

ELECTROSTATIC PRECIPITATOR PERFORMANCE WITH CHINESE COALS

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ABSTRACT

The electrostatic precipitator (ESP) performance is sensitive to fly ash properties. The ESP size and design for a new installation has to be carefully selected based on coal and coal ash data together with operating conditions. Experiences from similar installations are utilized as base for new ESP sizes and for upgrading of existing ESP's.

Chinese coals are now often seen in specifications for new plants together with other export coals from e.g. Australia, South Africa and Indonesia. In China new ESP's are built and existing ESP's are upgraded to encounter an increased power demand and comply with more stringent emission requirements. Knowledge about the properties of fly ashes from Chinese coals is necessary to provide a good basis for ESP performance predictions. Mineral analyses and laboratory combustion studies were made for selected Chinese coals to provide deeper knowledge about ash properties, which are of importance for the ESP operation.

Some Chinese coals are characterized by high aluminum contents in the ash compared to other commonly used coals. These coals often generate back-corona conditions in the ESP. A high content of aluminum in comparison with silica indicates high contents of minerals like kaolinite and aluminosilicate, which often have fine mineral size distributions in the coals. Sodium and iron are generally known to be beneficial for the ESP operation. In some Chinese coals more sodium and iron are associated with aluminosilicates than for non-Chinese coals. The influence of sodium and iron on ESP performance is certainly dependent on in which form sodium and iron occur in the coal.

INTRODUCTION

China has considerable resources of coal. About one third of the coal reserves in the world are located in China, where coal is the source for about two thirds of the primary energy. The last years there have been a significant increase in the export of Chinese coals. The Chinese coals vary to a large extent with respect to ash content, heating value and sulfur content. More than 50% of the coal has sulfur content $< 1\%$ (Michener, 2004). Wang and Rongbao (2001) give a detailed review of coal properties sorted by region.

Electrostatic precipitators (ESP's) are commonly used as particle collectors after coal fired boilers all over the world. ESP's are often the most cost-effective solution due to high removal efficiencies in combination with robustness and low maintenance cost. In 2003 almost 90% of the thermal power units in China were equipped with ESP's (Wang, 2004).

New power plants supplied with ESP's are built in China to meet the increasing demand for electricity. Many existing ESP's in China need to be upgraded to meet more stringent emission limits. Chinese coals are also specified for a number of new power plants around the world.

Existing experience and performance prediction models based on e.g. coals from Australia and South Africa cannot be directly transferred to Chinese coals. For example, the high content of Al_2O_3 in the coal ash for some Chinese coals is an important parameter that needs further investigations. Problems with ESP performance were previously addressed to negative effects of high Al_2O_3 and SiO_2 contents in the ash causing high ash fusion temperatures, which will give a finer particle size distribution (Wang and Rongbao, 2001). ESP performance for two new ESP's was studied in detail (Dexua, 2001). The investigations continued after upgrade of the ESP's. One conclusion from these investigations was that ash particles having the composition $3 Al_2O_3 \cdot 2 SiO_2$ forms low-density particles, which are sensitive to flue gas velocity in the ESP.

Fly ash consists mainly of non-burning material in the coal, i.e. inorganic components. Fly ash has also some minor fraction of unburned fuel. The inorganic material in coal is either found in mineral grains or associated to the combustible organic material in the coal. Minerals formed in geological processes are often present in a crystalline form. The occurrence of the inorganic material influences particle formation process and particle properties. Laboratory standard coal and coal ash analyses are generally available. In standard coal ash analyses the contents of inorganic components are given in their oxide forms, but the inorganic constituents in the coal do not normally occur as pure oxides. There are methods to distinguish between the different forms. Chemical fractionation by subsequent leaching is a method described by Benson (1985). The inorganic compounds are divided in four groups depending on their solubility:

- Water soluble (salts)
- Soluble in a weak acid (ion exchangeable)
- Soluble in strong acid (minerals like carbonates and sulfates)
- Residual fraction

Minerals are found in the two latter groups. Computer controlled scanning electron microscopy (CCSEM) can be used to measure mineral size and mineral composition in pulverized coal (Huggins, 2002). A pulverized coal sample or an ash sample is mounted and prepared. The computer-

controlled scanning electron microscope is programmed to detect particle size, composition and abundance in the sample. The automated method allows a large number of particles to be analyzed. Since the method can be used both for coal and ash samples, it is possible to make direct comparisons on mineral size and composition in coal and ash.

This paper presents the results from an investigation of selected Chinese coals. The objective is to get better knowledge about ash properties and its implication on ESP operation to allow improved performance predictions for these coal types.

EXPERIMENTAL METHODS

Six different coals were chosen to cover qualities of special interest, e.g. high Al_2O_3 contents in the ash. Coal samples, fly ash samples and operating data were collected from power plants in China firing the selected coals. Two Chinese export coals fired in power plants outside China were included in the study for comparison. Standard coal and coal ash analyses and CCSEM analyses were made for all coal samples. The results are compared with averages for eleven non-Chinese coals. These results originate from a previous study representing a large variety of coals of different origins, e.g. Poland, India, South Africa and Australia (Srinivasachar et. al., 1996). The ash contents were < 20% with exception for three locally fired coals. The sulfur contents were with one exception < 1%.

Three of the coal samples were selected for laboratory combustion tests to study the influence of combustion conditions on the mineral size distribution and mineral composition in so-called drop tube furnace (DTF) tests. The DTF consists of three separate furnaces to obtain a specified and repeatable temperature-time history for the particles. CCSEM mineral analyses were then made in a similar way on the ashes from the combustion tests. The mineral composition and mineral size distribution in the ash sample were compared with the mineral composition and mineral size distribution in the coal

Fly ash samples were collected in the Chinese power plants. These fly-ash samples were analyzed with respect to:

- Loss of ignition (LOI) at 750 °C
- Particle size distribution with net sieving and laser diffraction measurements (Malvern Mastersize MSX) for the fraction < 125 μm
- Resistivity measurements in air with 7% moisture by volume for the temperature range 110-190 °C

The power plant fly-ash samples originated from different locations in the ESP's due to local circumstances. Some samples were common samples from all fields whereas other samples are from separate fields.

Chemical fractionation was not made in this study.

POWER PLANT EXPERIENCE

The power plants firing the coals called China 1 and China 2 had problems with the ESP removal efficiencies. The ESP collecting fly ash from China 1 is designed with 300 mm spacing and has a

specific collecting area (SCA) of almost 150 m²/m³/s. The ESP could only achieve 99.15% collection efficiency. The ESP collecting fly ash from China 2 is also designed with 300 mm spacing. The reported 99.6% removal efficiency was below the expectations for the ESP with an SCA of almost 100 m²/m³/s. The coal Export 2 resulted in higher particle emissions than other low sulfur coals fired in that power plant.

COAL AND COAL ASH ANALYSES

The power plants were selected to get a variety in coal properties. Ultimate analyses are presented in table 1.

Table 1. Ultimate analyses of eight Chinese coals

Plant	China 1	China 2	China 3	China 4	China 5	China 6	Export 1	Export 2	Average non-Chinese
Carbon	47.4	50.5	51.2	51.3	51.5	31.6	68.6	67.7	54.1
Hydrogen (*)	3.2	3.3	3.1	3.7	3.5	2.2	4.2	4.5	3.5
Oxygen (*)	12.7	5.9	6.8	7.3	11.4	13.5	7.6	11.3	8.7
Nitrogen	0.9	0.9	0.9	0.9	1.0	0.6	1.2	1.0	1.1
Sulfur	0.5	0.3	1.1	2.3	0.9	2.4	1.1	0.3	0.7
Ash	30.5	37.0	35.0	31.6	29.9	41.7	14.7	11.0	18.9
Moisture	4.8	2.2	2.0	2.9	2.0	8.0	2.6	4.3	13.2

(*) Not including hydrogen and oxygen in moisture.

The ash contents are from 30% up to 42 % on as received basis for the coal samples collected in China. The high ash contents cause high inlet dust concentrations to the ESP's. The ash contents in the export coals are < 15%.

The sulfur contents range from below 0.3% to 2.4% on as received basis with the highest contents for the coals China 4 and China 6. Sulfur is generally enhancing the ESP collecting efficiency as it generates some SO₃ that has a conditioning effect on fly ash with high resistivity.

The coal ash compositions were obtained from the coal samples according to standard methods. The results are presented in table 2.

Table 2. Coal ash analyses

Plant	China 1	China 2	China 3	China 4	China 5	China 6	Export 1	Export 2	Average non-Chinese
SiO ₂	48.26	62.48	53.19	53.13	46.14	53.3	39.7	43.8	50.8
Al ₂ O ₃	42.62	20.83	38.09	35.57	40.69	27.94	42	32.4	23.6
Fe ₂ O ₃	1.83	8.45	2.62	7.2	2.81	7.44	4.2	6.4	6.7
CaO	2.48	3.36	0.81	1.02	4.11	3.71	5.8	5.9	6.9
MgO	0.2	1.02	0.29	0.18	0.54	0.55	0.2	1.6	2.1
Na ₂ O	0.26	0.17	0.27	0.21	0.25	0.31	0.3	0.5	0.7
K ₂ O	0.43	0.8	0.76	0.47	0.4	0.97	0.3	0.9	1.4
TiO ₂	1.64	1.87	1.28	0.99	1.41	0.98	1.5	1.5	1.3
SO ₃	1.85	0.85	0.85	0.82	3.65	4.75	4.8	4.2	4.7
P ₂ O ₅	0.2	0.13	0.19	0.2	0.23	0.16	0.6	0.05	1.0

The Al_2O_3 contents exceed 30% for six of the eight coals. The Na_2O contents are $\leq 0.3\%$ for six of eight samples. The Fe_2O_3 contents are low, $\leq 3\%$, for three coals. High sodium and iron contents are generally considered to enhance the ESP performance due to lower fly ash resistivities (White, 1977). Al_2O_3 and SiO_2 have the opposite influence contributing to high resistivity fly ashes. Ashes with high Al_2O_3 contents are in addition likely to have high ash fusion temperatures (Singer J, 1981).

COMPUTER CONTROLLED SCANNING ELECTRON MICROSCOPY (CCSEM)

The results from the CCSEM analyses are presented in table 3.

Table 3. Mineral composition of the Chinese coal

Plant	China 1	China 2	China 3	China 4	China 5	China 6	Export 1	Export 2	Average non-Chinese
Quartz	0.6	16.4	2.6	4.1	2.1	3.9	0.8	5	19.5
Iron Oxide	0.4	0	0.2	0	0.2	0.7	0.7	0	1.5
Rutile	0.3	0	0.1	0.1	0.6	0.3	0.9	0.4	0.4
Alumina	11.7	0	4.1	0.6	6.9	0	8.1	5	0.1
Calcite	1.6	3.3	0	0.3	2	0.4	6.3	4.1	1.2
Dolomite	0	0.1	0	0	0	0	0	0.2	2.5
Ankerite	0.1	0	0	0	0.3	0	0	0	0.1
Kaolinite	45.5	24.9	53.9	51.1	41.5	43.7	66.5	31.4	25.9
Montmorillonite	1.2	6.6	1.7	3.1	1.3	2.7	1.1	1.3	7.5
K Al-Silicate	1.7	2.2	4.1	2.4	3.3	4.8	1.1	2.1	11.7
Fe Al-Silicate	3.2	10.3	2.5	2.9	4.1	3.6	0.2	8.1	1.0
Ca Al-Silicate	1.8	0.5	1.1	1	1.6	2.9	0.4	1.8	0.8
Na Al-Silicate	1.5	0.2	0.6	1	1.2	0.8	0	3.4	0.0
Aluminosilicate	16.7	2.5	20.4	17	16.7	9.7	3.7	11.8	2.3
Mixed Al-Silicate	4	8.4	2	2.4	3	4.3	0.7	7.2	1.1
Fe Silicate	0	0.3	0	0	0	0	0	0	0.1
Pyrite	0.9	0.6	1.6	6.1	5.1	6.4	2.5	0.2	8.3
Pyrrhotite	0.1	0.1	0	0.2	0.2	0.1	0	0	0.3
Oxidized Pyrrho	0	0	0	0.3	0.1	0.1	0	0	0.3
Gypsum	0.1	0.1	0.2	0.1	0	1.5	0.1	0	0.6
Barite	0	0	0	0	0	0	0	0	0.1
Apatite	0	0	0.1	0.1	0.1	0	0	0	0.4
Ca Al-P	0	0	0	0.1	0	0	0	0	1.6
Gypsum/Al-Silicates	0.5	0.1	0	0.2	0.4	1.2	0.5	0.4	0.2
Si-Rich	0.2	4.5	0.7	2	1	1.3	0	0.3	2.6
Ca-Rich	0.8	1.6	0	0.1	0.9	0.2	0.2	3.3	0.4
Unknown	6.9	17.3	4	4.8	7.4	11.5	6.1	13.9	9.9

In Chinese coals quartz (SiO_2) contents generally are lower compared to non-Chinese coals, whereas minerals with aluminum like kaolinite, aluminosilicate and alumina are more abundant in Chinese coals compared to non-Chinese coals. This is in agreement with high Al_2O_3 contents as given in the standard coal ash analyses. The ratio between SiO_2/Al_2O_3 based on standard coal ash analyses is for non-Chinese coals from 1.5 up to above 3.5 for the Australian coals, whereas it is 0.9-1.5 for Chinese coals with high Al_2O_3 contents. The average content of the mineral alumina is 0.1 % for non-Chinese coals, whereas five of the eight Chinese coals have contents $> 1\%$ and in one case $> 10\%$.

Minerals containing iron are for example pyrite and Fe-Al-silicates. Figures 1-2 show the contents of these minerals plotted against the content of Fe_2O_3 in the standard coal ash analyses. For some

Chinese coals with high Fe₂O₃ content, e.g. China 2, there are low contents of pyrite compared to non-Chinese coals. Pyrite will react with oxygen during the combustion forming iron oxides or interact with other minerals forming Fe-Al-silicates. The sulfur in the pyrite will vaporize during the combustion and form SO₂ and SO₃.

Chemical fractionation of coals shows that sodium often is available in forms, which are soluble in water or weak acid. This sodium is contained as salts or as exchangeable ions in the coal structure (Lind, 1993 and Baxter, 2005). Sodium can also be associated with minerals like montmorillonite or Na-Al-silicate and is insoluble or only soluble in a strong acid. Averages from chemical fractionation of 21 US coals show 29% water soluble sodium (range 0-66%), 38% sodium soluble in weak acid (0-82%), 5% sodium soluble in strong acid (0-35%) and 28% in the residual fraction (0-87%) (Baxter, 2005).

Sodium in salts or associated with the organic structure will partly vaporize and later condense on ash particles and so influencing the particle surface properties. Sodium not vaporizing will interact with minerals in the coal and contribute to a lower ash smelting temperature, enhance the coalescence and result in larger particles. The sodium associated with minerals will in a similar way end up in the mineral structure.

In general sodium is beneficial for the ESP operation contributing to larger particles and increased ash conductivity. The influence of sodium on the ESP operation will be reinforced, if some sodium condenses on particle surfaces and improve the surface conductivity.

Some Chinese coals have unlike the other coals relatively high Na-Al-silicate contents but on the other hand low contents of montmorillonite. The fraction of sodium associated with minerals has not been determined yet. Chemical fractionation analyses of sodium in the Chinese coals are suggested for future studies.

The mineral size distribution varies greatly between the coals. The diameter corresponding to 50% of the analyzed cumulative mineral volume varies between < 10 μm for Export 2 up to 40-50 μm for China 2 and China 4. Fine mineral size distribution can be an indication of fine particle size distribution, which also will be influenced by the fragmentation and coalescence behavior during combustion.

DROP TUBE FURNACE TESTS

The coals China 1, China 2 and China 4 were selected for DTF tests.

The mineral compositions do not change a lot during the combustion, except that the fly ash does not contain any pyrite. The contents of different aluminosilicates are similar. The mineral size distributions before and after the combustion are compared in figures 3-5.

The results represent three completely different types of behavior during combustion. For China 1 the minerals form larger ash particles. In China 2 each mineral seems to form an ash particle resulting in approximately the same size distribution. China 4 has minerals, which seem to be agglomerates in the coal forming finer ash particle size distribution at combustion conditions.

ANALYSES OF POWER PLANT FLY ASHES

The loss of ignition was for all fly ashes < 5% at 750 °C varying from 0.2 to 4.3%.

The resistivity as measured in the laboratory was exceeding 10^{12} cm at 150°C for all collected fly ashes.

The particle size distributions for all fly ashes are presented in table 4. The fraction (in % of weight) having a diameter exceeding 125 µm was measured. The particle size distribution for the remaining fraction is represented by three diameters, d(0.1), d(0.5) and d(0.9), corresponding to the particle diameter for 10, 50 and 90% of the cumulative particle volume. China 1 has the finest particle size distribution, where 50% of the particle volume has a diameter \leq 6.3 µm.

Table 4. Fly ash particle size distribution

Coal	Sampling point	Particle size distribution			
		% weight >125 µm	Diameter (µm)		
			d (0.1)	d (0.5)	d (0.9)
China 1	ESP field 1	-	0.83	6.3	23
China 2		22	8.1	48.0	120
China 3		-	0.94	8.1	22
China 4	ESP field 1	6.7	6.6	35	100
China 4	ESP field 2	2.0	2.0	15	82
China 5	ESP field 1	34	18	60	130
China 5	ESP field 4		0.84	7.7	56
China 6	ESP field 1	27	7.6	54	130
China 6	ESP field 4	8.9	2.7	20	91

The fly ash particle size distributions have a similar size distribution as the mineral size distribution with considerably finer particles for China 1 than for China 2 and China 4. The DTF ash size distributions are slightly different. One reason could be, that the DTF tests are not adjusted to actual boiler conditions.

ELECTROSTATIC PRECIPITATOR PERFORMANCE

Particle size distribution and ash resistivity are of major importance for the ESP performance. Most prediction models are directly or indirectly estimating the resistivity and particle size distribution based on standard coal and coal ash analysis and other process conditions. Standard coal ash analyses present inorganic constituents as their corresponding oxides. Other methods like CCSEM are valuable tools to improve the performance assessment for new types of coal.

The minerals associated with high Al₂O₃ contents in comparison to SiO₂ are expected to give a finer particle size distribution, which influences the ESP performance negatively. A high content of Fe₂O₃ is generally expected to be favorable, but has probably a more significant impact as pyrite than as iron associated with aluminosilicates. The pyrite constitutes the combination of both iron and sulfur, where sulfur is known for its positive influence. In a similar way sodium is generally positive for the

ESP performance. Vaporized sodium has the ability to influence particle surface properties. Sodium associated with minerals or reacting with minerals will end up in the mineral structure.

So there are reasons to be cautious in using the ESP performance prediction models for Chinese coals especially if the Al_2O_3 contents are high in combination with low sulfur contents.

High concentrations of fine particles can cause severe corona suppression, i.e. high voltage levels are reached at low current densities. High-frequency power converters are one possibility to improve the performance at these conditions and are presently evaluated in some Chinese power plants (Ranstad et.al., 2004). The high-frequency power converters are predominantly installed in the first field of the ESP, where the highest dust concentration prevails.

Chinese coals generate often high resistivity fly ashes. Intermittent charging is an efficient measure to cope with high resistivity conditions. It is also important to keep the collection plates clean from high resistivity dust cakes. Modern ESP control systems have the capabilities to handle intermittent charging and power controlled rapping (PCR) and are presently evaluated for Chinese conditions. The final results are not available yet.

FUTURE WORK

There are several topics for future activities as continuation of the presented work:

- Better utilization of modern coal ash analysis methods for prediction of the particle formation process and particle properties
- Chemical fractionation studies of sodium and its effect on ESP performance
- Comprehensive field studies after a boiler firing Chinese low sulfur coal with high Al_2O_3 content with a upgraded and optimized ESP

SUMMARY

Six domestic Chinese coals and two Chinese export coals were analyzed with respect to their mineral composition and mineral size distribution to get an improved understanding of ash properties with implications on the ESP performance.

The selected Chinese coals have high contents of kaolinite, aluminosilicate and alumina in comparison with most other coals. This is also reflected by a high content of Al_2O_3 in the coal ash. Iron is known to be beneficial for the ESP performance. Iron is often available as pyrite, where also sulfur contributes to the ESP performance. Most Chinese coals have higher contents of Fe-Al-silicates than non-Chinese coals.

Sodium, also known to be beneficial for the ESP operation, is occurring as Al-Silicate. Sodium still needs to be further investigated by chemical fractionation analyses.

The influence of high-frequency power converters and modern ESP control systems on ESP performance in China is under evaluation. High-frequency power converters are increasing the power input in the front ESP fields, where the power input could be limited by corona suppression caused by high particle concentrations especially of fine particles. Modern ESP control systems can more efficiently cope with high resistivity conditions with intermittent charging and improved rapping control.

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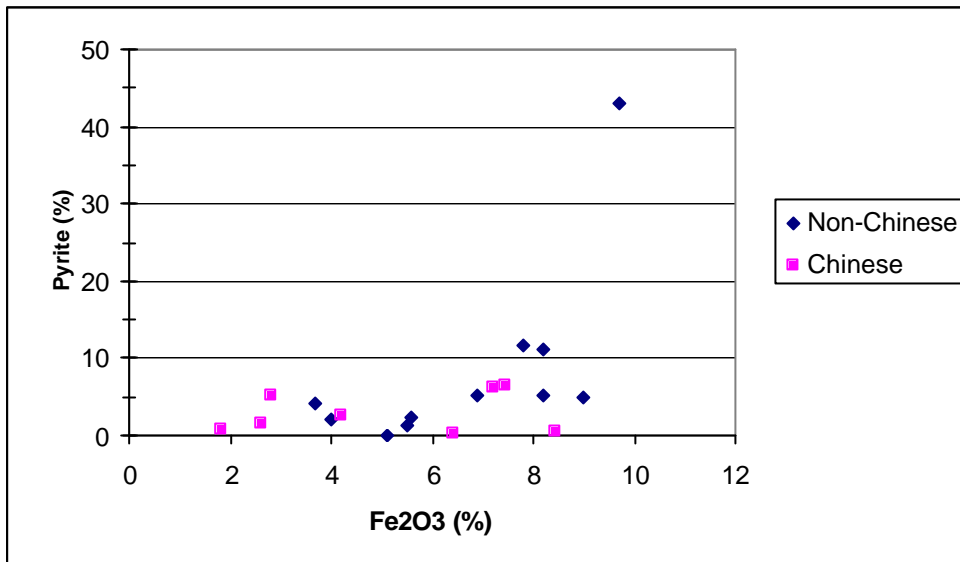


Figure 1. Pyrite content in the coal mineral composition as a function of Fe₂O₃ content according to the standard coal ash analysis

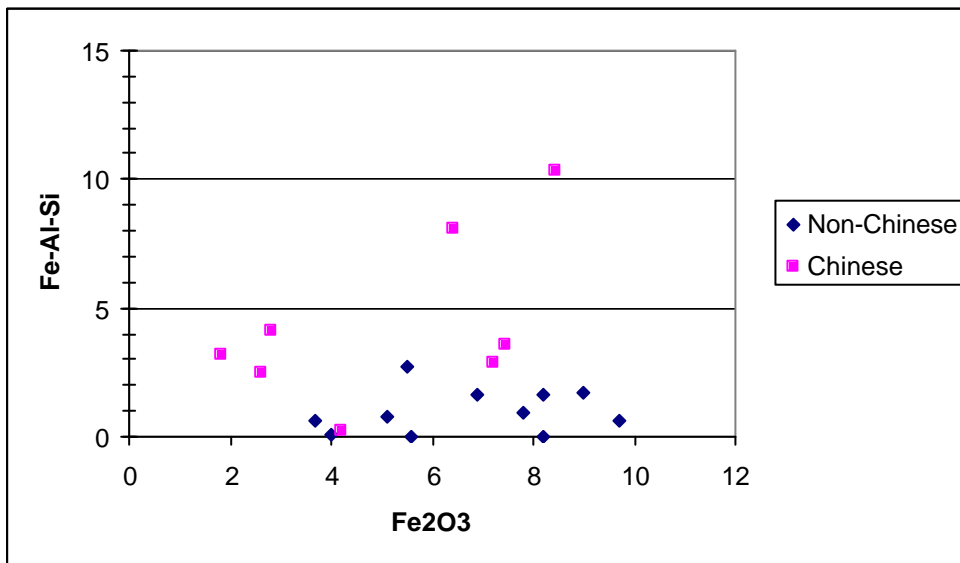


Figure 2. Fe-Al-Silicate content in the coal mineral composition as a function of Fe₂O₃ content according to the standard coal ash analysis

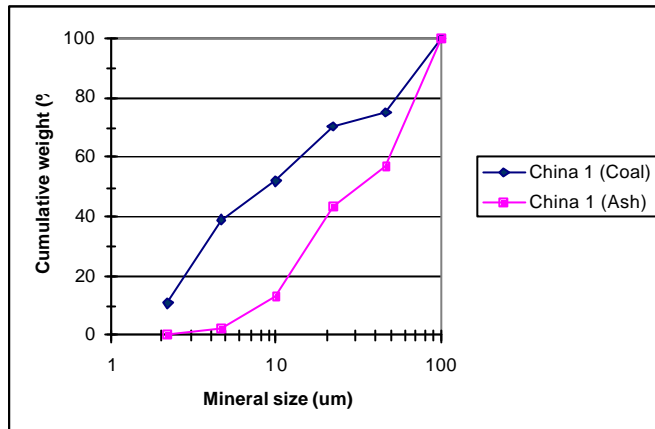


Figure 3. Mineral size distribution in the coal and in the fly ash from drop-tube furnace tests for the coal China 1

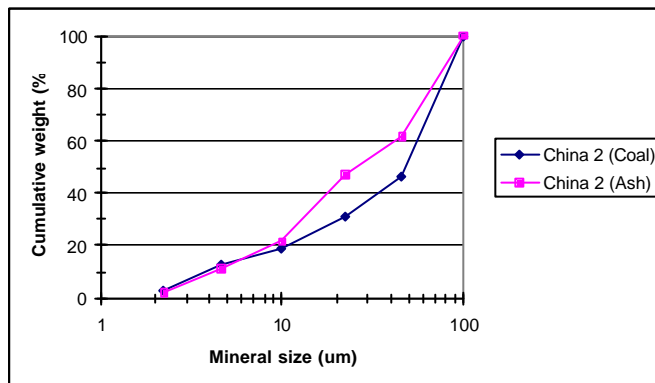


Figure 4. Mineral size distribution in the coal and in the fly ash from drop-tube furnace tests for the coal China 2

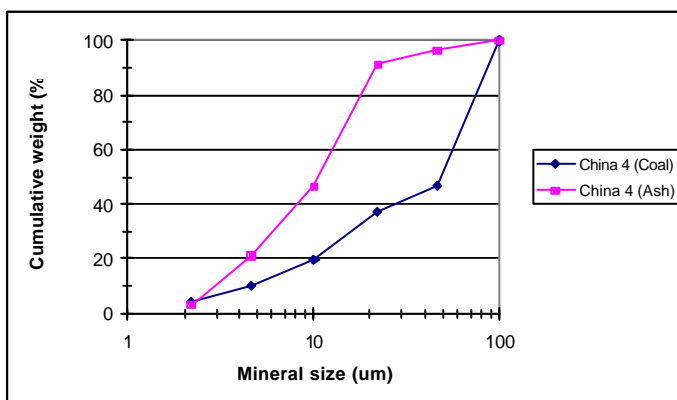


Figure 5. Mineral size distribution in the coal and in the fly ash from drop-tube furnace tests for the coal China 4