Investigation of Coal-Water Slurry Fuel Combustion in Reciprocating, Internal Combustion Engine

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Coal-water slurry(CWS) engine tests designed to investigate the ignition and combustion processes of the fuel are described in this paper. The effects of three different parameters, namely, (a) needle lift pressure, (b) fuel injection timing, and (c) percent coal loading in the slurry fuel are studied in detail. Successful operation of the engine using the coal water slurry required modifications to the engine and support systems. The physical trends of combustion under single parametric variations are presented in terms of the cylinder pressure, heat release rates, and cumulative heat release curves. The major conclusions of the work include : (a) higher needle lift pressures led to shorter ignition delay times for the CWS fuel ; (b) the ignition delay time of the advanced injection start was little different from that of retarded fuel injection timing due to poor atomization ; and (c) dilution of the slurry with water can significantly affect the combustion processes and ease of fuel handling.

Key Words: Coal-Water Slurry(CWS), Needle Lift Pressure, Fuel Injection Timing, Percent of Coal Loading, Heat Release Rate

1. Introduction

The development of alternative fuels for internal combustion engines is motivated by economic and strategic advantages offered by these fuels over petroleum fuels. New engine emission standards also motivate investigations using alternative fuels as a potential means of meeting the more strict pollutant emission requirements. One promising alternative fuel is coal which has had a long history of being a primary energy source.

Earlier attempts to operate a coal particle fueled piston engine were made nearly a century ago by Rudolf Diesel in Germany. Coal fuel handling, safety, and ash deposition problems discouraged Diesel from his pursuit of coal as an engine fuel. Coal fuel testing in compression ignition engines continued through 1944 with the work of Pawlikowski, but this testing was interrupted with the end of World War II. Since World War II, most coal-fuled engine research and development in the United States has been conducted using coal slurries. Within the past decade, most activities(Hsu et al., 1992; Kakwani and Winsor, 1992; Doup and Badgley; 1992) with coal-fueled engines have focused on direct injected locomotive engines and stationary power production engines. Problems associated with injection equipment, fuel atomization, and ignition of the slurry fuel have been reported in such studies. The objectives for the work reported here were to operate an engine using CWS fuel and investigate the impact of several operating parameters on the ignition and combustion processes of the fuel in the engine. Subsequent sections summarize the facilities and results of this work.

2. Experimental Setup

The engine used in this work was a single cylinder prechamber type diesel engine which required several modifications before it could be operated successfully with CWS. These modifica-

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tions included : (a) a fueling system for operating the test engine with CWS ; (b) fuel cam and cam shaft alterations for changing static fuel injection timings ; (c) an inlet air heater to obtain higher temperatures for improving the processes of evaporation of water, and devolatilization and ignition of the coal particles ; (d) modification of the needle valve in the injector to prevent CWS from migrating into the upper part of the needle valve ; and (e) a cooling system on the injector body to help prevent CWS from drying and clogging in the injector prior to injection.

A schematic of the test engine setup is shown in Fig. 1 and specifications of this engine are listed in Table 1. As seen in the Figure., the test engine was coupled to a waterbrake dynamometer. The dynamometer torque was measured using a strain gage load cell and the speed was monitored using a 60-tooth gear assembly. The intake air temperature was measured downstream of the heater and displayed on a digital readout. Pressure measurement was made in the main combustion chamber using a pressure transducer inserted into a water cooled adaptor. An incremental shaft encoder was coupled to the engine crankshaft to trigger the pressure data collection.

Advanced static fuel injection timings were achieved by modifying the fuel cam and fuel pump cam shaft. When the prominent point of the fuel cam meets the plunger head, the fuel inside fuel pump is pressurized and injected. To obtain earlier fuel injection, the prominent point of the cam was arranged to meet the plunger earlier than normal by combining new key notches in the fuel cam and key ways in the cam shaft. The fuel injection timing was changed statically by 10 and 20 degrees advance using these modifications. The static injection timing may be somewhat different from the actual needle lift time because of fluid dynamic effects in the line, however, the relative comparisons made here should remain valid. Previous work by other investigations(Leonard and Fiske, 1987; Bell and Caton; 1988) identified the inlet air temperature as an important parameter for ignition characterization. Therefore, a heater was designed and installed in the intake air pipe to allow varying the intake air temperature for this work. Four 660 watt heating elements were mounted in the heater enclosure which was mounted on the intake air duct. With one electric coil, the intake air temperature could be increased by around 18°C at 1400 revolution per minutes(rpm). The test engine prechamber wall was also coated with a thermal barrier plasma spray of zirconia to increase the gas temperature at the time of fuel injection by lowering the heat losses in the prechamber during the compression stroke. Again, ignition of the slurry was a concern based on previous reported work and plasma coatings had been used by others for improving slurry ignition(Badgley and Doup, 1991).

For CWS fueling, the needle valve in the injector was also modified. Two o-rings were incorporated on the needle shaft to prevent slurry fuel from migrating into close tolerance areas which might result in needle seizure. Early work by Nelson and Seeker(1985) of EER identified needle clogging and sticking as a problem in testing. Although the solution applied here is not a design intended for long term application, needle seizure was avoided for the majority of testing with this modification. Finally, a cooling system was designed into the injector body which held the pintle nozzle. The bottom part of the injector body was machined to serve as a coolant reservoir

Fig. 1 Schematic of test engine setup

Table 1 Specifications of the test engine

Type	Air-cooled, 4-stroke prechamber, single, diesel engine
Bore × stroke	102 mm × 106 mm
Compression ratio	19.5
Displacement volume	0.866 liter
Max. power	18 HP/2400 rpm
BSFC	204 g/(BHP hr)

to cool the pintle nozzle, thereby easing slurry drying and clogging problems. The modifications described above allowed repeatable operation of the engine with CWS.

3. Results and Discussion

In analyzing the processes that occur within the cylinder of the engine, the principal diagnostic parameter was the measured time history of the cylinder gas pressure. The cylinder gas pressure was measured by a piezoelectric pressure transducer mounted in the main combustion chamber. The heat release rates from the measured cylinder pressure as a function of crank angle were calculated using a heat release simulation developed for this work. The simulation includes an one-zone description of the combustion chamber. The model assumes uniform thermodynamic properties in the engine and the energy release rate is calculated according to the first law of thermodynamics for a single combustion zone as proposed by Heywood(1988). As discussed in Heywood, the one chamber assumption may lead to discrepancies in the heat release rate magnitude early in the cycle. However, for this work comparisons or relative heat release data was sought between the diesel and CWS results. The instantaneous cylinder heat transfer rate was calculated using a correlation developed by Woschni(1967).

As presented in subsequent paragraphs, a modified cycle simulation(Bell and Choi, 1990; Choi, 1992) for a coal-fueled engine was also used for comparing the experimentally determined pressure-time data and for further investigation of the detailed combustion processes. The cycle simulation developed earlier by Bell and Caton(1988) included individual models for describing the fuel-air mixing process, cylinder heat transfer, droplet evaporation, particle devolatilization. For this work, the simulation was modified for convection heat losses to the prechamber walls and geometrical modifications for the test engine.

Pressure data from the experimental engine using CWS fueling are shown for different inlet air temperatures ranging from 400 K to 440 K in

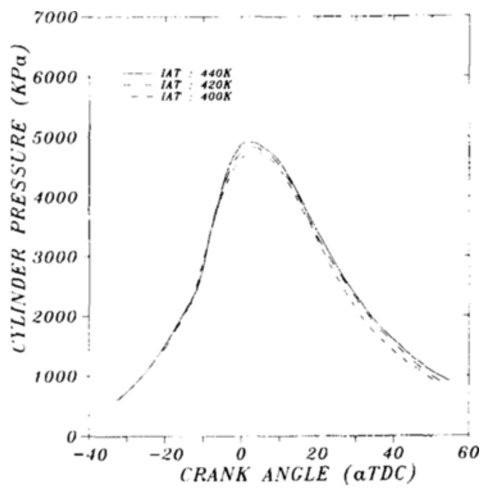

Fig. 2 Effects of inlet air temperature(IAT) on measured cylinder pressure as a function of crank angle

Fig. 2. Inlet air temperature variation was achieved using the inlet air heating system described earlier. Below an inlet air temperature of around 390 K the coal-fueled engine misfired. Other operating parameters were static fuel injection start of 28 crank angle degrees before top dead center(bTDC), engine speed of 1300 rpm, and coal loading in the slurry fuel of 51.6 percent. Work by Leonard and Fiske(1987) using a special combustion bomb apparatus designed to simulate an engine combustion chamber also showed a threshold temperature effect. Below approximately 1000 K (temperature at injection), combustion and ignition characteristics rapidly deteriorated with gas temperature. Hsu(1988) varied the inlet air temperature in a locomotive engine using coal slurry fuels and also noted a degradation in the combustion characteristics of the slurry with lowered air temperatures.

To examine the issue further, the inlet air temperature was varied in the engine simulation program. The simulation input variables were set to correspond as closely as possible to the operating conditions of the test engine. Similar to experimental data shown in the previous figure, Fig. 3 shows that the effects of increasing inlet air temperature were to increase the peak cylinder pressure and shift the peak cylinder pressure to the

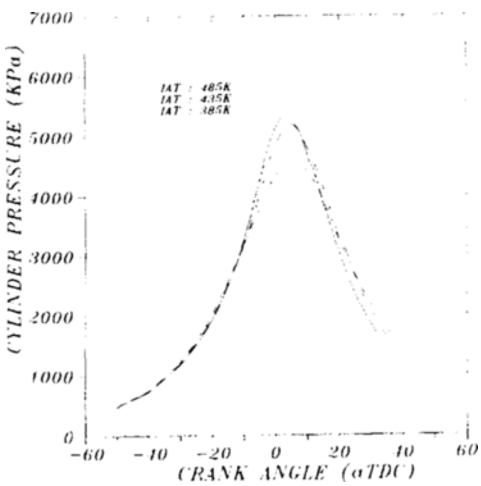

Fig. 3 Effects of inlet air temperature on analytical cylinder pressure as a function of crank angle

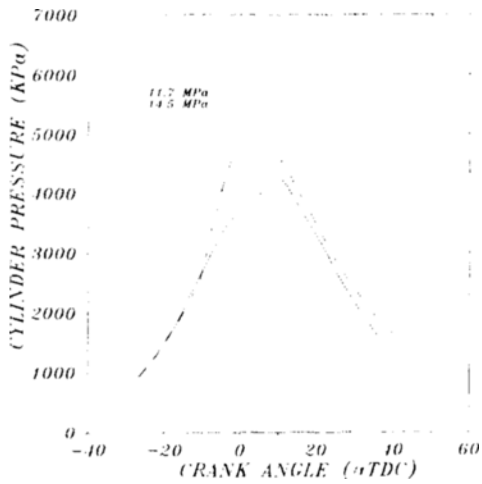

Fig. 4 Effects of needle lift pressure on cylinder gas pressure

left. From the detailed reaction rate information provided by the simulation, the increase in inlet air temperature serves to aid in the ignition process of the coal and thereby increasing the overall combustion rate of the fuel. As examined with the simulation, this increasing combustion rate is achieved as the higher inlet air temperature allows faster evaporation of water from the fuel and, secondly, faster heating of the coal to the ignition temperature for coal particle surface reactions and devolatilization. For the simulation results, the critical inlet air temperature for achieving ignition was approximately 380 K, close to the experimental value. This temperature was also seen to be sensitive to simulation input data such as the atomized droplet size and atomization configuration (number of particles in a droplet, etc.) for modeling injection.

3.1 Effects of needle lift pressure

The needle lift pressure was varied to influence injection pressure in this work. The needle lift pressure were set to 11.7 and 14.5 MPa by shimming the needle body in the injector. In an engine, a higher needle lift pressure retards the fuel injection timing and shortens the fuel injection duration as well as increasing the pressure during injection. The engine operating conditions chosen were : static fuel injection start of 18 crank angle degrees bTDC, inlet air temperature of 440 K, and a coal mass loading in the fuel of 51.6 percent. Under these operating conditions, a clogging problem in the fuel passages in the injector nozzle occurred with the higher needle lift pressure after about 10 minutes with the fueling method described earlier. Figure 4 shows the cylinder pressure as a function of crank angle for the two needle lift pressures. The predominant effect of increasing the needle lift pressure was to increase the peak cylinder pressure. The peak pressure was also shifted to the left by about 6 crank angle degrees. For the lower injection pressure, the combustion rate was so retarded as to almost lead to a dual peak in the pressure-time data.

In Fig. 5, the heat release rates are shown as a function of real time for different needle lift pressures. The real time converted from the slightly different engine speeds of each case represents a time basis to compare ignition and combustion processes. The zero real time in this figure corresponds to the static fuel injection start, 18 crank angle degrees bTDC. The effect of increasing the needle lift pressure was to shorten the ignition delay time by about 0.4 millisecond(ms). This may be explained by the fact that the higher injection pressure, which was achieved at the start of injection with higher needle lift pressure, initially led to smaller injected slurry droplet sizes.

Smaller slurry droplets would have shorter ignition delay times because water evaporation of smaller droplets would take less time than that of larger droplets. That is, the higher injection pressures led to improved atomization which resulted in earlier ignition and combustion. The peak heat release rates for the 11.7 and 14.5 MPa needle lift pressure were 0.034 MW at 3.5 ms and 0.030 MW at 2.3 ms after the fuel injection start, respectively. This may be explained by the fact that more fuel-air mixture is available for burning with longer ignition delay times. Figure 6 shows the cumulative heat release as a function of real time for different needle lift pressures. The figure indicates that the kinetic burning region is faster than that in the diffusion burning region for higher needle lift pressures. This may be explained by the fact that combustion of the CWS which has mixed with air within the flammability limits during the ignition delay period occurs rapidly in the kinetic burning period.

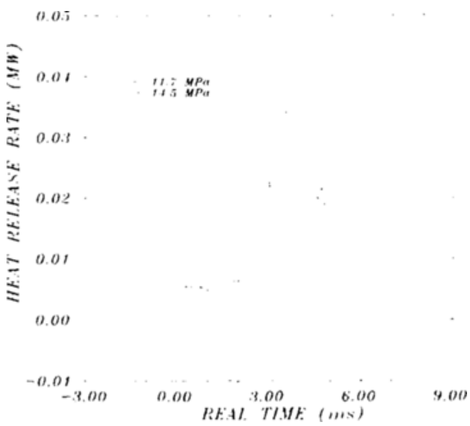

Fig. 5 Effects of needle lift pressure on heat release rate as a function of real time

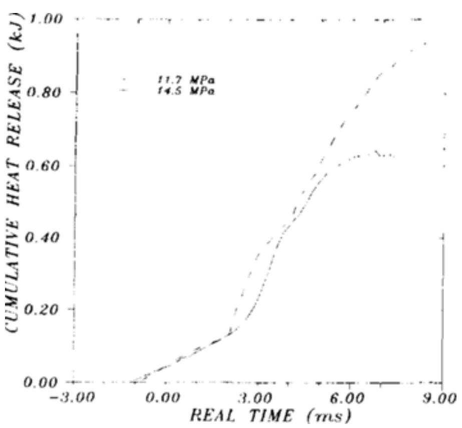

Fig. 6 Effects of needle lift pressure on cumulative heat release rate as a function of real time

3.2 Effects of fuel injection timing

The effect of the CWS injection timing on the ignition and combustion processes was investigated in this work by changing the relative angle between the cam shaft and fuel cam. Static fuel injection timings of 8, 18, and 28 crank angle degrees bTDC were investigated for this work. Results of 18 and 28 crank angle bTDC fuel injection timings are presented in this section as the coal-fueled engine misfired with 8 crankangles bTDC fuel injection timing. Inlet air temperature, needle lift pressure, and coal loading in the fuel were 182℃, 11.7 MPa, and 51.6 percent, respectively. Figure 7 shows the cylinder gas pressure as a function of crank angle for different static fuel injection timings. The figure shows that earlier introduction of the fuel to the cylinder leads to the higher peak cylinder pressure. This would occur because the earlier injection allows time for fuel and air mixing before ignition is achieved. Thus, more premixed reactants are present at ignition leading to faster burning and higher pressures. Perhaps more important is that the

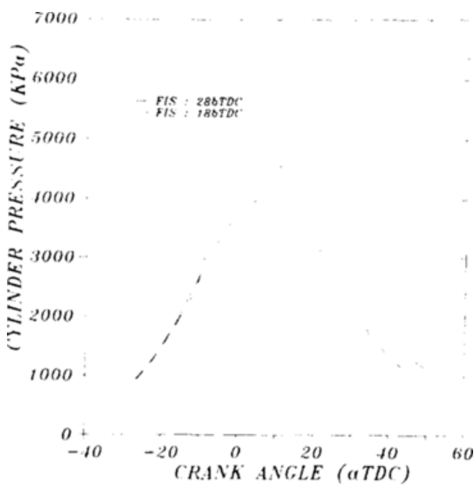

Fig. 7 Effects of fuel injection timing on cylinder pressure as a function of crank angle

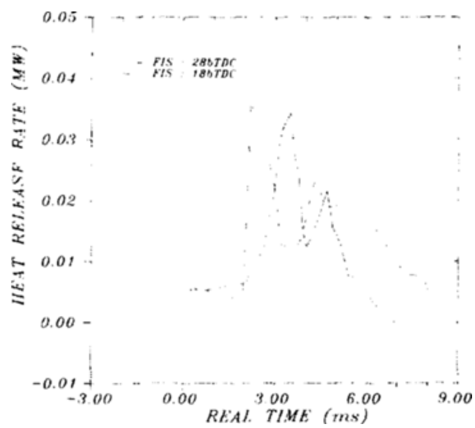

Fig. 8 Effects of fuel injection timing on heat release rate as a function of real time

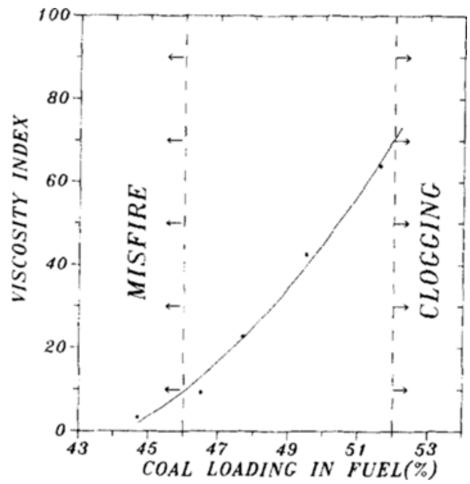

Fig. 9 Viscosity index as a function of coal percent in slurry fuel

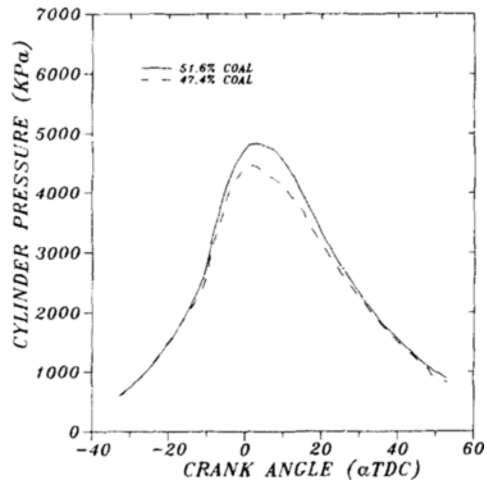

Fig. 10 Effects of coal loading in the fuel on cylinder pressure as a function of crank angle

advanced timing directly advances the combustion event relative to TDC. Therefore, the peak pressure is shifted close to TDC and increases the magnitude as combustion occurs in a smaller volume. For different fuel injection timings, the heat release rates as a function of real time are shown in Fig. 8. The zero real time correponds to the static fuel injection timing of each case. The figure shows that the ignition delay time of the advanced injection start was little different from that of 18 crank angle bTDC fuel injection timing.

3.3 Effects of percent coal loading

The effect of diluting the CWS with additional water was studied in this work. The CWS used was prepared by OTISCA Industries and the coal was cleaned to contain 1.25 weight percent ash and micronized to a mean particle size of 3.42 microns. The slurry fuel also contained 1.0 percent ammonium condensed naphtalene sulphonate as an additive which lowers slurry viscosity to improve transport property in the fuel supply system and for improving atomization quality.

The viscosity index of the slurry is determined from the elapsed time by the use of ASTM test (1944). In Fig. 9, the viscosity index number as a function of coal loading in CWS is shown. The figure shows that the effect of diluting CWS is to lower viscosity index number. From results of this work, it could be deduced that the lower viscosity slurry fuel by diluting could ease the fuel handling in the fuel line and improve the fuel atomization, but further diluting the slurry fuel, such as below 46 percent coal loading, might result in misfiring in the engine. Also, the clogging problem in the injector occasionally occurred with 51.6 percent coal loading in the fuel.

The base slurry was diluted to form two additional slurries of 47.4 and 46.4 weight percent coal. Since the engine often misfired with 46.4 percent coal loading, only results of 51.6 and 47.4

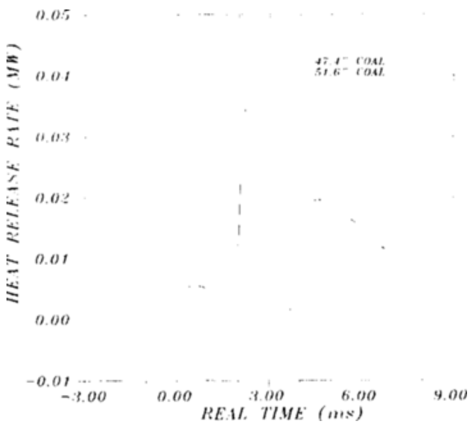

Fig. 11 Effects of coal loading in the fuel on heat release rate as a function of real time

percent coal loading are presented in this section. Figure 10 shows the cylinder pressure as a function of crank angle for different coal loadings. The static fuel injection start was set to 28 crank angle degrees bTDC, the needle lift pressure was 11.7 MPa, and inlet air temperature was 420 K. The figure shows that the peak pressure was lower for the diluted slurry case, however, because of the governor mechanism of the engine the amount of fuel supplied to the engine was not constant for the two cases. This is more evident from the instantaneous and cumulative heat release schedules calculated from the pressure data. Heat release rates from the different coal loadings as a function of real time are shown in Fig. 11. From the figure, the effect of diluting the slurry fuel is moderate for these two cases keeping in mind that misfire occurred in a third slurry mixture of 46.4 percent coal loading.

4. Summary and Conclusions

A prechamber type diesel engine was used for investigating the effects of needle lift pressure, fuel injection timing, and coal loading on ignition and combustion processes in a coal-fueled engine. A brief summary of the results and conclusions from this work include.

(1) Operation of the engine proved to be difficult using the coal slurry without engine modifications due to clogging and misfire.

(2) Higher needle lift pressure for injection led to shorter ignition delay times for the CWS combustion. This may be explained by the fact that the higher injection pressure, which was achieved at the start of injection with higher needle lift pressure, initialy led to a smaller injected slurry droplet size. Smaller slurry droplets would have shorter ignition delay times as a result of higher water evaporation rates.

(3) The peak heat release rate for the lower needle lift pressure was higher compared to the higher needle lift pressure since more fuel-air mixture was available for burning with longer ignition delay times.

(4) The ignition delay time of the advanced injection start was little different from that of retarded fuel injection timing. This may be a result of poor atomization with the retarded fuel injection timing case.

(5) Dilution of the slurry can significantly affect the combustion processes and fuel handling in the slurry line. Below some dilution ratio, 46 percent coal loading for this work, the combustion properties were sufficiently diminished to result in misfire. Above this dilution ratio, the impact on the combustion process was diminished. Although not verified here, it is expected that a second critical dilution ratio exists on the upper end in which the viscosity is increased with high coal loading such that poor atomization or possibly clogging would occur leading to poor performance.

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