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The properties and uses of mixtures of coal, and water or oil*

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SYNOPSIS

This paper reviews the properties and uses of mixtures of coal with fuel oil, methanol, or water, emphasis being placed on mixtures of coal and water.

The material presented is taken from studies conducted overseas, and it is recommended that similar studies should be conducted on mixtures containing South African coals, which differ from the coals of the northern hemisphere.

SAMEVATTING

Hierdie referaat gee 'n oorsig oor die eienskappe en gebruike van mengsels van steenkool met brandolie, metanol of water, met die klem op steenkool-en-watermengsels.

Die materiaal wat aangebied word, is geneem uit studies wat oorsee onderneem is en daar word aanbeveel dat dergelike studies gemaak moet word van mengsels met Suid-Afrikaanse steenkool wat verskil van die steenkool van die noordelike halfrond.

Introduction

It cannot be denied that, although coal has many virtues, it has one or two disadvantages. Principal among these are its mineral content, especially the sulphur-bearing component, and the problems created in the handling and storing of coal, such as dust and the need for expensive mechanical handling and reclamation systems. By contrast, liquid fuels are naturally low in mineral content, can be freed of their sulphur compounds, and are easily handled and stored. On the other hand, coal is abundant, widespread, and fairly cheap to produce; while oil reserves are much smaller and are concentrated in politically unstable areas, and the commodity can become very expensive indeed, regardless of production costs.

Consequently, there has long been a desire for coal with the properties of oil. The conversion of coal to true liquids has been investigated and practised for over fifty years. Oil-from-coal plants were built in the USA, UK, Germany, and other coal-producing countries in the 1920s, but all proved to be uneconomic in the face of competition from natural oil. Germany's use of oil from coal plants in World War II is well known, but a siege economy creates the conditions for operating and extending conversion facilities. From the end of the war, coal conversion virtually ceased as the growing oil industry threatened the economic basis of coal production itself, let alone permitting the production of relatively higher-priced derivatives.

The oil price increases of the 1970s changed the situation, and the coal-producing world became awash with schemes for coal conversion. However, this movement collapsed with the failure of OPEC's price-fixing tactics. Only in South Africa, where the strategic need for relative independence from oil imports overrode economic considerations, was coal conversion fostered and extended. In Germany and the UK, pilot-scale activities have continued, but there is none of the heady atmosphere prevailing fifteen years ago, and efforts are directed towards being prepared some time in the misty distant future when oil reserves run out.

Although the urge to convert coal to oil has now diminished, the siren call of oil remains. The desire to use coal in liquid-like form is strong, and an alternative approach to conversion is gaining ground. The alternative is to mix coal with a fluid to produce a suspension that behaves like a liquid. The suspensions developed are as follows:

- Coal–oil mixture (COM), a mixture of coal and fuel oil that may contain up to 10 per cent water
- Coal–oil–water mixture (COW), COM with more than 10 per cent water
- Coal–methanol mixture (Methacoal)
- Coal–methanol–water mixture (CMW)
- Coal–water mixture (CWM), a mixture of coal and water.

A comprehensive account of all the developments is beyond the scope of this review. Only the salient features of coal–liquid mixtures are covered, together with their relevance to the South African coal industry. At present, fairly intensive work is being carried out on CWM in Italy (as part of a joint programme with the US Department of Energy), and in Israel. Canada, the Republic of China, Sweden, and Japan are other countries with CWM research programmes.

Because, in the author's view, CWM has the best chance of being used in South Africa and the adoption of the process would bring considerable benefits, the focus of this paper is on CWM. However, it will be clear

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from the text that certain considerations, particularly those regarding coal quality, are applicable to any type of coal–liquid mixture.

History

Coal-oil mixtures have been investigated for over a century, and during World War I attempts were even made to use the fuel in submarines. Interest has fluctuated with coal and oil prices. Much work was carried out in the USA with the aim of eking out the dwindling oil reserves, but the price differential between coal and oil was too small to encourage development. In addition, the need to introduce expensive additives to improve the stability of COM further reduced its attraction. However, numerous tests in the 1970s proved the technical suitability of such mixtures in conventional oil-fired equipment, boilers up to 315 MW having been used for test purposes.

Methacoal has been proposed both for the transportation and use of coal. The suspending of coal in a liquid that itself burns yet has a low enough viscosity for pipeline transportation has obvious attractions. However, the practical development of Methacoal has not been to the extent of COM and CWM. Coal–water mixtures have been investigated since the 1950s, starting in the USSR, and several proprietary processes are available. As the required comminution of coal to give a stable suspension also liberates mineral matter, CWM processes tend to include a beneficiation step. It seems that the mixture remains pumpable and stable up to a solids content of about 75 per cent by mass.

Production of Coal–Liquid Mixtures

The production of coal–liquid mixtures essentially entails the following.

The coal has to be ground to a specific size grading. For COM, simple pulverized fuel techniques appear to be acceptable but, for CWM, it appears preferable to produce coal ground to a bimodal size distribution to get maximum solids loading of the suspension.

In the making of COM, the coal can be ground dry and then mixed with oil, or relatively coarse coal can be mixed with oil and 'wet' ground. In the production of CWM, the grinding can also be wet or dry.

If the feed coal is of the required quality, no additional processing is carried out. This appears to be the practice with COM; the use of some of the oil to beneficiate the coal by oil agglomeration would seem logical. In the case of CWM, where very low ash contents are desirable, a beneficiation stage can be introduced. Froth flotation is favoured because of the small particle size and consequently good liberation but, if pyritic sulphur is present, a gravity-treatment stage could be introduced (Fig. 1).

If dry grinding has been carried out, the pulverized coal is then mixed with the fluid and, if necessary, the suspension is stabilized by chemical additives, which may themselves be dispersed by ultrasonic vibration. However, such addition may be unnecessary if the coal is very fine and stabilizes by virtue of its small particle size.

The mixture must then be brought to the maximum solids concentration. If wet grinding with beneficiation is used for CWM, this step may require the use of a thickener and filter to remove surplus water.

A typical flowsheet for a plant producing coal–water mixtures is shown in Fig. 2. If the coal contains pyritic sulphur, gravity concentration may be required. Tables or spirals may be employed or, for really low-density separations, dense-medium cyclones.

Potential Markets

Coal–liquid mixtures are most likely to be used in boilers that were designed for coal but have changed over to oil, or in oil boilers that can burn coal–liquid mixtures without serious loss of output (de-rating). Other suggested uses have been in diesel engines, for blast-furnace injection, in process heating, and in rotary kilns. Because, for coal–liquid mixtures, the coal is transported by pipeline, a subsidiary attraction of the system is that coals remote from rail systems might be exploited more economically and sold as coal–liquid mixtures, than by the use of conventional beneficiation and transportation methods.

Requirements of Coal–Liquid Mixtures

The following are the general requirements of all coal–liquid mixtures.

- The suspension must be stable for extended periods so that it travels and handles like oil.
- The viscosity must be low to reduce pumping costs.
- The proportion of mineral matter must be low if the mixture is to be used as an oil substitute.
- The fuel must burn as pollution-free as possible.
- The suspension must be non-abrasive and non-corroding.

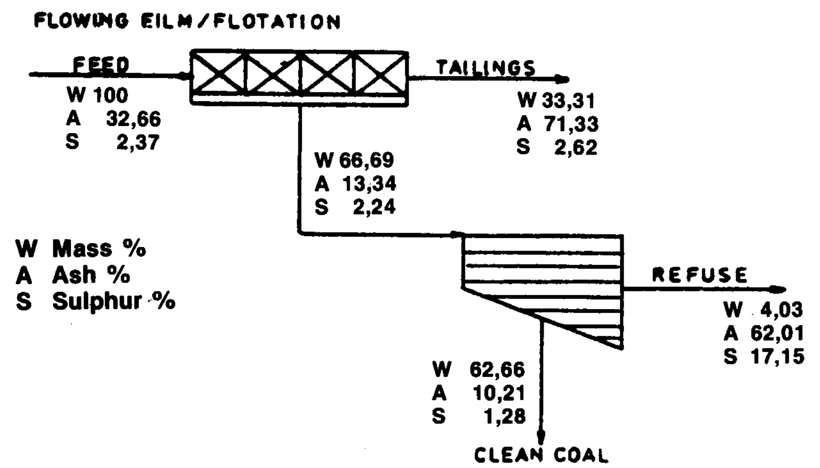

Fig. 1—Froth flotation and gravity concentration of 902 rank coal smaller than 500 μm (after Bienstock and Foo, p. 74)

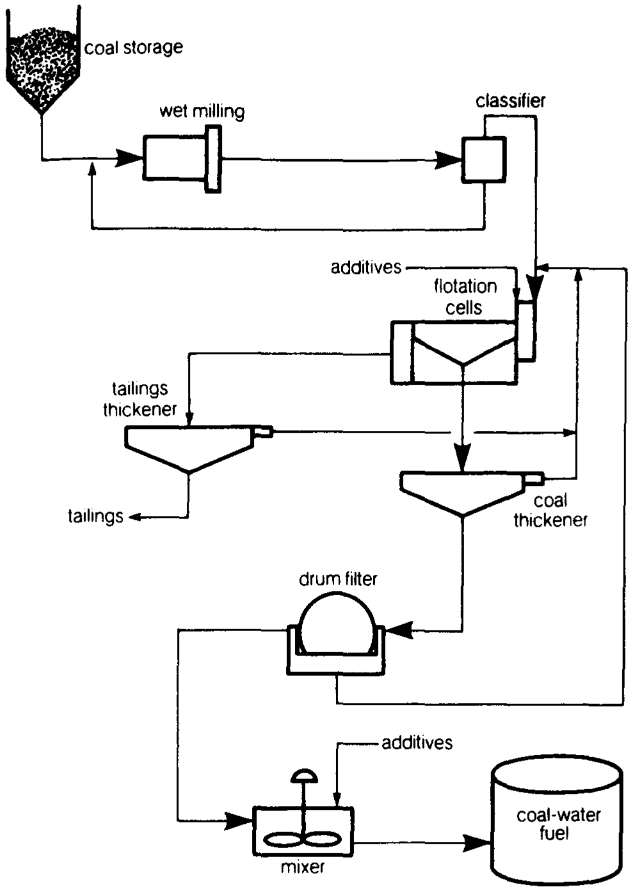

Fig. 2—Flowsheet of a plant producing CWM (after Siemon, p. 21)

- The combustion characteristics must resemble those of oil, especially residual fuel oil, which it is most likely to replace.

Coal Properties

From the foregoing, it will be apparent that the coal used in coal–liquid mixtures must

- be readily grindable to specific size analyses,
- have a very low ash content,
- be high enough in volatile matter to have good combustion characteristics,
- be of low sulphur content, and
- be of low price.

Size Analysis

The greater the solids content of a coal–liquid mixture, the greater the proportion of coal borne, and hence the greater potential economic advantage. If it is assumed that the particles are of uniform size, maximum volume packing gives about 60 per cent solids which is roughly equivalent to 65 per cent by mass for coal. However, if the interstices are themselves packed with still finer particles, the solids loading may increase.

Theoretical considerations show that if ds is the smallest particle present and dl the largest, maximum solids loading occurs with maximum dl/ds. Ideally, the size distribution should be bimodal. The practical limits to the ratio are that dl cannot exceed 250 μm; otherwise, burner blockage may occur. However, for ds to be below 1 μm requires considerable grinding energy. Hence, there must be close control of the grinding stage. In practice, the maximum particle size is 75 to 100 μm. Simply by the use of the conventional grinds for pulverized fuel, solids loadings of 70 per cent can be produced; expressed in ds/dl, a solids loading of up to 80 per cent can result.

To make the suspension handleable at high solids loadings, chemical additives are used, which 'lubricate' the particles by, for example, creating electrostatic repulsion (ionic additives). Other additives increase the liquid viscosity, which reduces the settling velocity and so improves the stability.

Ash Content

Opinions vary about the percentage ash that can be tolerated, and the intended application probably influences the figure. If CWM is to be used in a unit originally designed for coal and then changed to oil, a higher ash content may be acceptable, especially if ash-handling facilities are still available. Also, the actual design of the heat-transfer system will be attuned to coal, so that reverting to coal presents fewer difficulties. If CWM is to replace oil in equipment designed for oil, a much lower ash content, say 1 to 3 per cent, is required. If CWM is to be used in a gas turbine, it is suggested that less than 0,5 per cent ash is essential.

In addition, the ash level affects the overall calorific value (CV), and hence the de-rating of equipment designed for oil. Table I gives some CVs of CWM made from a Witbank coal high in volatile matter at different ash levels, together with similar data for RFO and some refined liquid fuels. For all the CWM, a solids content of 75 per cent by mass was assumed.

TABLE I
CALORIFIC VALUES OF CWM

Parameter	CWM			Oil	
Ash content, %	9	6	1	No. 4	No. 6 (RFO)
CV (MJ/kg)	30,0	31,5	32,5	–	–
CV of liquid fuel (GJ/t)	21,0	22,1	22,8	44,7	41,2

The CV of CWM does not approach that of even the most inferior oil, but an ash content of less than 5 per cent will reduce transportation costs and, more importantly, reduce the ash-handling problems in the combustion appliance. Moreover, as Italian research suggests, the higher the ash content of the coal, the greater the viscosity of the slurry, making a CWM more costly to pump. Also, several ash-forming minerals are abrasive, which increases the wear of pipelines and burners. Overseas experience leads to the conclusion that CWM feedstock coals should be beneficiated, the following being the desirable characteristics:

Feed-coal ash	6 to 15%
Product ash	1 to 4%
Recovery of carbon	90 to 99%
Removal of pyritic sulphur	40 to 90%.

The production of low-ash coals from potential CWM feedstocks should be a research priority in South Africa.

Content of Volatile Matter

There is no definitive information on the required level of volatile matter, and whether inertinite-rich South African coals with their lower volatiles content would be generally acceptable is not known. The coal volatiles in COM are, predictably, less critical than the volatiles required in CWM feedstocks. Studies suggest that coals for the manufacture of CWM should contain not less than 25 per cent volatile matter (dry basis). It is not known whether the volatiles of South African power-station smalls, which are not as rich in tar, especially those produced from two-stage separation, would be acceptable, and development work is necessary.

Sulphur Content

Acceptable sulphur levels are governed more by air-pollution legislation than by combustion characteristics. Attempts to reduce sulphur by the addition of alkaline absorbents to CWM have not been successful and have led to ash fouling. Therefore, the prior removal of sulphur compounds so far as is practicable is desirable. At present, South African export coals would appear to meet individual European requirements, but changed ECE standards may affect this situation. Some overseas standards are given in Table II. Even if more-stringent sulphur emission standards affect South African coal exports, the extent to which this might be offset by low-sulphur CWM mixtures is unknown. However, the investigation of the extent to which a low-sulphur CWM could be manufactured would be a wise precaution.

Friability

Coals for CWM should be readily friable to reduce comminution costs. Hard, inertinite-rich South African coals may be costly to crush, except for coals from the northern Transvaal, e.g. Waterberg, which have a vitrinite content of more than 90 per cent. From the combustion point of view, there may be little merit in crushing below a certain size. Studies have revealed that ultra-fine particles may agglomerate and be difficult to atomize in the combustion chamber. However, the need for low ash and sulphur contents may dictate the particle size since good liberation will be necessary.

Combustion Behaviour

Coal-liquid mixtures have been tested extensively, and with growing frequency, over the past decade. Figs. 3 and 4 show the scale of boilers used over the years.

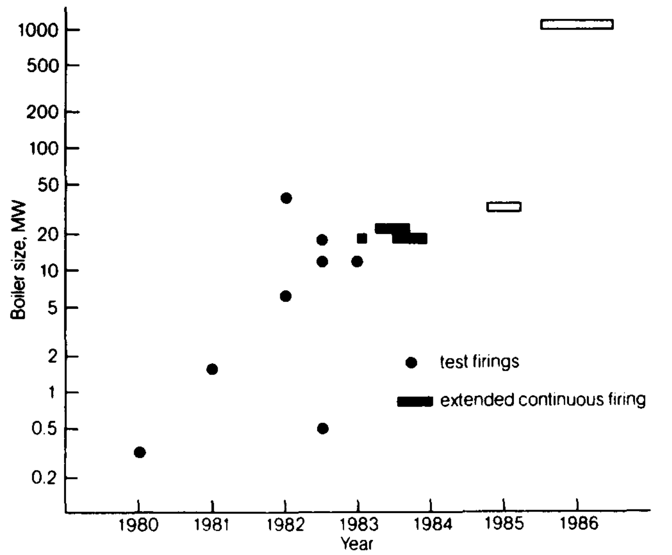

Fig. 3—Boilers used in the testing of CWM combustion (after Siemon, p. 22)

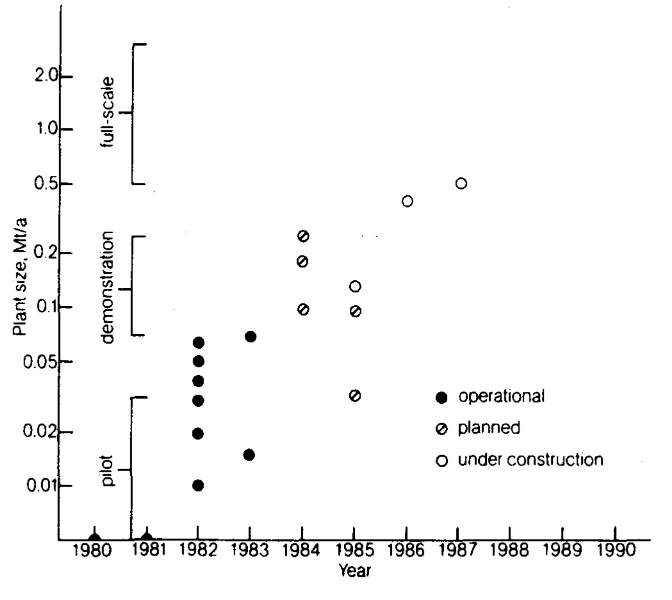

Fig. 4—Development of preparation facilities for CWM (after Siemon, p. 20)

TABLE II
AIR-POLLUTION STANDARDS FOR COAL AS FUEL

Country	Sulphur content %	Plant capacity	Emission limit g/GJ
Canada		All new capacity	258
Holland		Built before 1990	600
		Built after 1990	230
Germany (FR)		Existing + 50 MW – 300 MW	2500 (limited time)
		New excl FBC, 50 MW – 300 MW	2000 (and 15% res.em.)
		New and existing + 300 MW	400 (and 15% res.em.)
Italy	1	Industrial and power stations	
Japan		Boilers – 40 000 m^3/h gas	300
		Boilers + 40 000 to 200 000 m^3/h gas	200
		Boilers + 200 000 m^3/h gas	100
ECE (draft)		Boilers + 50 – 300 MW capacity	2000
		Boilers + 300 MW capacity	400

The use of coal–liquid mixtures in an oil-designed boiler presents two main problems: the attainment of complete combustion in the space available, and overcoming the effects of mineral matter introduced into the boiler. The first point is explained by Fig. 5 and Table III, which show the relative sizes of boilers designed for coal, gas, and oil. Obviously, a boiler designed for the high heat-emission rate of oil will not necessarily burn a coal–liquid mixture in the same manner. Longer residence times must be allowed, which reduces the rate of heat generation. This leads to de-rating the boiler.

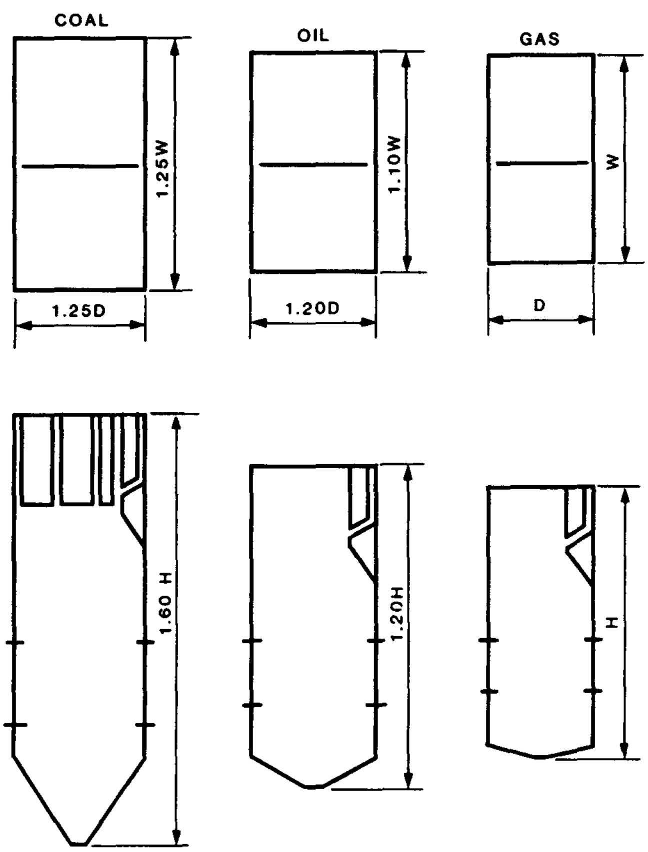

Fig. 5—Characteristics of coal, oil, and gas boilers (after Morrison, 1983)

TABLE III
CHARACTERISTICS OF BOILER DESIGN

Parameter	Gas	Oil	Coal
Furnace volume (relative)	1	1,3	1,9
Furnace surface area (relative)	1	1,3	1,7
Furnace heat-release rates (kW/m^3)	250 – 500	250 – 500	100 – 220
Tube bank velocities (m/s)	35	20 – 35	10 – 20
Convection pass spacing at >1050°C (mm)	50	100 – 180	150 – 750

Studies suggest that older, more generously designed boilers cope with coal–liquid mixtures better than newer, compact boilers designed for greater heating intensities. In a UK study of the conversion of oil-fired boilers to CWM, the de-rating shown in Table IV is suggested, based on the age of the boiler.

TABLE IV
DE-RATING OF BOILERS

Boiler	Age y	Evaporation t/h	Pressure bar	Heat rate m^3/MW	De-rating %
1	25	14	10	2,5	Nil
2	20	34	17	1,9	26
3	15	68	34	1,4	40

Other aspects of combustion are the degree of downturn and flame stability. Studies suggest that CWM has less flexibility in downturn, and requires oil-burner support at lower heating rates. Also, in view of ash formation, soot blowing must be possible at an appropriate rate.

However, the overseas studies show that satisfactory combustion of coal–liquid mixtures can be achieved with good carbon burn-out. It must be stressed that the foregoing applies to tests on coals from the northern hemisphere. Because there are marked differences between them and South African coals, the prediction of the combustion properties of the latter is difficult. CWM has been prepared from South African coal, but combustion testing of the material on an appropriate scale has not been reported.

Cost

In view of the processing entailed in the production of coal–liquid mixtures, low-cost feedstocks are desirable. This may not be feasible in South Africa since the potentially best feedstocks appear to be the coals of the northern Transvaal.

Future Developments

Possibly the most exciting developments are those being carried out under Italian auspices. Italian developments have led to co-operative studies being launched with the USA and the USSR. These developments include the following.

(1) Extended combustion trials in the UK, Italy, Austria, and the USA on burners with coal-feed rates ranging from 100 to 5200 kg/h.
(2) The design of a CWM plant with a capacity of 500 000 t/a of CWM for a petrochemical complex at Porto Torres in Italy, which involves the retrofitting of two oil-fired boilers. The plant was due for commissioning at the end of 1989.
(3) A contract to design and supply a CWM plant for the USSR. The plant has a CWM capacity of 5 Mt/a, which is equivalent to 3 Mt/a of dry coal. The CWM will be piped for a distance of 260 km in a 500 mm pipe to a power station at Novosibirsk.
(4) Feasibility studies into the production of a CWM plant capable of transporting 16 Mt/a of coal over a distance of 3700 km—also in the USSR.
(5) A long-term trial on a 75 MW set at an Italian power plant lasting 8000 hours and requiring 80 kt of CWM.
(6) An agreement with the US government to develop CWM using ultra-clean coal (with an ash content of less than 2 per cent) in boilers designed for oil and gas.

The published objective of the work is to increase the proportion of coal in the Italian energy mix, success in the project inevitably leading to increased coal usage in the ECE. In the USA, the successful employment of CWM based on ultra-clean coal will materially assist in conserving both the oil and the gas reserves.

Conclusions

The production of coal–liquid mixtures is a well-established aspect of coal technology. The use of such liquids in oil-fired appliances also appears to be well established, the performance of both COM and CWM indicating that oil replacement is feasible. The technology can therefore be expected to grow. Moreover, the ability to move coal–liquid mixtures by pipeline suggests lower transportation costs from areas lacking rail facilities. Finally, the need to crush coal provides an opportunity for beneficiation that should permit the production of liquids of low sulphur content to satisfy the planned air-pollution regulations.

However, there has been little work to date in proving South African coals in relation to coal properties and coal–liquid usage. It would appear that this type of technology should be investigated in some depth in view of the possible large-scale use of coal–liquid mixtures in the future.

This review suggests that the ideal type of coal is the low-ash, vitrinite-rich, high-volatiles, low-sulphur coal that is particularly scarce in South Africa. Coals need to be readily liberated to attain the properties suggested for coal–liquid mixtures. Coals from the Waterberg come close to having the ideal chemical properties, particularly in the matter of volatile-matter and vitrinite contents. Coals from Natal would probably be acceptable on the same grounds, but suitable coals are scarce and mainly committed for metallurgical use. Witbank coals from the number 2 seam may have the required characteristics and require investigation.

What is important is recognition of the potential importance of this technology to the South African coal industry. Almost half the country's allegedly economically extractable reserves lie in the Waterberg. From the point of view of mining costs, volatile-matter content, and reactive-maceral content, that coal is possibly the most suitable for the production of CWM. The major disadvantages are low yields, small liberation size, and high transportation costs. The liberation size, in terms of CWM production, is not significant since similar sizes are required to make the mixture stable and usable. At the same time, such comminution offers the possibility of enhanced yields. Finally, the transportation of CWM by pipeline may reduce transportation costs. It is suggested that, at the very least, work should be carried out on Waterberg and similarly abundant coals to determine the cost and quality of CWMs manufactured from them.

Bibliography

BIENSTOCK, D., and FOO, O.K. History and development of coal–liquid mixtures. First European Conference on Coal-Liquid Mixtures, 1983.

ERCOLANI, D. Snamprogetti's coal-water slurry technology. Fifth International Pittsburgh Coal Conference, Sep. 1988.

MORRISON, G.F. Combustion of coal–liquid mixtures. *IEA Coal Research Report* ICTIS/TR24, Nov. 1983.

SHIRES, M.J., and ANJUM, A. Economic and technical considerations in the preparation and utilisation of coal–water fuels. Coal Technology Europe, Amsterdam, 1983.

SIEMON, J.R. Economic potential of coal–water mixtures. *IEA Coal Research Report* ICEAS/E8.

Achema 91

ACHEMA 91, the 23rd Exhibition Congress and International Meeting on Chemical Engineering and Biotechnology, will take place in Frankfurt am Main from 9th to 15th June, 1991.

Experts from the fields of chemical engineering and biotechnology are invited to attend. This includes experts from the chemical and pharmaceutical industry, the petrochemical industry, the food-processing industries, the ceramic industry, and all the other process industries. Pollution control, biotechnology, savings in energy and raw materials, computer applications, and safety engineering are topical cross-sectional subjects that will be covered by ACHEMA 91.

Chemical engineering as represented by the industries dealing with the transformation and conversion of materials on the one hand, and chemical-plant, and mechanical and apparatus engineering on the other hand, are particularly intensive in terms of development. Successful innovations are characteristic features of chemical engineering and biotechnology. These results are based on the scientific work of the universities and research institutes, which are important interlocutors for experts from industry, both within the framework of the Exhibition and of the Congress.

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