Synchronization of a laser diffraction drop sizing technique with intermittent spray systems

K. D. Kihm and J. A. Caton

The authors are with the Combustion and Fuels Research Laboratory, Department of Mechanical Engineering, Texas A&M University, College Station, Texas 77843-3123.

Received 17 June 1991.
0003-6935/92/121914-03$05.00/0.

A precise synchronization scheme for a laser diffraction technique (Malvern system) is developed by employing laser light extinction as an instantaneous trigger source.

One of the most acceptable techniques for particle and drop size measurement in diverse engineering applications is based on the Fraunhofer diffraction principle, in which measured diameters generally range from one to several hundred micrometers. The Fraunhofer diffraction pattern of incident laser light provides the basic relationship between measured light energy and the size distribution of scatterers.[1] Many scientists and engineers have practiced the application of this technique to various spray systems, mostly steady and continuous sprays, and the measurements have been made by allowing the instrument to have a specified number of sweeps of data. In applying this technique to intermittent and developing sprays (such as Diesel injector sprays), however, a precise synchronization of the data acquisition is essential to obtain properly resolved size information both in space and time. A free-running integration of the spray characteristics gives a smoothed-out result of little use.

For providing synchronization of data collection with arrival of the spray several techniques exist. A simple technique, for example, can be designed to use the injector lift signal as a trigger source and specify a time delay in an attempt to match the arrival of the spray with data collection. The amount of time delay must be determined by estimating the time required for the spray to penetrate the distance between the nozzle exit and the location of the laser beam. The determination of delay time in this configuration must be obtained essentially by a trial-and-error procedure but, because of spray-to-spray differences in their penetrations, good accuracy in the synchronization will never be achieved.

Another scheme, as suggested by Malvern Instruments, Inc., Southborough, Mass., is to employ a separate infrared sensor to detect the presence of a spray and to generate a trigger signal. The infrared sensor beam cannot be positioned at the same location as the Malvern beam because of optical and geometric difficulties. This technique again needs to specify the time delay that compensates the spray penetration time from the infrared beam of the sensor to the laser beam of the Malvern instrument. Since penetration and development characteristics of individual sprays may vary from one spray to another in a pulsed-spray system, a measurement that employs this sensor technique is not capable of ensuring precise and consistent synchronization. The technique does not have proper control on the phasing of the measurement with spray development, i.e., the system will be triggered whenever the infrared beam is occupied by the spray despite its extinction level.

Here a synchronization technique without the need of a delay time estimate is designed and tested with a simple pulsed-spray system. Light extinction of the laser beam of the diffraction technique is used simultaneously as a source for feed-back triggering. The data-acquisition unit is automatically activated whenever a spray penetrates the laser beam and increases the extinction above a specified reference level. The relative measurement location with respect to a developing spray can be identified as the position in a spray in which the measured extinction matches the reference level. For combusting sprays the most crucial drop sizes are often located near the spray tip where ignition starts. For ensuring the drop size measurement at the spray tip the relative measurement location must be identified instantaneously. This is achieved with the present synchronization technique. The absolute measurement location is determined by the laser beam location that is measured from the nozzle exit.

For intermittent spray applications the data-taking initiation must be accurately triggered to ensure proper phasing. The Malvern takes data from all 31 ring diodes (30 diodes for particle sizing and one center diode for the extinction measurement), in parallel, in 10 μs. An additional 35 ms is required to send these data serially to the memory of a microprocessor and, therefore, a holding time of more than 35 ms is necessary to complete one sweep of data acquisition before the system becomes ready for another sweep of data acquisition. A modification of the Malvern data-acquisition computer program, which was first attempted by the authors, cannot provide a precise synchronization since such a synchronization technique would have at least a 35-ms time lag of the trigger signal processing. The duration of an individual spray in many practical cases, such as Diesel sprays, is shorter than 35 ms (see Ref. 2) and by the time the software sends a feedback signal to initiate data receiving the spray the spray itself is no longer present. Real-time analog signals, therefore, must be used to attain physically meaningful synchronization of the instrument. The maximum frequency of pulsed sprays that can be measured with the present synchronization scheme is limited to less than 30 Hz. At higher rates some pulses are ignored since the detector unit is locked so as to keep the information transfer rate at the nominal 35 ms.

An automatic synchronization for the initiation of data taking has been devised by monitoring the extinction signal (Fig. 1). Extinction is defined as $(1 - e/e_0)$, in which e and e_0 denote the amount of the light energy detected by the center diode with and without spray, respectively. A zero extinction indicates that no spray is present in the beam passage, and an extinction of 100% means that the laser beam is completely scattered by a spray and no light can reach the center diode. The analog voltage that corresponds

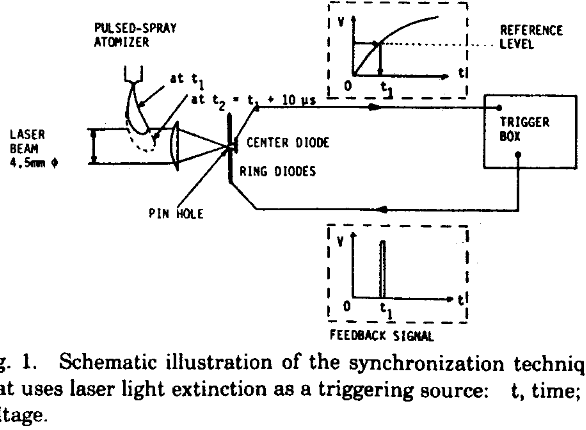

Fig. 1. Schematic illustration of the synchronization technique that uses laser light extinction as a triggering source: t, time; V, voltage.

to an instantaneous extinction level is sent to a specially designed trigger box, which sends a signal (5-V square pulse) back to the (30) ring diodes for data-taking initiation only if the instantaneous extinction exceeds the reference level. The reference level can be adjusted to identify a relative measurement location that corresponds to a specific extinction level. The time lag for signal processing through this analog electric circuit is far shorter than the 35-ms time lag, which would be necessary for software-controlled triggering.

For most sprays, for the 10-μs duration of data taking, the spray will proceed through the laser beam a short distance and this contributes to the spatial uncertainty of the measurement volume. (For a spray at a speed of 100 m/s, for example, one 1-mm penetration occurs during data taking and the measurement location is determined within 1 mm.) After one sweep of data taking, the trigger unit is locked until a new extinction signal is detected from the next spray. This was devised to avoid undesirable multi-sweepings for a single spray, which could deteriorate the measurement resolution by averaging out the data measured at several different relative locations that yield possibly the same extinction in the spray.

Example measurements were made for water sprays intermittently generated from an air-blast paint spray atomizer. Results are presented as functions of the reference extinction for two different liquid flow rates in Fig. 2. The measurement was made on the spray axis at 250 mm downstream from the nozzle exit for all data. The Sauter mean diameter (SMD) is defined as the diameter of a drop that has the same volume–surface ratio as the entire sample, i.e., $\Sigma_i N_i D_i^3 / \Sigma_i N_i D_i^2$, where N_i represents the number of concentration of drops of diameter class D_i. Each data point represents the average result of 10 pulsed sprays. As the relative location of the measurement volume recedes from the spray tip the spray becomes denser and the extinction is increased. The dependence of the relative measurement locations on different extinction levels is schematically illustrated in Fig. 2. The data obtained near zero extinction represent the mean diameters of drops sampled at the tip of the spray, where the drop concentration is expected to be low. The reason for smaller drop diameters at low extinction is believed to be because of high evaporation and vapor diffusion occurring near the spray tip. As the relative measurement location recedes from the spray tip by increasing the level of the reference extinction, the mean diameter increases gradually to a constant value. The data point measured with the highest extinction in each curve was obtained without synchronization, i.e., the measurement was done for a single steady spray that bypassed the synchronization logic.

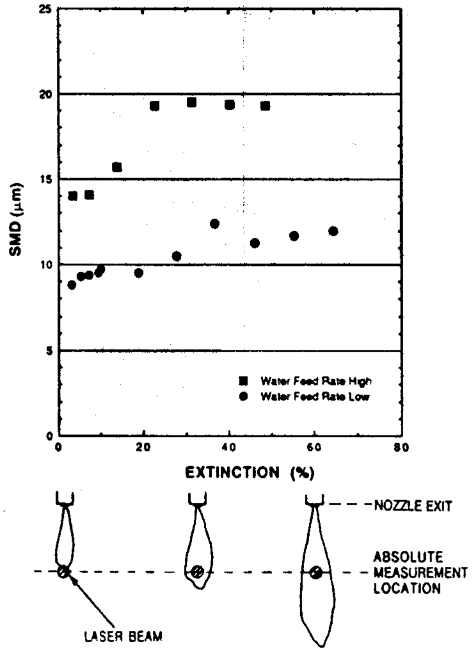

Fig. 2. SMD's measured for intermittent water sprays generated from an air-blast paint spray atomizer with a varied reference extinction level.

Figure 3 presents a comparison of the volume fraction distributions of drop diameters for two limiting cases measured at zero and at maximum extinction for the case of a higher water flow rate. The value of the SMD is 14 μm for the data obtained at the spray tip (white bars), and 19.3 μm at the maximum extinction. The drop diameter that corresponds to the highest volume fraction shifted from 27 to 35 μm as the extinction increased. Mean values as well as the spectra of drop diameter distributions of intermittent sprays can be strongly dependent on the relative location of the measurement. Therefore both the absolute and the relative locations of measurement must be carefully identified by instantaneously synchronizing the data taking with the extinction signal.

In addition we describe an improvement on spatial resolution of the instrument. The original 9-mm-diameter laser beam was too large for narrow sprays, such as fuel sprays of Diesel engines, to provide spatially meaningful data. The laser-beam diameter, which determines the spatial resolution, is reduced to half of its original size by rearranging the transmitting optics. The spatial resolution, which is determined by the cross-sectional area of the laser beam, has been improved by a factor of 4. Figure 4 presents a schematic illustration of reduction of the beam diameter by replacing the transmitting lens with one with a shorter focal length. The basic idea of the modification was suggested by Dodge.[3] The instrument was calibrated with a standard reticle.[4] The reticle consists of photographically etched circular images on a glass substrate and represents a model-independent distribution with a nominal median diameter of 46.5 μm. The volume median diameter (VMD) is measured to be 46.7 and 47.7 μm for 9- and 4.5-mm beams, respectively, and both VMD's are within the allowable uncertainty range of ±3% from the nominal value.

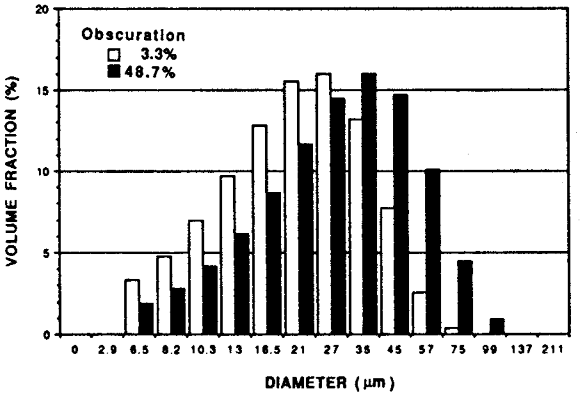

Fig. 3. Volume fraction distributions as functions of drop diameters for two different extinction levels.

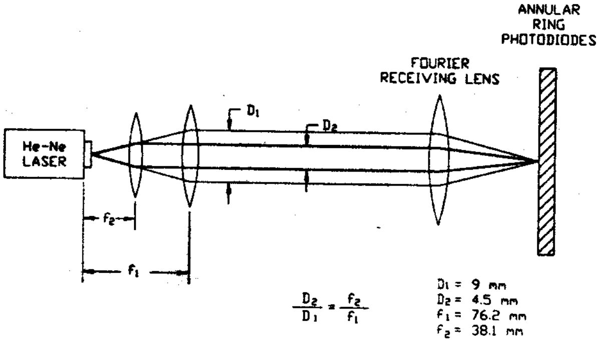

Fig. 4. Illustration of the beam diameter reduction of the Malvern instrument.

Values of the SMD measured for the reticle remain consistent within 1% (from 40.5 to 40.7 μm) as the beam diameter is reduced from 9 to 4.5 mm.

The small discrepancy between the two calibration results is believed to be caused by different waist diameters at the detector plane as the incident-beam diameter is changed. A simple consideration of geometrical optics[5] can give an expression for the waist-beam diameter d as a function of incident-beam diameter D, i.e., $d = (5\lambda f)/(\pi D)$, where λ represents the wavelength of the beam (632.8 nm for the He–Ne laser used) and f denotes the focal length of the receiving lens (300 mm for the present configuration). These diameters d and D are defined as diameters of the inner region where the light intensity has decreased to 0.1% of the center intensity. From this relationship the waist diameter is calculated to be 33.6 and 67.1 μm for beam diameters of 9 and 4.5 mm, respectively. When the beam diameter is reduced the original pinhole of 35 μm located at the focal point is not able to transmit the enlarged beam waist to the center diode, which is located right behind the pinhole (Fig. 1). The outer portion of the beam waist that is larger than the pinhole can be detected as false light energy by the ring diodes near the pinhole and can enhance the background noise level. Although a proper zero setting can provide compensation by subtracting the noise from the actual sampling nonlinear factors may result in a slight discrepancy in the calibration. Enlarging the pinhole to be slightly larger than 67.1 μm allows the entire beam waist to reach the center diode and may contribute to reducing this discrepancy. The extinction reading, nevertheless, is not affected since the ratio of the light energies e/e_0 is unaltered even if the individual values of the two energies may be lowered as the bean diameter is reduced.

The authors gratefully acknowledge the assistance of George Zicterman, a former undergraduate student at Texas A&M University, in designing and testing the electric circuit for the trigger box. The research was conducted with financial assistance from U.S. Department of Energy–Morgantown Energy Technology Center, Nashville, Tenn. contract DE-AC21-88MC23174 through subcontract L66-916987-09 from General Electric, Erie, Pa.

References

1. H. G. Barth, *Modern Methods of Particle Size Analysis* (Wiley, New York, 1984), Chap. 5, pp. 135–172.
2. J. A. Caton, K. D. Kihm, A. K. Seshadri, and G. Zicterman, "Micronized-coal-water slurry sprays from a Diesel engine positive displacement fuel injection system," in *Proceedings of the Spring 1991 Technical Meeting of the Combustion Institute/Central States Section*, A. M. Mellor, ed. (Combustion Institute, Nashville, Tenn., 1991), pp. 361–366.
3. L. G. Dodge, Southwest Research Institute, San Antonio, Texas 78228 (personal communication, 1990).
4. E. D. Hirleman and L. G. Dodge, "Performance comparison of Malvern instrument laser diffraction drop size analyzers," in *Proceedings of the Third International Conference on Liquid Atomization and Spray Systems* (Institute of Liquid Atomization and Spray System, Tokyo, 1985), paper 8564, pp. 1–14.
5. F. Durst, A. Melling, and J. H. Whitelaw, *Principles and Practice of Laser-Doppler Anemometry*, 2nd ed. (Academic, London, 1981), Chap. 4, pp. 116–126.