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Coal-Water Slurry Atomization Characteristics

Authors:
J.A. Caton
K.D. Kihm

Contractor:
GE Company
2901 East Lake Road, Bldg. 14-2
Erie, PA 16531

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CONTRACT INFORMATION

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Contractor	Texas A&M Research Foundation P. O. Box 3578 College Station, TX 77843-3578 (409) 845-4705
Contractor Project Manager	Dr. Jerald A. Caton
Principal Investigators	Dr. Jerald A. Caton Dr. Kenneth D. Kihm
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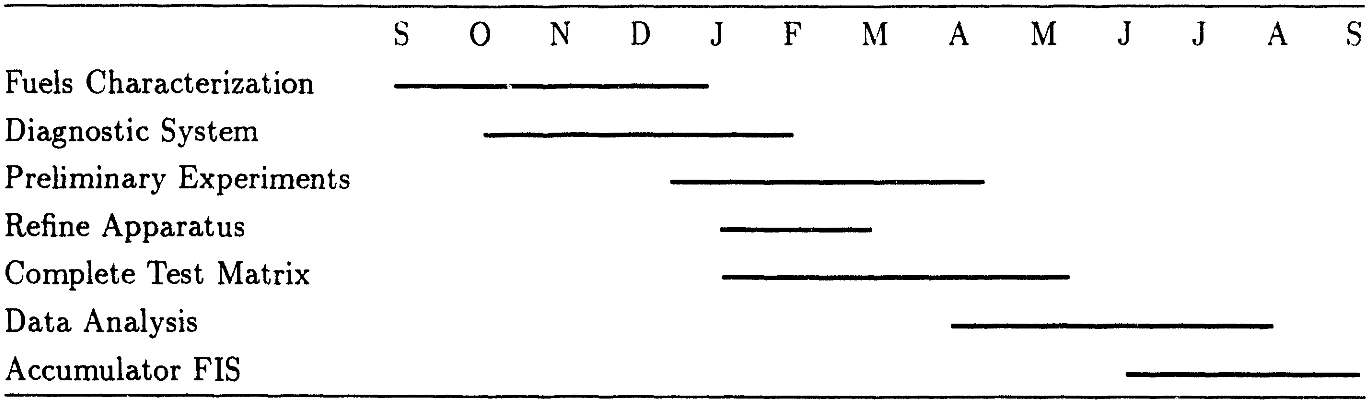

OBJECTIVES

The overall objective of this work was to fully characterize the CWS fuel sprays of a medium-speed diesel engine injection system. Specifically, the spray plume penetration as a function of time was determined for a positive-displacement fuel injection system. The penetration was determined as a function of orifice diameter, coal loading, gas density in the engine, and fuel line pressure. Preliminary droplet information also was obtained.

BACKGROUND INFORMATION

The successful development of a CWS fuel injection system is needed to assist the commercial development of engines which can operate with coal [1–3]. A successful commercial fuel injection system must (1) provide good fuel atomization with appropriate fuel penetration and (2) be tolerant of CWS fuels (*i. e.*, possess repeatability and durability). To progress in both these areas, fundamental information is needed on the fuel injection process of CWS fuels.

This paper is a description of a research project which is a sub-contract to General Electric [4–6] and which will result in the characterization of CWS fuel sprays as a function of operating conditions and fuel specifications. The results of this study will assist CWS engine development by providing much needed insight about the fuel spray. In addition, the results will aid the development and use of CWS engine cycle simulations which require information on the fuel spray characteristics [7–9]. For successful cycle simulations, the evolution of the fuel spray geometry, droplet sizes, and droplet size distributions are needed as a function of time for a variety of operating conditions and fuels.

In a diesel engine injector, the pressurized liquid fuel is the primary source of energy that produces the spray. Atomization is a result of jet instability due to the relative velocity of the liquid and ambient gas. This type of injector is categorized as a single fluid pressure atomizer, in contrast to the air-assist atomizer where pressurized air is the primary source of energy for atomization. In pressure atomizers, atomization quality is controlled by the injector design, fuel properties and injection pressure. For diesel engines, the fuel spray is injected into a confined combustion chamber that is under high pressure and high temperature conditions. Thus, the background air conditions are additional factors that affect the atomization quality of diesel engine injectors.

The first known study that included at least an attempt at characterizing a coal-slurry spray from a diesel engine injector was reported by Phatak and Gurney [10]. They obtained partial data on droplet size distributions from an experimental, air blast injector using coal-diesel (instead of coal-water) fuel slurries (20 or 40% coal by mass). Only limited data were reported, but they did show that for at least one operating condition, 80% of the fuel spray mass had droplet diameters of less than 20 μ for the air blast nozzle for one location and at one time. Nelson *et al.* [11] obtained both shadowgraphs and droplet size distribution data for CWS from engine injectors. The fuel injector was a modified 6 hole (0.35 mm dia) pencil nozzle (Stanadyne Roosa) with nozzle opening pressures of 800 and 2000 psig. For diesel fuel, 80% of the mass had droplet diameters less than 100 μ; whereas, for coal-water slurry, 80% of the mass had droplet diameters less than 400 μ. These results were for one location (1.25 inches from the nozzle tip) and for one time (0.5 ms after the spray tip passed). An air blast version of the nozzle showed improved (smaller droplets) performance. For both fuels, 80% of the mass had droplet diameters less than about 30 μ.

Yu *et al.* [12] have reported the most complete study to date. They used a pneumatic, single-shot fuel delivery system and the injector was a pintle nozzle with injection pressures from 10000 to 25000 psia (70 to 170 MPa). The fuel was injected into a constant volume chamber which contained pressurized room temperature gas with a density of 17.5 kg/m^3. Yu *et al.* [12] used a laser diffraction size analyzer with a 9 mm diameter laser beam. They examined two coal loadings (53 and 48% coal by mass) and three nozzle tip geometries, and reported their results as a function of injection velocity, fuel jet penetration distance, light transmission through the fuel spray, and mean droplet size. Average fuel injection velocity ranged from 220 to 450 m/s. They reported Sauter mean diameters (SMD) for the CWS of 25 and 54 μ for their limited tests.

PROJECT DESCRIPTION

Experimental Facility

Figure 1 shows the overall injection facility for this experiment which incorporates two fuel systems: one provides the diesel fuel used by the jerk-pump and the second provides the fuel, either diesel or slurry, which is injected by the nozzle. Figure 1 also shows the mechanical drive system which uses an electric motor to drive a cam. Attached to the drive shaft is a large (325 lbm) flywheel which minimizes variations in the rotational speed of the cam. The cam-follower mechanism translates the rotation of the cam into the reciprocating motion needed by the jerk-pump.

The high-pressure fuel system comprises: (1) the jerk-pump, (2) the diaphragm pump, (3) a check valve mounted on the diaphragm pump, and (4) the injector nozzle. The jerk-pump is a Bendix fuel pump which is used on many types

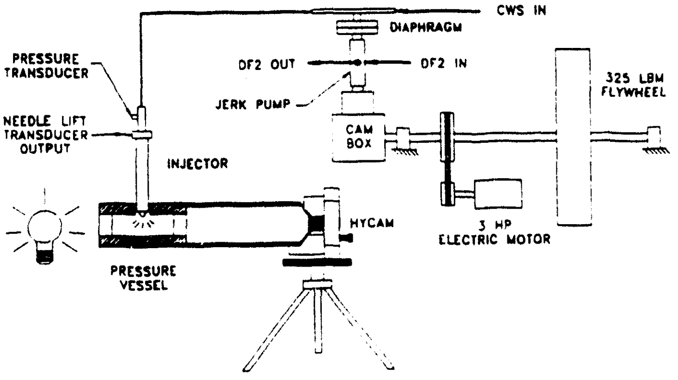

Figure 1. Injection Facility Schematic

of medium-speed diesel engines. The only modification to the pump is the addition of a diesel fuel outlet passage which enables the diesel fuel to circulate through the jerk-pump. A stainless-steel diaphragm has been inserted between the jerk-pump and the injector nozzle. This design is similar to that used by Leonard and Fiske [13]. The system operates in the same way as the conventional system except that in the modified system the diesel fuel which is forced out of the jerk-pump is used to increase the pressure on one side of the diaphragm. The pressure is transferred through the diaphragm to the CWS side of the pump—this forces CWS down the fuel line and into the injection nozzle. The purpose of the diaphragm is to isolate the jerk-pump from the abrasive coal particles by using diesel fuel on the jerk-pump side and coal-water slurry on the nozzle side.

For the results reported here, the nozzle tips had only one hole. Although the full displacement of the jerk pump was utilized, fuel line pressures were representative of multi-hole nozzles. This was because the volume of the overall injection system was significantly increased due to the diaphragm and additional pipe length. Actual applications have minimized this additional length to accomodate multi-hole nozzles [4–6].

Figure 2 shows a schematic of the nozzle, a Bendix injector, which is used on medium-speed diesel engines. Modifications to the nozzle have been limited to the installation of a needle lift transducer, increasing clearances in the needle valve assembly, and the use of custom nozzle tips. The fuel pressure is measured by the use of an in-line strain gauge pressure transducer.

The custom nozzle tips allow the use of various nozzle tip geometries with various numbers and sizes of orifices. Figure 3 shows a schematic of the nozzle tip geometry. Three sizes of single hole nozzle tips, listed in Table 1, were prepared for this study. As shown, the holes had a sharp-edged exit and a length-to-diameter ratio of 8. Although the details of the nozzle tip geometry are important in affecting the spray [14], this aspect was outside the scope of the present study.

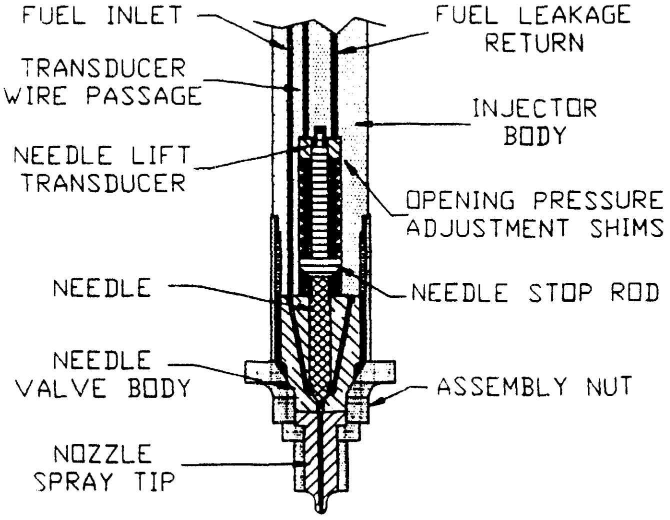

Figure 2. Injector Nozzle Schematic

The nozzle holes were obtained by electro-discharge machining (EDM). Figure 4 is a scanning electron microscope photograph of the hole. The size of the hole was determined from such SEM photographs.

The final aspect of the injection facility is the pressurized chamber. In one direction the fuel spray was directed while in the perpendicular direction visualization of the spray was possible through high pressure windows. The spray was back-lighted through one window and photographed through the other. High-speed (11,000 frames/sec), 16 mm movies of the spray

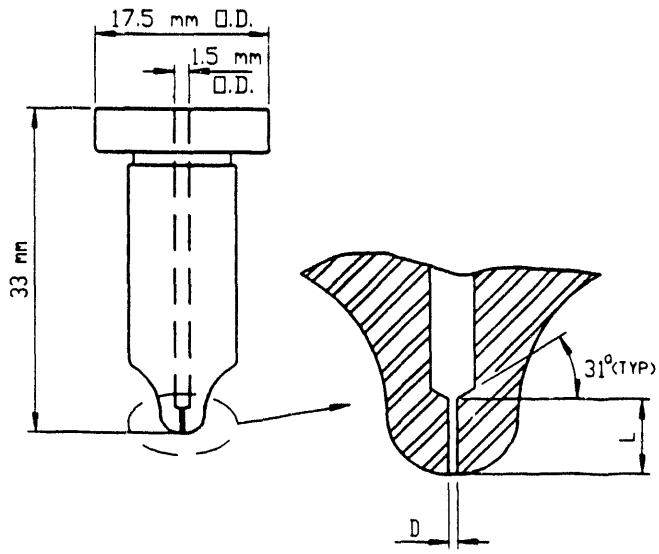

Figure 3. Nozzle Tip Schematic

Table 1. Nozzle Tip Hole Sizes

Nominal Diameter(mm)	Measured Diameter(μm)	Measured Diameter(in)
0.2	230	0.0091
0.4	380	0.015
0.6	570	0.022

and high-resolution still photography using a high intensity microflash were obtained. For the droplet size measurements, a Fraunhofer diffraction technique was used. The instrument, manufactured by Malvern, Inc., was modified to provide synchronization with the spray and better spatial resolution. These modifications are described below in the Results section.

Experimental Procedures

The experimental procedure included the following steps. First, the cam shaft was accelerated to a steady state speed of 525 rpm. The rack was pulled to a predetermined position and injection would begin. The movie camera was started and an electronic trigger signal was sent to the data acquisition system when the speed of the film was greater than about 3000 frames per second.

Experimental Test Matrix

Table 2 lists the major experimental test parameters which were investigated. The base case was the following set of parameters: 50% CWS, 0.4 mm diameter nozzle tip, full rack position (30 mm), and a chamber density of 25 kg/m^3 (which corresponds to the full load conditions of the GE locomotive engine [4–6]). The parameters which were varied were selected to represent the important features of the injection and atomization process. The fuels investigated included three additional concentrations of coal, water and diesel fuel. Two additional nozzle tip diameters were prepared: 0.2 and 0.6 mm. Rack positions of 10 and 20 mm also were studied. Finally, chamber density was examined at 1.2 and 17 kg/m^3 in addition to the base condition of 25 kg/m^3.

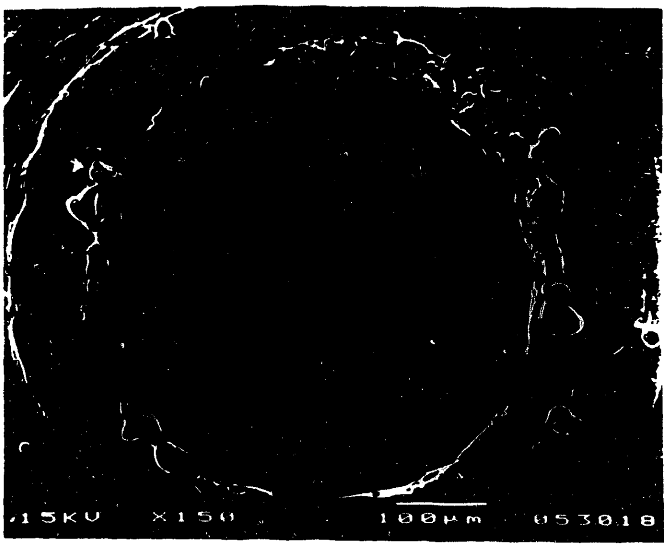

Figure 4. SEM of a Nozzle Tip Hole

RESULTS

Fuels Characterization

The basic slurry fuel was a commercially available coal-water slurry obtained from Otisca Industries. The details of this slurry have been reported elsewhere [4–6]. In summary, the base CWS contained 50% coal, 48% water, 1% lignosulphonate, and 1% Triton X-114. The coal used was a high-volatile subbituminous which was cleaned to less than 0.8% ash (on a dry coal basis) with a measured [15] Sauter mean particle diameter of 3.0 μ.

Several studies were conducted to better

Table 2. Experimental Test Matrix

Case	Fuel	Tip (mm)	Rack (mm)	Density (kg/m^3)
Base	CWM50	0.4	30	25
Fuels	CWM33 CWM43 CWM55 WATER DIESEL	0.4	30	25
Tip	CWM50	0.2 0.6	30	25
Rack	CWM50	0.4	10 20	25
Density	CWM50	0.4	30	1.2 17

(A) 0.16 msec (B) 0.32 msec (C) 0.48 msec (D) 0.64 msec

(E) 0.80 msec (F) 1.13 msec (G) 1.45 msec (H) 1.77 msec

Figure 5. Movie Frames of a Typical CWS Injection for the Base Case Conditions

characterize the CWS used in this investigation. These studies included particle size characterization using digitally processed images of scanning electron microscope photographs of dried CWS samples [15], settling properties [16], and viscosity [17]. These studies are continuing and will be reported in due course.

Spray Characterization

Figure 5 shows eight frames from a portion of a movie of one injection for the base case. The time between frames for this set of movie frames was about 0.16 ms. This particular set of frames was selected to illustrate the complete spray development within eleven frames. For detailed analysis, however, sets of frames were selected with film rates about twice as fast. Pointers at the left of each picture were 50 mm apart and served as a reference distance for the film analysis.

From these movie frames, spray propagation and development were determined. As shown, the propagation of the fuel jet is rapid at the start (pictures A-D). As the penetration of the fuel increases, the development of a head vortex is noted (picture E). The size of the head vortex increases due to additional fuel from the injector on one side (upstream) and due to entrained gas on the other sides. The final frame in this sequence (picture H) is representative of a fully developed spray for these conditions. Subsequent frames from this set had the same shape and character as picture H.

To complete the detailed analysis of the spray development, each movie set was traced using a motion analyzer. Figure 6 shows an example of the outline of the individual spray recordings for the base case conditions. For this set, the time between frames was 0.101 ms. These spray shapes are superpositioned on a scaled schematic of the piston bowl and cylinder wall locations. This schematic shows one spray plume; typically eight to twenty spray plumes would be used. Although not corrected for angle, the typical spray plume is directed downward toward the piston at a 15° angle. As shown, for this case, the fuel jet would impinge on the piston bowl about 1.5 ms after the start of injection. Typical ignition delays for these conditions are greater than 1.5 ms [4-6] and, hence, these results indicate that at least some fuel impingement occurs.

From the above spray outlines, the fuel jet penetration as a function of time was determined. Figure 7 shows the log of the fuel jet penetration distance as a function of the log of time for the base case. When plotted in this fashion, two distinct modes of spray development may be determined. The first mode is for an intact liquid core and, for constant fuel pressure, the fuel jet penetration is linear with time. This is shown in figure 7 by the dash line with slope equal to one. The second mode is for the spray after break-up of the liquid core. For this mode, penetration is proportional to time to the one-half power. In figure 7, this is represented by a dash line with slope equal to one-half. The intersection of the two lines represents the time of break-up. For the base case, this was about 0.4 ms. These results are consistent with results reported for diesel fuel sprays [18].

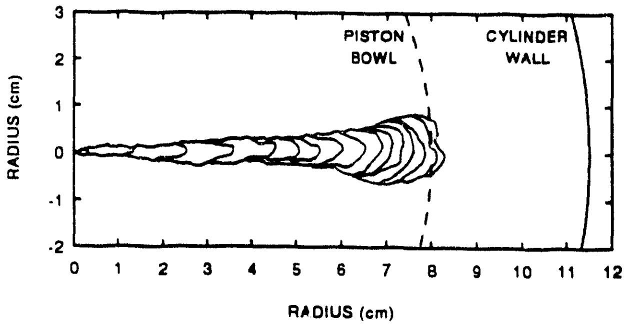

Figure 6. CWS Spray Penetration

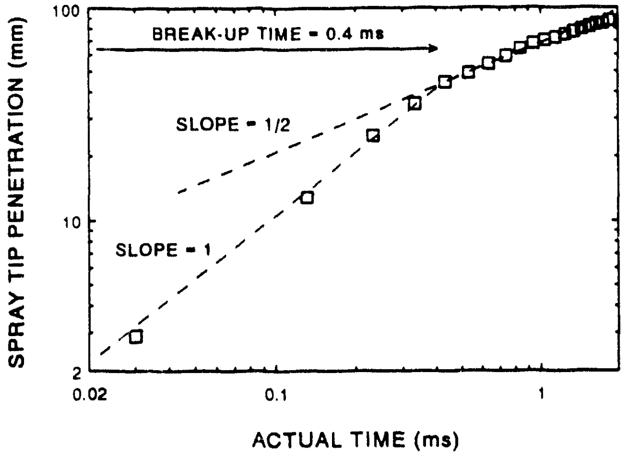

Figure 7. CWS Spray Tip Penetration

Figure 8 shows fuel jet penetration as a function of time for the base case CWS, diesel fuel and water. The dash lines are from the fits in figure 7. Note that all three fluids are well represented by the same power-law fits. This implies that the penetration and spray development are similar for the several fluids when injected at the same conditions. Additional results for other coal concentrations substantiate these findings. The one exception was for 55% (by mass) coal loadings. For this case, no successful injection was achieved. Loadings as high as 53%, however, were successful. This implies a highly nonlinear response of fuel injection with respect to coal loadings for coal loadings above 53%.

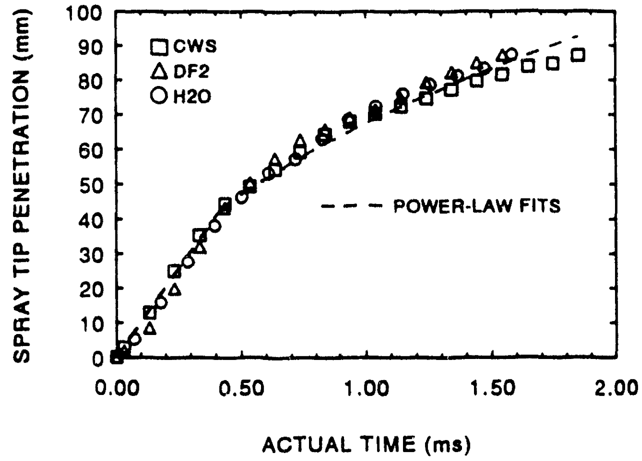

Figure 8. Spray Penetration of Three Fluids

Figure 9 shows the instantaneous fuel line pressure and needle lift as a function of time for the base case conditions. As shown, fuel pressure increases and when the pressure is about 29 MPa (4300 psia) the needle lifts. The pressure decreases slightly due to the start of injection and then continues to increase. The maximum pressure is 38 MPa (5600 psia) which occurs 3.0 ms after the start of injection.

The time period of most interest is from the start of injection to about 2 ms after the start of injection. During this time period, the spray plume may reach the piston bowl or cylinder walls. Figure 10 shows several parameters that were measured or computed during this early period as a function of time. The fuel line pressure is shown from figure 9 for reference. In addition, the exit velocities and penetration values are plotted.

From the fuel line pressures and a model based on work of Arai *et al.* [18], the spray tip penetration was computed. Although the correct fluid density of the CWS was used, the model [18] is based on diesel fuel injection. The agreement between the measured and computed values for penetration is good. Although preliminary, these results indicate that well atomized CWS fuel sprays may be similar to diesel sprays if the correct fluid properties are substituted and the correct fuel pressures are used. More work is planned on this topic.

To obtain instantaneous exit velocities, average coefficients of discharge (C_d) were determined. This was completed by the use of the instantaneous needle lift, fuel line pressure, total average mass of fuel injected and a simple incompressible flow model. Values of the coefficients of discharge depended on the fluid. For the base case conditions, the coefficients of discharge were 0.733, 0.843, and 0.797 for coal-water slurry, diesel fuel and water, respectively. As shown, the exit velocity increased rapidly to 120 m/s and then decreased slightly to 100 m/s.

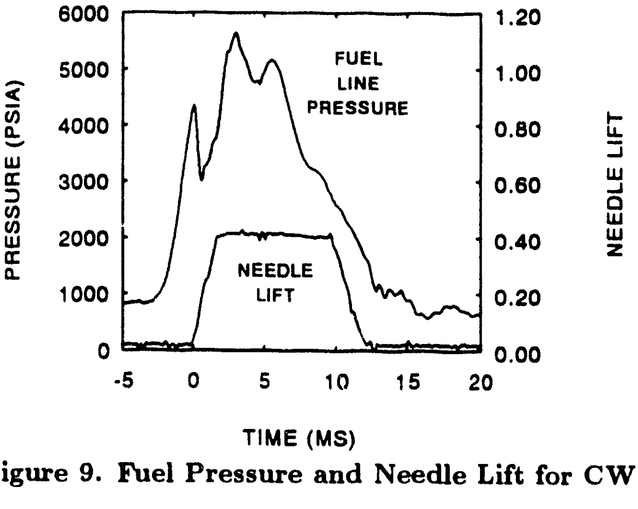

Figure 9. Fuel Pressure and Needle Lift for CWS

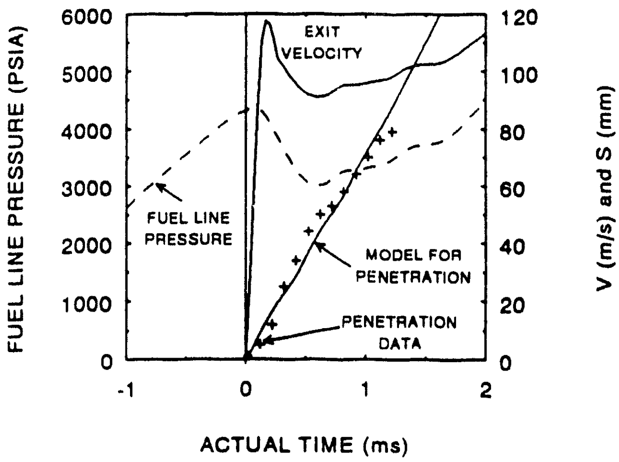

Figure 10. Penetration and Velocities for CWS

Additional results on the parametric effects of coal loadings, nozzle hole size, rack position, and chamber density on fuel jet penetration are available [19,20], but due to space limitations, can not be presented here.

Droplet Size Characterization

A set of preliminary measurements of droplet size for CWS sprays was completed using a laser-based diffraction sizing instrument manufactured by Malvern, Inc.

In using this instrument, one major concern was the spray-to-spray repeatability of the measurement since the laser beam was fixed and each spray does not evolve exactly the same. A synchronization technique, therefore, was developed [21] using light obscuration as an instantaneous trigger signal. Figure 11 is a schematic illustration of this technique. Whenever a spray penetrates the Malvern laser beam and increases the obscuration above a specified reference level, the data collection is automatically activated

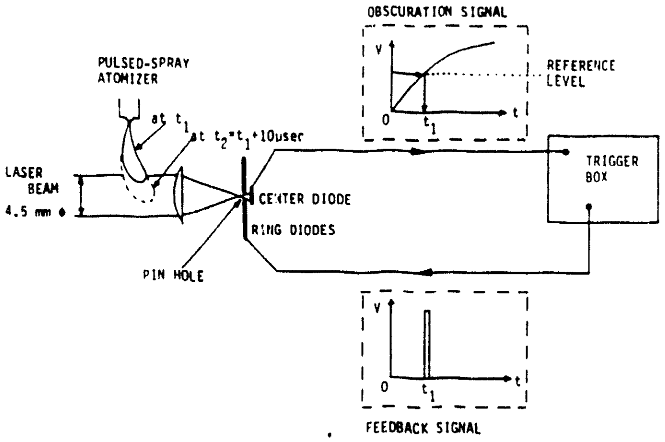

Figure 11. Synchronization Technique

for one sweep period of 10 μs. A single sweep-opening per spray is allowed for the data acquisition. For the current instrument, the maximum frequency of pulsed-sprays that is measureable with no skip is limited to less than 30 Hz since data processing requires 35 ms. In addition, the Malvern was modified to improve the spatial resolution by reducing the beam diameter by one-half to a diameter of 4.5 mm. This improved the spatial resolution by a factor of four [21].

Figure 12 shows preliminary results for the droplet SMD as a function of obscuration for CWS and water sprays for the base case conditions using the synchronization technique described above. For these preliminary tests, the sprays were injected into ambient conditions for simplicity. Future tests will be conducted using the pressurized chamber. The measurement location was 25 cm downstream of the nozzle tip on the centerline of the spray. At the bottom of the figure is a schematic representation of this measurement location for three different obscuration levels Each data point is the average of fifty sweeps of data (*i. e.*, fifty sprays). The obscuration is low at the spray tip and will increase as the spray passes through the laser beam. The obscuration of the CWS sprays ranged up to 92% whereas the maximum attainable obscuration for the water sprays was 36%.

As shown, the droplet SMD ranged between 15 and 50 μ depending on the location in the spray and on the fluid. The reason for smaller droplets near the spray tip at low obscurations is because of evaporation and diffusion of the larger droplets. As droplet concentration increases, the obscuration increases since the dense spray will scatter incident light rays more than dilute sprays. The decrease in SMD for the CWS as obscuration increases may occur as a result of multi-scattering at high droplet concentrations which tends to bias the droplet SMD to smaller sizes. Future data will be corrected by using formulas suggested by Felton *et al.* [22]. To aquire a more comprehensive understanding of CWS diesel sprays, detailed and extensive measurements will be completed as a function of injection conditions and fuels for the accumulator system.

FUTURE WORK

The major tasks remaining in this project include completion of the detailed analysis of the movies and fuel pressures associated with the test matrix for the positive displacement fuel

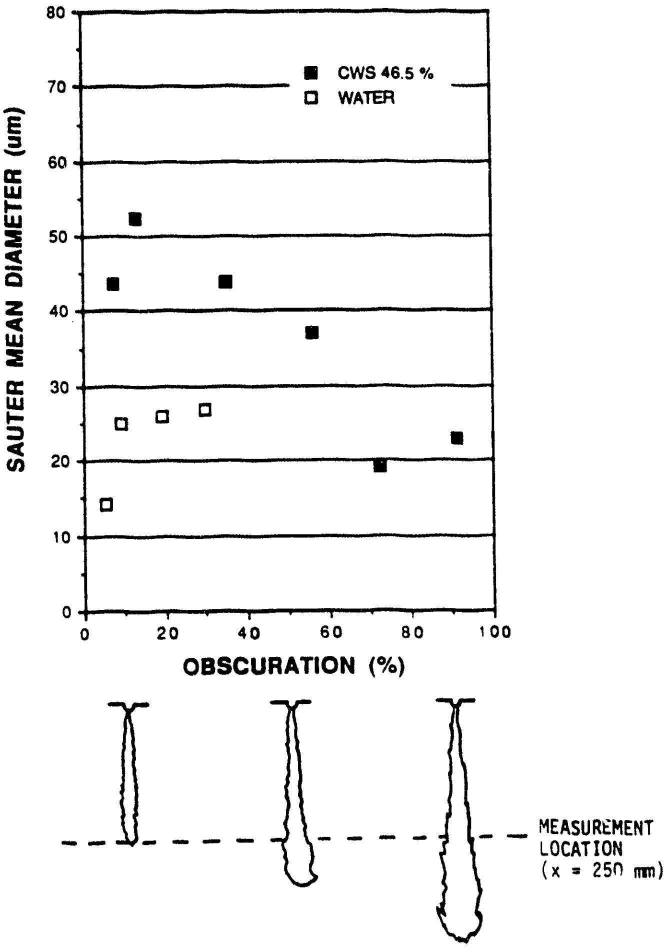

Figure 12. Droplet Diameters for CWS and Water

injection system. Current activities are directed at completing a similar set of experiments for the GE designed accumulator injection system [6]. In addition to the high-speed movies and fuel line pressures, detailed droplet size measurements and high-resolution still photography will be completed.

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