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Authors:
J.A. Caton
S.E. Payne
D.P. Terracina
K.D. Kihm

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COAL-WATER SLURRY SPRAYS FROM AN ELECTRONICALLY CONTROLLED ACCUMULATOR FUEL INJECTION SYSTEM: BREAK-UP DISTANCES AND TIMES

Jerald A. Caton, Stephen E. Payne, Dwayne P. Terracina and Kenneth D. Kihm

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

ABSTRACT

Experiments have been completed to characterize coal-water slurry sprays from an electronically-controlled accumulator fuel injection system of a diesel engine. The sprays were injected into a pressurized chamber equipped with windows. High speed movies, fuel pressures and needle lifts were obtained as a function of time, orifice diameter, coal loading, gas density in the chamber, and accumulator fuel pressure.

For the base conditions (50% (by mass) coal loading, 0.4 mm diameter nozzle hole, coal-water slurry pressure of 82 MPa (12,000 psi), and a chamber density of 25 kg/m^3), the break-up time was 0.30 ms. An empirical correlation for spray tip penetration, break-up time and initial jet velocity was developed. For the conditions of this study, the spray tip penetration and initial jet velocity were 15% greater for coal-water slurry than for diesel fuel or water. Results of this study and the correlation are specific to the tested coal-water slurry and are not general for other coal-water slurry fuels.

INTRODUCTION

Although engineering development activities for a successful coal-fueled reciprocating engine have continued for nearly one-hundred years[1,2], only recently have engines been operated with coal fuels for extended periods[3,4]. These recent successes have been dependent on successful fuel injection systems. To further progress in this area, fundamental information is needed on the fuel injection process of coal-water slurry fuels.

This paper is a description of the second phase of a research project to determine the overall characteristics of coal-water slurry fuel sprays as a function of operating conditions and fuel specifications using a state-of-the-art accumulator fuel injection system. The first phase of this project characterized coal-water slurry fuel sprays using a modified positive displacement fuel injection system[5]. This second phase of the project provides additional information on the atomization process of coal-water slurry fuels from an accumulator injector and extends the data to fuel pressures up to 109 MPa. In addition, this second phase provides an empirical correlation for a coal-water slurry fuel for spray tip penetration, break-up time and initial jet velocity as a function of time, orifice diameter, coal loading, gas density in the engine, and accumulator fuel pressure.

Five previous studies on characterizing coal-water slurry sprays from diesel engine injection systems have been reported. 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[6]. Nelson *et al.*[7] obtained both shadowgraphs and droplet size distribution data for coal-water slurry from engine injectors. Yu *et al.*[8] reported the results from experiments which used a pneumatic, single-shot fuel delivery system. The injector was a pintle nozzle with injection pressures from 70 to 170 MPa (10000 to 25000 psia). Dodge *et al.*[9] reported results from a continuous and an intermittent injection system. They observed that the atomization of coal-water slurry did not depend on the coal loading in the slurry.

As noted above, previous work completed in this laboratory was based on a positive-displacement fuel injection system[5,10–12]. 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. The sprays were injected into a pressurized chamber equipped with windows. High speed movies were obtained and, for injection pressures of order 30 MPa, 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) increased with increasing nozzle orifice size and with decreasing chamber density. The break-up time was not a significant function of coal loading for coal loadings up to 53%.

Engine tests conducted by General Electric–Transportation Systems in the mid-1980s demonstrated that modified conventional fuel injection systems were not completely satisfactory for coal-water slurry. An accumulator fuel injection system, therefore, was designed and constructed[13]. to provide better and more consistent atomization of coal-water slurry fuels. This new accumulator system has been successfully tested on single cylinder medium-speed locomotive engines[14]. In one configuration, a conventional jerk pump is used to pump diesel oil into one side of a small chamber which is divided into two sections by a diaphragm. The other side of the diaphragm contains coal-water slurry which would be pressurized by the action of diaphragm.

The pressurized coal-water slurry then flows into the fuel chamber of the accumulator injector. A fast acting servovalve, which is electronically activated, is mounted on the injector to open the needle. Further details of this accumu-

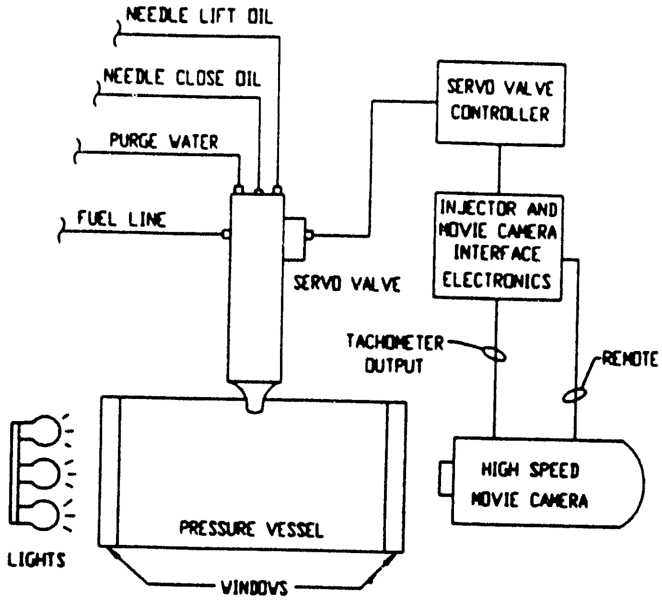

Figure 1. Schematic diagram of the experimental system.

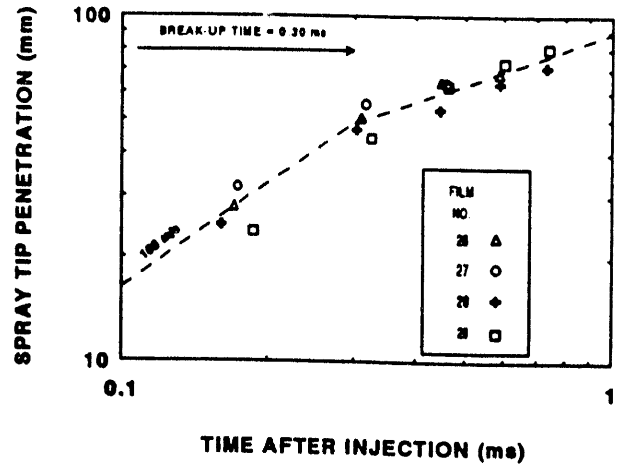

Figure 2. Spray tip penetration as a function of time after injection for coal-water slurry for the base case conditions (the symbols represent data from four spray injections).

lator fuel injection design and its operation are described by Hsu *et al.*[14]. For the current investigation, the pressurized fluids were provided by a separate and independent hydraulic system to avoid the complications of the use of a jerk pump.

Objectives

The objectives of this work were to fully characterize the coal-water slurry fuel sprays of a diesel engine accumulator injection system and to develop a correlation for computing the spray penetration. Specifically, the break-up time and distance were determined as a function of nozzle orifice diameter, coal loading, and accumulator fuel pressure.

PROJECT DESCRIPTION

Experimental Facility

Descriptions[13,14] of the accumulator injector are provided elsewhere. For purposes of this investigation, the original nozzle tip has been replaced with a two-piece assembly to permit construction and use of custom nozzle tips. Three sizes of single hole nozzle tips were prepared for this study with nominal nozzle hole diameters of 0.2, 0.4 and 0.6 mm. The actual hole diameters were determined by analyzing photographs from a scanning electron microscope and were 0.196, 0.39 and 0.57 mm. The holes had a sharp-edged exit and a length-to-diameter ratio of 5.

Figure 1 shows the overall injection facility for this experiment. A special hydraulic system (not shown) was used to supply all the pressurized fluids for this investigation. The accumulator injector was mounted on a pressure vessel. 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 (up to 11,000 frames/sec), 16 mm movies of the spray were obtained.

Experimental Procedures and Test Matrix

The experimental procedure included the following steps. First, the hydraulic system was used to pressurize all fluids. Once the accumulator was filled with coal-water slurry and pressurized to the desired pressure, the movie camera was started and, when the speed of the film was greater than about 7000 frames per second, an electronic trigger signal was sent to the servo-valve controller and to the data acquisition system. When the servo-valve was activated, oil at about 27 MPa flowed under the needle lift piston and forced the needle open. At the end of the injection, which is pre-set, the servo-valve switched off the 27 MPa oil and the close oil (at about 25 MPa) caused the needle to close.

The base case included the following set of parameters: 50% (by mass) coal loading, 0.4 mm diameter nozzle hole, coal-water slurry pressure of 82 MPa (12,000 psi), and a chamber density of 25 kg/m^3 (which corresponds to the full load conditions of the GE locomotive engine[14–16]. The fuels used included additional concentrations of coal-water slurry, water and diesel fuel. Other parameters which were investigated included nozzle hole diameters of 0.2 and 0.6 mm, coal-water slurry pressures of between 28 and 109 MPa (4000 and 16000 psi), and chamber densities of 1.2 and 17 kg/m^3.

RESULTS AND DISCUSSION

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[17]. In summary, the base coal-water slurry 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 Sauter mean particle diameter of 5.0 μ. This was the same slurry used in the previous study[5], but, due to a different measuring method, was reported as having a 3.0 μ particle diameter. A second sample of Otisca coal-water slurry fuel with a mean particle

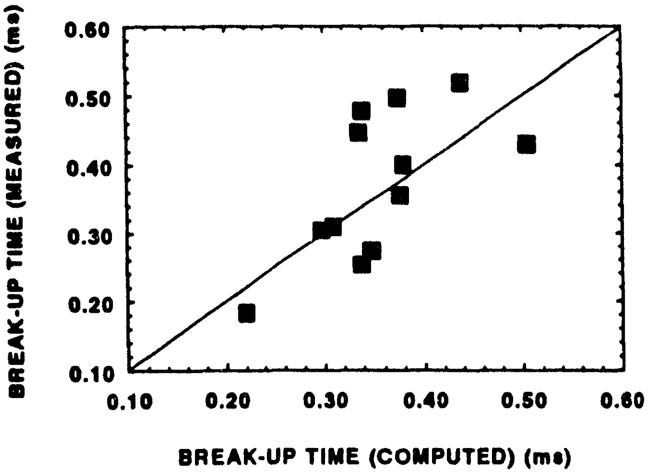

Figure 3. Measured break-up time as a function of the computed break-up time for a variety of conditions.

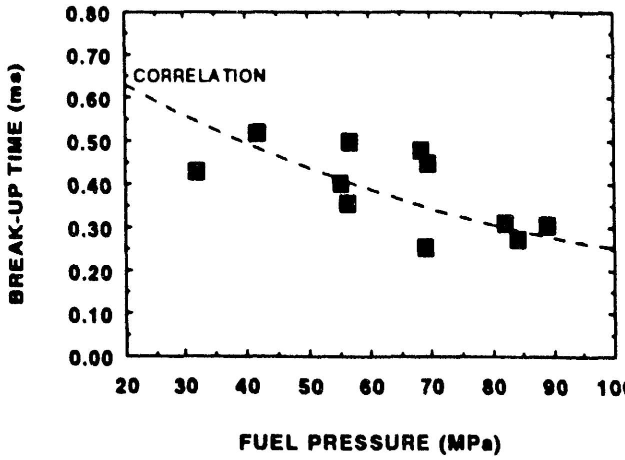

Figure 4. Break-up time as a function of fuel pressure (the square symbols are from the movies and the dashed line is from the correlation).

diameter of 8.0 μ was tried in these experiments, but no successul injections were achieved. The results of this study, therefore, should not be generalized to all coal-water slurry fuels.

Spray Characterization

From the movie frames, spray propagation and development were determined. The reference distance for the film analysis was estimated by using the diameter of the nozzle (25.5 mm). Each frame of each movie was traced using a motion analyzer. The edge of the spray was selected as the location of the edge of the dark image of the spray. The accuracy of this determination was estimated as 5% and is discussed below in more detail.

From the spray outlines, the fuel jet penetration as a function of time was determined. The propagation of the fuel jet is rapid at the start and this represents the period of penetration of a largely intact liquid core region. After this initial period, the liquid core breaks apart (break-up). Figure 2 shows the log of the fuel jet penetration distance as a function of the log of time for four different injection events for the base case. As shown, the penetration distances from these four events are in reasonable agreement with each other. The differences between the results of these four injections are due to experimental uncertainties which include items such as different needle lift performances, fuel pressure fluctuations and coal-water slurry non-uniformities. The dash lines in figure 2 are from a correlation described below. 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 2 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 2, this is represented by the 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 0.30 ms for this coal-water slurry. To determine the accuracy of the spray tip location, separate interpretations[18] of the movies were completed. In general, the interpretations were within about 5%. In fact, the experimental uncertainty described above generally was greater than the uncertainty in locating the spray tip.

Based on the experimental data from these experiments, a correlation was developed for computing the spray tip penetration as a function of time for coal-water slurry fuels. Although many correlations exist for spray tip penetration for diesel fuel[19,20], none have been reported for coal-water slurry fuels. The correlation that was developed was based on a modified form of a correlation originally presented by Arai *et al.*[21] for diesel fuel. The modifications included increased penetrations and initial jet velocities, and the use of coal-water slurry properties.

The expressions for the spray tip penetration, s, for coal-water slurry are as follows:

$$\text{For } 0 < t < t_b, \quad s = 0.39\,(1.0 + 0.3\,x_c)\left(\frac{2\,\Delta P}{\rho_\ell}\right)^{0.5} t \qquad (1)$$

$$\text{For } t > t_b, \quad s = 2.95\,(1.0+0.3\,x_c)\left(\frac{\Delta P}{\rho_g}\right)^{0.25} (d\cdot t)^{0.5} \qquad (2)$$

$$\text{where, } t_b = 28.65\,\frac{\rho_\ell \cdot d}{(\rho_g\,\Delta P)^{0.5}} \qquad (3)$$

$$\text{also, } V_{jet_{initial}} = 0.39\,(1.0 + 0.3\,x_c)\left(\frac{2\,\Delta P}{\rho_\ell}\right)^{0.5} \qquad (4)$$

where x_c is the mass fraction of coal in the slurry, ΔP is the difference between the fuel pressure and the chamber pres-

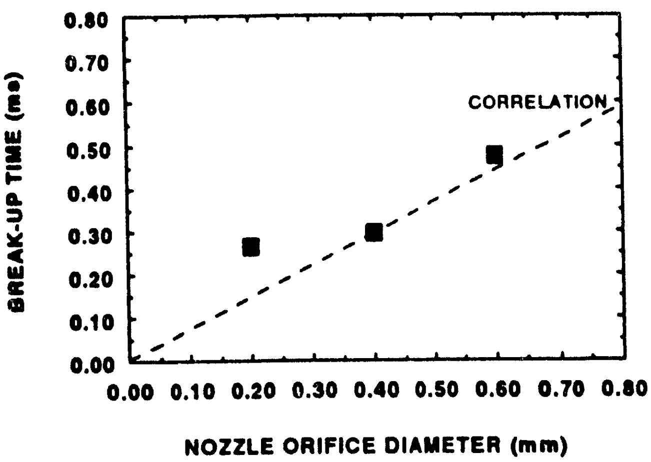

Figure 5. Break-up time as a function of nozzle orifice diameter for the base case conditions.

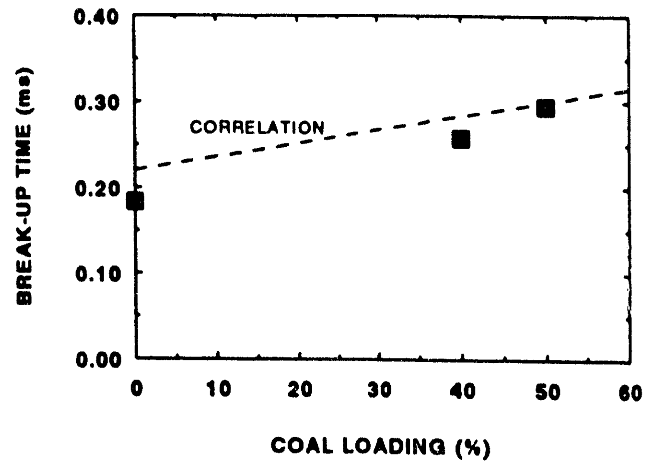

Figure 6. Break-up time as a function of coal loading for the base case conditions.

sure, ρ_l is the density of the injected fluid, t is the time since injection, ρ_g is the density of the chamber gas, d is the nozzle orifice diameter, t_b is the time until break-up of the spray jet, and $V_{jet_{initial}}$ is the initial jet velocity.

To demonstrate the agreement of the correlation with the experimental data, figure 3 shows the measured break-up time as a function of the computed break-up time for a variety of conditions for coal-water slurry and one case for water. Figure 4 shows the measured break-up time as a function of fuel pressure for the base case conditions for coal-water slurry. Also shown in figure 4 is the result of the correlation. Although some data scatter is evident, the correlation provides a good fit to the data. The correlation also provided a good fit to the earlier data from the positive displacement fuel injection system[5,22].

The following discussion will focus on the effects of the nozzle orifice diameter and the coal loading on the break-up times and distances. Figure 5 shows the break-up time as a function of the nozzle orifice diameter. The break-up time increases linearly with nozzle orifice diameter and the correlation is a good fit to the data. Figure 6 shows the break-up time as a function of coal loading. The break-up time is a modest function of coal loading and, again, the correlation provides a good fit. Injections were not possible for 55% coal-water slurry. Also, as mentioned above, a second sample of coal-water slurry with a mean particle size of 8 μ could not be successfully injected.

Figure 7 shows the break-up distance as a function of the nozzle orifice diameter. The break-up distance increases linearly with nozzle orifice diameter. Figure 8 shows the break-up distance as a function of coal loading. The break-up distance is a modest function of coal loading. The correlation provides good agreement for both the break-up times and distances.

SUMMARY and CONCLUSIONS

Experiments were completed to characterize coal-water slurry sprays from an electronically-controlled accumulator fuel injection system of a diesel engine. Injection pressures between 28 and 109 MPa, nozzle orifice diameters between 0.2 and 0.6 mm, and coal-water slurry fuels with between 0 and 55% (by mass) coal were studied. The sprays were injected into a pressurized chamber equipped with windows. High speed movies and instantaneous fuel pressures were obtained.

The conclusions of this investigation include the following:

1. For the base conditions, the break-up time was 0.30 ms for this coal-water slurry. Break-up times increased with increasing nozzle orifice size, with decreasing fuel pressure, and with decreasing chamber density.
2. An empirical correlation was developed for coal-water slurry for both spray tip penetration and initial jet velocity. Results of this study and the correlation are specific to the tested coal-water slurry and are not general for other coal-water slurry fuels.
3. For the conditions of this study, the spray tip penetration and initial jet velocity was 15% greater for coal-water slurry than for diesel fuel or water.
4. For this coal-water slurry, no injections were possible for fuel pressures less than 25 MPa (3700 psi) or for coal mass fractions greater than 0.53.

ACKNOWLEDGEMENTS

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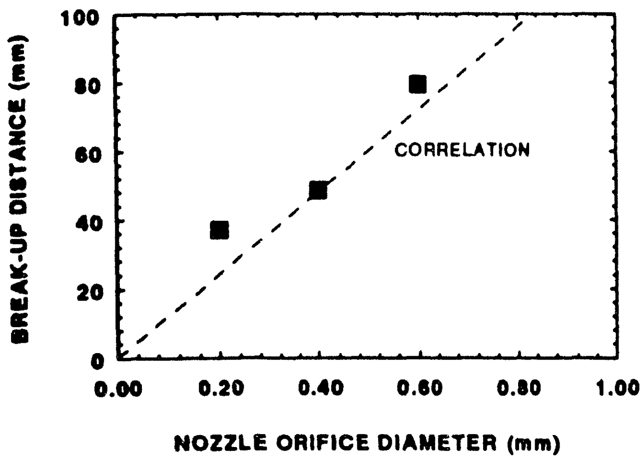

Figure 7. Break-up distance as a function of nozzle orifice diameter for the base case conditions.

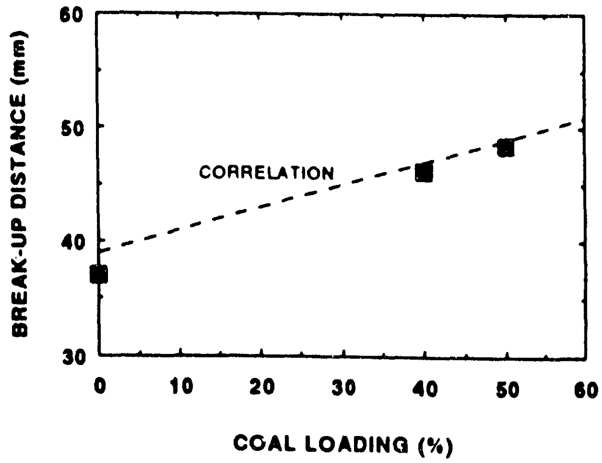

Figure 8. Break-up distance as a function of coal loading for the base case conditions.

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