

1 Partitioning behavior of trace elements in a 2.5MW_{th} pilot circulating
2 fluidized bed combustor burning anthracite and bituminous coal

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9 Abstract: Coal, as the major energy resource in countries like China and India, introduces large
10 amounts of pollutants into the atmosphere, including trace elements originally bonded to the coal
11 matrix. These trace elements pose an environmental and human health risk, to which more
12 attention needs to be paid, but few studies have been done, particularly for circulating fluidized
13 beds (CFB). This paper discusses tests with anthracite and bituminous coal combustion carried out
14 in a 2.5MW_{th} CFB combustor with multi-stage control of solids. The partitioning of seven
15 elements (As, Ba, Cd, Cr, Cu, Mn and Pb) into different solid streams was investigated. The mass
16 balance ratio of the studied elements ranges from 56%-137%, which is, with respect to their
17 concentrations, satisfactory and reasonable. Most of the elements were found in bottom ash and
18 fly ash during CFB combustion, while small amounts of As, Cd and Pb were emitted into the
19 atmosphere with fine particulates. The trace elements are more likely to be retained in bottom ash
20 when burning bituminous coal than when burning anthracite. For the volatile elements, the
21 enrichment in solid streams follows the trend of: bag filter ash > cyclone ash > IBHX (In-bed heat
22 exchanger) solids > bottom ash, which confirms the expectation that the volatile elements tend to

23 be enriched in fine particles. Anthracite, compared to bituminous coal, shows lower emission
24 factors for all monitored elements, except for Pb, which has a higher emission factor during
25 anthracite combustion. This study should serve as a good reference for trace element control
26 strategies in coal-fired CFB boilers.

27 Key words: Trace elements; circulating fluidized bed; mass balance ratio; enrichment; emission
28 factor

29 **1. Introduction**

30 Coal combustion is one major source of pollutants in the atmosphere. During the coal combustion
31 process, some trace elements bonded with the coal's mineral and organic matter components will
32 be released and may pose an environmental and human health risk depending on their
33 concentration, toxicity and partitioning behavior in the combustion and environmental control
34 systems ^[1-3].

35 Generally, the trace elements that are not volatilized during combustion will be retained in the coal
36 ash, while the volatile elements will mostly vaporize. As the flue gas flows through the
37 downstream sections of the boiler, some elements will condense on the surface of particles and
38 will recombine with the particulate by physical adsorption or chemical reaction at low temperature.

39 The trace elements absorbed on particles will be collected by the flue gas clean-up devices, such
40 as wet scrubbers, ESPs and fabric filters, while the most volatile elements will be emitted into the
41 atmosphere. The final distribution of the trace elements into different product streams is strongly
42 influenced by their occurrence in the coal matrix, the combustion temperature, the configuration of
43 the furnace and the gas clean-up devices.

44 Circulating fluidized bed (CFB) combustion has been recognized as an important clean coal
45 technology due to its use of low temperature combustion (normally around 850°C) and good
46 emission control of SO₂ and NO_x by injecting limestone and by air staging, respectively. Since
47 there are big differences in combustion temperature, ash split and flue gas clean-up devices
48 between pulverized coal (PC) combustion and CFB combustion, the trace elements partitioning
49 behavior should also be different. For example, the PC furnace temperature is usually around
50 1300°C and more elements will experience the vaporization-condensation process, so there will be
51 greater enrichment of trace elements in fine particles. Due to the hydrodynamic differences, the
52 ash during PC combustion is mainly released as fly ash, while, during CFB combustion, the fly
53 ash and bottom ash ratio varies over a wide range from 2:8 (when burning coal waste) to 9:1
54 (when burning coal sludge). Furthermore, PC boilers are usually equipped with a wet flue gas
55 desulfurization unit (WFGD), while, in CFB boilers, the desulfurization takes place inside the
56 furnace by means of limestone injection. All of these differences will affect the trace element
57 transformation processes. However, there is little published on trace element partitioning behavior
58 in CFBs compared with PC boilers ^[4-5]. Further, trace element studies in fluidized beds have
59 focused mainly on emissions when burning or gasifying fuels like biomass and municipal solid
60 waste rather than coal ^[6-11]. But since there are huge amounts of coal used in fluidized beds in
61 countries like China and India, it is also very important to study the trace element partitioning
62 behavior during coal combustion in CFBs. Although there are papers on element partitioning
63 during bituminous coal and lignite combustion in fluidized beds ^[12-14], this study is the first one to
64 report the trace element partitioning behavior during anthracite combustion in a fluidized bed.

65 In this study, one anthracite and one bituminous coal were combusted in a 2.5MW_{th} CFB

66 combustor with multi-stage solid control system. The distribution of trace elements (As, Ba, Cd,
67 Cr, Cu, Mn and Pb) in various solid streams was studied. The results will serve as a reference on
68 trace element partitioning behavior during coal combustion in CFBs.

69 **2. Experimental**

70 *2.1 Fuel analysis*

71 Two typical Chinese coals, one anthracite and one bituminous coal, were used to carry out the
72 experimental program. The ultimate and proximate analyses of the coal samples are provided in
73 Table 1. The coal samples were crushed to produce particles with a maximum diameter of 6mm.
74 The particle size distribution is shown in Fig. 1. The Sauter Mean Diameters (SMDs) are
75 calculated as 0.51 mm and 0.61 mm for anthracite and bituminous coal, respectively.

76 The trace element content in the samples was analyzed by inductively-coupled-plasma mass
77 spectrometer (ICP-MS, 7700x, Agilent, USA) after the acid digestion procedures described in
78 reference 13. The results for the seven trace elements, Arsenic (As), Barium (Ca), Cadmium (Cd),
79 Chromium (Cr), Copper (Cu), Manganese (Mn) and Lead (Pb), as well as the detection limit of the
80 ICP-MS are shown in Table 2. Some other trace elements, Beryllium (Be), Cobalt (Co),
81 Molybdenum (Mo) and Antimony (Sb), were also measured, but the results are not included here,
82 since the content in the two samples was low and high accuracy could not be guaranteed. The Ba
83 content is higher than 100ppm and so cannot be strictly named as a trace element, but the results
84 are included here since it is usually treated as trace element when burning other fuels. The ash
85 composition of the two coal samples was also analysed by X-ray fluorescence (ARL9800XP,
86 Thermoscientific, USA). The results are presented in Table 3.

87 *2.2 Facility description and operation*

88 Each test was carried out in a pilot CFB combustor with a heat input of 2.5MW. The system is
89 shown schematically in Fig.2. There are several critical characteristics of the system. First, two
90 stages of solid separation are involved including an in-furnace U-beam separator operated at high
91 temperature, around 850°C, and a downstream cyclone separator operated at medium temperature,
92 from 350°C to 450°C. Second, there is an in-bed heat exchanger (IBHX) installed parallel to the
93 riser which allows exchange of solids between it and the main riser and approximately 16% of the
94 total heat load can be removed by the heat surface in the heat-exchanger. Third, the system is
95 equipped with an advanced operating control and data acquisition system, based on a
96 programmable logic controller (PLC) platform, which can facilitate the operation very
97 conveniently.

98 In terms of operation, the heat input was strictly controlled at 2.5MW_{th} by fixing the coal-feeding
99 rate as constant. The bed temperature of the CFB was controlled at $880\pm 20^\circ\text{C}$. The primary air
100 ratio was kept in the range of 60%-65%. The excess oxygen concentration before the bag filter
101 was controlled at 3.5%-4.2%, with the excess air coefficient at 1.20-1.25. The gas temperature in
102 the bag house was around 150°C to avoid the condensation of moisture. The bed material was the
103 conditioned bottom ash from the same coal combustion for each test, with a size range of 1-3 mm.
104 No limestone was injected into the furnace during these tests.

105 *2.3 Sample collection*

106 After the operation was stabilized for more than 8 h, which means the solid flow of each loop was
107 established and remained steady, the solid sampling was carried out. The bottom ash of the riser

108 was drained and collected from the bed drain duct after purging the cold material accumulated in
109 the drain duct, to make sure the drained solids were indeed the hot bed ash produced under the
110 appropriate experimental conditions. The fly ash was collected at the discharge hopper of the bag
111 filter. The discharge of fly ash was continuous, so the fly ash was considered as being well
112 conditioned. The solids captured by the cyclone were collected from the loop-seal exit, which is
113 marked as ③ in Fig.2. The IBHX bed solids were sampled by a specially designed in-bed probe
114 to extract the solids from an open port in the back wall of the IHBX, which is shown as ④ in
115 Fig.2. Two samples were collected from each location every half hour and then well mixed for
116 elemental analysis. Each mixed sample was split equally into 4 samples and one of them was
117 tested twice to ensure the reproducibility of trace element measurement. The concentration of trace
118 elements in the flue gas was not measured in the test, since all the trace elements, except for the
119 very volatile ones like Hg (which is not considered here), were assumed to be completely
120 condensed and recombined with the ash when the flue gas temperature dropped down to 150 °C.

121 *2.4 Sample analysis*

122 The unburnt carbon content in all ash samples was analysed by the measurement of weight loss
123 after heating the samples in a muffle furnace for 7 minutes at 900 °C. A microwave dissolver
124 (MDS-6, Zhongnuo Chemical Technology, China) was used to acid digest the ash sample
125 according to EPA Method 3050B. Then the content of the same seven elements was analysed
126 using the ICP-MS (7700x, Agilent, USA).

127 **3. Results and discussion**

128 3.1 Mass balance of the trace elements

129 After the combustion is stabilized, the elements introduced into the furnace will exit the system in
130 three streams: bottom ash, fly ash and flue gas into the stack. The total mass balance can be
131 expressed by the following equation:

$$132 \quad M_{oi} = M_{bi} + M_{fi} + M_{gi} \quad (1)$$

133 Where M_{oi} is the total amount of element i introduced into the furnace within coal, mg/h; M_{bi}
134 is the amount of element i discharged with the bottom ash, mg/h; M_{fi} is the amount of element i
135 leaving the system with the fly ash, mg/h; and M_{gi} is the amount of element i leaving the system
136 with flue gas, mg/h.

137 The trace elements in the gas phase can be collected as described in EPA Method 29.
138 However, as pointed out in the experimental section, nearly all the elements in the gas were
139 considered as being re-condensed on the solids, so the parameter M_{gi} can be neglected in this study.
140 This assumption has already been validated by many previous studies ^[6-10], which found that
141 nearly all the elements are present in the ash stream rather than in the flue gas.

142 The ash split into bottom ash and fly ash is usually not easy to determine in CFB combustion
143 because it continues to change as the operating conditions change. In this study, the ash recovery
144 rate was closed at 97% based on the long period of operation and the bottom ash/fly ash ratio was
145 calibrated as 4:6 by weighing the purged bottom ash and fly ash separately. Also, the elements
146 carried by the fines into the stack were not taken into account due to the very high capture
147 efficiency (>99%) of the bag filter. In consequence, the total of all elements leaving the system
148 M_{hi} can be expressed as:

$$149 \quad M_{hi} = M_{bi} + M_{fi} = \left(0.4 * \frac{C_{bi}}{A_b} + 0.6 * \frac{C_{fi}}{A_f} \right) \cdot M \cdot A \quad (2)$$

150 Where M_{hi} is the total amount of element i leaving the system, mg/h; C_{bi} and C_{fi} are the
151 concentrations of element i in the bottom ash and fly ash, mg/kg; A_b and A_f are the ash contents in
152 the bottom ash and fly ash, which is 1 minus the unburnt carbon content in the ash; M is the coal
153 feeding rate, kg/h; A is the ash content in the original coal.

154 The unburnt carbon content in the bottom ash for both anthracite and bituminous coal is less
155 than 1%. The unburnt carbon content in the fly ash is $22.6 \pm 0.8\%$ for anthracite and $12.7 \pm 0.5\%$ for
156 bituminous coal. Anthracite is more difficult to burn out completely in the CFB combustor due to
157 its lower volatiles and higher fixed carbon. By calculating the M_{hi}/M_{oi} , a picture of the mass
158 balance ratio of each element can be obtained, as shown in Fig.3.

159 As can be seen from Fig.3, for anthracite, the mass balance ratio for all the elements ranges from
160 77%-115%, except for Mn and Cd, which are 131% and 56%, respectively.; For bituminous coal,
161 the mass balance ratio for all the elements ranges from 85%-122%, except for Cr and Mn, which
162 are 137% and 134%, respectively. The results are consistent with the results from previous studies.
163 Selcuk et al ^[15] investigated element partitioning behavior by burning coal in a 0.3 MW_{th} fluidized
164 bed and found the mass balance of Cd, As and Mn to be 25%-45%, 95%-175% and 150%-250%,
165 respectively. Reed et al ^[16] argued that the mass balance ratio of $100 \pm 30\%$ is normally satisfactory
166 for trace element studies in pilot gasifier plants. Åmand and Leckner ^[6] found the recovery ratio of
167 different elements varies from less than 10% to more than 200% when burning sewage sludge and
168 coal/wood in their 12 MW_{th} CFB boiler. In circulating fluidized bed combustion, a complete
169 closure of element mass balance is very difficult to achieve because a certain amount of solids of
170 the proper size will be captured by the cyclone and accumulate in the furnace rather than purging
171 out, and the trace elements combined with these particles will not leave the system particularly in
172 the start-up periods. Furthermore, the element distributions in both the coal being fed and the ash
173 product are not completely uniform themselves. Also, there is always a measurement error with
174 the ICP-MS. Nonetheless, the results in this study are reasonable.

175 3.2 Trace element partitioning in bottom ash and fly ash

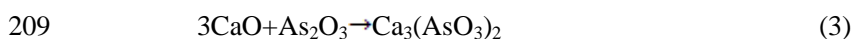
176 By quantifying the M_{bi}/M_{hi} and M_{fi}/M_{hi} , the partitioning of each trace element in the bottom ash
177 and fly ash is shown in Fig.4.

178 During anthracite combustion, most of the trace elements are present in the fly ash, which takes up
179 80%-90% of the M_{hi} . Only 10%-20% of the elements are retained in the bottom ash, where Pb is
180 the most enriched metallic element. When burning bituminous coal, roughly half of the Ba, Cr and
181 Mn are retained in the bottom ash, while all other elements in the bottom ash are no more than
182 30%. More than 80% of Cd is present in the fly ash, which is the highest share in fly ash for
183 bituminous coal.

184 For both coals, the mass balance ratios of As, Cd and Pb are all less than 100%, as shown in Fig.3,
185 which indicates these three volatile elements may be emitted into the atmosphere along with the
186 fine particles from the bag filter. Bunt and Waanders ^[17] consider these three elements to be
187 volatile ones that are prone to be present in the flue gas. Syc et al. ^[18] found 80%–90% of Cd will
188 not condense at temperatures higher than 380°C in a fluidized bed biomass gasifier. This may
189 cause the Cd to be emitted into the atmosphere before complete condensation. The presence of
190 CdCl₂ in the gas phase in an 850°C fluidized bed was also verified by both experimental and
191 model study ^[19]. It is also well known ^[20] that As will be present mostly in the gas phase during
192 combustion and as the temperature falls, a substantial amount of it will still be present in the gas
193 phase. For both coals, about 80% of the Cu is present in the fly ash. In anthracite, the Cu yield is
194 less than 100%, which indicates the Cu also has some volatility, but obviously this is weaker than
195 that observed for As, Cd and Pb. The mass balance ratios of Ba, Mn and Cr are all higher than

196 100% and most of them are present in the bottom ash, which confirms that they are all
197 non-volatile at the CFB combustion temperature.

198 The partitioning of trace elements depends very much on the coal type, as shown in Fig.4. The
199 trace elements in bituminous coal are more likely to be present in bottom ash, which may be
200 caused by the differences of element occurrence and ash composition between bituminous coal
201 and anthracite. The case for As is more easily verified because several studies have been done on
202 As transformation during combustion. In this study, 14% of As goes into the bottom ash when
203 burning anthracite and 30% when burning bituminous coal. A previous study ^[21] revealed that the
204 As bonded with the organic sulfur is vaporized and then condensed on the surface of the fine
205 particles while the As bonded with the scattering minerals is retained in the ash residues. As shown
206 in Table 3, the ash of bituminous coal has about 20% CaO, which has a clear effect on its
207 absorption ability towards As. The following reaction during combustion will definitely help to
208 retain the As in the bottom ash of bituminous coal as the product is quite difficult to vaporize.



210 3.3 Relative enrichment factor of trace elements in different solid streams

211 Due to the large variation in specific element concentration in different coals, it is better to use the
212 relative enrichment factor, which normalizes the enrichment behavior of different elements in
213 different coals. The relative enrichment factor proposed by Meij et al ^[22] is often used to describe
214 the relative enrichment behaviors. Taking the relative enrichment factor of element i in the fly ash
215 as an example, this can be expressed as:

216
$$RE_i = \frac{C_{fi}}{C_{oi}} \cdot A \quad (4)$$

217 Where RE_i is the relative enrichment factor of element i in the fly ash, C_{fi} is the
218 concentration of element i in the fly ash, C_{oi} is the concentration of element i in the original coal,
219 and A is the ash content in the original coal.

220 For this definition of relative enrichment, only the ash content in the original coal is
221 considered while the ash content in the solid product is neglected which may cause the factor to be
222 influenced by the unburnt carbon content in the solid product. In this paper, the relative
223 enrichment factor is modified as

224
$$I_{RE} = \frac{C_{fi}}{C_{oi}} \cdot \frac{A}{A_o} \quad (5)$$

225 Where I_{RE} is the modified relative enrichment factor and A_o is the ash content in the solid
226 product. If $I_{RE}=1$, the element neither concentrates nor depletes in the sample; if $I_{RE}>1$, the
227 element tends to concentrate in the sample; if $I_{RE}<1$, the element tends to deplete in the sample.

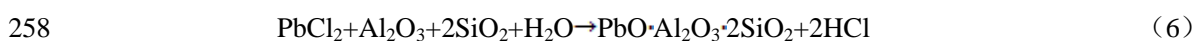
228 The relative enrichment factors of the seven elements in the four different solid streams
229 (bottom ash, IBHX solid, cyclone ash and bag filter ash) are presented in Fig.5.

230 For anthracite, the I_{RE} of all the seven elements in the bottom ash is less than 1, indicating all the
231 elements tend to be depleted in the bottom ash and enriched in the fly ash. The I_{RE} of all the
232 elements in IBHX solid is larger than bottom ash but smaller than fly ash except for the Cr which
233 is larger than 1. For bituminous coal, the As, Cd, Cu and Pb tend to be depleted in the bottom ash
234 and enriched in the fly ash. These four elements are also depleted in the IBHX. Ba, Mn and Cr
235 tend to be enriched in the bottom ash, while their relative enrichment factors in fly ash are from
236 0.9-1.2, which are also not depleted. For these three elements, because their mass balance ratios

237 are all higher than 100%, they may be enriched either in bottom ash or fly ash. The results are to
238 some extent counter intuitive, but the following should be considered:

239 1) The volatile elements like As, Cd, and Pb as well as the semi-volatile Cu may experience a
240 vaporization and condensation process, so they can be expected to tend to be enriched in the fine
241 particles, which usually have bigger surface areas. The particle size distribution of the bottom ash
242 and the IBHX were sieved and measured, as shown in Fig.6. The SMDs of bottom ash and IBHX
243 solids for anthracite are 0.390mm and 0.277 mm, and they are 0.337mm and 0.273mm for
244 bituminous coal. At the same time, the particle size distribution of the cyclone ash and filter ash
245 were determined by a laser particle size analyzer (Mastersizer 3000, Malvern, UK). The results are
246 presented in Fig.7. The SMDs of the bag filter ash and cyclone ash for anthracite are 11.05 μ m and
247 23.48 μ m while they are 8.09 μ m and 26.5 μ m for bituminous coal. So it is easy to demonstrate that
248 the solid particle sizes in the four main four streams are: bottom ash > IBHX solid > cyclone ash >
249 bag filter ash. This sequence is in good agreement with the enrichment degree of the volatile
250 elements in them. Furthermore, the pore size, surface area and pore volume of cyclone ash and bag
251 filter ash were measured by a physisorption analyzer (ASAP 2000M, micromeritics, USA) and the
252 result in Fig.7 shows that the bag filter ash has a smaller pore size, as well as larger BET surface
253 area and BJH pore volume, which indicates the gas phase elements are more easily condensed on
254 it and absorbed by it physically and chemically.

255 2) Pb in coal will fully vaporize at around 850 $^{\circ}$ C in the form of PbCl₄ and PbCl₂ ^[23] and then the
256 gas phase Pb can be captured by the Al₂O₃ and SiO₂ particles as the temperature falls, which can
257 be express as the following equation ^[24]:



259 As the cyclone in the study was operated at temperatures around 350°C–450°C, the Pb leaving the
260 furnace was condensed and absorbed by the cyclone ash again. As a consequence, the Pb in
261 anthracite is even more enriched in cyclone ash than bag filter ash.

262 3) The most volatile elements, like As and Cd, will be mostly enriched in the fine particles that
263 have larger surface areas. The enrichment factor of As and Cd in bag filter ash is bigger than that
264 in cyclone ash, except for the case of As in bituminous coal. The As in bituminous coal is slightly
265 more enriched in cyclone ash than in bag filter ash, which is probably because the As_2O_3 in the
266 flue gas can be captured by the high concentration of CaO in the cyclone ash by the reaction
267 $3CaO + As_2O_3 \rightarrow Ca_3(AsO_3)_2$.

268 4) The non-volatile elements, like Ba, Cr and Mn, do not vaporize at CFB combustion
269 temperatures. All these elements will stay in the ash, either retained in the bottom ash or in the fly
270 ash, which is elutriated from the furnace. Their partitioning therefore depends on their occurrence
271 in the coal matrix. Mn is bonded with the mineral matter in the coal. Cr will be present in the form
272 of Cr_2O_3 during combustion and always behaves as a solid. Ba, with its most common naturally
273 occurring minerals of barite and witherite, is also difficult to vaporize. In the study, the Ba, Mn
274 and Cr in bituminous coal are enriched in bottom ash. However, these three elements in anthracite
275 are all depleted in the bottom ash, which might be due to their different occurrences in the original
276 coal matrix as well as the fragmentation property of the coal samples. Similar results can be found
277 in reference 13 where different combinations of lignite and biomass were fired.

278 3.4 Emission factors of trace elements into the atmosphere

279 The above discussion doesn't consider the trace elements released by the fines into the atmosphere,
280 because it is assumed to be very low. However, if we want to evaluate the effects of the trace

281 element emissions on the environment, the elements emitted into the atmosphere relative to the
282 energy consumed must be quantified. The emission factor of a certain element i is used here and
283 defined as:

$$284 \quad EF_i = (C_i/H)F_i \quad (7)$$

285 Where EF_i is the emission factor of elements i into the atmosphere, mg/kJ; C_i is the
286 concentration of element i in the coal, mg/kg; H is the low heating value of coal, kJ/kg; F_i is the
287 emission ratio of element i into the atmosphere.

288 For the non-volatile elements, assuming the bag filter was operated at reasonable separation
289 efficiency, which is 0.99 here, the F_i can be calculated as:

$$290 \quad F_i = 0.01 * \frac{M_{fi}}{M_{hi}} \quad (8)$$

291 And for the volatile elements, the F_i is calculated as the difference between 100 and the mass
292 balance ratio in Fig.3. The results of F_i and EF_i are shown in Table 4 and Table 5.

293 The emission factor of each element depends on the coal type, the element content in the coal and
294 the physical and chemical property of the element itself. It can be seen from Table 5 that the
295 emission factors of anthracite are higher than those of bituminous coal for all elements, except Pb.

296 The emission factors are dependent on the fine particulate emissions during combustion. In
297 pulverized coal combustion, due to the higher combustion temperature, more elements vaporize
298 into the gas and condense on the fine particulates. Lind et al ^[14] revealed that the ultrafine particle
299 emission in CFB combustion is one to two orders of magnitude lower than that observed in PC
300 combustion. Also, it has been reported ^[25] that the emission factors of Mn in PC combustion can
301 rise to 15% while that of Cr can reach 61%, which is much higher than what was found here. Thus

302 it is clear from these results that CFB combustion may be superior in terms of the control of trace
303 element emission, when compared with PC combustion.

304

305 **Conclusions:**

306 Partitioning behaviors of seven trace elements (As, Ba, Cr, Cu, Pb, Mn and Cd) were investigated
307 in a 2.5MWth CFB combustor burning anthracite and bituminous coal, and the results show that:

308 1) The mass balance ratio of all the seven elements ranges from 56%-137%, and for most of them
309 from 77%-115%.

310 2) Nearly all the elements are present in bottom ash and fly ash during CFB combustion, while a
311 small amount of As, Cd and Pb is emitted into the atmosphere with fine particulate.

312 3) When burning bituminous coal, the trace elements are more easily enriched in the bottom ash
313 than when burning anthracite.

314 4) For the volatile elements, the enrichment in solid streams follows the trend: bag filter ash >
315 cyclone ash > IBHX solids > bottom ash, which indicates the volatile elements tend to be enriched
316 in the fine particles.

317 5) Anthracite has a smaller emission factor than bituminous coal for all elements except Pb, which
318 is the opposite.

319

320 **Acknowledgement**

321 Financially supported by the National Natural Science Foundation of China (51206023).

322 Supported by National Key Technology Research and Development Program of the Ministry of

323 Science and Technology (2012BAA02B01-02). Special acknowledgement to Dave Kraft and Scott

324 Anderson from Babcock & Wilcox Company, US regarding their financial and technical support

325 on the facility.

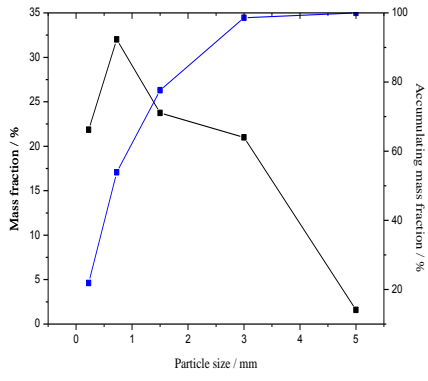
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327 **Reference**

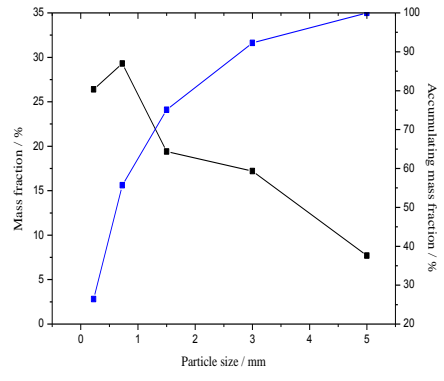
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- 379
- 380



(a) anthracite



(b) bituminous coal

Figure 1 Particle size distributions of the coal samples

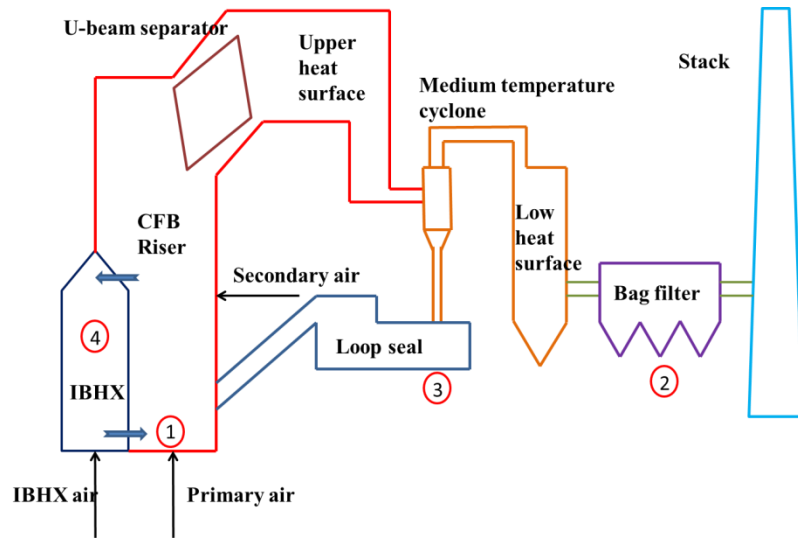


Figure 2 The 2.5 MW_{th} CFB combustion system

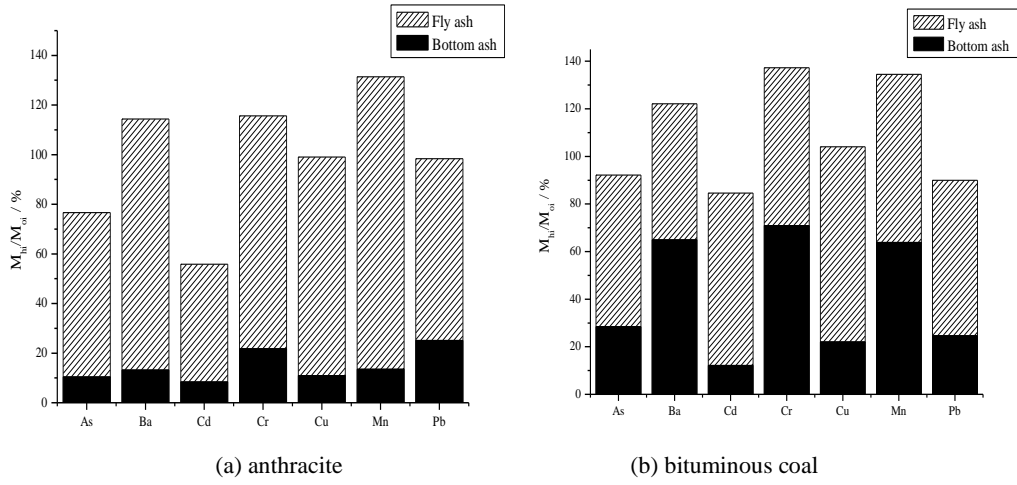
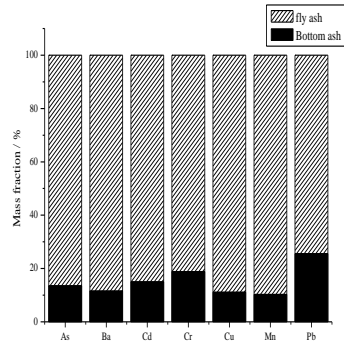
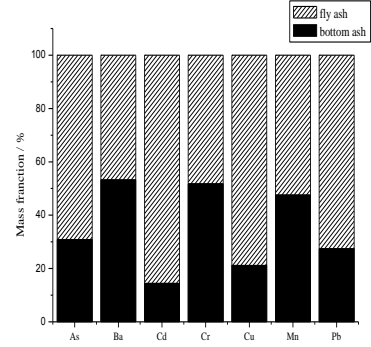


Figure 3 Mass balance ratio of trace elements in anthracite and bituminous coal

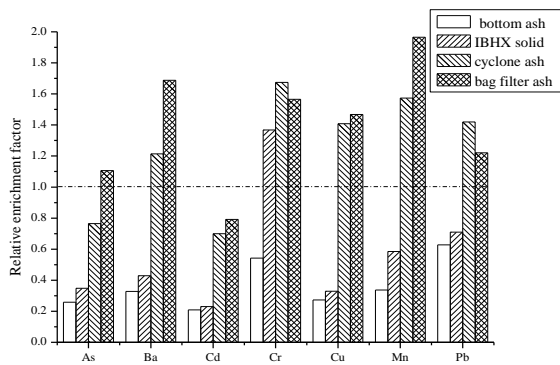


(a) anthracite

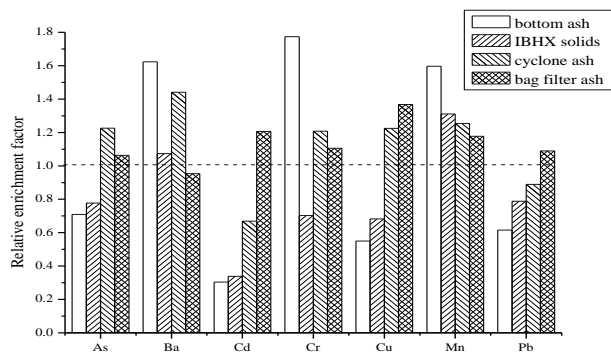


(b) bituminous coal

Figure 4 trace elements partitioning into fly ash and bottom ash

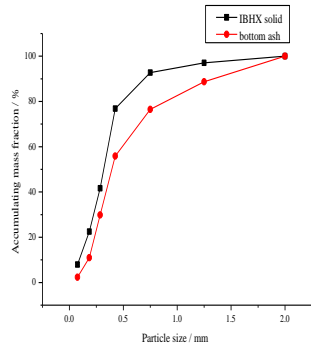


(a) anthracite

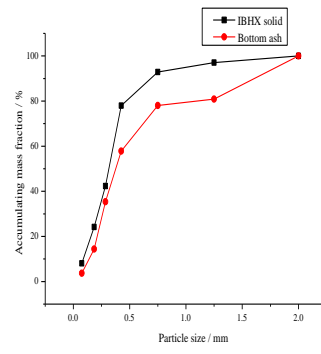


(b) bituminous coal

Figure 5 Relative enrichment factors of elements in different solid stream

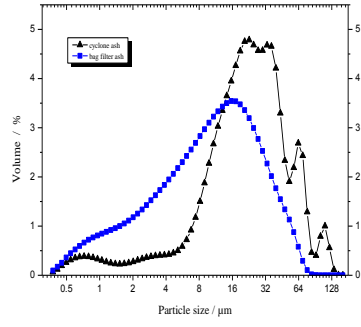


(a) anthracite

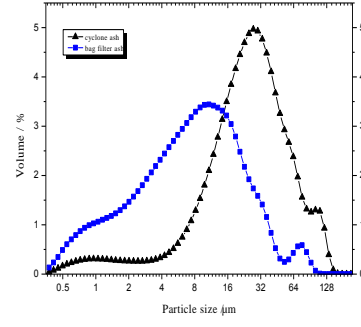


(b) bituminous coal

Figure 6 Particle size distribution of the IBHX solid and bottom ash



(a) anthracite



(b) bituminous coal

Figure 7 Particle size distribution of the cyclone ash and bag filter ash

Highlights

> Pilot CFB combustor with multi-stage solid management. > Mass balance ratio ranges from 56%-137%. > Volatile elements tend to be enriched in fine particles. > Anthracite shows lower emission factors.