Effect of Atmosphere and Additive on Enrichment Characteristics of Trace Elements during Fluidized Bed Coal Combustion

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Abstract. The enrichment characteristics of trace elements (Cr, Mn, Co, Ni, Cd, Pb, Hg, As, Se) were investigated under air and O$_2$/CO$_2$ atmosphere during fluidized bed coal combustion. Results showed that Co, Ni, Cd, Pb, Hg, As, Se were more volatile than Cr and Mn. The increase of temperature promoted Mn, Co, Ni, Cd and Pb to migration from bottom ash to fly ash, and contributed Hg, As and Se to vapor phase. Cr, Mn, Co, Cd, Se tended to decrease in bottom ash and increase in fly ash during oxy combustion, while 21%O$_2$/79%CO$_2$ atmosphere led to the emission of gaseous As and the enrichment of Ni, Pb in both bottom ash and fly ash. With the increase in O$_2$ concentration, the relative enrichment of all the trace elements except As increased, suggesting that their volatility were inhibited. Adding limestone and mixture of limestone and kaolinite had an inhibiting effect on volatilization of trace elements (especially Mn, Cd, Pb, Hg, As, Se) and the inhibiting behavior was strengthened under the oxy atmosphere.

1. Introduction

O$_2$/CO$_2$ combustion technology is considered to the most promising CO$_2$ emission reduction technology[1]. Compared with traditional combustion, O$_2$/CO$_2$ combustion technology has the low NOx emission, enhanced radiant heat transfer and reduced boiler volume to save initial investment[2-6]. Circulating fluidized bed (CFB) combustion technology is recognized as a highly efficient and low-cost clean coal combustion technology[7]. Oxy-coal circulating fluidized bed combustion technology integrated the advantages of two kinds of technology, realizing emission control of SO$_2$ and NOx and recovery of CO$_2$ at low cost.

During coal combustion, trace elements are regarded as the most serious environmental concern. The enrichment of trace elements in coal ash has exerted an effect on pollution control and residue disposal[8, 9]. Many researches have conducted to explore the partitioning of trace elements in pulverized coal fired power plant[10-12]. However, the distribution of fly ash and trace elements in CFB boilers is different from that of pulverized coal boilers because of the characteristics of fluidized bed including strong mixing, effective gas-solid contact, high heat and mass transfer rate and high thermal stability. These characteristics make the fluidized bed operate stably and facilitate the capture of trace elements in the bed. Clemens[13] found that fluidized bed combustion was beneficial to control volatilization of As and Se. Edward[14] indicated that for pulverized coal furnace combustion, most As, Pb and Cd entered into fly ash while most Se and Hg were in gas phase. For CFB combustion, more trace elements were enriched in the bottom ash than fly ash.

The enrichment characteristics of trace elements differ in atmosphere condition. Oboirien[15]...
reported the concentration of 27 major and trace elements in bottom ash generated from oxy-coal combustion and found that concentrations of the most of trace elements (Cu, Zn, Rb, Co, Ga, Pb and U) from air combustion were higher than those from oxy combustion at 900°C. The concentrations of the trace elements in bottom ash enhanced with the increase of oxygen concentration from 21% to 50% and similar trend was observed at 1000°C. However, Tang [16] obtained contradictory results for solid waste combustion and reported that the enrichment factors of Cd, Cr, Cu, Zn, Pb and Ni from 80%N2/20%O2 combustion were lower than those under 80%CO2/20%O2. There was no obvious difference of enrichment for the trace elements between 80%CO2/20%O2 atmosphere and 70%CO2/30%O2 atmosphere. These studies investigated the emission characteristics of trace elements in bottom ash under air and O2/CO2 atmosphere in horizontal tube furnace, which is quite different from the intensely gas-solid mixing combustion environment in fluidized bed. Different conclusions may be drawn from fluidized bed experiments due to the dissimilar combustion mode. The trace elements emission characteristics are of great importance for the design and operation of gas treatment equipment of fluidized bed combustor.

Using solid sorbents to capture trace elements is considered as a promising technique. Sorbent can adsorb with some trace elements before the metal vapors nucleate. Solid sorbent can provide more surface area to condense gaseous substances and effectively react with certain trace elements steam, thus promoting the migration of trace elements to the coarse particle which can be easily captured by precipitator. Limestone is a common desulfurizer in fluidized bed combustion. It not only remove gas sulfide in flue gas, but also has a certain adsorption effect on trace elements [17, 18]. The use of limestone in fluidized bed combustion is expected to achieve the synergistic removal of sulfide and trace elements at low cost. Kaolinite can adsorb alkali metal vapor and some heavy metal vapor simultaneously at high temperature. So it can be used as an adsorbent in furnace to remove heavy metal and alkali metal [19]. It can effectively prevent slagging, ash accumulation and corrosion of boiler, and reduce the emission of trace elements and submicron particulate from combustion and other high temperature processes. However, the control effect of additive on trace elements during oxy combustion in fluidized bed are rarely reported. Therefore, to investigate the effect of additive on distribution characteristics of trace elements during fluidized bed coal combustion, limestone or a mixture of limestone and kaolinite is added in the coal to combust under air atmosphere and O2/CO2 atmosphere.

This study compared partitioning characteristics of trace elements (Cr, Mn, Co, Ni, Cd, Pb, Hg, As, Se) under O2/CO2 atmosphere with different O2 concentration and regular air atmosphere in a 6 kWth fluidized bed. The effects of additive (lime and kaolinite) on enrichment characteristics under two atmospheres were also explored. The results have implications for the design of operating condition and the emission control of trace elements during oxy-coal combustion in fluidized bed.

2. Experimental equipment and procedure

The fluidized bed combustion system is shown in Fig. 1. The system mainly consists of the fluidized bed body, gas distribution system, feeding system, fly ash sampling system, flue gas online analysis system, electric heating and temperature control system.

The height of combustor was 1500 mm with a dense phase zone of 68 mm inner diameter and a dilute zone of 80 mm inner diameter. The combustor was equipped with 5 thermocouples along the fuel gas path, which were arranged at 155 mm, 285 mm, 815 mm and 1205 mm above the gas distributor and at the fly ash sampling point. The dense phase zone and the dilute phase zone had the electrical heater. The temperature in the furnace can be set by the temperature control system. Air was supplied by air compressor and O2/CO2 atmosphere was a proportional mixture of O2 and CO2. The primary air duct was arranged with an air preheater to stabilize combustion. Coal feed rate was at 1 kg/h and static bed height was maintained at 350 mm. Bed material was quartz sand with diameter range of 0.3~0.8 mm.
The cooled bottom ash was sieved to the size greater than the 0.9 mm in order to reduce the interference of bed material. The ash captured by glass fiber filter and cyclone was collected as fly ash. The concentrations of trace elements in coal, bottom ash and fly ash were examined by ICP-MS.

Xuzhou bitumite was chosen in the experiment. The proximate analysis and ultimate analysis are shown in Table 1 and the trace elements contents in coal are shown in Table 2. Two additives were selected in the experiment: limestone (added at Ca/S=2.5) and a mixture of limestone and kaolinite (added at Ca/S=2.5 and kaolinite at 5% of the raw coal quality). The experiments were arranged in 14 experimental conditions (shown in Table 3) to study the effects of temperature, atmosphere, O2 concentration and additive on the enrichment characteristic of trace elements.

Table 1 Ultimate and proximate analysis of Xuzhou bitumite

| Ultimate analysis/% | Low calorific value | Proximate analysis/% |
|---------------------|---------------------|----------------------|
| C_{ad} | H_{ad} | O_{ad} | N_{ad} | S_{ad} | MJ/Kg | F_{C_{ad}} | V_{ad} | A_{ad} | M_{ad} |
| 58.97 | 3.65 | 7.30 | 0.67 | 1.76 | 23.54 | 47.33 | 25.02 | 25.55 | 2.10 |

Table 2 Trace element contents in Xuzhou bitumite

| Trace element | Cr | Mn | Co | Ni | Cd | Pb | Hg | As | Se |
|---------------|----|----|----|----|----|----|----|----|----|
| Content (μg/g)| 30.71 | 74.62 | 4.02 | 14.37 | 0.067 | 7.3 | 0.051 | 1.89 | 0.95 |

Table 3 Experimental parameters of coal combustion

| Test | Temperature/℃ | Atmosphere | Pulverized coal particle size/mm | Additive |
|------|---------------|------------|---------------------------------|----------|
| 1    | 800           | air        | 0.4–0.6                         | None     |
| 2    | 850           | air        | 0.4–0.6                         | None     |
| 3    | 900           | air        | 0.4–0.6                         | None     |
| 4    | 800           | 21%O₂/79%CO₂ | 0.4–0.6                        | None     |
| 5    | 850           | 21%O₂/79%CO₂ | 0.4–0.6                        | None     |
| 6    | 900           | 21%O₂/79%CO₂ | 0.4–0.6                        | None     |
| 7    | 850           | 30%O₂/70%CO₂ | 0.4–0.6                        | None     |
| 8    | 850           | 40%O₂/60%CO₂ | 0.4–0.6                        | None     |
| 9    | 850           | air        | 0.4–0.6                         | Limestone |
| 10   | 850           | air        | 0.4–0.6                         | Limestone+Kaoline |
11 850 21%O2/79%CO2 0.4~0.6 Limestone
12 850 21%O2/79%CO2 0.4~0.6 Limestone+Kaoline

3. Results and Discussion
The relative enrichment factor (RE) was calculated using Eq.(1)[10]:

\[ RE = \frac{C_i}{C_{coal}} \times \frac{A}{R} \]  

Where \( C_i \), \( C_{coal} \) were the concentrations of trace element in product and coal, \( A \) and \( R \) represented the ash contents in coal as dry basis and the ratio of products to total ash, respectively. \( RE > 1 \) indicated that trace element tended to increase in ash while \( RE < 1 \) indicated that trace element tended to decrease in ash. \( RE = 1 \) indicated that trace element was non volatile.

To eliminate the effect of additive on RE, Normalized enrichment factor (NEF) was introduced to measure the degree of enrichment of element during combustion taking other nonvolatile element as reference. Mg was selected as reference element in present work.

\[ \text{NEF} = \frac{C_j/C_{rj}}{C_{coal}/C_{rccoal}} \]  

Where \( C_j \), \( C_{rj} \), \( C_{coal} \) and \( C_{rccoal} \) represent concentrations of element “j” and reference element in products and coal. \( \text{NEF} > 1 \) indicates the enrichment degree of the element surpasses that of reference element while \( \text{NEF} < 1 \) suggests the enrichment degree of the element is weaker than that of reference element. \( \text{NEF} = 1 \) indicates two elements are similar in volatility.

3.1. The enrichment characteristic of trace elements in fly ash and bottom ash under air and oxy atmosphere
The temperature and atmosphere have the significant impact on the partition of trace elements in the fluidized bed. Fig. 2(a) showed the relative enrichment factors of trace elements of the bottom ash at different temperatures in air atmosphere and 21%O2/79%CO2 atmosphere. The RE of Cr and Mn were slightly more than 1 and the RE of Hg and Se approached 0. The RE of the other elements were less than 1. The RE of trace elements in the fly ash were shown in Fig. 2(b). The RE of Cr and Mn were nearly equal to 1. The RE of Co, Ni, Cr, Pb and Se were greater than 1 while the RE of Hg and As were below 1. The results indicated that Cr and Mn belonged to non-volatile elements and tended to be enriched in the bottom ash. Co, Ni, Cd, Pb, Hg, As and Se were prone to be depleted in bottom ash and be enriched in fly ash. With the increase in the temperature, the RE of trace elements (Mn, Co, Ni, Cd, Pb) decreased in bottom ash and increase in fly ash, indicating that increasing temperature facilitated most of elements to migrate to fly ash from bottom ash. The enhancement in coal combustion rate promoted the decrease of diffusion resistance and the destruction of molecular structure associated with trace elements. Then the evaporated trace elements can be immobilized by fly ash through heterogeneous condensation, physical adsorption and surface reaction[20]. The RE of Cr in bottom ash showed an opposite trend compared with other elements. The low volatilization of Cr was mainly attributed to the occurrence mode[21]. With the increase in the bed temperature, Cr in the organic mode was partly released from organic matter to form nonvolatile Cr2O3 (melting point 2300°C) which can be captured by minerals especially hematite, and consequently increased the RE in bottom ash. The Cr associated with clay was more stable and hard to evaporate. The RE of highly volatile As and Se decreased in fly ash with the increase of the temperature. As and Se were both easily immobilized by calcium oxide or hematite via surface reaction[22]. However, the absence of adsorption site could result in the release of As and Se in gaseous form. The RE of Hg and As in bottom ash were lower than those in fly ash, which were both less than 1. Results indicated that a considerable amount of Hg and As emitted as gas phase because the condensation and adsorption were inhibited by increasing temperature. The RE of Hg were not sensitive to bed temperature due to
relatively low melting and boiling points. In Fig. 2, the RE of Cr, Mn, Co, Cd and Se decreased in bottom ash and increased in fly ash when atmosphere transferred from air to 21%O2/79%CO2, suggesting that Cr, Mn, Co, Cd and Se were more inclined to volatilize under 21%O2/79%CO2 atmosphere. The RE of Ni and Pb in bottom ash and fly ash both increased under 21%O2/79%CO2 atmosphere. Results showed that 21%O2/79%CO2 atmosphere contributed to the migration from gas phase to the solid phase, which was consistent with the result observed by Wang[23]. The RE of As in bottom ash under 21%O2/79%CO2 was greater than that under air and the RE of As in fly ash under 21%O2/79%CO2 was lower than that under air, indicating that volatilization of As is restrained by 21%O2/79%CO2 atmosphere. Different atmosphere did not show obvious effect on the volatilization of Hg.

The partitions of trace elements under 21%O2/79%CO2 atmosphere were mainly determined by three mechanisms. Firstly, the lower O2 diffusion rate and the bigger thermal capacity of CO2 reduced the combustion temperature under 21%O2/79%CO2 atmosphere, which decreased the vapor pressure of trace elements and then hindered their volatilization. In addition, 21%O2/79%CO2 atmosphere promoted the surface gasification of char particles and increased CO concentration in the furnace[24]. Most trace elements tended to be reduced to volatile compounds such as suboxides and sulfides in reducing atmosphere, which conducd to the volatilization of trace elements[25]. Finally, 21%O2/79%CO2 atmosphere had the inhibiting effect on the development of pore structure of coal char, which enhanced the diffusive resistance, so as to suppress the volatilization of trace elements[26].

Fig. 2 The effects of atmosphere on the RE of trace elements in the bottom ash (a) and in the fly ash (b)

3.2. The effect of O2 concentration on the RE of trace elements

The effects of O2 concentration on the relative enrichment factors of trace elements in bottom ash and fly ash were shown in Fig. 3(a) and Fig. 3(b). It can be seen from Fig. 3(a) that with the increase of O2 concentration, the RE of Cr, Mn, Ni, Pb, Co and Cd in the bottom ash increased, and the RE of Hg and Se almost kept stable while the RE of As declined. As shown in Fig. 3(b), the RE of trace elements except Hg in the fly ash decreased with the O2 concentration increases. The increase in O2 concentration inhibited the volatilization of Cr, Ni, Pb, Co and Cd, indicating that higher O2 concentration promoted the enrichment in the bottom ash and inhibited the enrichment in the fly ash. Conversely, the volatility of As enhanced with the increasing of O2 content. The volatility of Hg and Se maintained stable.

The higher O2 concentration weakened the reducing atmosphere in the combustion zone and thereby suppressing the volatilization of inorganic components. The trace element volatilization process was mainly dominated by the following three reactions:

\[
\text{MAO}_y(s) \rightleftharpoons \text{MO}_x + \text{AO}_{y-x}(s\cdot g) \quad (3)
\]

\[
\text{MO}_x + \text{CO}(g) \rightleftharpoons \text{MO}_{x-1}(s) + \text{CO}_2(g) \quad (4)
\]

\[
\text{MO}_{x-1}(s) \rightleftharpoons \text{MO}_{x-1}(g) \quad (5)
\]
A represented the major and minor elements in coal, such as C and N. MOx represented trace element oxide and MOx-1 represented the or more substance[27, 28]. The increase of O2 concentration was not conducive to the development of the reducing atmosphere, thereby inhibiting the formation of volatile suboxide trace elements. In addition, for the certain coal feed rate and excess oxygen coefficient, the O2/CO2 gas volume flow rate was significantly reduced when the O2 concentration increased. The gas volume flow rate in 21%O2/79%CO2 was 1.9 times that in 40%O2/60%CO2. The fluidization velocity in the dense phase region decreased and the gas-solid mixture was weak, which may increase the diffusion resistance of trace elements in the gas phase and curbing their volatilization.

Many researchers also observed that the retention of As in ash decreased with the increase of O2 concentration under oxy combustion[29, 30]. The volatilization of As below 900°C was mainly attributed to the decomposition of organic arsenic and sulfide arsenic. The higher O2 concentration promoted the oxidation reaction of arsenic to gas arsenic[29]. The migration of trace elements was not only controlled by thermodynamics, but also by fluid mechanics and kinetics (reaction kinetics and diffusion kinetics)[31]. The As in sulfides mode was extremely volatile. A part of volatilized As reacted with the active sites of Ca or Fe from the mineral of coal and formed insoluble compounds such as calcium arsenate or iron arsenide, thereby being fixed in the bottom ash or fly ash[22]. When the concentration of O2 increased, the combustion rate of coal particles accelerated and the release rate of As also enhanced. Most As vapors had not enough resident time to react with the active sites of Ca or Fe and discharged into the atmosphere with the flue gas. Therefore, the enrichment of As in the bottom ash decreases with the increase in O2 concentration. Wang[32] found that As volatilized intensely during rapid heating and combustion. While most of As remained in bottom ash or fly ash during pyrolysis and slow heating. Result showed that the resident time during combustion and the reaction of As with minerals in coal had a great influence on the migration of As.

Although the increase of O2 concentration may increase the surface temperature of coal particles, auxiliary heating (electric heating) and heat dissipation (changing the thickness of the insulation layer) were adopted in experiment. The thermal capacity of the bed material was large, so that the bed temperature can be accurately controlled at different O2 concentrations. The effect of the O2 concentration on the coal particle temperature was reduced to the minimum.

![Fig. 3 The effects of O2 concentration on the RE of trace elements in the bottom ash(a) and in the fly ash(b)](image)

3.3. The effect of additive on the NEF of trace elements

The effects of additives on the NEF in bottom ash and fly ash were shown in Fig. 4(a) and Fig. 4(b), respectively. Results showed that NEFs of the trace elements in the bottom ash and fly ash increased with the additive. NEFs in the fly ash and bottom ash under the adding limestone + kaoline were bigger than those under adding limestone or kaolinite separately. It indicated that additive effectively adsorbed trace elements in the flue gas and the adsorption effect of the mixture of limestone +
kaolinite was better than that of limestone. The normalized enrichment factors of Mn, Cd, Pb, Hg, As and Se increased significantly, while the normalized enrichment factors of Cr, Co and Ni increased slightly.

![Fig. 4 The effects of additive on the NEF of trace elements in the bottom ash (a) and in the fly ash (b)](image)

The adsorption mechanisms included physical adsorption, chemisorption and exchange adsorption[33], which were related to the volatility of trace elements and their chemical reactions with adsorbents. Experiments with quartz sand and limestone found that the chemical reaction was the main adsorption for nonvolatile elements of Cr and Cu. Physical adsorption was the main adsorption mechanism for most volatile elements and metal chlorides. Both physical and chemical adsorption were important for the Pb.

During combustion volatile trace elements diffused to the surface of CaCO3 and were immobilized by CaCO3 through adsorption or chemical reaction. At the same time, porous CaO arising from the decomposition CaCO3 provided the attached site. Trace element particles generated from homogeneous condensation after the temperature dropped were captured by CaO. Volatile As can react with CaO to form non-volatile calcium arsenate while Se may react with CaO to form non-volatile calcium selenate[22]. Additionally, CaO could capture Pb by generating non-volatile calcium plumbite[34]. Reactions are as follows:

\[
3\text{CaO} + \text{As}_2\text{O}_3 + \text{O}_2 = \text{Ca}_3(\text{AsO}_4)_2
\]

\[
\text{CaO} + \text{SeO}_2 + 0.5\text{O}_2 = \text{CaSeO}_4
\]

\[
2\text{CaO} + \text{PbO} + 0.5\text{O}_2 = \text{Ca}_2\text{PbO}_4
\]

The limestone during coal combustion had certain effect on mercury emission control. The addition of limestone increased greatly the amount of particles in the fluidized bed. Thus, the contact area between particles and mercury vapor increased, greatly strengthening the adsorption of the particles surface on mercury vapor. The presence of SO2 had contributed to the elemental mercury adsorption. The adsorption efficiency of calcium-based adsorbents on mercury in the presence of SO2 was higher than that in the absence of SO2. The reaction of SO2 with calcium-based adsorbents produced an active region, thereby oxidizing Hg0 to Hg2+ and improving the capture efficiency[35].

Kaolinite was often used to capture alkali vapors during low-rank coal combustion to improve slagging problem. Kaolinite had adsorption effect on As vapor and the adsorption efficiency can be promoted with the existence of sodium. Co-adsorption also contributed to the conversion to high valence state As which is less toxic[36]. Kaolinite can effectively capture Pb and Cd by reaction with PbCl2 to generate PbO·Al2O3·2SiO2, and reaction with CdCl2 to generate CdO·Al2O3·2SiO2 or further reaction to generate 2CdO·Al2O3·2SiO2[37, 38]. Kaolinite mixed with fuel and kaolinite injected with secondary air both had efficient effect of Pb capture during fluidized bed combustion[39], and the capture mechanism are shown in follows:

\[
\text{Al}_2\text{O}_3·2\text{SiO}_2 + \text{PbO}→ \text{PbO}·\text{Al}_2\text{O}_3·2\text{SiO}_2
\]

\[
\text{Al}_2\text{O}_3·2\text{SiO}_2 + \text{Pb} + 1/2\text{O}_2→ \text{PbO}·\text{Al}_2\text{O}_3·2\text{SiO}_2
\]

\[
\text{Al}_2\text{O}_3·2\text{SiO}_2 + \text{PbCl}_2 + \text{H}_2\text{O}→ \text{PbO}·\text{Al}_2\text{O}_3·2\text{SiO}_2 + 2\text{HCl}
\]
The enhancement effect of eutectic melting of kaolinite can effectively achieve capture of multiple trace elements (Na, Pb, Cd) [40]. Eutectic melting facilitates the disintegration of kaolinite, which provides more active site to accommodate trace elements. Meanwhile, the reaction product diffuses into the inner layer of the kaolinite and the active surface is re-exposed and continues to react with the metal vapor [41]. In addition, high temperature in furnace could lead to excessive melting and further deactivation of kaolinite. While kaolinite can basically reach the simultaneous removal of multiple elements within the temperature range of fluidized bed combustion (below 1000°C).

Adding limestone during fluidized bed combustion not only greatly reduced the emission of SO2, but also could absorb most trace elements and reduce their emission to the atmosphere. Ho [42] found that the calcined limestone in fluidized bed can effectively achieve the cooperative control of SO2, HCl and trace elements. Therefore, using limestone and kaolinite as additive during oxy combustion in fluidized bed was conducive to the realization of zero emission of multiple atmospheric pollutants.

In Fig. 4, the adsorption effects of additives in the atmosphere of 21%O2/79%CO2 was better than that in the air atmosphere. It may be attributed to that the surface gasification reaction of coal particles was strengthened under the atmosphere of 21%O2/79%CO2. The local reducing atmosphere in the combustion area promoted the volatilization of trace elements. So the additive can absorb more gaseous trace elements. In addition, atmosphere can affect the development of lime pore structure [43]. The specific surface area and the pore volume of lime under O2/CO2 combustion were bigger than those under air combustion because of the lower sintering level, which favored trace element capture. Although O2/CO2 atmosphere made no obvious difference on transformation of kaolinite, it facilitated the formation of eutectic calcium aluminosilicate, thereby immobilizing trace elements in matrix [44].

Compared with conventional air combustion, oxy-coal combustion in fluidized bed facilitated the volatilization of most trace elements from bottom ash to fly ash, which presented a challenge to the operation efficiency of precipitator. However, increasing O2 concentration or adding sorbents (lime and kaolinite) conducted to reverse this trend.

4. Conclusions
(1) Cr, Mn belonged to low-volatile trace elements and tended to be enriched in bottom ash. Co, Ni, Cd, Pb, Se were semi-volatile trace elements and tended to be enriched in fly ash. The high-volatile Hg, As tended to emit as gas phase.

(2) With the increase in the temperature, Mn, Co, Ni, Cd, Pb, Se migrated from bottom ash to fly ash. Oxy atmosphere conducd to volatility of Cr, Mn, Co, Cd and Se, and restrained volatility of Ni, Pb and As. The enrichment of Hg was not sensitive to the change of temperature and atmosphere.

(3) The increase in O2 concentration inhibited the volatility of most trace elements except As, which improved their enrichment in bottom ash while decreased that in fly ash.

(4) Although 21%O2/79%CO2 atmosphere enhanced the volatilization of trace elements, additive including limestone and the mixture of kaolinite and limestone had a more efficient capture effect on trace elements under oxy combustion than air combustion, especially for Mn, Cd, Pb, Hg, As and Se.

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