size and velocity data successfully. For the moment, we note only that the spray-formation region is often optically dense, and postpone further discussion until we consider near-field measurement needs and techniques in section 4.2.

### 3. Prominent spray measurement techniques

Before enumerating measurement needs, challenges and associated techniques for each of the four spray regions (which we will do in section 4), we first note recent trends and then describe at a conceptual level the more prominent measurement techniques themselves.

Several trends in spray measurement technology have emerged over the last few decades. A principal driver of these trends has been the need for more detailed understanding of spray physics in order to develop more predictive spray models. Experimentally, these trends have been enabled largely by advances in lasers, digital cameras, electronics and computers. The references in the list of trends here point the reader to related review papers:

- From macroscopic (e.g. spray pattern, penetration [14], rate of injection) to microscopic measurements [2, 5, 15]
- From qualitative to quantitative characterization (e.g. droplet size and velocity; vapor-phase concentration) [2, 5, 15, 16]
- From single-point to planar to 3D volume measurements
- From single-shot to high-speed imaging [1, 17, 18]
- From far-field/dilute-spray to near-field/dense-spray and in-nozzle measurements [3, 4, 19].

#### 3.1 Macroscopic spray characteristics

Traditional spray testing has focused largely on macroscopic characteristics, viz., spray visualization, penetration (axial and radial) [14, 20], cone angle, mass flow rate (rate of injection) [21–25], patternation (mass distribution across a plane downstream from the nozzle) [15, 26], and momentum flux [27]. Optical imaging has been used for a century and continues to be used with volume illumination [28], back-illumination [20, 29], shadowgraph and schlieren [30] techniques. These approaches, now using digital cameras, are still prominent.
The advent of powerful pulsed lasers (especially Nd:YAG and copper vapor) has led to many applications of planar Mie scattering using laser sheets for 2D spray visualization [1, 2, 15, 17, 31–33]. Pickett et al address uncertainty in several techniques to measure macroscopic spray penetration [14], concentrating on vaporizing sprays. Optical patternation systems using planar extinction tomography [34] or planar laser Mie scattering combined with laser-induced fluorescence (LIF) [2, 15, 35–38] (section 3.3.3) are now commercially available and have largely replaced the older technique of collecting liquid in an array of small tubes [15, 26].

Coincident with the trend toward optical measurements of sprays has been a trend from macroscopic toward microscopic characteristics, e.g. droplet size, velocity, number density or volume flux, temperature, etc. Tropea [16] surveys a variety of diagnostics primarily at the microscopic single particle/droplet level, although he also touches on LIF and related techniques that are usually employed for planar measurements using laser-sheet excitation, as discussed briefly below (sections 3.3.2–3.3.6).

3.2 Phase Doppler interferometry

Widely recognized as a major step forward in quantitative spray measurements, phase Doppler interferometry (PDI) (also called phase Doppler anemometry) was developed in the 1980s to measure droplet size and velocity simultaneously [2, 39–42]. Like laser-Doppler velocimetry (LDV), PDI relies on light scattered from two intersecting, coherent laser beams. The scattered light interferes at three detectors placed at carefully designed locations to generate sinusoidal Doppler burst signals whose frequency is proportional to droplet velocity and whose phase (for spherical scatterers) is related by Mie-scattering theory to droplet diameter. After extensive refinement, PDI has become the established pointwise measurement technique for droplet size, velocity and volume flux at rates up to tens of thousands of measurements per second [2, 16, 43], and commercial instruments are available. See [2, 16] for compact reviews and [43] for a full book.

3.3 Planar and volume spray measurements

Mapping a spray using a series of point measurements is time-consuming and cannot give an instantaneous 2D or 3D representation, so it is not surprising to see a trend from single-point toward planar and volume measurement techniques. Reviews of combustion diagnostics with substantial material on planar and volume techniques for sprays include [15, 31, 44]. Non-linear techniques based on wave mixing using high-intensity lasers are reviewed in [45].

3.3.1 Line-of-sight measurements

Line-of-sight imaging, as mentioned above, has been used for many years. With back-illumination, the image represents total extinction (light deflected due to elastic scattering plus light absorbed). Shadowgraph and schlieren imaging respond to refractive-index
changes along the line of sight and therefore are sensitive not only to extinction but also to local temperature and concentration variations. These parameters usually cannot be extracted quantitatively, although with simultaneously recorded Mie-scattering data to mark the liquid, one can determine liquid- and vapor-phase envelopes from schlieren images [46, 47]. The laser absorption and scattering (LAS) technique measures line-of-sight-integrated liquid and vapor mass distributions using back-illumination imaging at two laser wavelengths, only one of which is absorbed appreciably [48–50]. With the assumption of axisymmetry or with images taken from several angles (typically ~10 or more), tomographic inversion of line-of-sight images can yield a 3D representation of the measured quantity. Optical-imaging examples include [34, 51, 52]. X-ray-absorption tomography has been used for 3D imaging of sprays [53, 54] and cavitating internal flow [55, 56].

The ability to measure droplet size throughout an extended region is highly desirable. For many years, forward-diffraction-based sizing has provided droplet-size measurements that are averaged over an ensemble of droplets along a line of sight and over the laser beam width (typically several millimeters or more for this approach) [2, 57, 58]. Diffraction-based sizing—also known as laser-diffraction, Fraunhofer diffraction, small-angle light scattering and ensemble light scattering—is convenient, can provide time-resolved data, and is commercially available. Although the technique was originally based on the Fraunhofer approximation, the full Mie-scattering theory for small-angle scattering is now used. Experimental realizations of the technique often employ a set of concentric ring detectors, but beam steering by refractive index gradients limitations of this arrangement to isothermal situations (basically, cold flows) and non-vaporizing sprays [5]. Appropriately imaging and analyzing the forward-diffracted light can circumvent this problem [59].

3.3.2. Planar velocity measurements. Particle image velocimetry (PIV) is a now-standard technique in experimental fluid mechanics [60, 61] that has been adopted for planar measurements of droplet velocity fields in sprays [1, 2, 62–64]. In the most common approach, two laser-sheet images, closely separated in time, are recorded. The full image area is divided into a grid of small interrogation windows (16–64 pixels square, typically), each containing ideally ~10–20 droplet images. Cross-correlating the droplet-image intensity distributions within the interrogation window between the two successive exposures yields the displacement of the droplet group and hence the local velocity within the interrogation window. Many algorithms to improve accuracy and reject spurious velocity vectors are now available in commercial PIV software.

For situations that are sufficiently dilute that the same droplet or tracer particle can be identified in two or more successive images, the subset of PIV called particle tracking velocimetry (PTV) is possible. PTV can sometimes provide a closer approach to a solid surface or to a flame front than PIV.

To measure gas-phase velocity in the presence of spray droplets with PIV, it is necessary to seed the gas with particles whose scattering can be distinguished from that of the droplets. One approach is to rely on scattered-light intensity, assuming that the gas-phase seed particles are much smaller than the droplets [65]. The other principal approach is to distinguish the two phases based on the different wavelengths of elastically scattered and fluorescent light. Either the liquid phase is doped with a fluorescent dye while elastic scattering is detected from seed particles in the gas phase [66, 67], or, taking the opposite approach, Mie scattering marks the liquid droplets while the gas phase is seeded with fluorescent particles [68–71].

Figure 3. Instantaneous false-color images of spray-wall interactions. (a) Planar Mie-scattering image of an iso-octane fuel spray from a pressure-swirl injector impinging onto a flat plate at atmospheric pressure and room temperature. The injector is 35 mm above the plate and at an angle of 45°. The laser sheet, which is incident from the right, is attenuated as it crosses the spray. Time after start of injection: 2 ms. (b) Bottom view of the liquid fuel film measured by refractive-index-matching (RIM) imaging at 5 ms after start of injection in a separate experiment under the same conditions. (c) High-speed RIM images of the evaporation of a liquid gasoline film deposited by a similar pressure-swirl injector on the piston of a wall-guided stratified-charge spark-ignition engine running at 2000 RPM engine speed [13]. The images are excerpts from one engine cycle recorded at 4500 frames s−1. The edge of the wetted region is outlined in red. The spray enters from the bottom of the field of view in (c). Time is given in terms of crankshaft angular position after the top-dead-center (ATDC) piston position.
imaging to measure the third velocity component [65, 70] and to high-speed PIV in order to follow the evolution of spray structures quasi-continuously in time [1, 71–74]. PTV at ultra-high-speed (500kHz) using digital holography has been demonstrated in a supersonic jet laden with ~100µm solid particles [75].

Doppler global velocimetry (DGV) is a laser-sheet variation of LDV which passes the light scattered by droplets or tracer particles through a molecular (e.g. iodine) absorption cell. The narrow absorption band and the laser wavelength are selected (and possibly tuned) so that the Doppler shift corresponding to the velocity range of interest is on one side of the absorption profile where the transmitted intensity varies rapidly with frequency (wavelength). Calibration converts the transmitted light intensity into a map of one velocity component. Precise laser wavelength stabilization and a reference image are required. Instantaneous two- and three-velocity component measurements are possible with multiple light sheets and cameras, although more commonly this complicated technique is implemented for average measurements in steady flows. Advantages of DGV include reduced sensitivity to beam steering (refractive-index variations) and the capability to measure high velocities (hundreds of m/s). DGV has seen limited application to sprays [76, 77].

Without particle seeding, gas-phase velocity fields in sprays have been measured using a technique sometimes called gaseous-image velocimetry (GIV) which combines double-exposure LIF (section 3.3.3) and PIV-like (“optical-flow”) analysis with NO as the fluorescent tracer [78]. Single-laser-pulse techniques for droplet and gas-phase velocity fields, known as laser flow tagging (LFT) [79] or molecular tagging velocimetry (MTV) [80], involve seeding the liquid or gas with an appropriate phosphorescent tracer. A short-pulse laser ‘writes’ a line or grid pattern into the dispersion of phosphorescent molecules. The velocity of the tracer-seeded phase is evaluated from images of the relatively long-lived phosphorescing line or grid as it is distorted by the flow field. A double-pulse version of LFT/MTV instead uses a fluorescent tracer; a second laser pulse generates LIF from the molecules excited or tagged by the first pulse [81]. LFT/MTV can have advantages in dense sprays and is relatively insensitive to beam steering compared to PDI and PIV. Simultaneous droplet and gas velocity measurements have been demonstrated near the nozzle of a diesel spray using LFT with spectrally distinguishable phosphorescent tracers [79, 82].

3.3.3. Planar laser-induced fluorescence. A very powerful and widely adopted technique both for spray visualization and for more quantitative measurements is planar laser-induced fluorescence (PLIF) [2, 15, 16, 83], in which molecules that have absorbed laser light emit fluorescence (usually) at a long wavelength. Such a tracer species may be naturally present (e.g. aromatic hydrocarbons in fuels) [33, 84] or may be added to a non-fluorescing base liquid (e.g. an organic dye such as rhodamine in an alcohol spray or a ketone tracer in a reference fuel such as iso-octane) [83]. Ideally, LIF from the liquid phase is proportional to the number of fluorescing molecules and therefore to droplet volume, so that quantitative measurements of liquid volume or mass distribution are possible. Quantitative LIF measurements require calibration as well as corrections for background, laser-sheet non-uniformity, shot-to-shot variation in laser pulse energy, and non-uniform camera response [83, 85, 86], as well as for the effects of absorption and scattering (section 4.2.3).

Naturally occurring and tracer LIF species usually have relatively broad absorption and emission spectra, so that fixed-wavelength rather than tunable lasers can be used, but the absorption and emission spectra are generally temperature-dependent. This dependence is an issue for non-isothermal situations, but it also provides the basis for a number of schemes to measure liquid- or gas-phase temperature, typically involving the ratio of planar LIF images either at two excitation wavelengths or at two detection wavelengths [2, 16, 31, 83, 87–91], as discussed further in section 3.3.6.

Especially for combustion applications, knowledge of the concentration or mass distribution of the vapor phase is critical. Furthermore, vaporization remains one of the weaker areas of spray modeling, due in large part to a lack of quantitative data. Visualization and especially quantitative measurements of the vapor phase are challenging.

Fortunately, LIF provides relatively strong signals from the vapor as well as from the liquid phase. Unfortunately, oxygen quenches the fluorescence from many tracer species. Furthermore, the fluorescence absorption and emission spectra usually do not differ significantly between the phases [83], so discrimination between LIF from liquid and vapor is often difficult or impossible without additional measurements. One approach is to record simultaneous planar Mie-scattering as a liquid marker, permitting unambiguous vapor-phase imaging where droplets are not present [33].

For LIF measurements in vaporizing sprays, coevaporation of the tracer(s) and base liquid is important but not easily achieved or verified. Matching the boiling points of the tracer and base liquid is insufficient in most cases due to non-ideal solution effects [83, 92, 93]. LIF tracers for multicomponent fuels present particular challenges [83, 94–98].

Schulz and Sick [83] have comprehensively reviewed fuel-related LIF techniques, with special attention to fundamental aspects and to corrections for the effects of temperature, pressure and collision partners (quenching).

Other laser-based techniques that have seen more limited use in measuring liquid- and/or gas-phase mass distribution in sprays include Rayleigh and Raman scattering. Elastic light scattering from the gas (Rayleigh scattering) [99] is many orders of magnitude weaker than scattering from the liquid but is useful under carefully controlled conditions [44, 100, 101]. Inelastic Raman scattering can provide quantitative measurement of major species (e.g. fuel, oxygen, nitrogen) and temperature at a point or along a focused laser beam, but the signals are very weak [16, 102, 103]. Except for special cases such as alcohols, Raman scattering does not distinguish between liquid and vapor phases [104].

3.3.4. Laser-induced exciplex fluorescence. Melton’s exciplex variation on the LIF theme, which provides spectrally separated fluorescence from the liquid and vapor phases [105,
was a novel and significant advance for imaging and quantifying vaporizing sprays. The essence of the technique is to add two organic tracer species to a non-fluorescing base liquid. For example, fluorobenzene (FB) and diethylmethylamine (DEMA) in hexane are a coevaporative model fuel for the more volatile components of gasoline [83, 107]. Upon ultra-violet (UV) laser excitation, one species (e.g. FB*), called the monomer, emits fluorescence in the gas phase. In the liquid phase, however, the excited monomer (e.g. FB*) can combine with the other tracer (e.g. DEMA) in its ground state to form an excited-state complex—an exciplex, for short—which is bound only in the excited state and which has no stable ground state. Fluorescence from the exciplex is red-shifted due to the binding energy of the complex and hence can be distinguished from the monomer (e.g. FB*) fluorescence. The concentrations of the exciplex-forming tracers must be adjusted so that essentially all the excited species bind in the liquid phase and none bind in the gas phase.

Laser-induced exciplex fluorescence (LIEF) has been used successfully for both visualization [107–109] and quantitative measurements with both diesel-like (TMPD-naphthalene [110–117]) and gasoline-like (FB-DEMA [87, 118–122]; TEA-benzene [120, 123]) tracer-fuel mixtures. One complication is that the broadband exciplex fluorescence from the liquid usually overlaps some or all of the vapor fluorescence band. This liquid-vapor crosstalk causes liquid signal (which is usually orders of magnitude more intense due to the greater liquid density) to masquerade as vapor. Crosstalk and the difficulty of liquid-phase exciplex calibration have often rendered vapor-phase LIEF measurements difficult or impossible in regions where vapor and liquid coexist [114, 115].

As with garden-variety LIF, the spectroscopic properties of the tracers and the exciplex (and therefore the crosstalk) depend on temperature (which may vary locally due to evaporative cooling). Quantitative LIEF measurements therefore require not only calibration of both phases as a function of temperature, but also correction for the temperature-dependent crosstalk. Direct liquid-phase calibration is particularly difficult. Figure 4 illustrates a successful approach [119] based on thorough characterization of the temperature-dependent spectroscopy of the FB-DEMA-hexane exciplex system [93]. Specifically, knowledge of the crosstalk and of the relative quantum yields of the exciplex and FB fluorescence as a function of temperature allowed a room-temperature vapor-phase calibration to provide quantitative data for both phases at various ambient-gas temperatures, including regions of coexisting liquid and vapor. Another successful approach—performed in an IC engine, no less—was to correct for crosstalk using the liquid-phase temperature evaluated from exciplex fluorescence at two wavelengths [87]. (See section 3.3.6 for more on two-wavelength LIF thermometry.)

3.3.5 Planar dropsizing. Planar dropsizing (PDS), also called laser-sheet dropsizing (LSD), uses the ratio of a planar LIF image (ideally proportional to total droplet volume, i.e. \( d^3 \)) to a planar Mie-scattering image (ideally proportional to total droplet surface area, i.e. \( d^2 \) for droplets whose diameter is a few \( \mu \text{m} \) or larger) [35, 36, 124–126]. Averaged over a large number of droplets, the ratio yields \( D_{32} = \langle d^3 / d^2 \rangle \), the Sauter mean diameter (SMD).

Although PDS is appealingly simple in concept and attractive in potential capability, the real situation is much more complex than the ideal due to optical absorption, non-linear LIF response (saturation), multiple scattering, vaporization, and the need for calibration (usually with PDI) [127–136]. As discussed further in sections 4.2.3 and 4.2.4, multiple scattering can bias PDS results even for relatively dilute sprays.
signals proportional to $d_{sc}$ scattering from the liquid phase instead of LIF to generate illustrated in figure 5. Planar dropsizing has also been demonstrated using Raman scattering from the liquid phase instead of LIF to generate signals proportional to $d_{sc}^2$ [137]. This approach can eliminate problems with absorption and fluorescence saturation, but the Raman signals are very weak.

### 3.3.6. Liquid- and gas-phase temperature

As mentioned in section 3.3.4, the temperature dependence of the absorption and emission spectra in LIF is exploited in schemes to measure the temperatures of the liquid [2, 16, 87, 103, 138] and the gas [83] phase. The simpler approach uses a single laser wavelength for excitation and evaluates the liquid- or gas-phase temperature from the ratio of fluorescence intensity in two [87, 88] (occasionally three [139]) wavelength bands. Alternatively, fluorescence can be excited at two carefully selected wavelengths [89–91, 140]. The added complication of two-line excitation (typically requiring two UV lasers or one laser plus a Raman wavelength-shifting cell) offers improved accuracy for gas-phase temperature measurements. Typically, two-line-excitation LIF is applied after the liquid phase has fully evaporated, although gas-phase temperature data have been correlated with PDI measurements of biofuel droplet size and momentum under spark-ignited direct-injection engine conditions [91].

Temperature measurements using LIF require careful calibration and attention to complicating factors such as vaporization (for liquid-phase temperature measurements), fluorescence quenching, tracer decomposition at elevated temperature, and pressure dependence of the absorption and emission spectra [83]. For liquid-phase temperature measurements in vaporizing sprays, LIEF emission at two wavelengths provides unambiguous discrimination against contributions from vapor-phase signals that would occur with ordinary LIF [87, 141].

Another laser-excited approach for droplet temperature is to disperse microscopic thermophoretic phosphor particles in the liquid [103, 142–144]. Temperature is evaluated from either the lifetime of the phosphorescence or from the ratio of phosphorescence intensity in two emission bands. Temporal resolution (for the lifetime approach, in particular) and signal strength can be problematic, especially for single-shot or high-speed (as opposed to multi-shot-average) measurements. Micro-particle seeding of thermophoretic phosphors into the gas phase can also be used to measure gas-phase temperature [142, 145].

Raman scattering has been used successfully for temperature measurements of alcohol droplets in an automotive fuel spray [104]. As always, the weak Raman signals require a high-pulse-energy laser and careful suppression of stray light [16]. Raman scattering can be used to measure vapor-phase temperature, although this is very difficult in the presence of droplets except in rare cases where there is a spectral shift between the liquid and vapor phases [104].

Four-wave mixing techniques, reviewed in [45], such as CARS (coherent anti-Stokes Raman spectroscopy) and laser-induced thermal grating (LITGS) spectroscopy, require the intersection of high-intensity laser beams and are therefore used almost exclusively for pointwise measurements. These techniques have the advantage that the signal emerges as a spatially coherent beam, but CARS in particular requires tunable lasers and a thorough knowledge of non-linear molecular spectroscopy. CARS [146, 147] and LITGS [148] have both been used for measurements of vaporization-induced cooling in gasoline-direct-injection sprays.

The rainbow due to second-order refraction by a droplet yields a scattered-intensity peak whose angular location in the scattering plane ($\pm 137^\circ$ for water) depends strongly on the droplet refractive index and hence on its temperature [2, 16, 103]. Rainbow refractometry has been used both for individual-droplet temperature measurement together with PDI [149] and as an ensemble or global measurement that averages over

![Figure 5. Planar dropsizing using the ratio of LIEF (fluorobenzene-DEMA-hexane) (a, d) and Mie-scattering images (b, e) of the fuel spray from an eight-hole injector under ambient (a–c) and flash-boiling (d–f) conditions [136]. The resulting Sauter mean diameter distributions in (c, f) were calibrated using phase-Doppler interferometry combined with geometric-optics analysis to account for laser-sheet reflection, refraction and absorption within droplets following [128]. Note the dramatic effect of flash boiling on the spray structure. The radial profiles of SMD from LIEF/Mie, LIF/Mie and PDI at 40 mm (g) and 50 mm (h) distances from the injector tip for the flash-boiling spray illustrate the need to use an unambiguous liquid signal (viz., LIF) for fluorescence-based planar dropsizing in a vaporizing spray. Ordinary LIF (FB-hexane), which does not distinguish between liquid-phase and vapor-phase fluorescence, leads to a substantial overestimate of droplet size. The systematic error with ordinary LIF increases with distance from the injector due to increasing vaporization. Reproduced with permission of The Combustion Institute.](Image 312x467 to 546x777)
many droplets [150–152]. The global approach reduces the effects of droplet non-sphericity and interference from other scattering orders. Femtosecond laser pulses also suppress such interferences [16, 153].

For recent reviews on droplet temperature measurement, see Tropea [16] and Lemoine and Castanet [103]; the latter paper also addresses measurement of chemical composition.

3.3.7 3D measurements. 3D spray measurements are highly desirable but very challenging. For averaged data, one can stack a series of planar LIF, LIEF, Mie-scattering or PIV results [84, 117]. Tomographic inversion of line-of-sight data (nearly always on an average rather than an instantaneous basis) is another approach [34, 50–54, 154]. Holography has been used with some success [2, 155, 156], particularly with large-diameter (~10 mm) nozzles [157–161], but the need to resolve individual droplets requires high resolution, and the interrogation procedures are often very demanding of human and computer resources [162].

3.4. High-speed imaging

Another major trend is from single-shot imaging (e.g. with flashlamps or 10 Hz Nd:YAG laser sources and CCD cameras) to high-speed imaging, which allows the evolution of fluid-structural mechanics to be followed throughout individual spray events. The ability to acquire many images during each spray event is also valuable for measurements of transient sprays in high-temperature, high-pressure chambers that may require seconds to minutes between injections [163, 164].

Fast LED sources are now available for volume-illumination, back-illumination and schlieren imaging, while high-repetition-rate lasers are available for planar imaging and PIV. Early high-speed planar imaging and PIV were done primarily with copper-vapor lasers or multi-Nd:YAG laser clusters [31]. The latter offer high pulse energy (hundreds of mJ at visible wavelengths) but a limited number of pulses (e.g. 8). More complex pulse-burst lasers also offer high pulse energy and ~100 pulses at kHz–MHz rates, with bursts typically repeatable at intervals of ~0.1–1 s [18]. Laser clusters and pulse-burst lasers are custom systems. More compact diode-pumped high-repetition-rate Nd:YAG and Nd:YLF lasers are now available commercially at infrared, visible and UV wavelengths with near-unity or peak intensity per pulse. Commercial high-speed CMOS digital cameras are widely available at frame rates up to ~1 MHz.

Recent applications include high-speed spray PIV [73, 74] and LIF. Effectively simultaneous Mie and LIF imaging of a vaporizing diesel spray at a 10 kHz image rate is illustrated in figure 6 [33]. Frame straddling, widely used in high-speed PIV, allowed the Mie and LIF image pairs to be acquired with only a 3 µs separation using a single high-speed camera. The fact that these high-quality LIF images were obtained with only ~0.25 mJ UV laser pulse energy and without image intensification suggests that high-speed LIEF should also be feasible.

High-speed imaging with very low light levels or with UV light (to which CCD and CMOS detectors are insensitive) requires the addition of a high-speed image intensifier. Another use is as a fast gate to reduce detection of stray light, e.g. due to combustion. Fiber-coupled intensifiers use the available signal light more efficiently, but lens-coupled intensifiers are more flexible. All are extremely sensitive and can easily be damaged by overexposure (which may occur with far less light than one might naively expect). All image intensifiers also introduce some non-uniformity and non-linearity. Several commercial high-speed image intensifiers are available.

See [1, 17, 31] for reviews that focus primarily on high-speed imaging of sprays and combustion in IC engines. Ultrafast lasers and imaging are reviewed in [18, 165]. Selection factors and detailed characterization of CCD, CMOS and intensified cameras for quantitative imaging are discussed in [85, 86].

3.5. Image analysis

Any quantitative measurement based on optical imaging requires image analysis. This is a vast subject in itself and will only be touched briefly here.

Quantitative planar LIF and related techniques require subtraction of a background image (which may not be spatially uniform) and ‘flat-field’ correction for non-uniform camera response, non-uniform illumination and shot-to-shot variation in laser pulse energy [83]. For LIF, the non-uniformity corrections typically require dividing the spray image by a reference image acquired with a homogeneous distribution of the fluorescing species in the test section. Low-pass filtering (e.g. a median filter which preferentially rejects intensity outliers)
or pixel binning (spatial averaging) may be needed to improve the signal-to-noise ratio at the cost of reduced spatial resolution. The effect of attenuation of the incident light sheet due to scattering as it crosses the spray can be corrected if the attenuation is not too severe (section 4.2.3).

Segmentation is the process of identifying objects of interest in an image and separating them from everything else. Uniquely identifying the edges of a spray, which are often not sharp, can be problematic with simple intensity-based thresholding. Nevertheless, for macroscopic measurements such as spray penetration, thresholding at a fixed intensity (e.g. 3% of maximum image intensity for scattering) or a fixed extinction level has been used widely and has proven useful when applied consistently [14, 20, 166]. More sophisticated segmentation algorithms are described in [167–171]. Extracting the size, shape or velocity of multiple droplets and/or non-spherical liquid structures from high-resolution images requires algorithms to identify in-focus liquid structures, separate overlapping images, and extract a viable statistical sample [16, 162, 172–174].

4. Measurement needs and challenges

In discussing measurement needs and challenges for the four principle spray regions identified earlier in section 2, we will not try the patience of our readers (assuming there are any at this point) by repeating material already discussed in section 3. Rather, we will use tables 1–4 to organize needs, techniques and related references while highlighting below a subset for further attention. The references in tables 1–4 are a representative selection rather than an exhaustive collection. We generally do not cite the earliest work on a topic, nor do we claim that the papers all represent best practices. In some cases, there are so many papers that we cite reviews plus a few primary-source examples that piqued our interest.

4.1. Upstream internal nozzle flow region

The flow within the nozzle (table 1) largely governs the spray shape and primary atomization [175–177], as well as the mass flow rate (rate of injection) and momentum flux, which are important in determining penetration, mixing and entrainment [27]. The internal flow is sensitive to local temperature, pressure (including upstream pressure fluctuations [178] due, e.g. to a pump [2]) and the thermophysical properties of the liquid (e.g. non-ideal behavior of biofuels). Cavitation [7, 175, 177, 179–183], flash boiling [10, 136, 180, 184, 185] or supercritical [186–189] conditions may result. Figure 5 illustrates the dramatic effect of flash boiling on the spray from a high-pressure multi-hole gasoline injector [136]. Fluctuations associated with unsteady cavitation have been linked to appreciable (~10%) fluctuations in the instantaneous injection rate as well as to hole-to-hole and injection-to-injection variations in spray characteristics [179, 182], including droplet clustering [17, 178].

Visualization, LDV and other measurements with highly idealized nozzle geometries (e.g. 2D), often under steady conditions, have yielded useful fundamental measurements of the effects of cavitation and other internal flow phenomena on breakup and the external spray [190–193]. In practical spray systems, however, the internal and exiting flows are strongly affected by the (possibly complex) geometry of the atomizer’s internal flow passages, as well as details of their surface finish and radii of curvature [176, 194]. Knowledge of the internal nozzle geometry for real spray equipment is therefore necessary to relate these features to external spray characteristics and to facilitate predictive simulation. Furthermore, for transient sprays—particularly for the multi-pulse injection strategies [24, 195–197] that are increasingly common in automotive applications—the geometry changes rapidly as the needle moves within the injector. Indeed, small quantity injections can be composed entirely of the transients associated with opening and closing of the injector.

Not surprisingly, manufacturers are often reluctant to share internal-geometry details with outsiders. Indirect measurements can be helpful (e.g. laser-Doppler vibrometry combined with fast-response pressure measurements to probe aspects of cyclic cavitation in real diesel injectors [198]). But for direct measurements, outsiders must resort to designing their own nozzles for research or to micro-casting [176, 199] or X-ray [56, 194, 200, 201] techniques. Industrial X-ray inspection services can now provide tomographic internal geometry data with reasonable cost and turnaround time. As illustrated in figure 1, if the internal geometry is known, one can fabricate a transparent nozzle tip to allow visualization [11, 179, 180, 202] and even quantitative measurement of the internal flows using e.g. LDV [191] or micro-PIV [11]. Material properties (e.g. quartz or acrylic) may, however, limit the injection pressure or the number of nozzle holes. High-speed phase-contrast X-ray imaging [200, 201, 203] can image needle-motion and aspects of the internal flow data for all-metal injectors. Cavitation in model nozzles has been visualized using time-integrated unfocused synchrotron X-ray absorption [193, 204], while void fraction due to cavitation has been measured using focused synchrotron X-rays [7, 193, 204] and also, on a larger spatial scale, using a medical computed tomography facility [55].

Measurements of the nozzle-exit flow conditions are critical for fundamental and practical spray modeling. Laser-Doppler velocimetry (LDV) [177], laser correlation velocimetry [205] (essentially a two-point time-of-flight technique), ultrafast phase-contrast X-ray imaging [206], and laser flow tagging [82, 207] using laser-induced fluorescence (LIF) or phosphorescence have had some success for nozzle-exit velocity and turbulence profiles.

4.2. Near-nozzle spray-formation region

Measurements just downstream in the near-nozzle spray-formation region (table 2) are as important and at least as challenging as those within the nozzle. Techniques for this (usually) optically dense region are also developing rapidly, and some are subject to controversy. The length of this section reflects the complexity of the physical processes of interest and the difficulty of the measurements. Subsections here summarize general measurement needs and some techniques applicable to lower-pressure sprays (4.2.1), discuss definitions
and characteristics of optically dense sprays (4.2.2), and then outline techniques for progressively more dense sprays (4.2.3–4.2.6).

### 4.2.1. Near-nozzle measurement needs

For lower-pressure sprays (e.g. agriculture, pharmaceuticals, some fuel sprays), liquid typically exits the nozzle as a column or sheet whose instability (e.g. growth of surface waves) leads to primary atomization. In such cases, high-speed high-resolution optical imaging can visualize the breakup process [208–211] and, more quantitatively, can yield sheet or column thickness, void fraction [209] and surface-wave properties [208, 209, 211–214]. Image correlation velocimetry [215, 216] can provide liquid-sheet velocity, while PDI can measure droplet size and velocity [214]. Single- and double-pulse holography, together with photography and LDV, have yielded insight into primary and secondary breakup of large-diameter (9.5 mm), pressure-atomized liquid jets [157–160], including aerated jets in supersonic crossflow [161].

With increasing injection pressure, however, breakup occurs progressively closer to the nozzle exit, and measurement of an intact liquid core becomes progressively more difficult. Indeed, for the ~100–2000 bar pressures of direct-injection gasoline and diesel engines, an intact liquid column or sheet may not even exist except perhaps within a few nozzle diameters [187, 217]. Techniques based on electrical connectivity and optical connectivity [218–220] are useful. With the optical approach, the liquid is doped with a fluorescent tracer, and laser light is coupled into the spray core (e.g. by an optical fiber within the injector). Total internal reflection at the liquid–gas interface confines most of the laser light to the intact core, where it excites fluorescence. Despite some issues [4, 219], optical connectivity is preferable to the earlier electrical technique because it is relatively simple and less invasive. It also reveals more about the structure of the liquid core since it produces images rather than pointwise temporal data.

To complicate matters further, near-field atomization depends on nozzle surface finish (e.g. laser-drilled, hydro-ground or electric-discharge-machined bores) as well as on geometry [176, 194, 221, 222]. For example, for a high-pressure diesel spray from a smooth, slightly converging (non-cavitating) nozzle, synchrotron x-ray absorption tomography has found evidence for an intact core (liquid volume fraction \( \eta = 1 \)) extending ~20 nozzle diameters [223]. In contrast, for airblast

### Table 1. Upstream internal nozzle-flow region—measurement needs and techniques.

<table>
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Table 2. Near-nozzle spray-formation region—measurement needs and techniques.

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<td>Near-nozzle gas entrainment</td>
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<td>Droplet volume flux</td>
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<td>Droplet interaction (collision, coalescence, breakup)</td>
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and air-assist injectors, the high-velocity co-flowing airstream can lead to flow instability and breakup within the nozzle [224].

Section 4.1 mentioned and figure 5 illustrates how strongly flash boiling can affect the near-field and developed-spray structure. Even more extreme effects can occur in rocket-engine and diesel injection when the ambient gas pressure exceeds the thermodynamic critical pressure of the liquid. Detailed analysis shows that transport processes then dominate inter-molecular (surface tension) forces. The fuel enters the high-pressure, high-temperature gas as a compressed liquid, and the gas–liquid interface develops as a diffusion-dominated mixing layer rather than breaking up into a classical two-phase spray [186, 225].

The relative velocity or slip velocity between gas and liquid is critical to primary and secondary breakup as well as to heat and mass transfer between the phases at all locations throughout the spray. Even under dilute conditions, slip-velocity measurements typically require some level of approximation since it is difficult to measure the velocity of both phases simultaneously at precisely the same location [2]. At the nozzle exit and immediately downstream, the situation is much more difficult since the liquid phase may exist as an intact stream or sheet, ligaments, droplet clusters or individual droplets; in some cases, all these forms may be present. For the near field of an airblast atomizer, high-speed flow visualization and PDI measurements provided detailed insight into breakup mechanisms as well as slip-velocity data [224]. Time-averaged near- and far-field slip velocity has been measured using Doppler global velocimetry (DGV) in a kerosene spray flame [77]. Laser flow tagging (LFT) has yielded simultaneous planar measurements of near-field droplet and gas-phase velocity in a diesel spray [79, 82], although slip velocity was not explicitly evaluated.

Droplet–droplet interactions (e.g., breakup or coalescence due to droplet collisions) are typically most prominent in the near-field region where the droplet number density \( n \) is highest. If \( n \) is not too high, high-resolution imaging can provide direct observations of collisions, but it can be difficult to obtain statistical data. Pointwise measurements using PDI offer complementary statistical information in which, e.g., coalescence in non-vaporizing sprays is inferred from observed increases in droplet diameter with downstream distance or from bimodal droplet size or velocity distributions [213, 214].

Also critical to near-field atomization and liquid/vapor transport, but difficult to measure, are near-nozzle gas entrainment [226], turbulence generation, aerodynamic drag forces, and the vapor-phase distribution.

4.2.2. Optically dense sprays and multiple scattering. In addition to the complications presented by unstable liquid columns or sheets, ligaments and large non-spherical drops, the surrounding dense cloud of small droplets can render near-field (and sometimes far-field) optical measurements difficult or impossible. In a detailed review, Linne [4] has analyzed key features of optically dense sprays using Mie-scattering calculations for droplet scattering and a Monte Carlo simulation for photon propagation [227, 228]. These results lead to the conclusion that no single parameter adequately defines a dense spray. Here we follow the less rigorous approach of Coghe and Cossali [3] for rough estimates of several spray parameters, summarize several key points from these recent reviews, and add a bit of our own perspective.

As noted in section 2, there is no clear consensus on how to define a dense spray [2, 4, 5]. The most basic physical parameters to characterize spray density are the mean droplet number density \( n \), the mean droplet spacing \( \Delta \), and the liquid volume fraction \( \eta \). For order-of-magnitude estimates, consider the over-simplified situation of an ensemble of monodisperse spherical droplets. Then in terms of the droplet volume \( V \) and diameter \( D \),

\[
\text{Mean droplet spacing: } \Delta = n^{-1/3} \quad (1)
\]

\[
\text{Liquid volume fraction: } \eta = \frac{nV}{6} \quad (2)
\]

For optical measurements, basic spray-density parameters also include the optical thickness or optical depth \( \tau \), the photon mean free path \( \delta \), and the optical transmission or attenuation along a path of length \( L \).

The optical thickness or optical depth \( \tau \) describes the integrated effect of all processes that attenuate light along a path of length \( L \) across the spray:

\[
\text{Optical depth: } \tau = \int_{0}^{L} n(z) \sigma_{\text{ext}}(z) \, dz \approx n \sigma_{\text{ext}} L \quad (3)
\]

where the extinction cross section \( \sigma_{\text{ext}} \) includes both scattering and absorption. The number density and extinction cross section in the integral in equation (3) are local quantities. The approximation on the right expresses the optical depth in terms of the average number density and cross section along the path, and the average implicitly includes the local droplet size distribution.

The optical depth determines the fraction of incident light \( H(0) \) transmitted in traversing the path:

\[
\text{Transmission: } T = I/I_0 = \exp(-\tau) = \exp(-\mu_L L) \quad (4)
\]

where \( \mu_L = n \sigma_{\text{ext}} \) is the extinction coefficient [3, 4]. A possible source of confusion is that optical components such as filters are often specified in terms of optical density, which is the base-10 logarithm of transmission, whereas the optical depth \( \tau \) is the natural logarithm (base \( e \)).

For non-absorbing droplets, the extinction cross section reduces to the scattering cross section and is simply

\[
\sigma_{\text{ext}} = \sigma_{\text{scat}}(\pi R^2) \approx 2(\pi R^2) \quad (5)
\]

where \( R \) is the droplet radius and \( \sigma_{\text{scat}} \) is the scattering efficiency. For droplets whose Mie parameter \( \alpha = nD/\lambda \gtrsim 10 \), \( \sigma_{\text{scat}} \approx 2 \); this is the case for \( D \gtrsim 5 \mu m \) and wavelengths \( \lambda \) in the near-infrared (\( \lambda \sim 1.5 \mu m \)) and shorter. Equation (5) expresses the result from classical electromagnetic theory that in this regime, the total scattering cross section is twice the geometric cross-sectional area of the droplet [229].

To connect the optical parameters to the physical parameters of the spray, use the liquid volume fraction \( \eta \) defined in...
equation (2) along with equations (3) and (5) to express the optical depth as

$$\tau = 3\eta L / D$$

(6)

For non-absorbing droplets in the Mie regime, light is scattered predominantly in the forward (i.e., propagation) direction. The optical depth then approximates the average number of times a photon is scattered as it traverses a path of length \(L\) [3, 4]:

$$\tau \approx L / \delta$$

(7)

where

Phantom mean free path: \(\delta \approx D / (3\eta)\)

(8)

Normalizing the photon mean free path and the path length by the droplet diameter, i.e.

$$\delta^* \equiv \delta / D$$

$$L^* \equiv L / D$$

(9)

provides convenient relationships between these optical parameters and the liquid volume fraction:

$$\delta^* = 1 / (3\eta)$$

(11)

$$\tau = 3\eta L^*$$

(12)

These parameters characterizing spray density vary strongly with droplet diameter: \(\delta^* \propto D^{-3}\), \(\eta \propto D^3\), \(\tau \propto D^2\). Figure 7(a) plots the normalized photon mean free path \(\delta^*\) and the liquid volume fraction \(\eta\) as a function of number density \(n\) for three droplet diameters, while figure 7(b) plots the optical depth \(\tau\) and transmission \(T\) as a function of liquid volume fraction for three values of the normalized path length. Also shown as individual points are corresponding values for three specific examples that we discuss next; each example has droplet diameter \(\sim 10\) \(\mu\)m but different number densities and optical path lengths.

First, as a sanity check, we apply the estimates above to the measurements by Berrocal et al [133] of a homogeneous suspension of 15 \(\mu\)m diameter spheres in water with number density \(n = 254\) mm\(^{-3}\) and path length \(L = 44\) mm. The estimated transmission \(T = 0.019\) agrees well with the measured value of 0.018. In this case, the local number density and liquid volume fraction are modest, but the path length (\(L^* \sim 3000\)) leads to an optical depth of \(\tau = 4\).

Second, for an example of a real spray, we consider the thin red zone which extends about 8 mm from the exit of the pressure-swirl injector shown in the inset to figure 4(a). This zone of relatively dense liquid (maximum density \(\sim 3\) mg cm\(^{-3}\) as measured by LIEF [119]) has an optical path length \(L \sim 1\) mm along the horizontally propagating laser sheet. PDI measurements of this automotive fuel injector in our laboratory give
The transmission estimated here is consistent with the observed laser attenuation across the spray (which cannot be judged directly from figure 4(a) since the spray images have been corrected for laser attenuation [119]). This consistency offers some reassurance that these simple estimates are at least not outrageously bad. Although the number density here is ~10 times greater than in the preceding example, the normalized optical path length $L*/\delta = 79D/\delta$ is much shorter, so that multiple scattering is not severe even relatively close to the nozzle in this practical spray.

Third, for a much more severe example, we quote Coghe and Cossali’s [3] hypothetical near-field diesel spray with 10 µm droplet diameter, 1 mm path length, number density $n = 64,000$, and optical depth $\tau = 10$, which is reasonable in view of observed near-field diesel spray attenuation [4], as discussed further below. The transmission in this example is $<10^{-4}$. Conventional optical measurements (e.g. imaging, PDI, LIF), then, can provide information only on the periphery of this region (e.g. radial and axial penetration, size of relatively isolated peripheral droplets), but not structure or droplet size within the interior. The situation can be even worse, given that the estimates assume monodisperse spherical droplets and that non-spherical liquid structures may occur near the nozzle.

Since the optical depth $\tau$ characterizes the number of times a photon is scattered over a given path length (also called the scattering order), the single-scattering regime is often identified as $\tau \sim 1$. Conventional optical techniques such as PDI, LIF and LIEF retain considerable utility for moderate levels of multiple scattering, say $\tau \sim 1$–2 (see section 4.2.3). For optical depths $\tau \geq 2$, however, the performance of these techniques deteriorates, and progressively more sophisticated techniques such as SLIPI (section 4.2.4) and ballistic imaging (section 4.2.5) are needed to image or measure reliably within the interior of the droplet cloud. For $\tau \geq 10$, uncorrected optical imaging of the interior of the spray-formation region appears unlikely, although x-ray techniques can provide data (section 4.2.6) [3, 4].

### 4.2.3. Techniques for moderately dense sprays

Except in very dilute sprays, optical measurements usually encounter some degree of multiple scattering. The effects range from annoying (added background noise or some loss of spatial resolution) to misleading (e.g. apparently filling in the interior of a hollow-cone spray) to debilitating (e.g. total obscuration of near-nozzle features).

For planar Mie and LIF imaging of sprays with non-absorbing droplets of diameter ~10–100 µm and optical depths $\tau \lesssim 2$, multiple-scattering effects are mitigated to some extent by the fact that most of the incident light is scattered in the forward direction, i.e. continues with only a small angular deviation from its original direction [4, 230]. The image is thus somewhat degraded by an effective thickening of the light sheet as it traverses the spray. As the optical depth increases, however, photons scattered at larger angles can illuminate parts of the spray outside the light sheet, producing a distorted and potentially misleading image.

Scattering and absorption attenuate the light sheet as it crosses the spray. Bidirectional illumination (e.g. from the left and right sides) offers possibilities to correct for this attenuation if it is not too severe, say transmission $T \geq 0.1$ ($\tau \lesssim 2$). The simplest (but approximate) approach is to illuminate the spray simultaneously with light sheets from opposite directions. This is equivalent to taking the arithmetic average of images acquired separately with illumination from each side. Exact compensation for attenuation can be achieved in principle by taking the geometric average of the images acquired separately with left-side and right-side illumination [231], provided that the local signal and the local laser attenuation are linearly correlated and that the total attenuation follows Beer’s law. At optical wavelengths, Beer’s law breaks down due to multiple scattering as the spray becomes more dense [4, 232] or, for LIF, due to fluorescence saturation (non-linear response caused by high incident light intensity or high concentration of the fluorescing species [83]). Compensation with single-sided illumination is possible using an iterative approach [233]. See [119, 122] for recent quantitative applications of these approaches. These schemes do not account for attenuation of the scattered or fluorescent light signal en route to the detector, however [234].

As we will discuss further in sections 4.2.4 and 4.2.5, more optically dense regions can be measured reliably by techniques that select unscattered (ballistic) photons and quasi-ballistic photons [4, 232] that have scattered once or at most a few times. Such discrimination can exploit the spatial, temporal, polarization and coherence properties of the scattered light [2, 4, 165]. For example, planar extinction tomography [34], mentioned earlier (section 3.1) with respect to spray patterning, spatially selects unscattered photons and is effective as long as a statistically adequate number of unscattered photons can be detected. The technique has been demonstrated at transmission levels down to 0.01 (optical depth $\tau = 4.6$) [235, 236]. The measured quantity is total droplet surface area per unit volume, which is not simply related to droplet size for polydisperse sprays, but the resulting spray cross-sectional images are nonetheless highly informative.

Holography intrinsically discriminates against multiply scattered light since the amplitude and phase information in holographic recording and reconstruction must retain the coherence of the laser source; multiply scattered light contributes background noise [5]. A practical limit exists because as multiple scattering increases, coherent signal photons decrease while background noise due to multiply scattered photons increases.
PDI also intrinsically employs coherence to discriminate against multiple scattering. The Doppler burst signals arise from interference of singly scattered light from the coherent intersecting laser beams. Multiple scattering in PDI therefore contributes to the incoherent background and degrades the signal-to-noise ratio \([2, 3]\). PDI can be successful in relatively dense sprays if the measurement volume is so small that it contains only one droplet at a time. For high-pressure sprays, this may require careful optimization even at substantial distances (e.g. 50 mm) downstream \([237, 238]\). Off-axis detection helps by limiting the length of the probe volume, but measurement accuracy requires a minimum number of oscillations (~15–20) in the Doppler bursts and thus constrains how much the measurement-volume diameter can be reduced in order to reduce the probability of encountering two or more droplets. Another issue for PDI in optically dense sprays is measurement bias toward larger droplets due to attenuation of the incident and scattered light \([2, 3]\).

These factors currently imply a maximum droplet number density for PDI of \(\sim 10^3 \text{mm}^{-3}\) \((\sim 10^{12} \text{m}^{-3})\) \([3, 43]\) or a minimum mean droplet spacing \(\sim 10\) droplet diameters \([2, 5]\). Wigley et al estimate a maximum number density of \(5 \times 10^3 \text{mm}^{-3}\) (minimum droplet spacing \(\sim 4\) diameters) for their system \([239]\), which has been used for PDI measurements (incorporating validation for spherical droplets) within \(\sim 1\)–10 mm of the nozzle exit of a pressure-swirl gasoline injector (nozzle length-to-diameter ratio \(\sim 1\)–10). LDV was used simultaneously to measure the liquid-phase velocity independent of size or shape, i.e. including partially atomized liquid \([239]\). However, the low PDI validation rate (~30%) in the densest region leaves some concern as to possible measurement bias.

Extension of PDI to more dense sprays (perhaps by an order of magnitude) using additional phase data from a fourth detector looks promising \([240]\). This approach allows the measurement-volume diameter to be reduced to the order of the droplet diameter or even less, and also improves rejection of noise from multiple scattering.

Planar dropsizing has also been used in moderately dense sprays with some success \([35, 36, 125, 126, 128]\), although multiple scattering can still be problematic at substantial downstream distances. The reason is that (contrary to early expectations \([125, 126]\)) the contributions of multiple scattering to the LIF and Mie signals are different and hence do not cancel in the LIF/Mie ratio \([132–134, 241]\). Mishra et al found appreciable corruption of the LIF/Mie ratio for optical density as low as \(\tau \sim 1\) \([134]\), while Pastor et al \([241]\) suggest that multiple scattering can corrupt PDS measurements for number densities \(n \geq 100 \text{mm}^{-3}\) or liquid volume fractions \(\eta \geq 10^{-3}\), which is \(-10\) times less than the upper limit that has been suggested for PDI. The validity and accuracy of PDS measurements need to be assessed on a case-by-case basis. PDS has recently been combined with SLIPI \([133, 134]\) to reject multiply scattered light, as discussed briefly in the next subsection.

### 4.2.4. SLIPI

For optical depths \(\tau \lesssim 5\)–6, structured laser illumination planar imaging (SLIPI), a result of which was shown in figure 2, rejects multiply scattered light effectively. Adapted from the medical field by the Lund University group \([4, 31, 132, 133, 154, 242–244]\), SLIPI impresses a sinusoidal or stripe-like intensity modulation on the incident laser sheet (typically using Ronchi gratings). As originally performed, SLIPI required recording three images of LIF or Mie scattering with 120° phase offsets of the intensity modulation. Singly scattered light retains the intensity modulation, while two or more scattering events increasingly blur the intensity modulation in the image. When the three phase-shifted images are properly combined, the contributions from singly scattered light add while multiple scattering contributions are strongly suppressed. It may be helpful to think of SLIPI as a spatial analogue of phase-sensitive detection (e.g. lock-in amplification) in the time domain \([4, 245]\).

The attraction of planar dropsizing has led to substantial effort to combine SLIPI with PDS \([134]\). Applications include a diesel spray \([133]\). As mentioned above, multiple-scattering corrupts PDS more strongly than expected from earlier arguments \([125, 126]\) that the LIF and Mie-scattered signals would be affected similarly by multiple scattering and that therefore the effects would cancel out in the LIF/Mie ratio \([3, 4, 132–134, 241]\). With SLIPI, the differing contributions of multiple scattering to the LIF and Mie signals can be removed before taking the LIF/Mie ratio.

3D tomographic imaging using more complex structured transillumination combined with filtered backprojection analysis has yielded impressive results for the near field (optical depth \(\tau \sim 5\)) of air-assist sprays \([154]\). As optical depth increases, SLIPI must reject a progressively larger fraction of the incident photons. This is similar to the situation discussed for holography and PDI in section 4.2.3. This signal-to-noise degradation places a premium on using cameras with the highest possible dynamic range in intensity. For thermally non-uniform environments such as combustion, beam steering by temperature gradients may degrade or destroy the stripe patterns of the incident laser sheets \([4]\).

Despite its attractions, SLIPI has not been used widely for spray imaging beyond the Lund group. SLIPI on a steady-spray or multi-injection ensemble-average basis is available commercially \([4]\), but single-shot SLIPI with the original implementation requires the three phase-offset images to be taken within a sufficiently short time that the spray motion is effectively frozen (a few \(\mu\)s at most for high-pressure sprays). The Lund group accomplished this with a multi-YAG laser cluster and custom camera system \([31]\).

A major simplification of the structured-illumination approach—two-image or two-pulse SLIPI—has recently been demonstrated \([12]\). The two images are modulated 180° out of phase. When these opposite-phase images are combined, the reduced information (relative to three-image SLIPI) leads to incomplete demodulation, so that stripes appear in the combined image at twice the spatial frequency of the original modulation (i.e. at half the spacing). However, this 2f residual modulation is at a well-defined spatial frequency. Furthermore, with careful choice of the original modulation frequency \(f\), the residual 2f stripes appear near the resolution limit of the optical system (which in many cases will be
dictated by the pixel density of the camera). Low-pass spatial filtering can therefore remove the residual \(2\pi\) modulation with little loss of spatial resolution. Figure 2 (right) is an example of an effectively instantaneous two-pulse SLIPI spray image.

The two-pulse simplification should make SLIPI imaging of sprays—including high-speed imaging—much more accessible. Two-pulse SLIPI can be implemented with standard PIV equipment (a double-pulsed laser and an interline-transfer CCD camera or a frame-straddling CMOS high-speed camera) by adding two gratings plus standard beam-splitting and beam-combining optics [12].

4.2.5. Ballistic imaging. For sprays that are still more dense optically (\(\tau \gtrsim 5\))–6, ballistic imaging (BI) [4] can provide line-of-sight images of liquid structures that are otherwise buried within the dense cloud of droplets in the near-nozzle region [165, 246–251], as illustrated in figure 8 for a rocket spray [251]. BI can also image details of the gas–liquid interface; in a double-pulse arrangement with PIV-like cross-correlation analysis, BI can yield the velocity of structures and droplets at the interface [249].

Developed for spray imaging largely by Linne and colleagues—and also adapted from medical imaging—BI is essentially a highly sophisticated version of shadowgraphy. As reviewed in depth in [4], when a femtosecond laser pulse crosses a spray, the earliest photons to arrive at the detector are unscattered or ballistic photons, but for \(\tau \gtrsim 5\)–6, these are too few to create a useful shadow image. Quasi-ballistic (sometimes called ‘snake’) photons, which have scattered only a few times, propagate primarily in the forward direction and typically arrive a few picoseconds later. Picosecond image gating together with spatial and polarization filtering preferentially pass ballistic and quasi-ballistic photons while rejecting photons that have suffered more severe multiple scattering (sometimes called diffuse photons) [165, 246–251].

Spatial resolution and image contrast in BI decrease with increasing optical density because high-quality imaging photons (ballistic and quasi-ballistic photons) become increasingly rare. BI has demonstrated spatial resolution \(\sim 30–40\) \(\mu\)m in a suspension of monodisperse scattering particles with optical depth \(\tau \sim 13–14\). In less strongly scattering environments (e.g. the near field of a diesel spray with \(\tau \sim 10\)), BI produces resolution \(\sim 20–25\) \(\mu\)m [4]. Ongoing research is applying BI to near-nozzle spray formation as a diesel spray goes supercritical [188].

A system in an early stage of development for holographic imaging in very dense sprays also uses picosecond laser pulses and image gating to suppress multiply scattering [252, 253].

4.2.6. X-ray techniques. X-rays interact with droplets or other liquid structures primarily through absorption rather than scattering and are therefore essentially unaffected by multiple scattering. X-ray absorption (radiography), which detects the total liquid mass (droplets and intact liquid structures) along a line of sight, is now an established technique that has yielded important near-nozzle results (e.g. liquid volume fraction and mass distribution) [54, 254–259]. Most x-ray absorption measurements have mapped the spray with focused beams and single-point detectors, but a fast-framing x-ray camera has been used for microsecond imaging and 3D tomographic reconstruction [54]. Ultra-small-angle x-ray scattering is being explored for near-nozzle drop sizing [260].

High-speed phase-contrast x-ray imaging (which may be thought of, roughly, as x-ray shadowgraphy) has demonstrated a unique ability to reveal needle motion [201, 206] and internal flows (e.g. cavitation [7, 56, 204]) in all-metal injectors under realistic pressure conditions. Phase-contrast x-ray imaging has also been applied extensively to the spray-formation region and has produced a number of intriguing observations that have attracted considerable attention [200, 203, 261, 262]. Recent detailed analysis, however, shows that phase-contrast x-ray images superimpose the phase changes from all liquid/gas/solid interfaces in the beam path. The resulting images can therefore be very difficult to interpret in dense sprays, and a number of early claims have been questioned [4].

4.3. Far-field developed spray region

Most detailed spray measurements have been made in the far-field developed-spray region (table 3) where life is easier for experimenters and modelers alike. Indeed, all the measurements techniques surveyed in section 3 have been applied in this region, and most of the entries in table 3 are now self-explanatory. To avoid undue repetition, we highlight only a few.

In regions of the developed spray with modest droplet number density and optical depth (\(\tau \lesssim 1\)), measurements of droplet size and velocity based on imaging of single droplets become feasible. Size measurements based on direct
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<td></td>
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4.4. Spray-wall interaction

The spray-wall interaction, which nearly always occurs in the relatively dilute developed-spray regime, represents the final measurement challenge for some applications (table 4; figure 3). Accurate modeling is especially difficult because the spray-wall interaction is the ‘tail end’ of many coupled processes, viz., atomization, in-flight transport and vaporization, droplet-surface interaction, film transport, heat transfer and vaporization, none of which is simple to measure. The droplet-surface interaction itself depends on droplet momentum and liquid properties (e.g. viscosity, surface tension, temperature) and on surface properties (e.g. temperature, roughness, pre-existing liquid film). The literature is replete with single-droplet-impact experiments that have yielded visually impressive images (droplet impact, disintegration, rebound, splashing, ‘crowns’, etc) as well as some helpful data and numerical correlations. Except for the most dilute situations, however, isolated-droplet impacts are of limited relevance to the interaction of many real sprays with surfaces (e.g. figure 3) [271–273].

PDI is useful to measure droplet size and velocity in spray-wall interactions (e.g. [2, 274–276]), but care is needed to distinguish impinging from rebounding or disintegrating spray droplets, especially for curved surfaces [2, 277–279]. Planar Mie scattering (figure 3(a)), LIF and LIEF are effective to visualize the near-wall liquid- and vapor-phase distributions [113, 274–276, 280], and PDS has been applied for near-wall droplet-size measurement [281]. Line-of-sight-integrated near-wall liquid and vapor mass distributions have been measured by LAS [50]. Two-wavelength PLIF has been used for near-wall droplet temperature [282], while molecular tagging thermometry based on phosphorescence lifetime has been used to measure surface droplet temperature and size [283].

The area of the liquid film on a surface is often relatively easy to measure with imaging techniques [284, 285], but film thickness is much more difficult. Interferometry is an approach that seems natural but has had surprisingly few applications [286, 287]. LIF has been successful for relatively thick films (~10–100 µm) [281, 288–291], but can encounter difficulty with interfering background light, especially in an enclosed environment like an engine cylinder. Total internal reflection has been used both directly to measure film thickness [292] and to couple light into the film for LIF [288, 289].

Figure 3(c) illustrates quantitative measurements of liquid films (area, thickness, and mass) using a very different approach: continuous high-speed (4.5kHz) refractive-index-matched (RIM) imaging of thin (~0.1–3 µm) fuel film formation and evaporation on the piston surface in a direct-injection gasoline engine [13, 293]; see [294, 295] for later applications. The RIM method exploits the increased transmission of light that occurs when a liquid film is in contact with a slightly roughened quartz or glass surface. The initial RIM measurements, which differed strongly from most simulations at that time, had consequences in terms of fundamental understanding (reversing the then-current understanding of the relative contributions of fuel films to unburned hydrocarbon and soot emissions), spray simulation (stimulating improved modeling of in-flight vaporization and the spray-wall interaction [272]), and engine design and operation (showing the importance of spray structure and injection timing for reducing fuel films and attendant soot production) [13].

5. Summary and perspective

Spray measurement technology now includes a wide variety of techniques that are capable of quantitatively characterizing many key spray phenomena, especially for the far-field developed-spray region and for spray-wall interactions (tables 3 and 4). In these regions, optical techniques work well
because multiple scattering is often moderate or insignificant. Unfortunately, voids, non-spherical liquid structures and high droplet number density greatly complicate and in many cases preclude the use of standard optical techniques in the near-field spray-formation region. Access to the nozzle interior is often difficult for real-scale equipment at the correct injection pressure. Despite the recent development of such advanced techniques as SLIPI, ballistic imaging and x-ray imaging, there are no established techniques to measure some of the desired quantities and phenomena within the injector and just downstream in the near-nozzle spray-formation region, as indicated by the blank entries in tables 1 and 2.

This final section offers our perspective on issues, ongoing challenges and directions in spray measurement technology, without claiming that we are the first to have had these thoughts.

5.1. Cost and complexity

As reviewed here, spray measurement technology ranges from relatively simple and modest in cost (e.g. white-light or back-illuminated spray imaging) to dauntingly complex and expensive (e.g. synchrotron x-ray imaging). Cost and complexity tend to increase as measurements focus more on fundamental understanding of spray physics rather than on spray engineering and as the spray is probed progressively closer to and inside the nozzle. Cost and complexity also increase with the need to perform measurements under relevant conditions (section 5.2) and with application of simultaneous diagnostics (section 5.3).

5.1.1. Spray physics

Only recently have laser-based techniques such as SLIPI [4, 31, 242] and ballistic imaging [4, 246–248] been developed to suppress the strong multiple scattering that usually obscures details of the near-nozzle spray structure. The two-pulse SLIPI approach [12] promises significant simplification, but ballistic imaging remains experimentally complex and requires a high level of both expense and expertise in picosecond lasers and electro-optics. Furthermore, the limited market for the most highly specialized components will likely impede cost reductions for BI, although growing interest in applications of femtosecond lasers to manufacturing (e.g. laser ablation) may help.
Prospects are better for high-repetition-rate laser sources and especially for cameras. The rapidly increasing capability of high-speed CMOS cameras at a given price point is driven by entertainment and defense rather than by scientific applications.

A potentially lower-cost approach to imaging in optically dense sprays that is in a very early stage of development involves dark-field volumetric imaging using an array of pulsed LED sources for multi-angle illumination and an array of detectors with varying focal depths. In this scheme, secondary scattering of the incident light is actually beneficial since it helps illuminate the entire surface of the droplets or liquid structures; however, extinction of the incident light and signal photons will degrade performance as optical depth increases [296].

The highest-performing x-ray techniques require a synchrotron light source, which is typically available only at national laboratories and which usually involves significant user-time and space constraints. This situation has motivated recent exploration of commercial x-ray sources and detectors to measure liquid mass distributions across a spray [53, 297–299].

The difficulty and expense of the most advanced techniques remains a major challenge to their widespread adoption.

5.1.2. Spray engineering. Fortunately, many aspects of practical spray engineering do not require SLIPI, BI, or synchrotron x-ray sources. Much can be accomplished with simpler methods to visualize the spray pattern, quantify spray penetration and angle, obtain some measure(s) of droplet size (and perhaps velocity), and, if needed, visualize the spray-wall interaction. In addition to what is learned directly from such measurements, they are often needed to calibrate or tune the semi-empirical model parameters (‘constants’) in spray simulations that will be used to design the system in which the spray will ultimately be employed, e.g. fuel injection in the cylinder of an IC engine, where—among other goals—the designer needs to optimize the vapor-phase fuel–air distribution and minimize or eliminate liquid fuel on the combustion chamber surfaces.

A spray laboratory equipped with basic imaging and drop-sizing capabilities can provide much valuable information for such purposes. Time-resolved diffraction-based sizing offers simple measurements of the volume-averaged droplet size distribution. PDI provides more detailed information (pointwise droplet size, velocity and droplet volume flux) but requires greater expertise. For basic imaging, considerations include the light source (e.g. fast LEDs versus laser), the imaging mode [back-illumination (i.e. extinction), schlieren, white-light volumetric imaging, or planar imaging], and the digital camera (single-shot versus high-speed). Much of the equipment is available commercially, including systems for optical patterning using planar LIF and Mie scattering or planar extinction tomography.

5.2. Measurements under relevant conditions

For both spray physics and spray engineering, measurements under conditions relevant to the application can be extremely important. Atomization, spray structure, penetration, and (obviously) vaporization can depend crucially on liquid temperature, injection pressure, and on the temperature, pressure and flow velocity of the ambient gas, as illustrated by the major differences in basic spray structure seen in figures 4 and 5. Measurement of the vapor phase—which generally exhibits substantially greater variability than the liquid phase—is rightly receiving increasing attention. Test chambers to provide elevated temperature and pressure conditions add appreciable complexity and cost. Detailed descriptions are beyond the scope of this review. Reference [163] briefly reviews the relative merits of several types of spray test chambers, including constant-pressure flow chambers (e.g. [24]) and constant-volume pre-combustion chambers (e.g. [163, 164]), as well as less commonly used devices such as rapid compression machines [11, 300] and shock tubes [301, 302]; see also [323]. High-pressure chambers have been used at synchrotron x-ray facilities [221, 258], but high-temperature chambers appear not to have been used yet.

On the one hand, high-temperature conditions can actually reduce the difficulty of some optical measurements since evaporation reduces the number density of small droplets. For example, an optical depth $\tau \approx 2.5$ has been measured ~5 mm from the injector tip in a diesel spray under engine-relevant ambient-gas conditions (900 K temperature, 60 bar pressure) [14, 20, 303], compared to $\tau \sim 10$ under cold conditions [3, 4]. On the other hand, temperature and vapor concentration gradients cause beam steering which—although it is the essence of the schlieren technique—can complicate diffraction-based sizing, PDI, planar imaging, and extinction measurements using diffuse back-illumination imaging.

As is often the case, the measurements depicted in figures 2, 3(a), 3(b) and 4–6 were made under essentially quiescent flow conditions. The interaction of the spray with gas flow is critical in many applications such as IC engines or agricultural spray drift. As reviewed recently by Miles [304], optically accessible engines with transparent windows, cylinder walls and piston crowns have been used extensively for visualization and to a lesser extent for quantitative spray measurements (e.g. [13, 17, 140, 305, 306]). Optical engines and field-portable instrumentation for agricultural sprays [263, 307] or painting [274] are also beyond the scope of this paper.

5.3. Simultaneous measurements

Spray physics is governed by complex stochastic and often nonlinear interactions that lead to complex stochastic flow structures with steep gradients in key physical quantities. These features are largely washed out when time-averaged or ensemble-averaged over many repeated events. Simultaneous rather than sequential measurements are therefore important to understand processes such as internal nozzle flows, breakup, and the transfer of heat, mass and momentum between the liquid and vapor phases.

PDI is already capable of simultaneously measuring droplet size, droplet velocity and gas-phase velocity (using the Doppler signals from droplets that are small enough to follow the local turbulent flow) [2]. As mentioned in section 3.3.2,
simultaneous droplet and gas-phase velocity measurements have also been performed with PIV using the different wavelengths of Mie scattering and fluorescence to distinguish droplets from gas-flow tracers [67, 68, 71], while LFT has been used for simultaneous droplet-gas velocity-field measurements without particle seeding [82]. Wieske et al [87] measured exciplex fluorescence at two wavelengths to measure liquid-phase temperature along with liquid and vapor distributions.

The frame-straddling technique offers an important simplification that enables nearly simultaneous pairwise application of imaging diagnostics with a single camera (e.g. high-speed Mie scattering plus schlieren [46, 47] or LIF [33]). In addition to reducing the physical complexity of the experiment, this approach can also eliminate the need for spatial registration of the image pairs.

Experimental complexity increases greatly with simultaneous application of multiple diagnostics that differ in their underlying physics and time scales. Figure 1 illustrates an already challenging combination: simultaneous high-speed back-illuminated visualization and micro-PIV of in-nozzle cavitation plus high-speed shadowgraphy of the resulting near-field spray [11]. Now imagine extending this experiment to add ballistic imaging of the optically dense spray-formation region, calibrated LIEF with two-pulse SLIPI to measure the liquid- and vapor-phase distributions and droplet size via PSD in the developed spray, high-speed droplet PIV measurements in the developed spray, and gas-phase PIV using fluorescent seed particles to measure entrainment. Finally, liquid- and gas-phase temperature measurement would require detection of LIEF emission at two appropriate wavelengths for each phase (and additional calibration). This hypothetical ‘everything except the kitchen sink’ experiment would certainly be very informative (not to mention costly), but its complexity would demand extensive engineering and refinement to produce a robust and reliable system for systematic measurements. Like many experimentalists, we have personally (and painfully) verified that the probability of getting everything to work at the same time decreases rapidly (and nonlinearly) with the amount and sophistication of the equipment involved!

5.4. Comparing simulation and measurement: a sermon

Given that spray modeling is important for the design of spray hardware and spray applications, and that improvement of spray simulations is a stated goal of many spray measurements, this section touches on the (hopefully) symbiotic and complementary interaction of simulation and measurement. Comparisons are important for tuning model parameters in semi-empirical engineering simulations, for informing the development of semi-empirical and fundamental submodels, and for validating the submodels and overall simulations. Although this review is not the place to discuss details of spray modeling (see [5, 8, 308] for reviews), a brief conceptual summary of pertinent aspects of the major simulation approaches and some of the associated issues should be helpful.

Reynolds-averaged Navier–Stokes (RANS) simulations dominate spray engineering calculations. In essence, RANS simulations solve the ensemble-averaged conservation equations for mean quantities and some variances (e.g. turbulence kinetic energy, mixture-fraction fluctuations, turbulent flame-front probability [309]). Higher-order terms for quantities involved in processes such as turbulence production and dissipation, spray breakup and scalar mixing are modeled. The RANS formulation naturally suggests comparing simulation results to ensemble-averaged measurements (e.g. multi-injection-averaged spray penetration, local droplet Sauter mean diameter, vapor concentration in a plane). In practice, however, RANS simulations and ensemble-averaged measurements will differ for several reasons, e.g. the limited number of droplets tracked in the simulations, the fidelity of the submodels, the spatial and temporal resolutions of the experiment and the simulation, and the uncertainty of the measurements (including statistical convergence [310, 311]). As a result, the agreement that can be expected between RANS and ensemble-averaged measurements tends to become poorer as the level of stochastic fluctuations about the mean increases (e.g. a free spray under controlled temperature and pressure conditions in a quiescent chamber versus a spray in the dynamically varying, geometrically complex and turbulent environment of an IC engine).

Large-eddy simulation (LES) retains more of the flow structures, eddies and vortices induced by the non-linearities in the conservation equations than RANS simulation. This is especially important for the vapor phase, which, as mentioned earlier, generally exhibits much more spatial structure and variability than the liquid phase. In LES, the equations of motion are spatially averaged or filtered on a scale that is comparable to the numerical grid resolution. The sub-grid-scale models for turbulence, scalar mixing, etc, are appreciably simpler than their RANS counterparts since more of the flow physics is resolved on the computational grid [5, 8]. Because they retain more detailed flow structure, individual LES realizations typically look a lot like individual experimental realizations. Unfortunately, quantitative comparisons on a statistical basis typically just average the LES and experimental results over multiple realizations to produce ensemble-mean and rms quantities. As noted earlier, ensemble averaging washes out the detailed flow structures that are seen in individual experimental and LES realizations. Furthermore, computational and experimental constraints often limit the number of realizations to substantially fewer than the minimum of \(\approx 100\) samples needed to approach reasonable statistical convergence [310, 311]. The question of whether there are more informative ways to compare experiment and LES remains open.

Neither RANS nor LES simulations resolve the full range of spatial scales or the huge number of droplets in most real sprays. Typical computational grids span a length-scale range \(\approx 10^{-2} - 10^{3}\), whereas the physical scales (taking the Kolmogorov scale or the droplet size as the minimum) span a range \(\approx 10^{-3} - 10^{5}\). A passenger-car engine at moderate load may inject \(\approx 10^7\) droplets of fuel per cylinder per cycle (\(\approx 15\) mm\(^3\) of fuel dispersed into \(\approx 15\) \(\mu\)m diameter droplets). RANS and LES spray simulations typically perform Lagrangian tracking of \(\approx 10^3 - 10^4\) representative parcels (sometimes called stochastic parcels or computational droplets) that represent a group of...
physical droplets that experience the same local environment. Quantities affecting the parcels (e.g. local temperature) or generated by the parcels (e.g. vapor) must be interpolated from or to the Eulerian grid. By definition, then, the Lagrangian representative-parcel-tracking approach legitimately applies only to volumetrically dilute regions of a spray [5]. Recent LES studies of sprays include [8, 189, 312–315].

Direct numerical simulation (DNS) and LES both come to grips with stochastic flows at a more fundamental level than RANS simulations. Indeed, DNS seeks to resolve all the relevant scales in space and time. For sprays, however, resolution is always inadequate at phase interfaces during topological changes (e.g. rupture of thin liquid sheets during atomization). The problem here is that material properties change on scales down to the molecular mean free path, which is orders of magnitude smaller than the Kolmogorov scale and the smallest droplets [5, 308, 316]. These interfacial processes therefore require some modeling (e.g. [317]), and spray DNS is arguably better referred to as high-resolution simulation (HRS) [318]. DNS/HRS is extremely demanding of computational resources and is typically restricted in the size and geometric complexity of the spatial-temporal domain. Recent examples of near-field spray phenomena simulated with DNS/HRS include [6, 319–321].

The CPU times for RANS, LES and DNS/HRS computations depend strongly on their spatial and temporal resolution and on the complexity of the submodels for non-resolved processes. Typically, LES and especially DNS/HRS use many more grid points than RANS. Very roughly, for a single spray event, an ‘engineering’ LES computation that employs well-constructed submodels may need only slightly more time than a RANS simulation [8], while a higher-resolution ‘scientific’ LES computation may need one to two orders of magnitude more CPU time. A DNS/HRS computation can easily consume four or more orders of magnitude more CPU time than a RANS simulation [318].

5.4.1. Compare the same quantities. One important issue for effective comparison of experiment and simulation is to compare the same physical quantities. This sounds trivial—even ridiculous—when stated so baldly, but in fact it is not, even for a traditional macroscopic quantity like liquid-phase penetration [14], which continues to be used for comparison even with high-resolution LES simulations. For example, in [225], simulated and measured liquid- and vapor-phase penetration were compared quantitatively for a vaporizing diesel spray under transcritical conditions, whereas a single LES realization of the vapor distribution was compared visually to a few single shots of the vapor distribution measured quantitatively by Rayleigh scattering.

The criteria used to locate the spray tip in the simulation and the measurement are often not directly comparable. For example, a small fraction of the maximum liquid density in the simulation (which can be uncertain because of the relatively small number of spray parcels near the tip) may be compared to a small fraction of the maximum measured optical extinction or scattered-light intensity. In schlieren imaging, which depends on refractive-index gradients, the liquid and vapor phases become more difficult to distinguish as the liquid phase becomes more disperse. Although the two phases can sometimes be distinguished by eye, automated image analysis to identify their boundaries is not simple, nor is it simple to estimate the vapor concentration or mass fraction that corresponds to the schlieren boundary for comparison with simulations [47, 322].

A common way to depict the liquid phase in RANS and LES simulations is with a droplet parcel plot, i.e. a line-of-sight overlay of all the droplet parcels. This gives a measure of the boundary of the liquid distribution, subject to uncertainty due to the limited number of droplet parcels near the boundary. However, visual comparison of parcel plots with experimental spray images to assess the liquid distribution can be misleading because the droplets overlap in the denser regions, and the eye responds very differently to this pattern than it does to, e.g., a back-illuminated (extinction) image. Comparing droplet parcel plots to planar Mie-scattering or LIF images is even less warranted. CFD also readily yields 3D isosurfaces of, say, vapor concentration or mass fraction, but 3D isosurfaces are rarely available from experiments.

We urge our modeling colleagues to expend the extra effort needed to post-process their simulation results to render quantities that are more directly comparable to experimental results. For example, for comparison with planar Mie-scattering, post-process the simulation to evaluate the distribution of total droplet surface area within the corresponding plane. Similarly, render the distribution of total injected mass (liquid plus vapor) in a plane to compare with planar LIF. Evaluating the local droplet surface area per unit volume would allow quantitative comparison with planar extinction tomography measurements [34].

5.4.2. Simulate the experiment. Even when comparing the same physical quantity, experimental results may be subject to systematic effects such as laser-sheet extinction or the temperature dependence of LIF or LIEF, and measurements to quantify or correct the resulting bias may not be available. A 3D CFD simulation typically produces vastly more information (in space, time and number of physical quantities) than an experiment—even with multiple diagnostics. These observations suggest that more effective experiment-simulation comparison can result from extending the CFD model to simulate the experiment, or at least critical aspects of it.

For example, to compare with spray penetration measurements by diffuse back-illumination imaging, Magnotti and Genzale [303] are incorporating detailed Mie-scattering calculations into a RANS simulation framework to evaluate the optical extinction signal using the droplet diameter, number density and liquid volume fraction distributions predicted by the representative droplet parcel model. A generally similar approach has been taken in an LES simulation to calculate the 2D extinction-coefficient distribution for comparison to SLIPI measurements in a diesel spray [314]. To assess high-resolution LES modeling of cavitation, Duke et al [7, 56] simulated x-ray absorption measurements of the vapor distribution within the nozzle by propagating several thousand rays through the calculated fuel distribution.
Planar LIF and LIEF images are temperature dependent through the absorption and emission spectra of the fluorescent species. Spatially and temporally resolved experimental data on the local temperature within the spray are only rarely available [87, 146, 147]. In their absence, one approach would be to use calibration measurements of the temperature dependence of the fluorescent signals together with a 3D CFD spray simulation to render a hybrid LIF or LIEF image in which the simulated temperature field is used to ‘correct’ the measured fluorescence image. Thermodynamic mixing models have been used to apply this scheme to LIEF measurements of vaporizing diesel sprays with less computational effort than a full 3D simulation [114, 115].

A different reason to simulate the experiment is to understand in greater detail and to optimize the experiment itself. Monte Carlo simulations of photon propagation in optically dense media, recently accelerated using graphics processing units [228], have been used extensively in developing ballistic imaging and SLIPI [4, 227]. Less highly detailed simulations have been used to understand the characteristics of x-ray absorption and phase-contrast imaging of sprays [4].

5.4.3. Compare early and often. ‘Model validation’ is often given as a reason for experimental measurements. Unfortunately, validation is sometimes claimed after comparison of a few simulated results for a limited set of quantities (often macroscopic, such as spray penetration). In our view, rigorous model validation needs to be an ongoing and systematic partnership rather than an occasional interaction. Documentation of experimental conditions and uncertainty is also critical [2, 5].

Our experience suggests, furthermore, that the most effective approach to spray engineering is to focus experiments and simulation on the same problem and to compare the results and insights frequently. Clearly, this—like model validation—is an activity between consenting adults that requires substantial commitment of both parties.

5.4.4. Coordinate the efforts and share the wealth. Even a cursory look through this article shows a wide variety of measurement techniques available—many of them commercially—to characterize sprays. Unfortunately, the variety of techniques and test conditions has led to wide variability in measurements even for the same or closely similar spray systems [2]. One approach to decreasing this variability is to establish agreed-upon best practices. For example, based on several years of round-robin testing and committee discussion, a comprehensive set of spray-parameter definitions, measurement practices and test conditions has been recommended to characterize gasoline sprays in the worldwide automotive engineering community [26].

A complementary approach that includes numerical simulation as well as systematic application of conventional and advanced diagnostics is the Engine Combustion Network (http://www.sandia.gov/ecn/index.php) [323]. This growing research collaboration, coordinated by Sandia National Laboratories, provides an ongoing international forum for experimental and computational research on high-pressure fuel sprays. Goals include the accumulation of extensive data sets from thoroughly documented experiments on standardized injectors under standardized conditions, as well as systematic comparison with simulations. Activities include monthly teleconferences and periodic meetings with remote access and proceedings archived on-line.

Neither of these efforts toward coordinated application of complementary techniques quite reaches the extent of Bachalo’s bold vision of extensively equipped, internet-linked strategic laboratories conducting highly automated measurements with simultaneous diagnostics, all coupled directly into detailed numerical simulations [2]. Even apart from the experimental difficulties, organizing such an effort and commandeering the necessary resources would be most challenging.

Directionally, however, Bachalo’s vision remains laudable. Undoubtedly, simultaneous measurement of multiple spray characteristics and closer coupling with numerical simulation can yield new and valuable information on the fundamental couplings and nonlinearities that make fluid mechanics in general and spray physics in particular so challenging.

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