Coal-Water Slurry Spray Characteristics of a Positive Displacement Fuel Injection System

A. K. Seshadri

J. A. Caton

K. D. Kihm

Department of Mechanical Engineering,
Texas A&M University,
College Station, TX 77843

Experiments have been completed to characterize coal-water slurry sprays from a modified positive displacement fuel injection system of a diesel engine. The injection system includes an injection jerk pump driven by an electric motor, a specially designed diaphragm to separate the abrasive coal from the pump, and a single-hole fuel nozzle. The sprays were injected into a pressurized chamber equipped with windows. High speed movies and instantaneous fuel line pressures were obtained. For injection pressures of order 30 MPa or higher, the sprays were similar for coal-water slurry, diesel fuel, and water. The time until the center core of the spray broke up (break-up time) was determined both from the movies and from a model using the fuel line pressures. Results from these two independent procedures were in good agreement. For the base conditions, the break-up time was 0.58 and 0.50 ms for coal-water slurry and diesel fuel, respectively. The break-up times increased with increasing nozzle orifice size and with decreasing chamber density. The break-up time was not a function of coal loading for coal loadings up to 53 percent. Cone angles of the sprays were dependent on the operating conditions and fluid, as well as on the time and location of the measurement. For one set of cases studied, the time-averaged cone angle was 15.9 and 16.3 deg for coal-water slurry and diesel fuel, respectively.

Introduction

The use of coal as an alternate fuel is receiving renewed attention due to the diminishing supply of oil and its dependence on the political infrastructure. To assist the commercial development of coal-water slurry engines, the successful development of a fuel injection system is needed (Soehngen, 1976; Caton and Rosegay, 1984). A successful commercial fuel injection system must (1) provide good fuel atomization with appropriate fuel penetration and (2) be tolerant of coal-water slurry fuels (i.e., possess repeatability and durability). To progress in both these areas, fundamental information is needed on the fuel injection process of coal-water slurry fuels.

This paper is a description of a research project to determine the overall characteristics of coal-water slurry fuel sprays as a function of operating conditions and fuel specifications. The results of this study will assist coal-water slurry engine development by providing much needed insight about the fuel spray. In addition, the results will aid the development and use of coal-water slurry engine cycle simulations that require information on the fuel spray characteristics (Bell and Caton, 1988; Branyon et al., 1990; Wahiduzzaman et al., 1990). 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 (1985). 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 percent coal by mass). Only limited data were reported, but they did show that for at least one operating condition, 80 percent of the fuel spray mass had droplet diameters of less than 20 μm for the air blast nozzle for one location and at one time. Nelson et al. (1985) obtained both

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Contributed by the Internal Combustion Engine Division and presented at the Energy-Sources Technology Conference and Exhibition, Houston, Texas, January 26-30, 1992. Manuscript received by the Internal Combustion Engine Division September 3, 1991. Associate Technical Editor: J. A. Caton.

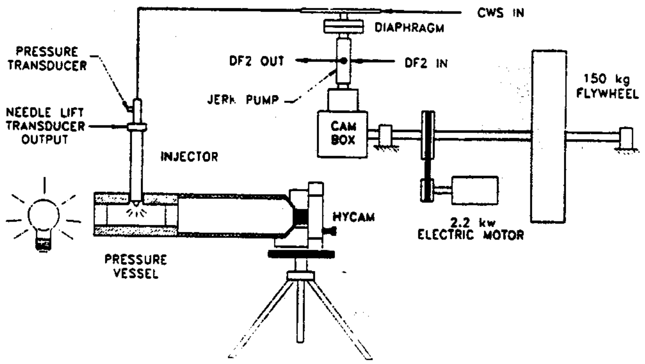

Fig. 1 Schematic diagram of the experimental system

shadowgraphs and droplet size distribution data for coal–water slurry from engine injectors. The fuel injector was a modified six-hole (0.35 mm dia) pencil nozzle (Stanadyne Roosa) with nozzle opening pressures of 5.5 and 14 MPa. For diesel fuel, 80 percent of the mass had droplet diameters less than 100 μm; whereas, for coal–water slurry, 80 percent of the mass had droplet diameters less than 400 μm. These results were for one location (32 mm 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 percent of the mass had droplet diameters less than about 30 μm.

Yu et al. (1989) reported results from experiments that used a pneumatic, single-shot fuel delivery system. The injector was a pintle nozzle with injection pressures from 70 to 170 MPa (10,000 to 25,000 psia). The fuel was injected into a constant volume chamber which contained pressurized room temperature gas with a density of 17.5 kg/m^3. They used a laser diffraction size analyzer with a 9-mm-dia laser beam. These investigators examined two coal loadings (53 and 48 percent 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. The average fuel injection velocity ranged from 220 to 450 m/s. They reported Sauter mean diameters (SMD) for the coal–water slurry of 25 and 54 μm for their limited tests.

Benson et al. (1991) reported results from a continuous and an intermittent injection system. The continuous injection was provided by an intensifier using a hydraulic system as a power source. The intermittent injection was provided by a jerk pump injection system. Their results indicated that cone angles of the coal–water slurry increased with the increase in the injection pressure in contrast with the cone angles for diesel fuel which were constant with injection pressure. Based on their experimental results, they estimated that the penetration time to the piston bowl was 1.3 ms and the penetration time to the cylinder wall was 2.1 ms. They also observed that the atomization of coal–water slurry did not depend on the coal loading in the slurry.

Objectives: The overall objective of this work was to characterize fully the coal–water slurry 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.

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 (150 kg) 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 of medium-speed diesel engines. The only modification to the pump is the addition of a diesel fuel outlet passage that 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. 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. This design is similar to that used by Leonard and Fiske (1986). The system operates in the same way as the conventional system except that in the modified system the diesel fuel that 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 diaphgram to the coal–water slurry side of the pump. This forces coal-water slurry down the fuel line and into the injection nozzle. Typical injection pressures for this study were of the order of 30 MPa.

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 multihole nozzles. This was because the volume for the overall injection system was significantly increased due to the diaphragm and additional pipe length. Actual applications have minimized this additional volume to accommodate multihole nozzles (Hsu, 1988a, 1988b; Hsu et al., 1989).

The nozzle was a standard Bendix injector used on medium-speed diesel engines. Modifications to the nozzle were 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 was measured by the use of an in-line strain gage pressure transducer.

The custom nozzle tips allowed the use of various nozzle tip geometries with various numbers and size of orifices. Three sizes of single-hole nozzle tips were prepared for this study. 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 (Reitz and Bracco, 1982), this aspect was outside the scope of the present study. The nozzle holes were obtained by electro-discharge machining (EDM).

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

Experimental Procedures and Test Matrix. The experimental procedure included the following steps. First, the cam shaft was accelerated to a steady-state speed of 525 rpm. Next, the rack was pulled to a predetermined position and injection would begin. Finally, 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. This procedure would result in recordings of about 8 consecutive injections.

Table 1 lists the major experimental test parameters investigated. The base case included the following set of parameters: 50 percent (by mass) coal loading, 0.4-mm-dia nozzle tip, full

Table 1 Experimental test matrix

Case	Fuel	Tip (mm)	Rack (mm)	Density (kg/m³)
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

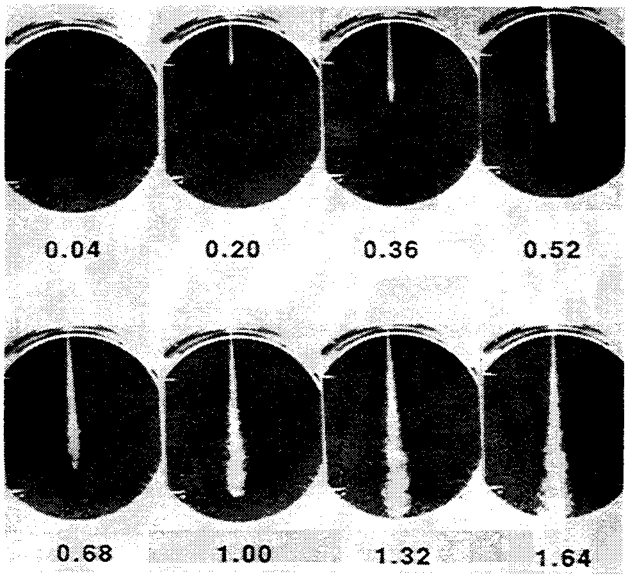

Fig. 2 Eight frames from a portion of a movie of one injection of coal-water slurry at the base case conditions (the numbers denote the time in milliseconds from the start of injection)

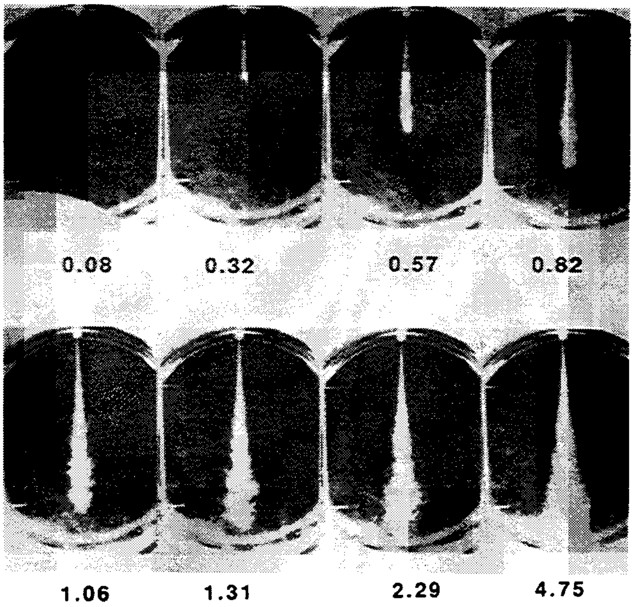

Fig. 3 Eight frames from a portion of a movie of one injection of diesel fuel at the base case conditions (the numbers denote the time in milliseconds from the start of injection)

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 (Hsu, 1988a, 1988b; Hsu et al., 1989). The parameters that were varied were selected to represent the important features of the injection and atomization process. The fuels used included additional concentrations of coal-water slurry, water, and diesel fuel. Additional parameters that were investigated included nozzle tip diameters of 0.2 and 0.6 mm, rack positions of 10 and 20 mm, and chamber densities 1.2 and 17 kg/m^3. The nozzle tip diameters listed are nominal values and the actual values were determined by analyzing photographs from scanning electron miroscopy. The actual values are used in subsequent figures.

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 (Hsu and Confer, 1991). In summary, the base coal-water slurry contained 50 percent coal, 48 percent water, 1 percent lignosulphonate, and 1 percent Triton X-114. The coal used was a high-volatile subbituminous, which was cleaned to less than 0.8 percent ash (on a dry coal basis) with a measured Sauter mean particle diameter of 3.0 μm.

Spray Characterization. Figures 2 and 3 each show eight frames from a portion of a movie of one injection for the base case conditions for coal-water slurry and diesel fuel, respectively. The time between frames for these sets of movie frames was about 0.16 and 0.24 ms, respectively. For detailed analysis, 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. The general qualities of the sprays were similar for the coal-water slurry and diesel fuel. The diesel fuel spray is generally broader and somewhat more stable. Other cases of coal-water slurry sprays also were obtained and are discussed elsewhere (Seshadri, 1991). As shown, the propagation for the fuel jet is rapid at the start (0-0.6 ms). This represents the period of penetration of a largely intact liquid core region. After this initial period, the liquid core breaks apart (break-up). Associated with this break-up is the development of a head vortex. This is first noted in these pictures at 0.68 ms for the coal water slurry and at 0.82 ms for the diesel fuel case. 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 last two frames in each of these sequences are representative of fully developed sprays for these conditions and illustrate the spray differences. Subsequent frames from these sets had shapes that fluctuated between the shapes of these two frames.

To complete the detailed analysis of the spray development, each frame of each movie set was traced using a motion analyzer. Figure 4 shows an example of the outline of the individual spray recordings for coal-water slurry for the base case conditions. The edge of the spray was selected as the location of the edge of the dark image of the spray. The maximum error in this determination was estimated as 5 percent. For this particular movie set, the time between frames was 0.101 ms. These spray shapes are superpositioned on a scaled schematic of the piston and cylinder. This schematic shows one spray

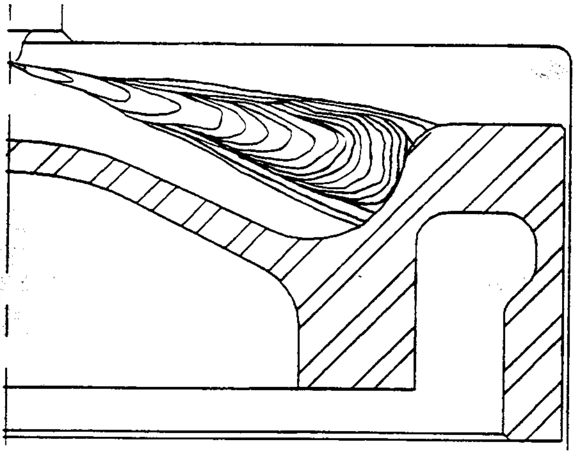

Fig. 4 Outlines of sequential spray plumes (0.101 ms apart) superpositioned on a schematic diagram of the piston and cylinder for coal-water slurry for the base case conditions

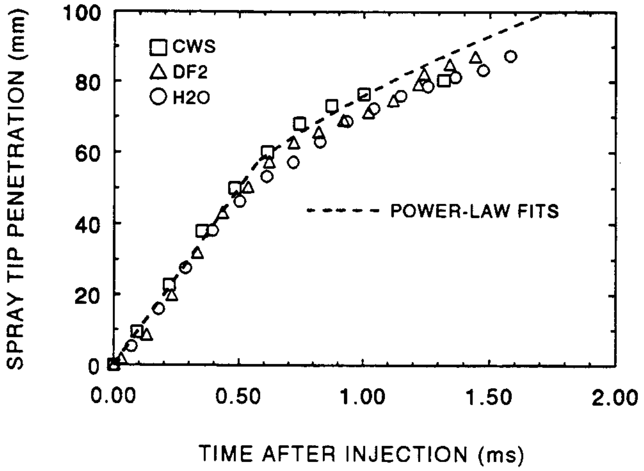

Fig. 6 Spray tip penetration as a function of time after injection for three fluids for the base case conditions

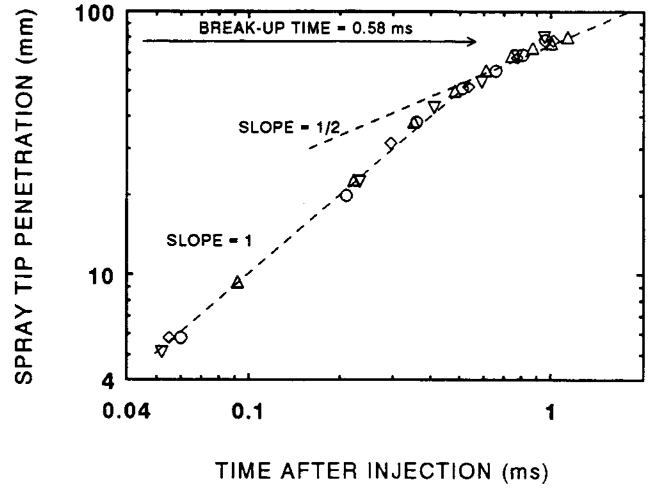

Fig. 5 Spray tip penetration as a function of time after injection for coal-water slurry for the base case conditions (the symbols represent data from four consecutive spray injections)

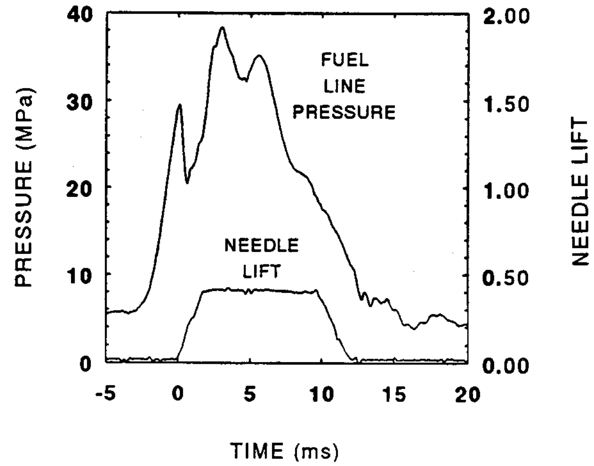

Fig. 7 Instantaneous fuel line pressure and needle lift as a function of time for coal-water slurry for the base case conditions

plume; typically eight to twenty spray plumes would be used. The typical spray plume is directed downward toward the piston at a 15 deg 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 coal-water slurry for these conditions are greater than 1.5 ms (Hsu, 1988a, 1988b; Hsu et al., 1989) and, hence, these results indicate that at least some fuel impingement occurs. The consequences of this finding on the ignition and combustion processes in the engine are discussed by Hsu et al. (1992).

From the above spray outlines, the fuel jet penetration as a function of time was determined. Figure 5 shows the log of the fuel jet penetration distance as a function of the log of time for four consecutive injection events for the base case. As shown, the penetration distances from these four events are in good agreement with each other. 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 Fig. 5 by the dashed 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 Fig. 5, this is represented by a dashed 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 0.58 ms for coal-water slurry and 0.50 ms for diesel fuel.

As an example of the type of information obtained from the movies, Fig. 6 shows the spray tip penetration as a function of time for three fluids: coal-water slurry, diesel fuel, and water. The dashed lines in the figure are from the previously described power-law fits. The coal-water slurry penetrated slightly faster than the other fluids and had a 0.08 ms longer break-up time. Although detailed differences such as these exist, all three fluids are in general agreement with the same power-law fits. This implies that the penetration and spray development are similar for several fluids when injected at the same conditions. Additional results for other coal concentrations substantiate these findings. The one exception was for 55 percent (by mass) coal loadings. For this case, no successful injection was achieved. Loadings as high as 53 percent, however, were successful. This implies a highly nonlinear response of fuel injection with respect to coal loadings for coal loadings above 53 percent.

In addition to the values based on the movies, the fuel jet penetration was estimated according to a model using the experimental fuel line pressures. Figure 7 shows the instantaneous fuel line pressure and needle lift as a function of time for the base case coal-water slurry 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.

Many models exist for computing the fuel jet penetration

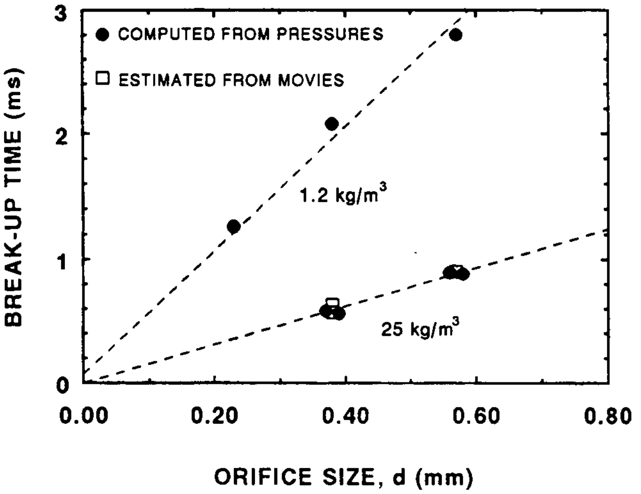

Fig. 8 Break-up time as a function of orifice size for two chamber densities for 50 percent coal-water slurry

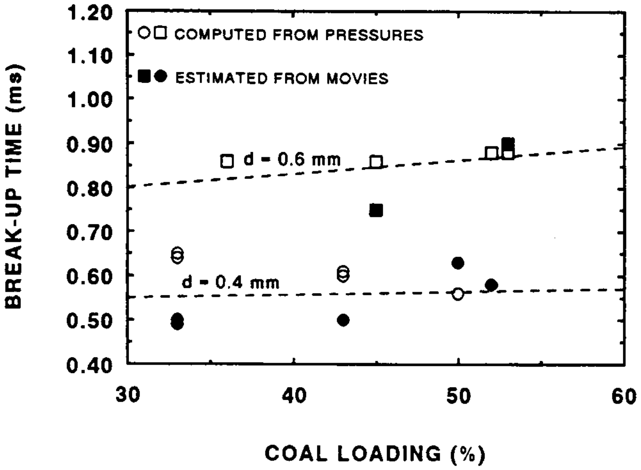

Fig. 9 Break-up time as a function of coal loading for two orifice sizes for a chamber density of 25 kg/m³

and the break-up times using the fuel line pressure. For this study, the model described by Arai et al. (1984) was selected as representative. Further work is planned to evaluate other models. Using the instantaneous fuel line pressures and the model for jet penetration developed by Arai et al. (1984), break-up times and penetration distances were determined. This model is based on diesel fuel and the only modification was to use the correct fluid density of the coal-water slurry. The expressions for the spray tip penetration, s, are as follows (Arai et al., 1984):

$$\text{For } 0 < t < t_b,\ s = 0.39\left(\frac{2\,\Delta P}{\rho_l}\right)^{0.5} t \tag{1}$$

$$\text{For } t > t_b,\ s = 2.95\left(\frac{\Delta P}{\rho_a}\right)^{0.25}(d\cdot t)^{0.5} \tag{2}$$

$$\text{where, } t_b = 28.65\,\frac{\rho_l\cdot d}{(\rho_a\,\Delta P)^{0.5}} \tag{3}$$

where ΔP is the difference between the fuel line pressure and the chamber pressure, ρ_l is the density of the injected fluid, t is the time since injection, ρ_a is the density of the chamber gas, d is the nozzle orifice diameter, and t_b is the time until break-up of the spray jet.

The following discussion will focus on the effects of the major parameters of the injection process on the break-up time. The break-up time is a good indication of the quality of the atomization process. Break-up times indicate when the liquid core of the spray jet has disintegrated. The penetration of the spray, therefore, will be less rapid for short break-up times. Figure 8 shows the break-up time as a function of nozzle orifice size for two chamber densities. The symbols represent data from the movies or pressures, and the dashed lines are linear fits of the data. These results demonstrate the good agreement between the break-up times determined from he movies and the break-up times estimated from the model using the measured instantaneous fuel line pressures. As shown in Fig. 8, the break-up time increases with the increase in nozzle orifice sizes for both chamber densities of 1.2 kg/m³ and 25 kg/m³. As expected, as the orifice size approaches zero, the break-up time approaches zero. The effect of chamber density on the spray character is significant. For the low chamber density, the spray penetrates rapidly and does not spread out when compared to the high chamber density case. The break-up times for the low chamber density are 3.5 times greater than the break-up times for the high chamber density case.

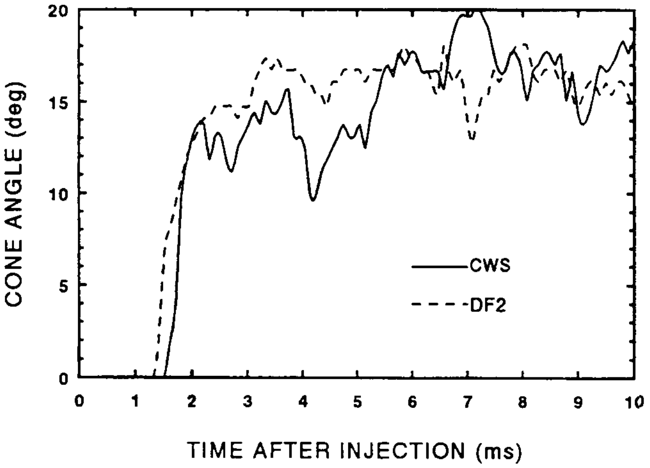

Fig. 10 Instantaneous cone angle as a function of time after injection for coal-water slurry and diesel fuel for the base case conditions

Figure 9 shows the break-up time as a function of coal loading for two nozzle orifice sizes for the base case conditions. Again, the symbols represent data from the movies or pressures, and the dashed lines are linear fits of the data. The break-up times are not significantly different from each other for the different coal loadings. The average values of the break-up time for all coal loadings were 0.55 and 0.85 ms for the 0.4 and 0.6 mm orifice sizes, respectively.

In addition to penetration distances, the cone angles of the sprays were determined from the movies. The cone angle of a spray is not well defined and no standard procedure is available. One approach is to use the arctangent of the spray width divided by the axial distance from the nozzle tip to the measurement location. For this study, the measurement location was 80 mm (200 nozzle orifice diameters) downstream from the nozzle tip. This location was selected so as to include as much of the spray as possible without being near the wall region. This distance is also representative of the distance to the piston bowl in a medium-speed diesel engine. As noted below, similar results were obtained at a measurement location of 60 mm (150 nozzle orifice diameters) downstream from the nozzle tip.

Figure 10 shows the cone angle as defined above as a function of time after injection for the base case conditions for diesel fuel and for coal-water slurry. The cone angle is similar for the two fluids for these tests. As shown, for the chosen measurement location the spray arrives at about 1.3 ms after injection. Within the next half of a millisecond, the cone angle at this location increases rapidly. For the period between 3 and 10 ms, the time-averaged cone angles for these diesel fuel and coal-water slurry cases were 16.3 and 15.9 deg, respectively. For the nearer location (60 mm downstream of the nozzle tip), the time-averaged cone angles for the above diesel fuel and coal-water cases were 17.0 and 16.4 deg, respectively. Other tests with the coal-water slurry at these conditions resulted in narrower sprays. These narrower sprays had time-averaged cone angles of 11.2 and 13.0 deg and may be a result of needle sticking or blockage in the fuel delivery passages (Seshadri, 1991). Other investigators (Benson et al., 1991) have reported narrower coal-water slurry sprays with cone angles of between 1 and 10 deg, depending on fuel injection pressure.

The measured cone angles were unsteady with respect to time and several fluctuation frequencies exist. The high-frequency (between 5000 and 10,000 Hz) fluctuation is due to the finite movie frame rate and illustrates the frame-by-frame differences. The lower frequency (about 600 Hz) fluctuation may be a result of the wave dynamics of the injection system or from fluid instabilities associated with the atomization process. For example, these fluctuations maybe related to the time scales of large-scale fluid structures in the spray. (For reference, the injection frequency was 8.8 Hz and the pressure fluctuations were about 300 Hz.) The coal-water slurry cases resulted in larger amplitude fluctuations than for the diesel fuel cases. Note the importance of a time-averaged value as opposed to an instantaneous value even for a fully developed spray.

Additional results on the parametric effects of coal loadings, nozzle hole size, rack position, and chamber density on fuel jet penetration are available (Seshadri, 1991; Caton and Kihm, 1991) but due to space limitations, they cannot be presented here.

Summary and Conclusions

Experiments were completed to characterize coal-water slurry sprays from a modified positive displacement fuel injection system of a diesel engine. The injection system included an injection jerk-pump driven by an electric motor, a specially designed diaphragm to separate the abrasive coal from the pump, and a single-hole fuel nozzle. Injection pressures were of order 30 MPa and nozzle orifice diameters were between 0.2 and 0.6 mm. Coal-water slurry fuels with between 30 and 55 percent (by mass) coal were studied. The sprays were injected into a pressurized chamber equipped with windows. High-speed movies and instantaneous fuel line pressures were obtained. The time until the center core of the spray broke up (break-up time) was determined from both the movies and from a model using the fuel line pressure. Results from these two independent procedures were in good agreement.

The conclusions of this investigation include the following:

1 For the base conditions, the break-up time was 0.58 ms for coal-water slurry and 0.50 for diesel fuel. Break-up times increased with increasing nozzle orifice size and with decreasing chamber density.

2 The break-up time was not a significant function of coal loading for coal loadings up to 53 percent.

3 For the conditions of this study, the spray tip penetration as a function of time was similar for three fluids: coal-water slurry, diesel fuel, and water.

4 Cone angles of the sprays were dependent on the operating conditions and fluid, as well as the time and location of the measurement. The time-averaged cone angle ranged between 11.2 and 15.9 deg for the coal-water slurry and was 16.3 deg for the diesel fuel.

Future Work

The major remaining tasks of this project include additional detailed analysis of the movies and fuel pressures from the positive displacement fuel injection system. Current activities are directed at completing a similar set of experiments for an accumulator injection system. In addition to the high-speed movies and fuel line pressures, detailed droplet size measurements and high-resolution still photography will be completed.

Acknowledgments

This work was supported by a subcontract from General Electric—Transportation Systems as part of a contract with the U.S. Department of Energy, Morgantown Energy Technology Center. The contents of this paper do not necessarily reflect the views of General Electric or the Department of Energy.

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