". . . CWF can be fired successfully and economically as a replacement for residual fuel oil . . ."

Development of Coal-Water Fuel Technology*

by

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INTRODUCTION

Coal-water fuel (CWF) is a slurry consisting of finely ground coal and water with approximate weight ratio of 70 per cent coal and 30 per cent water. When small but significant amounts of surface active agents or surfactants are added, the coal particles remain in suspension for an extended period but when subjected to a shearing stress, the mixture flows like a liquid. CWF has the viscosity of residual No. 6 fuel oil, can be stored in tanks, pumped through pipes, atomized in burners and burned in air to produce heat. It has been called by a commercial manufacturer as "liquid coal".

Introduced in the U.S. during the early '70s at the height of the global oil crisis, CWF's potential markets are the existing industrial and utility boilers originally designed to burn heavy fuel oil, many of which are under-utilized and more than 80 per cent less than 20 years old.

For the boilers originally designed for coal but which were converted to oil when the latter was cheap, the recourse is merely to switch back to coal. However, for the oil-designed boilers, the options are:

1. to continue to burn fuel oil, in spite of the rising cost of fuel;
2. to convert to pulverized or stocker coal, which, although cheaper, will require major capital investments to cover cost of boiler retrofit (pulverizer, fans, soot blowers, ash handling equipment, controls, convection pass modification); or
3. to convert to CWF, an intermediate-cost fuel and intermediate capital investment.

While the economics[1] are site- and boiler-specific, the third alternative appears to be cost effective according to several sources.

CWF has also been considered as an injection fuel for blast furnaces and as locomotive fuel in the marine and railway transport sector.

ADVANTAGES OF CWF

Coal-water fuel possesses several advantages:

1. Ease in handling, transport and storage; it can be transported by pipeline over short to medium distances.

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[1] Typical U.S. fuel costs (June, 1984): Oil ($28/bbl), $4.75/mm Btu; coal, $2.80; CWF, $3.56.

2. It is a relatively low-cost fuel, intermediate between oil and coal.

3. Although dependent on boiler configuration, the cost of retrofit[2] is relatively low compared with the cost of new installations.

4. Coal is an abundant source of energy with many developing countries having significant coal reserves. Philippine reserves are placed at 1.5 billion metric tons of which 263 million are proven reserves.[3]

5. Unlike synthetic fuel from coal and other alternative energy sources, CWF is undergoing accelerated research and development and can be commercially available within a short period of time.

6. Consisting of standard equipment such as crushers, grinding mills, mixing and storage tanks, a CWF processing plant is inexpensive and easy to operate.

7. CWF processing can be integrated with coal beneficiation, eliminating the need for dewatering and drying, and ensuring utilization of fines.

COAL WATER SLURRY PREPARATION

To be suitable for slurry processing, coal must possess certain characteristics. Various slurry manufacturers in the U.S. generally agree that parent coals must have:

1. high volatile matter for flame stability;
2. high heating value compatible with high volatile matter;
3. low ash content and high ash fusion temperature to minimize related problems of fouling and slagging;
4. high grindability index to reduce grinding costs;
5. low sulfur content to minimize atmospheric pollution; and,
6. low inherent moisture to provide fluidity at a given (dry) coal-water ratio.

The high volatile bituminous coals from the Appalachian region in the eastern part of the United States have been found to be ideal for CWF manufacture.

To produce a slurry, coal is either dry- or wet-ground to at least 70 per cent minus 200 mesh (74 microns) and no more than one per cent plus 50 mesh (300 microns). Particle size distribution is an important consideration as it reportedly affects viscosity and particle packing.[4]

The slurry is made by mixing the ground coal with water in the ratio of 70 parts coal and 30 parts water. To impart certain desirable characteristics, the following surfactants are added (about one per cent):

1. dispersant – bituminous coals being hydrophobic, dispersants wet the coal particles, prevent flocculation and permit increased loading;
2. stabilizer – prevent settling while in storage;
3. other additives – pH control, biocide action, etc. The range of CWF properties observed in most commercial slurries prepared from U.S. coals is shown in Table 1.

RHEOLOGICAL PROPERTIES OF CWF

Coal-water slurries exhibit interesting rheological properties, being classified as non-Newtonian, Bingham pseudoplastic.

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[2]Retrofit costs: oil to pulverized coal, $3.32/mm Btu; oil to CWF, $0.62. R.S. Sapienza, et al, "Coal/Water Fuels in America's Energy Future", May, 1984. NPC Calaca Coal Thermal Plant estimated cost: $1,000/kw.

[3]From U.S. Geological Survey report submitted to U.S. AID, September, 1984.

[4]Zheng-Kong-zeng, et al., "Research on CWM Preparation Technique with Chinese Coals." Proceedings, 6th International Symposium on Coal-Water Combustion and Technology, U.S. Dept. of Energy, 1984.

The flow of various types of fluids under the influence of an external shearing stress is illustrated in Figure 1 which shows the relationship between shear stress and shear rate according to the general power law equation:

$$T - T_y = K(\dot{\gamma})^n$$

where

$$T = \frac{dF}{dA} = \text{shear stress}$$

$$\dot{\gamma} = \frac{-dv}{dx} = \text{shear rate}$$

n = power law index

K = constant (consistency coefficient)

T_y = yield stress

For simple Newtonian fluids, $n = 1$, $T_y = 0$ and shear stress is proportional to shear rate. The slope of the curve (a) is called the coefficient of dynamic viscosity.

Bingham plastic is a model which approximates non-linear flow behavior by a straight line with an initial stress, T_y needed to start flow. The slope of the curve (b) is called "plastic viscosity" or simply "plasticity".

For pseudoplastics, $n < 1$, and the slope at any point of the curve (c) is called the apparent viscosity. As the rate of shear increases, the apparent viscosity decreases and the fluid is said to be shear-thinning.

A pseudoplastic which exhibits a yield stress (Bingham pseudoplastic, curve d), as exemplified by coal-water slurries, is stable under stresses lower than the yield stress. This yield stress should be large enough to prevent settling under static and dynamic forces encountered during storage and transport but small enough to prevent excessive gelation and thus permit pouring.

When $n > 1$ (curve e), the fluid becomes more viscous with increase in shear rate. Such shear thickening fluids are called dilatant fluids.

For certain fluids (curve f), the apparent viscosity is time-dependent. In thixotropic fluids, the viscosity decreases with time under constant shear rate probably as a result of structural changes. A decrease in viscosity with time is desirable during pipeline transport and in atomization.

COMBUSTION CHARACTERISTICS OF CWF

The combustion performance of CWF has been evaluated under a variety of combustion conditions using specially designed burners and test combustion facilities.

The general observation is that CWF can be atomized with atomizing air pressure of 150 psig, forming droplets with mean diameters between 100 and 150 microns, indicating good atomization quality. The degree of atomization accounts, in a large measure, for the successful combustion of CWF. Studies are presently being conducted towards correlating the degree of atomization with easily measurable characteristics of the coal-water slurry. For example, it has been observed that for a particular coal, atomization improves with reduction in viscosity but different coals exhibit different atomization qualities at a given value of viscosity.

High carbon conversion (to CO and CO_2) in excess of 99 per cent has been reported. Adiabatic flame temperatures were calculated[5] to be 100 to 150 degrees centigrade lower than for No. 6 fuel oil; furnace temperatures have reached up to 3100 deg F with air preheat of 1000 deg F, 20 percent excess air for 70/30 CWF in actual tests.

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[5]C. B. Henderson, et al., "Coal Water Slurries – A Low Cost Liquid Fuel for Boilers". Energy Progress, June 1983.

Good flame stability has been observed particularly for CWF with high volatile content, the stability improving with degree of air preheat. Heat transfer rates are intermediate between those of coal and oil.

The presence of 30 parts by weight of water in the slurry does not appreciably reduce the heating value of CWF. Calculations[6] show that about 3.1 per cent of the heating value of the coal is required to vaporize the moisture and heat it to the temperature of the flue gas leaving the air preheater.

For many U.S. coals depending on the ash content and composition, slagging and fouling problems have been found to be predictable and manageable, particularly in the case of slurries containing additives which are not sodium-based.

CURRENT DEVELOPMENTS

Developments in the preparation and formulation of CWF have been progressing at a rapid pace in the U.S. so that it can now be said that virtually any type of coal can be converted into a slurry with appropriate grinding to an optimum particle size and size distribution and with the use of proprietary additives. What remains at this point in time and which will hasten its acceptance by the industry is to demonstrate that CWF can be fired successfully and economically, as a replacement for residual fuel oil, in a utility boiler with a rated capacity of at least 100 megawatts.

To date, the largest scale demonstration of the use of CWF in an industrial boiler in the U.S. has been a 35-day firing test by Du Point of Memphis Unit No. 1 boiler rated at 60,000 lbs steam/hr, 150 psig, saturated, from August to September, 1983. A larger scale demonstration with a 140,000 lbs steam/hr industrial boiler has been on-going for interrupted periods since mid-1983 in Chatham, New Brunswick, Canada and with a 55,000 lbs steam/hr boiler in Sundyberg, Sweden.

A feeling of confidence in the advantages of CWF has been demonstrated by several U.S. producers (Babcock & Wilcox, Combustion Engineering, Foster Wheeler, Atlantic Research, etc.) who had announced or completed construction of commercial CWF processing facilities. There is now a need to evaluate economic factors affecting over-all cost of conversion, such as boiler retrofit, loss of capacity due to boiler derating, CWF shipment costs, storage, burner design, etc. under near-actual conditions. Demonstration is important as an insurance against uncertainties in the technology and economics of commercial scale utilization of CWF.

INTRODUCTION OF CWF TECHNOLOGY IN THE PHILIPPINES

The U.S. Agency for International Development (USAID) conducted a feasibility study from August, 1984 to March, 1985 on the introduction of CWF technology in the Philippines on request of the Philippine government. Samples of five Philippine coals were sent to Brookhaven National Laboratories in Long Island, New York for characterization and formulation into coal-water slurries. Table 2 lists the characteristics of the samples submitted.

It will be noted from the table that:

1. Philippine coals have medium to high ash content. Malangas coal contains less ash than indicated.

2. Ash fusion temperature of the lower rank coals is low because of the high Na_2O content of the ash. With a high slagging tendency, a significant power derating is predicted in order to minimize slagging problems.

3. The heating value is low on account of the low fixed carbon which characterizes low rank coals.

4. The inherent moisture is high as a result of the high porosity typical of lignites and sub-bituminous coals. Problems of viscosity will be encountered for the 70/30 formulations which will impose a limit on the coal content of the slurry.

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[6] *Ibid.*

5. The sulfur content is low, a plus factor when environmental impacts are considered.

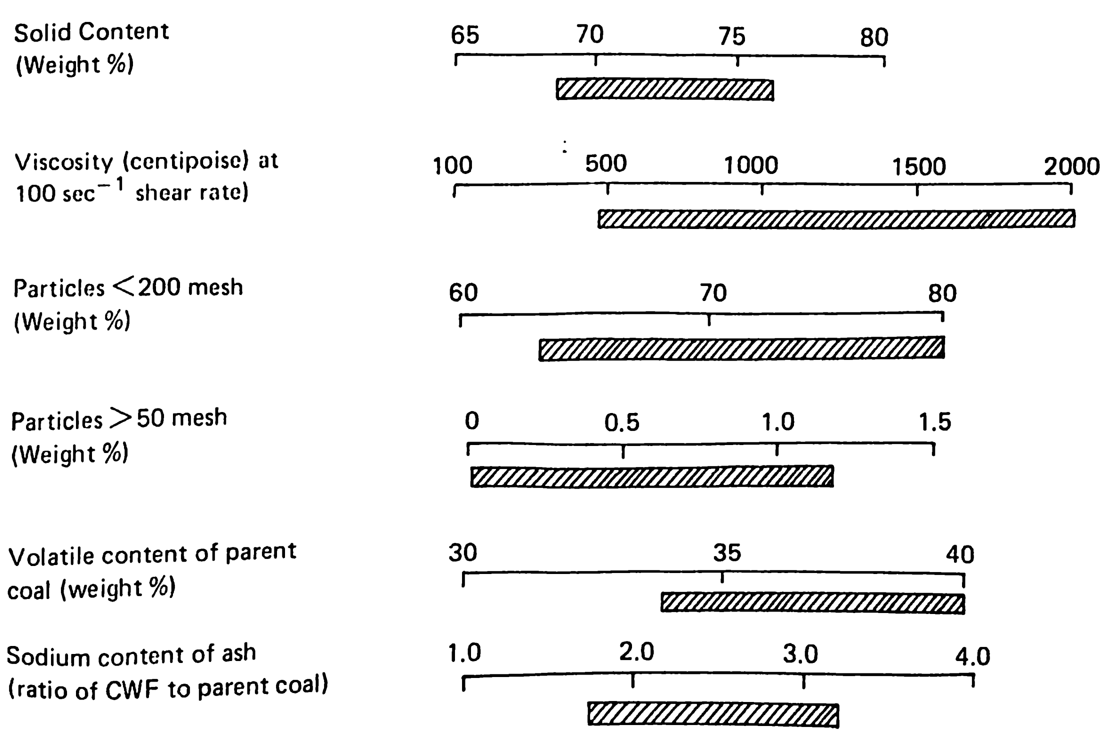
To date, slurries of up to 55 per cent Semirara coal without the use of additives have been formulated and found to possess good rheological properties, the most promising being a blend of 75 per cent Semirara and 25 percent Malangas, combining the high volatile content of the former and the heating value of the latter. Beneficiation of Semirara coal is under current investigation at the Department of Mining and Metallurgical Engineering, University of the Philippines to reduce its ash content and upgrade its heating value.

In addition to the studies at Brookhaven, private slurry manufacturers in the U.S. have formulated their own mixtures, thereby contributing to the wealth of information on Philippine coals.

Preliminary performance data on the combustion of the various formulations have already been gathered. An economic information package on the feasibility of adapting CWF technology was submitted by USAID to the National Economic Development Authority in April, 1985.

The USAID feasibility report recommended an on-site demonstration of CWF technology using the 200 MW utility boiler of the National Power Corporation at Sucat, Metro Manila. Pre-demonstration activities are now underway in preparation for the various aspects of the large-scale test.

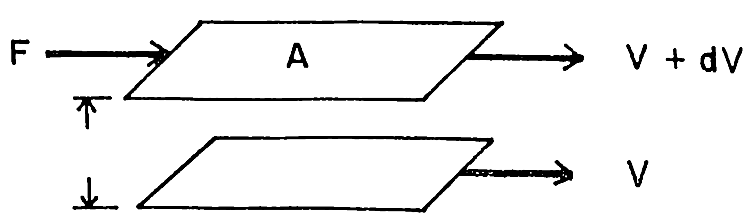
Table 1. Range of Values of CWF Property



from "Coal-Water Slurry Evaluation. Vol. 2"
The Babcock & Wilcox Co. 1984

Table 2. Composition of Philippine Coals
(U.S. Geological Survey 1984)

	So. Cebu	Malangas	Bislig	Semirara	US Coal
As received basis:					
Ash, %	4.43	15.18	14.49	8.86	4.5
Moisture, %	9.93	1.94	18.92	25.66	----
Volatile matter, %	42.35	19.63	30.73	32.08	31.4
Fixed carbon, %	43.29	63.25	35.86	33.04	64.1
HHV, Btu/lb	12,212	12,909	8,742	8,209	14,740
Sulfur total	1.74	0.49	0.57	0.58	0.74
Ash fusion temperature					
Init. deform. ^{o}F	2050	2600	2530	2300	2750
Fusion temp. ^{o}F	2160	2720	2660	2410	2750
% Na_2O in ash		0.89		2.15	0.7
COAL RANK	HVB bitum	Med Vol bitum C	Sub bit B	Sub bit C	HVA bitum



Power law: $T - T_y = k(\ddot{\gamma})^n$

where $T = \frac{F}{A}$

and $\ddot{\gamma} = \frac{dv}{dx}$

Figure 1.A. Rheological behavior of Newtonian and non-Newtonian Fluids. A. Power law equation.

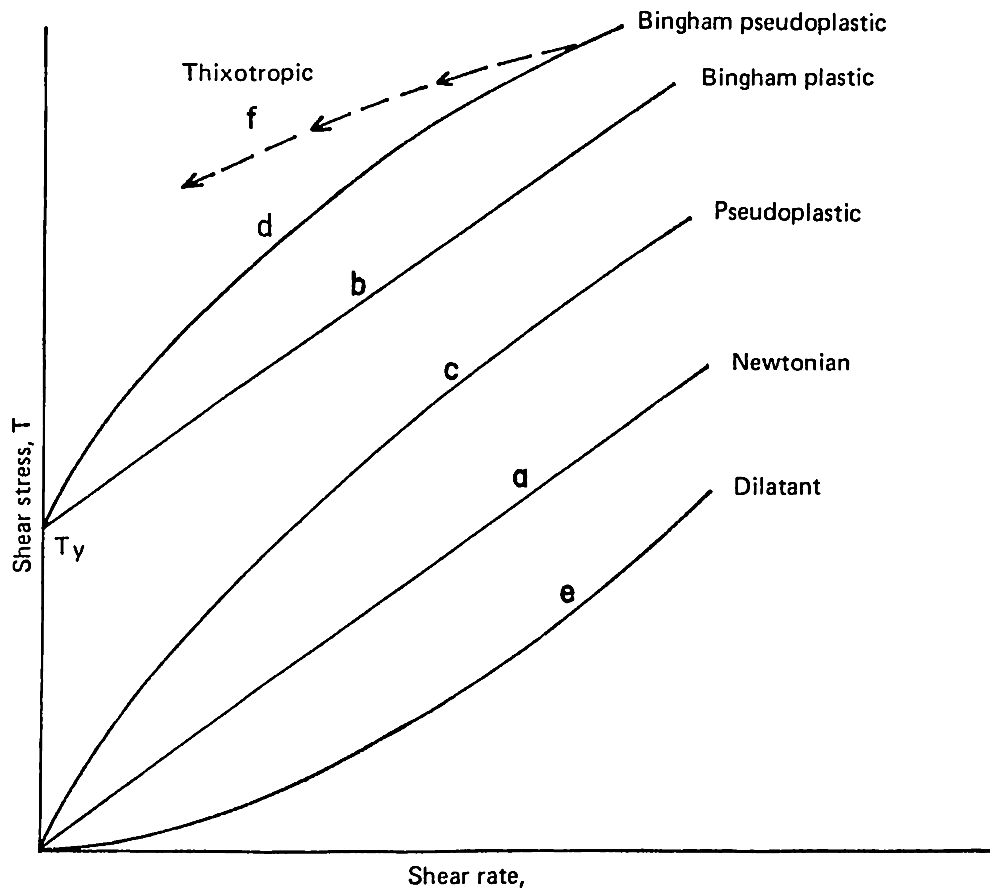


Figure 1.B. Rheological behavior of Newtonian and non-Newtonian fluids. B. Stress-strain relationships of various fluids.