COAL-WATER SLURRY (CWS) OPTIMIZATION, FLOW AND COMBUSTION TESTS AT THE UNIVERSITY OF THE PHILIPPINES

by

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INTRODUCTION

Philippine interest in the subject of Coal-Water Slurries (CWS) began in February 1983, in line with efforts then underway to develop indigenous coal resources to help reduce the country's dependence on imported petroleum. A Project Agreement with USAID Office of Energy was implemented in 1984 with the objective of assessing CWS potential in the Philippines. Work began in the Philippines (referred to as Phase I activities) with the preparation and shipping of coal samples to the United States for CWS formulations of acceptable properties. Field work was undertaken in the Philippines in October and November 1984, while experimental work on the coal samples continued in the United States. Evaluation of Phase I activities were completed in late February 1985 with the following findings:[1]

1. Production of combustible slurry from Philippine coal is feasible
2. Retrofit of Sucat Power Station to use CWS is feasible.

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3. Philippine coal reserves are sufficient to support conversion to CWS
4. Conversion to CWS is less costly than conversion to pulverised coal.
5. Net foreign exchange savings of US$1.4 Billion over 15 years can result from use of CWS in Sucat.

Although the above findings are positive, the level of information and experience in the production and performance characteristics of CWS made from low-rank coals (high moisture and ash contents, low heating value) is quite limited. Thus further work is deemed essential to adapt the technology to low rank Philippine coals to minimize the technical risk involved in subsequent commercialization efforts.

The objectives of the present Phase II activities are enumerated below.

OBJECTIVES

The project aimed at accomplishing several objectives under three studies as follows:

1. Optimization of fuel formulation studies aim to determine the optimum CWS which will possess the desirable levels of viscosity, good combustion characteristics, and manageable ash disposal potential.
2. Pipe loop tests aim to generate information which would be useful in identifying and addressing the engineering problems that may be expected in the handling and pipeline transport of coal-water slurries.
3. Atomization and combustion tests aim to characterize the combustion behaviour of selected slurries, including atomization quality and propensity for ash deposition, and to determine appropriate operating conditions and practices which would result in optimum carbon conversion and flame stability.

RESULTS

Optimization of Fuel Formulation

1. Slurribility of Coal Samples.

   Coal-water mixtures were formulated from coal samples (a) BPPCI from Bicol (b) Sicahoy 1B from Surigao, (c) Kawasan from Cebu, (d) Semirara, and (e) Batan Island. It was found that slurries could be formed from beneficiated coal samples ground to a fineness where 99% pass 325 mesh.

2. Effect of Size Distribution on Coal Loading.

Test materials were prepared by mixing samples of different grinds, namely; (a) "coarse" (2 hours grinding), (b) "fine" (5 hours grinding), and (c) "superfine" (10 hours grinding). The coal loading at different size distribution is shown in Table 1.

Table I

Effect of Size Distribution on Coal Loading

Coal Sample	Composite	% Coal Loading	Viscosity, cps
Sicahoy 1B	100% hrs grind	52.0	1000
"	75% - 2 hr/25% - 10 hr	51.6	1000
"	50% - 2 hr/50% - 10 hr	51.2	1000
BPCCI	75% - 2 hr/25% - 5 hr	51.4	1000
"	85% - 2 hr/15% - 10 hr	50.8	1000
"	75% - 2 hr/25% - 10 hr	50.2	1000

Apparently, there was a slight improvement on coal loading with coarser grind. The stability of the slurry, however, was another matter. It was observed that settling of the solids in the slurries used in the combustion test started within 2 hours.

3. Effect of Additives on Coal Loading.

Locally available viscosity-modifiers used were (a) UPPC black liquor, (b) Cyanamid GPC surfactant, (c) calcium hydroxide and (d) detergent (Tide). Only the last additive (Tide) was found to be slightly effective. However, large dosages were needed to effect substantial increases in loading. Roughly 2% detergent was needed to increase the coal loading of Sicahoy slurry by 1%.

4. Static Stability of Slurries.

The slurries prepared from coarse grind were definitely unstable, there being a tendency for the solids to settle immediately. More stable slurries could be prepared from finer grinds or coarse/fine composite materials, but viscosity of coal loading suffered.

5. Best Slurry Formulation.

Considering size distribution, slurry viscosity and stability, the trend in results suggest that the best slurry formulations are as shown in Table 2:

Table 2
Best Slurry Formulation

Coal Source	Composite	% Coal/Water	Viscosity, cps
Sicahoy 1B	75% - 2 hr/25% - 10 hr	51.6/48.4	1000
BPCCI	75% - 2 hr/25% - 5 hr	51.4/48.6	1000

Pipe Loop Tests

The pipe loop test system was incorporated with the combustion test rig such that the instrumention for pressure drops and flow measurements was common to both tests. The bottle neck in the pipe loop test was the fabrication of measuring instruments. Because of economy measures, it was decided to design and fabricate pressure sensors in the U.P. College of Engineering. The sensors were made out of metallic diaphragms installed along strategic points in the pipe loop. Deflection of the diaphragms when pressure of the fluids in the pipes were applied to them could be measured by means of strain gages mounted on the diaphramgs. The material for the diaphragms initially was mild steel. It was found out after fabricating the sensors and calibrating them with a dead-weigth tester that mild steel underwent permanent deformation at the pressures used during calibration. The pressure measurements therefore would be inaccurate and would become increasingly worse as cumulative permanent deformation occured with prolonged use. A second set of sensors were therefore fabricated out of stainless steel and calibration procedures were completed in December 1988.

Combustion Tests

Experimental burn tests of CWS fuel were conducted from June to December 1988 in a batch system consisting of a pressurized fuel tank with appropriate pipe and valving scheme, and a CWS burner designed and fabricated by the Department of Mechanical Engineering, University of the Philippines. Studies were concentrated on improvement of atomization of CWS fuel in the experimental burner.

Initially, steam (at boiler pressure of 75 psig) was used to atomize CWS (at fuel tank pressure of 100 psig). It was observed that although burning of CWS was continuous (in the presence of a pilot flame), the CWS was not fully atomized and therefore, combustion conversion efficiency was quite below 100 percent. When compressed air (at air tank pressure of 100 psig) was used for atomizing, similar result was observed-less than satisfactory atomization.

For Instance, during a burn test lasting 27.5 minutes, 115.2 kilograms of CWS was fired which was equivalent to a combustion rate of 251 kg/hour. This also correspond to a heat release 2.5 million Btu/hour. (The burner was originally designed for a heat release of 2 million Btu/hour). After the burn test, when the furnace had cooled down, total unburned fuel which dribbled from the burner and accumulated on the furnace floor was 18.4 kilograms. (See proximate analyses of parent coal, CWS and unburned residue in Table 3). The combustion conversion efficiency, therefore, was calculated to be approximately

$$\frac{115.2 - 18.4}{115.2} * 100\% = 84\%$$

In an attempt to study the atomization pattern more closely, cold tests were conducted by simply passing CWS thru the burner at varying CWS and atomizing air pressures without igniting the fuel. It was observed that at lower CWS flow rates (corresponding to lower CWS pressures at the burner nozzle), fuel atomization was quite satisfactory. CWS flow rates were varied by means of a gate valve installed along the fuel pipe line leading to the burner. During actual burn tests, this valve was fully open at maximum CWS fuel flow. A problem was observed when the valve was partly closed to reduce the flow: the tendency for CWS to plug the valve openings. On several occasions, CWS flow stopped completely when the valve was partially closed, or when it was closed completely for a short while and then opened fully again.

Literature indicated that in pilot plant demonstration projects, control of CWS flow rates was done through varying the rotational speed of the slurry pump supplying CWS to the burner. In the existing laboratory set-up where no slurry pump was available, some better way of controlling the CWS flow rate other than a gate valve was needed.

Table 3. Proximate Fuel Analysis (Average of 2 samples each)

Fuel	Sample	%M	%VM	%FC	%Ash
Parent Coal	1	19.2	47.4	46.8	5.8
	2	14.5	47.7	45.1	7.2
	Average	16.9	47.6	46.0	6.5
CWS*	1	53.5	47.4	46.8	5.8
	2	52.6	47.7	45.1	7.2
	Average	53.1	47.6	46.0	6.5
Residue	1	50.0	48.3	45.4	6.3
	2	50.4	46.8	46.7	6.5
	Average	50.22	47.5	46.1	6.4

*HHV of CWS = 4460 BTU/lb (2478 Kcal/Kg) at 53.1% M
= 9510 BTU/lb (5283 Kcal/Kg) dry basis

Table 4. Higher Heating Value of Philippine Coal Samples
(Determined by Bomb Calorimetry at the Department of Mechanical Engineering, University of the Philippines)

	Higher Heating Value (HHV)				
Coal Sample	Sample 1 kcal/Kg	Sample 2 kcal/Kg	Sample 3 kcal/Kg	Average kcal/Kg	Average BTU/Kg
1. Bicol (Middle Seam	5196	4961	4816	4991	8,984
2. Seam I Kawasan	6686	6941	6855	6827	12,289
3. Sicahoy 1B	4550	4510	4774	4611	8,300
4. Open Pit (Bilbao), Lower Seam	5258	5339	5094	5230	9,415
5. Bayabas Shaft B	6950	6514	6313	6592	11,866

Atomization Tests

Since observed atomization of CWS during the burn tests was less than satisfactory, improvement of atomization was studied more intensively through cold tests. Experimental work was done with the assistance of a graduate student (Mr. Daniel L. Lim) in the M.Sc. Energy Program of the College. The objectives of the cold tests were as follows:

1. To obtain better visual observation of the atomizer spray pattern or shape, and the quality of spray at different fluid flow rates.
2. To be able to identify the needed modifications to the present setup so that an acceptable spray pattern and quality is achievable.
3. To measure the fluid flow rates that produce the best spray possible from the setup.

The atomizer used in the test was an external mixing, twin-fluid type using air as the atomizing fluid. A brief discussion of the mechanism of liquid fuel atomization is given in the following sections.

The schematic diagram of the atomizer used is shown in Figure 1. The CWS passes through the central tube to the 0.18-inch diameter hole, and the atomizing air through the annular space surrounding the central tube to the six 0.12-inch diameter holes. Both fluids meet as they exit the nozzle of the atomizer. For twin-fluid atomizers, experiments and experience have shown that good atomization depends on the relative velocity between the two fluids and their mass ratio. The atomization fluid which is usually that with the higher velocity, imparts the energy needed by the slow-moving fluid to break into a spray. The best spray occurs when the relative velocity and the atomizing fluid to fuel mass ratio are both high. To obtain the highest relative velocity, the atomizing fluid which is air in this case, should be at sonic condition as it exits the nozzle, while the fuel when flowing without the atomizing air should just sort of drool out of the nozzle. Although it is desired to have a high air to fuel mass ratio for good atomization, it is not practical since the higher the mass of air used, the costlier the system becomes. The mass of air should therefore be kept to the minimum level that will produce an acceptable spray quality for good combustion.

There are several mechanisms in which a liquid breaks into a spray, but the most observed mechanism for twin-fluid atomizers is the initial formation of liquid ligaments which eventually break into droplets as the liquid issues out of the nozzle of the atomizer. The high relative velocity between the fluids results in high shear forces at the interface of the fluids causing the formation of the ligaments and droplets.

Figure 2 shows the setup used in the initial tests where the liquid atomized was water. Water was supplied from the tap. This was done to verify if the atomizer is working more or less satisfactorily before trying it out on CWS. It was necessary to conserve CWS because there was bottleneck in its preparation as explained above.

The basis for the water atomization test is the work of Meyer and Chigier[2.] Their work showed that at the same operating conditions the spray qualities of water and CWS are very different. However, as the air to fuel mass ratio for CWS is increased, there is a point where the spray quality of CWS resembles that of water which is at a lower air to fuel mass ratio. For the atomizer used in their work, an air to fuel mass ratio of 1.2 for CWS produced a spray resembling that of water at an air to fuel mass ratio of 0.3. For the atomizer under test, if a good spray is obtainable with water, it can be presumed that it will produce a good CWS spray at a higher air to fuel mass ratio.

Figure 3 shows the setup used in the CWS atomization tests. CWS was made to flow into the atomizer by pressurizing the tank with compressed air. Both atomizing air and pressuring air were supplied from one line. It was found that it was difficult to control the atomizing air flow in this scheme. Figure 4 shows a modified setup where the atomizing air and pressurizing air supply lines were separate.

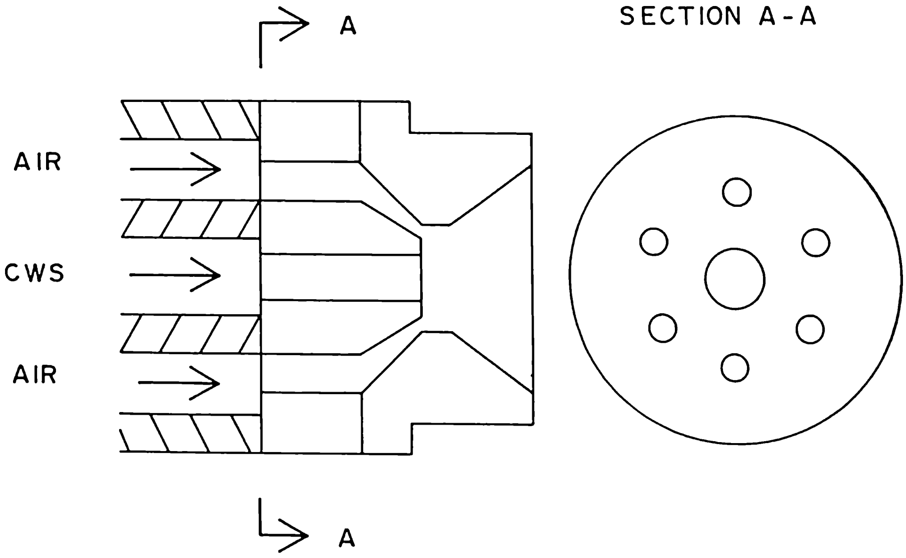

FIG. 1 ATOMIZER SCHEMATIC

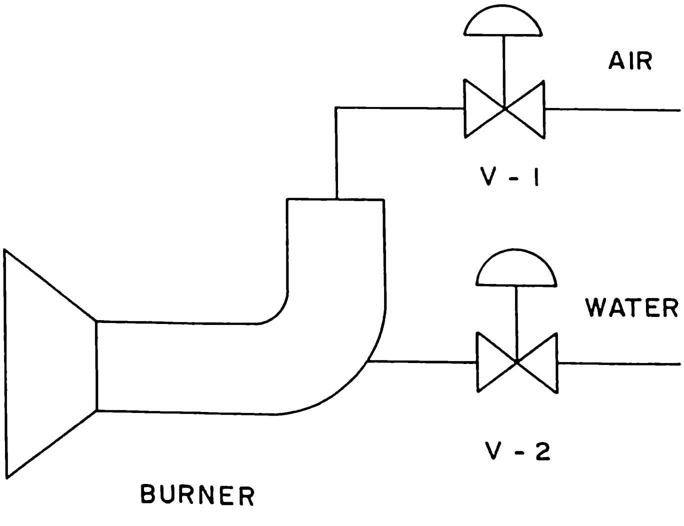

FIG. 2 SETUP FOR WATER ATOMIZATION TEST

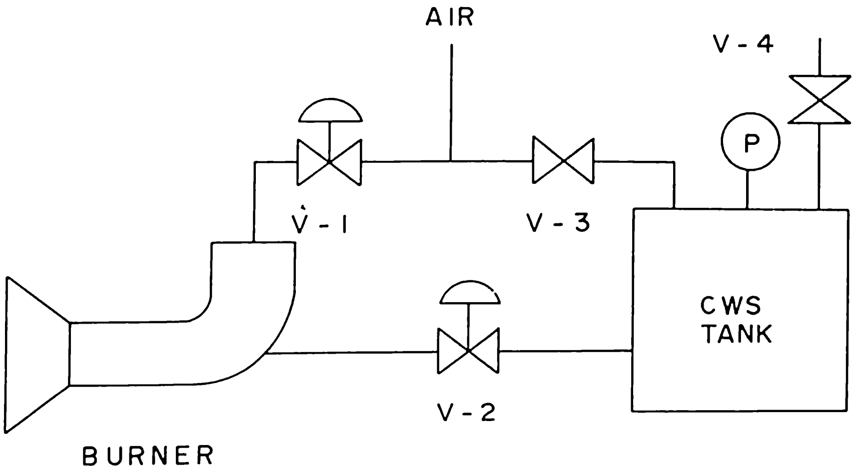

FIG. 3 SETUP FOR CWS ATOMIZATION TESTS

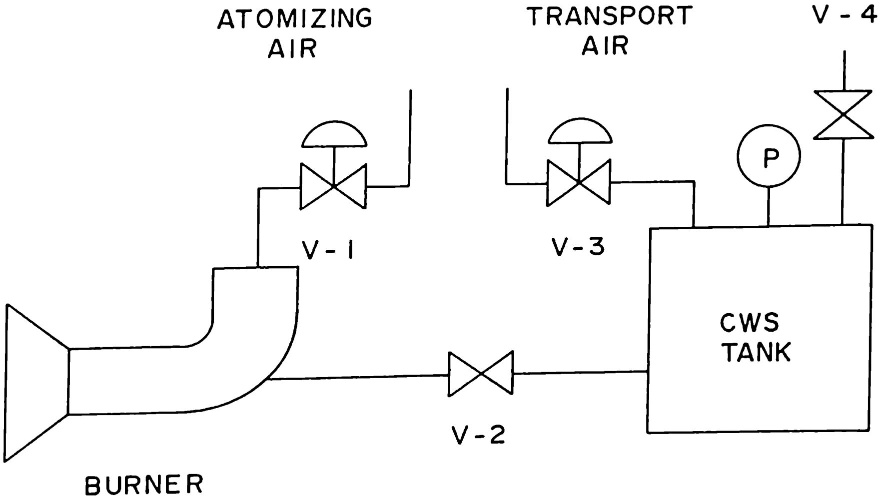

FIG. 4 MODIFIED SETUP FOR CWS ATOMIZATION TESTS

Water Spray Tests.

The schematic diagram for the water spray test is shown in Figure 2. Valve V-1 was used to control the flow of atomizing air and valve V-2 to control the flow of water. Both V-1 and V-2 were globe valves. Since the fabrication and calibration of instrumentation for pressure differences and fluid flows (transducers) had not been completed, the pressure in the air receiver was noted as reference for succeeding tests. Valve V-1 was fully opened at the start and during the test to allow maximum air flow available from the compressed air supply system. Valve V-2 was then slowly opened and the spray observed visually. The spray was considered good when the spray contained fine droplets of water. The maximum flow rate which resulted in the best spray was also recorded by closing V-1 and using the catch-time-weigh method of measuring the water flow rate. The results of the tests are as follows:

1. No difficulty was experienced in producing a good water spray; the spray shape is narrow. However, the water flow rate at which an acceptable spray is produced is quite low (calculated at 4 lb/min).

2. Increasing the water flow rate at the maximum air flow rate possible from the laboratory air supply system resulted in a poor spray; a good portion of the water issuing from the nozzle was not atomized but gushed out as solid jet.

CWS Spray Tests.

The schematic diagram for this is shown in Figure 3. Globe valves V-1 and V-2 were for controlling the flow rates of atomizing air and CWS respectively. CWS was transferred to the fuel supply tank via gate valve V-4 which was kept closed for the duration of the test. Pressurizing air was admitted into the tank through valve V-3 which was then closed when the tank pressure reached 50 psig. The test was started by fully opening valve V-1 to obtain the highest air mass flow possible. Valve V-2 was then slowly opened until a good spray was observed. The CWS flow rate was measured in the same manner flow was measured in the water spray test. The results of the CWS spray tests are as follows:

1. The atomization of CWS using the setup shown in Figure 3 was very difficult. The main problem was in controlling the rate of CWS flow. As in the water test, at the maximum available atomizing air flow rate, a good spray could be obtained only when CWS flow rate was low which required a small opening in the control valve. Blockage of the valve often resulted. To remove the blockage, the opening in the valve was made larger resulting in a higher flow rate of CWS. Poor atomization occurred at higher CWS flow rates.

2. A procedure tried was to have a fully opened valve and to control the flow by varying the air pressure in the CWS tank. Using the setup of Figure 3, the pressure in the tank was raised slowly until the CWS started to flow. To overcome the initial resistance, pressure had to be raised to a level higher than that corresponding to the desired flow rate, so that for a few seconds the flow rate was higher than that required for good spray formation. Again, some stoppage of flow was experienced and the pressure had to be raised to remove the blockage. Flow control was still very difficult. A possible cause for the blockage in the control valve even when fully opened was the tortuous path that CWS had to traverse through the globe valve. Another cause was the presence of lumps in CWS.
3. The globe control valve V-2 was replaced with a ball valve which had a straight flow path from inlet to outlet and which was capable of quick control action. Better control was achieved but flow stoppage was still experienced at low flow rates due to the small valve opening. The blockage was removed by opening the valve wider very quickly and returning to the low flow rate opening once the flow started again. The quick control capability of the ball valve saved much time in adjusting CWS flow rates compared to the previous tests.
4. Flow control was further improved by modifying the setup such that the CWS pressure tank and the atomizer of the burner were supplied with air from separate lines as in Figure 4. In this way, flow in one line was not affected by any changes in flow in the other. Continuous flow of CWS was possible and a relatively good spray was achieved. The CWS spray had a wider angle than that achieved wih water. Some stoppage of flow was experienced when the nozzle got clogged with coarse coal particles, but this was easily cleared by inserting a thin rod through the nozzle. An extended atomization test was however not possible because of the limited supply of CWS and the time to prepare it.
5. Atomizing air and CWS flow rates were not measured due to lack of instrumentation. The important information, however, is that despite limitations in equipment, a good CWS spray is achievable using the setup in Figure 4. The air pressure in the compressor receiver was form 100 to 150 psig for all the tests. Poor atomization resulted when the air pressure dropped below 100 psig.
6. It can be expected that if CWS flow could be controlled with the use of a slurry pump at varying speeds, CWS atomization could be further improved.

Atomization tests using steam as the atomizing medium was not done as extensively as with air. However actual burn tests proved that steam can very well be used for atomizing. It was necessary however, to provide a pilot flame to keep the flame stable. In the burn test set-up, there were two burners: the CWS burner and the auxiliary oil burner that provided the pilot flame.

CONCLUSIONS

The following are the important conclusions of this study:

1. The best coal-water slurry preparations done in the laboratory were those for coal samples Sicahoy 1B and coal sample BPCCI. The coal loading for Sicahoy 1 B was 51.6% solids and 48.4% water when 75% coal particles ground for 2 hours were mixed with 25% coal particles ground for 10 hours. For the coal sample BPCCI, the coal loading was 51.4% solids and 48.4% water at 75% coal ground for 2 hours mixed with 25% coal ground for 5 hours.

2. CWS prepared in large quantities and used for the burn tests were found to have a coal loading of 47% solids (53% water). It was possible to burn this in the CWS burner but in the presence of a pilot flame. Removing the pilot flame resulted in a flame-out. It may be possible to use a better quality coal sample with a higher heating value (e.g. Kawasan or Bayabas, Table 4) in the preparation of CWS which could have a higher coal loading and which could burn with a more stable flame (without requiring a pilot flame).

3. CWS atomization in the burner in the preliminary tests was not satisfactory resulting in low combustion efficiency. Cold CWS atomization tests indicated that good atomization could be achieved if CWS and atomizing air flows could be better controlled. It was quite difficult to achieve this in the present setup which used pressurized air for controlling the flow in a batch system.

4. Better flow controls are necessary for good CWS atomization which could be achieved with the use a slurry pump capable of pumping pressures of 100 psig or more. At the same time, continuous burn tests could be achieved which were not possible in the batch system test rig.

5. CWS prepared at the maximum coal loading of 51.6% (48.4% water) could not be burned with a stable flame during the burn tests unless a supplementary kerosene burner provided a pilot flame at all times.

RECOMMENDATIONS

Since better control of CWS flow rates and longer duration of burn tests are essential for more meaningful data, a slurry pump must be used in additional experimental work. One additional study that could be recommended is that on oxygen-enriched air combustion of CWS, aimed at achieving better flame stability.

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