

Article

Study on Characteristics of Ash Accumulation During Co-Combustion of Salix Biomass and Coal

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Abstract: Co-combustion of coal and biomass for power generation technology could not only realize the effective utilization of biomass energy, but also reduce the emission of greenhouse gases. In this study, a system of a settling furnace with high temperature is applied to study the ash deposition of the co-combustion of coal and salix. The effects of salix blending ratio, flue gas temperature, and wall temperature on ash deposition are studied. The micro-morphology, elemental content, and compound composition of the ash samples are characterized by scanning electron microscopy and energy-dispersive spectroscopy (SEM-EDS) and X-Ray Diffraction (XRD), respectively. The results show that with the biomass blending ratio increasing from 5% to 30%, the content of Ca in ash increases from 8.92% to 20.59%. In particular, when the salix blending ratio exceeds 20%, plenty of the low-melting-point compounds of Ca aggravate the melting adhesion of ash particles, causing serious ash accumulation. Therefore, the salix blending ratio is recommended to be limited to no more than 20%. With the increase in flue gas temperature, ash particles melt and stick, forming ash accumulation. Under the condition of flue gas temperature ≥ 1200 °C, a serious ash particle melting flow occurs, and CaO covers the surface of the ash particles, making the ash particles adhere to each other, which makes them difficult to remove. Therefore, controlling the flue gas temperature below 1200 °C is necessary. When the temperature crosses the threshold range of 500–600 °C, the Ca and K contents increase by 35.6% and 41.9%, respectively, while the Si content decreases by 9.7%. The increase in K and Ca content leads to the thickening of the initial layer of the ash deposit, which facilitates the formation of the sintered layer of the deposited ash. Meanwhile, the reduction in Si content leads to the particles' adhesion, which markedly increases the degree of ash slagging. Once the wall temperature exceeds 600 °C, severe ash slagging becomes a threat to the safe operation of the boiler. Therefore, the wall temperature should not exceed 600 °C.

Keywords: salix; ash accumulation characteristics; blending ratio; flue gas temperature; wall temperature



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1. Introduction

With the expansion of the global economy and the concomitant increase in industrial output, the consumption of fossil fuels is also rising [1,2]. The emission of a considerable

quantity of CO₂ and other harmful gases has resulted in the greenhouse effect and environmental pollution [3]. China is a significant consumer of coal. To alleviate the environmental damage caused by coal combustion, the pursuit of renewable energy sources to gradually substitute coal has attracted great attention [4,5]. In recent years, biomass has emerged as a prominent alternative energy source, attracting considerable interest due to its characteristics of cleanliness, extensive availability, and cost-effectiveness [6,7]. The prevailing approach to utilizing biomass is through thermochemical conversion. And among various techniques, combustion is the most significant means [8,9].

But the abundance of alkali metals in biomass results in serious ash accumulation during combustion, which has become the primary impediment to the advancement of biomass power generation technology [10]. The study of Liao et al. [11] indicates that in comparison with the combustion of biomass alone, the co-combustion of coal and biomass could serve to relieve the accumulation of ash and slag on the pipe surface. Therefore, co-combustion power generation technology is the most common method of utilizing biomass [12–14]. On the one hand, co-combustion can potentially incite a reduction in the consumption of coal resources, thereby contributing to the “carbon peaking and carbon neutrality” target of China [15]. On the other hand, leveraging the capabilities of large coal-fired units can enhance the utilization rate of biomass resources [16].

Nevertheless, the proportion of alkali metals in the fuel blends increases when more biomass is added, resulting in significant ash accumulation and challenging removal processes. Prior studies have preliminarily elucidated the correlation between biomass blending proportions and ash deposition patterns under specific combustion conditions [17]. Lv et al. [18] reported an inverse relationship between straw loading in fuel composites and deposition efficiency, with the latter displaying non-monotonic attenuation, whereas sintering metrics manifested substantial augmentation. However, this phenomenon was not subjected to a comprehensive analysis and investigation to elucidate the process of deposit formation during co-combustion. The ash deposition characteristics of heated surfaces are influenced by the environmental temperatures present, such as those of flue gases and walls, as well as the melting temperatures of the mineral constituents [19–21]. Ma et al. [22] demonstrated that varying combustion temperatures exert a pronounced effect on the precipitation of alkali metals and chloride ions, as well as the deposition of ash. The research of Lv et al. [23] identified temperature-dependent sedimentation behavior where sintering enhancement at higher flue gas temperatures compensates mass reduction by producing denser, mechanically robust sediments. The wall temperature dependence of ash accumulation mechanisms differs substantially among Zhundong high-alkali coal varieties [24]. The academic community remains divided in its interpretations of how ambient temperature influences ash deposition patterns in biomass–coal co-combustion systems, with a notable gap in elucidating the underlying micro-scale mechanisms governing these thermal interactions.

Furthermore, numerous scholars have demonstrated that controlling the content of alkali metals can change the melting point of ash, consequently affecting the ash accumulation characteristics of the heated surface [24–28]. The extant literature is largely concordant in its findings that acidic oxides (SiO₂, Al₂O₃, and TiO₂) can elevate the melting temperature of coal ash, whereas alkaline oxides (Fe₂O₃, CaO, MgO, Na₂O, and K₂O) can decrease it [25,29,30]. The ash deposition mechanism differs from the sintering stage in terms of the initial stage, during which the deposition behavior occurs [31]. This initial stage of ash accumulation is of particular importance, as it affects the subsequent adsorption of the settled ash. A lot of studies have concentrated on the impact of temperature on the deposited ash. However, further research is required to enhance our understanding of the migration patterns of mineral elements under different temperature conditions.

In recent years, salix has emerged as a novel fuel source for biomass power plants [32–34]. Salix, a principal afforestation species in China's arid regions, has given rise to a substantial planting industry in Inner Mongolia [35]. The volume of pruned salix branches locally exceeds the fuel requirements of power plants, indicating a diverse range of sources [36]. Additionally, the S content in salix is minimal, and the SO₂ emissions following combustion are notably modest [37]. Furthermore, the ash produced by the combustion of salix is an exemplary fertilizer for the land and can be utilized for the enhancement and fertilization of arid soil [38]. It is also noteworthy that salix possesses an elevated calorific value, which is higher than the calorific value of coal utilized in numerous conventional thermal power plant boilers [39]. A considerable number of domestic boiler plants have been designed and implemented with salix or other biomass fuel boilers [40]. However, as with other biomass materials, the high alkali metal content of salix can lead to issues such as ash accumulation and slag formation [41]. Integrating salix biomass into conventional coal-fired systems provides an effective technical pathway for controlling ash accumulation. While previous studies have predominantly focused on herbaceous biomass (e.g., wheat straw and corn stover), the unique ash chemistry of high-alkali woody biomass like salix, characterized by elevated CaO and K₂O content, remains underexplored in deposition dynamics. This omission is critical, as salix's distinct inorganic composition induces dual-phase interactions: alkaline-earth-dominated eutectic melting and alkali-induced viscous sintering, mechanisms divergent from conventional coal or herbaceous biomass systems.

In this study, a multifunctional experimental platform comprising a 32 kW one-dimensional sedimentation furnace is designed to investigate the sedimentation characteristics of the ash produced by co-combustion. The impact of varying the ratio of salix, as well as the wall and flue gas temperatures, on the accumulation of ash is examined. This study combines the in situ ash microstructure from scanning electron microscopy and energy-dispersive spectroscopy (SEM-EDS) and the compound composition of the ash samples from X-Ray Diffraction (XRD) to elucidate the underlying micro-scale mechanisms governing thermal interactions, revealing the critical blending ratio and critical temperature of salix and coal co-combustion. The experimental evidence establishes technical references for the practical applications of salix in power plants.

2. Materials and Methods

2.1. Mechanism of Ash Deposition and Slagging

Ash deposition and slag formation on heat exchange surfaces encompass four distinct stages: (1) ash particle formation and transport, (2) initial slag layer formation, (3) cohesive growth on established layers, and (4) dynamic equilibrium between deposit accumulation and detachment.

The ash formation process in coal combustion involves multiple physicochemical transformations, including inorganic element volatilization, particle agglomeration, nucleation, condensation, and coagulation [42]. Biomass combustion differs significantly from coal combustion in ash formation through its volatile components, which contain substantial alkali metals. These alkali metals either chemically interact with other minerals to form low-melting-point compounds or adhere to heat exchanger surfaces and fly ash particles via aerosol phase deposition—both mechanisms enhancing surface adhesion [43,44], thereby intensifying ash deposition and slagging.

The formation of ash deposition initiates when gaseous components and submicron particles migrate to clean heat exchange surfaces through diffusion and thermophoretic forces. These substances undergo condensation and adhesion processes, forming a chemically reactive deposit layer (termed the primary layer) with elevated thermal resistance [45]. This layer significantly accelerates ash deposition and plays a critical role in heat transfer

deterioration throughout the slagging process [46,47]. In biomass combustion systems, alkali and alkaline earth metals substantially influence primary layer formation. Alkali compounds react with aluminum silicates to create low-temperature eutectics, increasing ash viscosity and promoting rapid slag growth [48]. Alkali-rich aerosols exhibit three key behaviors: condensing on heat exchanger surfaces to accelerate primary layer nucleation, adhering to fly ash particles to enhance particulate capture efficiency, or accumulating on existing deposits to facilitate molten phase formation.

Following the formation of the initial slag layer, the increased thermal resistance elevates the surface temperature (though still below the ash melting point), initiating the primary deposition process [49]. During this stage, selective particle capture occurs: thermally softened or partially molten particles with higher viscosity adhere effectively through inertial impaction, while unmelted particles or those lacking alkali metal aerosol coatings exhibit insufficient adhesive strength to bond with the surface. As particle deposition continues, slag thickness increases, further raising the surface temperature until it exceeds the ash melting point. This triggers ash particle softening and melting, forming a highly viscous molten slag layer. Secondary deposition then commences, where the viscous molten surface no longer exhibits selective adhesion. Over 90% of impacting particles are captured, driving rapid slag growth. The adhered particles subsequently melt on the surface, forming new adhesive layers that sustain continuous deposition [50].

As slag growth continues, heat transfer deterioration intensifies, causing the molten slag layer's viscosity to gradually reach its gravitational limit. This triggers slag flow and detachment under gravity [51]. Additionally, under thick slag conditions, erosion, gravitational shedding, and gas-flow shear forces collectively promote slag detachment [52]. Ultimately, the dynamic equilibrium between deposition and detachment mechanisms stabilizes slag thickness, halting further growth or maintaining minor fluctuations [53,54].

2.2. Raw Material

The coal and salix for this experiment were provided by Yantai Longyuan Electric Power Technology Co., LTD. Before the commencement of the experiment, the coal and salix raw materials were subjected to a pre-treatment process involving crushing. The results of the industrial, elemental, calorific value, ash composition, and ash melting point analyses of biomass, coal, and blends of the two in varying proportions are presented in Tables 1–3, respectively. The ultimate and proximate analyses, ash composition analysis (except K), and their standard deviation were obtained from the Comprehensive Laboratory of Coalfield Geological Bureau (Xi'an, Shaanxi Province), which has the national certification of China. The ash preparation was followed by ASTM E830 at 575 °C [55]. Before experiments, the coal and salix samples were dried in a drying oven at 105 °C for 12 h, and then kept in an airproof desiccator. It is important to highlight that in this experiment, the receiving base for fuels has been selected for further investigation.

Table 1. Proximate analysis and ultimate analysis of biomass and raw coal.

Sample	Proximate Analysis <i>w</i> /%				Net Calorific Value $Q_{\text{net,ar}}$ (MJ·kg ^{−1})	Ultimate Analysis <i>w</i> /%				
	M_{ar}	A_{ar}	V_{ar}	FC_{ar} *		C_{ar}	H_{ar}	N_{ar}	O_{ar} *	$S_{\text{t,ar}}$
Biomass	8.20	2.75	75.49	13.56	17.14	45.00	5.82	0.43	37.72	0.08
Raw coal	4.50	18.03	29.66	47.81	23.52	61.17	3.93	0.79	10.95	0.63

* By difference.

Table 2. Ash composition analysis of raw coal, biomass, and different blended proportions of coal and biomass.

Sample	Ash Composition/%									
	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO	SiO ₂	TiO ₂	SO ₃	K ₂ O	Na ₂ O	MnO ₂
Pure coal	4.96	14.04	9.16	1.10	54.51	0.85	5.39	2.68	1.32	0.127
5% biomass	5.52	16.60	8.71	1.12	53.52	0.80	5.45	2.64	1.18	0.132
10% biomass	5.44	16.64	8.82	1.12	53.20	0.85	4.94	2.69	1.28	0.133
15% biomass	5.60	16.46	9.61	1.14	53.65	0.81	5.04	2.84	1.26	0.13
20% biomass	5.36	16.01	9.83	1.18	54.53	0.85	5.50	2.89	1.29	0.12
30% biomass	5.60	14.51	10.84	1.21	50.58	0.77	4.75	3.17	1.34	0.14
Pure biomass	3.27	5.62	31.94	3.06	13.22	0.14	1.85	7.02	0.52	0.225

Table 3. Ash melting point analysis of different fuels.

Sample	Deformation Temperature (DT)/°C	Softening Temperature (ST)/°C	Hemisphere Temperature (HT)/°C	Flow Temperature (FT)/°C
Pure coal	1130	1170	1200	1260
5% biomass	1120	1180	1210	1280
10% biomass	1140	1210	1220	1290
15% biomass	1170	1200	1210	1300
20% biomass	1170	1230	1250	1290
30% biomass	1210	1250	1280	1350
Pure biomass	1460	>1500	>1500	>1500

Table 1 shows that the coal has a pore water content of 4.5%. The content of carbon in salix is relatively low at 13.56%, compared to 47.81% for raw coal. Conversely, the hydrogen and oxygen contents are both higher at 5.82% and 37.72%, respectively. The calorific value of salix is not as good as that of raw coal, while the volatile content is significantly higher.

Table 2 shows the analysis of ash composition from raw coal, salix, and blends of the two in varying proportions. Al₂O₃ and SiO₂ make up a large proportion of the ash of raw coal (about 68.55%), while the ash of salix consists mainly of CaO, SiO₂, and K₂O (about 52.18%). The content of CaO and K₂O in salix is much higher than that in raw coal. Compared to typical woody and herbaceous biomass, salix ash demonstrates a distinct CaO-SiO₂-K₂O ternary dominance (collectively 52.18%). Its exceptionally high CaO content (31.94%)—significantly surpassing herbaceous biomass like rice straw—effectively suppresses sulfur oxide emissions (1.85% in pure salix combustion). However, this CaO readily forms low-melting eutectics (e.g., anorthite) with SiO₂, escalating slagging risks, which demands combustion temperature optimization to regulate ash morphology. Salix's elevated K₂O content (7.02%), exceeding woody biomass (e.g., pine), introduces critical ash adhesion risks from alkali metals. Consequently, rigorous control of blending ratios during co-combustion is essential to maintain ash deposition below critical thresholds.

The analysis of the ash melting point is shown in Table 3. The four characteristic temperatures of pure biomass ash are the highest. With the enhancement of biomass blending ratio, these characteristic temperatures of blended fuel ash all increase in fluctuation.

2.3. Experiment

The high-temperature settling furnace experiment system is shown in Figure 1. The experimental system consists of a micro-feeder, a one-dimensional settling furnace, and an ash deposition probe. During the preheating phase, the furnace chamber is calibrated to achieve uniform thermal conditions at 1200 °C prior to testing. Subsequently, the ash probe is inserted into the furnace from below. To guarantee fuel burnout, the air supply system is opened and the volume flow of incoming air is regulated to 1.1 m³·h^{−1}. Finally,

the micro-feeder is deployed and feeds the powder at a rate of $2 \text{ g} \cdot \text{min}^{-1}$. Following the completion of one hour, the feed is terminated, and the ash probe is removed to gather the ash accumulated on the probe for subsequent analysis. First, a calibration experiment is performed to obtain a curve of the flue gas temperature and the depth of the probe into the furnace. During the experiment, the depth of the probe into the furnace is changed according to the curve to adjust the flue gas temperature. The wall temperature is adjusted by the cooling air flow and displayed by the temperature sensor. Under standard working conditions, the flue gas temperature and wall temperature are 1000°C and 600°C , respectively, with a biomass blending ratio of 15%.

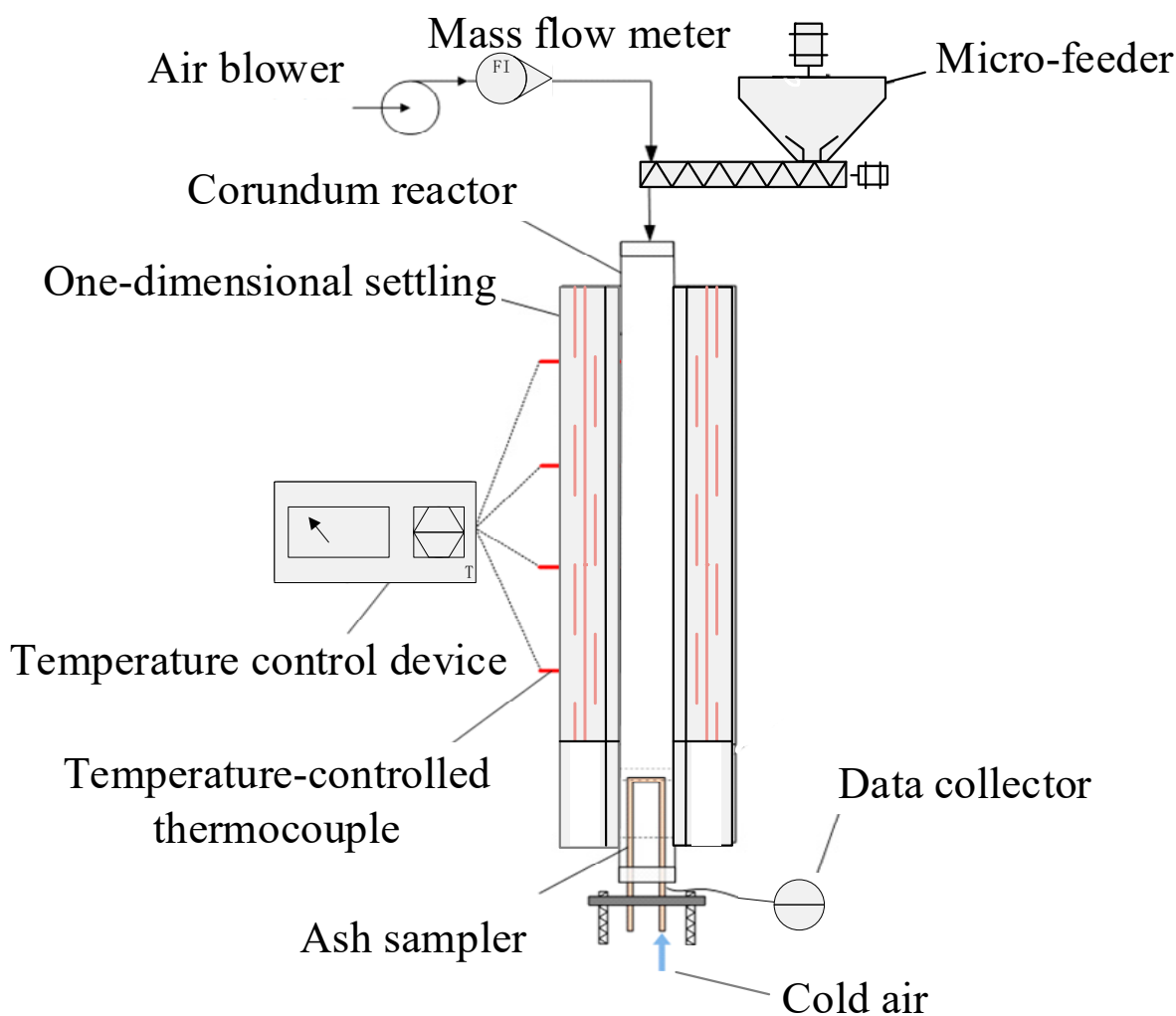


Figure 1. The 32 kW one-dimensional sedimentation furnace multifunctional experimental platform.

2.4. Analytical Instruments

Ash deposition mechanisms are primarily dictated by the elemental distribution and mineral phase characteristics within particulate residues. In this study, a tungsten filament scanning electron microscope (SEM-EDS, JSM6390A, Jeol, Tokyo, Japan) is applied to observe the micro-morphology of the collected ash samples, and the local areas requiring elemental analysis are analyzed by the energy spectrum analyzer. The ash deposition samples are then examined by an X-ray diffractometer (XRD, D8 ADVANCE, Bruker, Berlin, Germany), and the chemical composition of the materials is determined by the diffraction peaks generated by the X-ray irradiation.

3. Results and Discussion

3.1. Effect of Biomass Blending Ratio on Ash Deposition

3.1.1. SEM-EDS Analysis

Figure 2 illustrates the microscopic morphology of the accumulated ash under 200 and 500 times scanning electron microscopy, respectively. The red numbers 1–5 in the figures indicate the position where the elemental composition is analyzed using EDS. Morphometric analysis reveals that sub –20% salix co-firing yields ash with some particulate matrices, where spherical and angular geometries prevail in formations. At a proportion of biomass blending of 25%, the shape of the ash particles becomes irregular, with the particles adhering to each other and exhibiting a melting flow phenomenon. The experimental evidence establishes a positive correlation between biomass co-firing percentages and ash sintering propensity, which induces fly ash agglomeration through enhanced surface liquid phase formation.

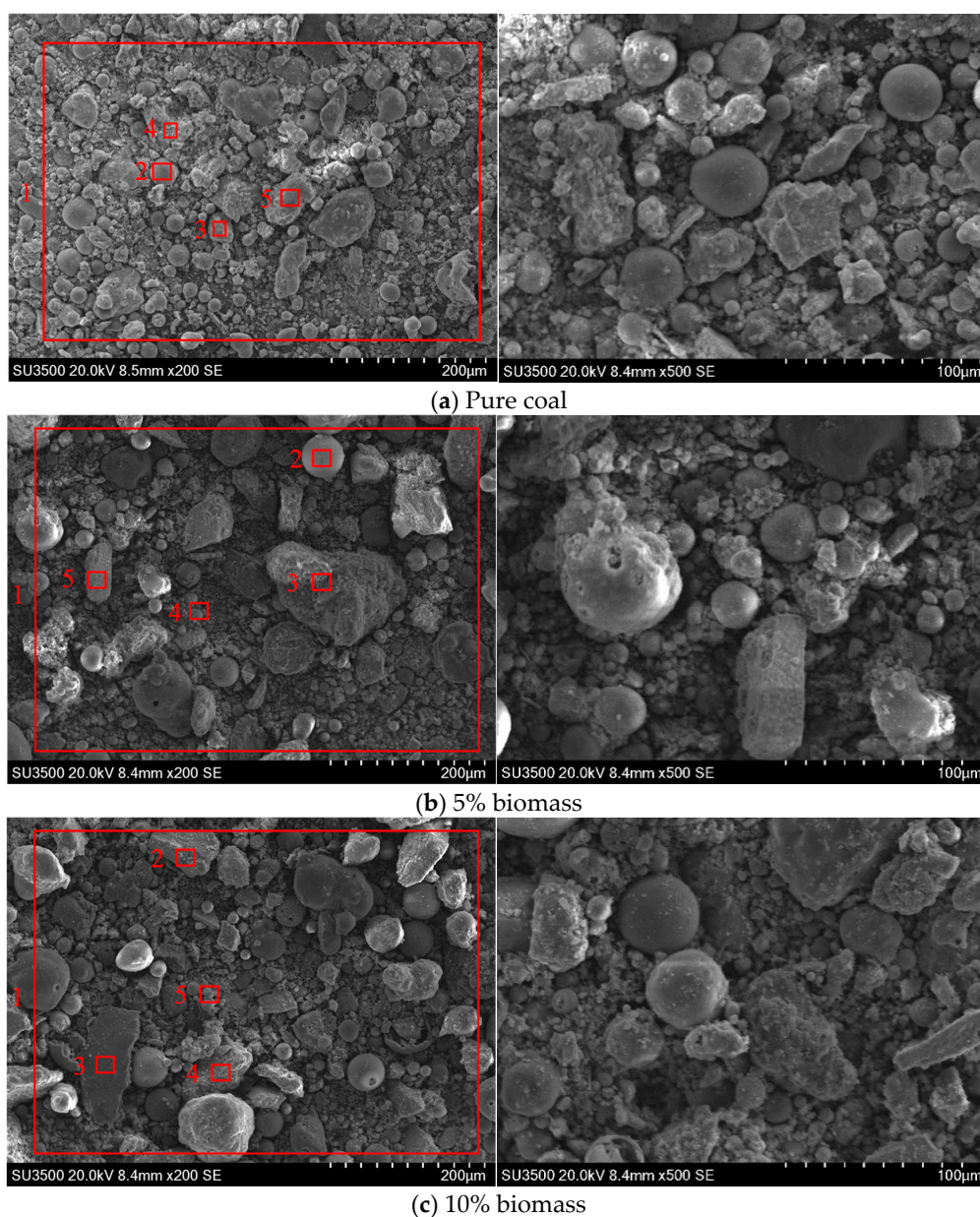


Figure 2. Cont.

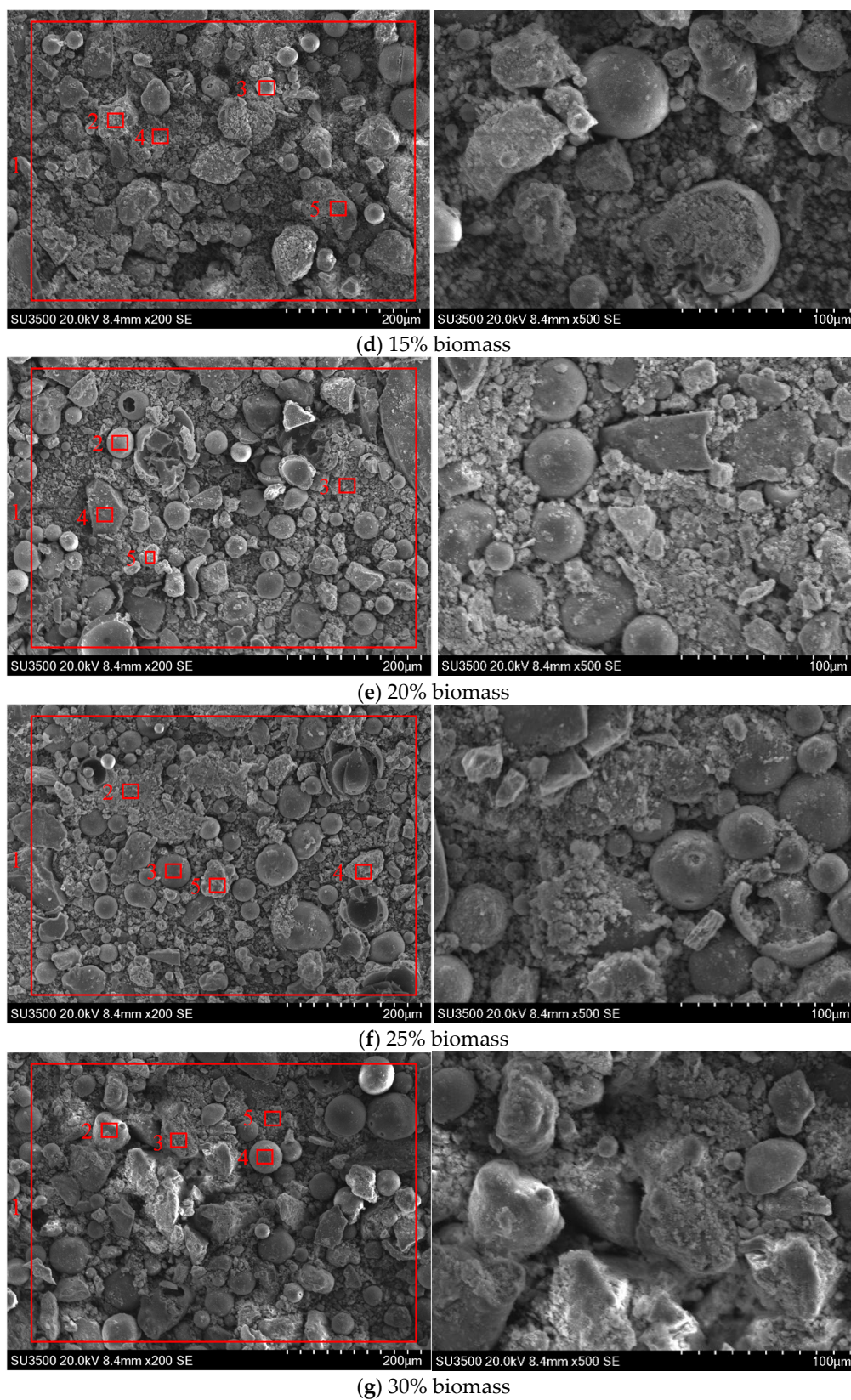


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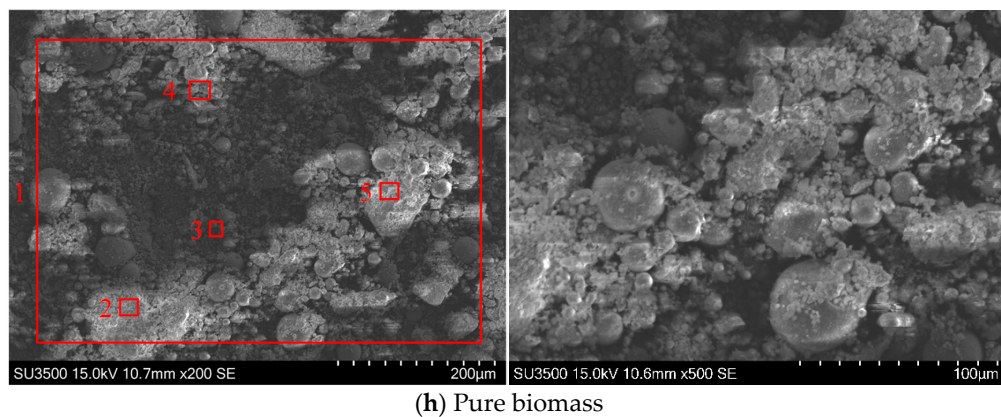


Figure 2. Micrograph of ash samples at different biomass blending ratios under 200 and 500 times.

Figure 3 shows the energy spectrum analysis outcomes for coal and biomass blended fuel in disparate sections of the ash sample across varying biomass blending ratios. Elevated biomass ratios trigger surface Ca enrichment in ash residues, while the Al and Si contents demonstrate a gradual decrease. This resulted in a notable intensification of the phenomenon of ash accumulation. During combustion, calcium exhibits relatively low volatility, facilitating the formation of molten substances at elevated temperatures. These substances tend to deposit on the surface and adhere, leading to the formation of deposits. Concurrently, Al and Si may undergo reaction with other components to form volatile compounds under conditions of elevated temperature, without contributing to the formation of caking. This ash agglomeration behavior finds experimental consistency with Maria's co-firing trials, particularly in alkali metal migration patterns [56].

As illustrated in Figure 3, the section with a larger agglomeration exhibited a higher concentration of alkali metals (Na and K) and alkaline earth metals (Ca and Mg) compared to the surrounding areas. This phenomenon can be attributed to the adhesive nature of the compounds formed by these elements, which render fly ash more prone to adhesion on metal surfaces. Concurrently, these elements form compounds with low melting points during high-temperature combustion, such as NaCl or CaSO₄. The molten materials flow and adhere to one another at elevated temperatures, resulting in the formation of larger ash agglomerates over time. This is consistent with the pattern summarized by Niu et al. [57]. The higher amounts of Na, K, Ca, and Mg that are contained in ash form alkali metal chlorides and sulfates. These compounds tend to accumulate in the initial layer of accumulated ash, which can lead to serious corrosion of metals.

The above data reveal a 25% biomass ratio as the inflection point for ash agglomeration intensification within the parametric optimization domain. It is therefore recommended that the biomass blending ratio be limited to a maximum of 20%.

3.1.2. XRD Analysis

Figure 4 delineates the crystalline phase evolution in co-combustion residues across biomass proportion gradients (0–30%). The ash samples with varying biomass blending ratios predominantly comprise the following mineral phases: SiO₂, CaO, CaSO₄, Fe₂O₃, KAl(SO₄)₂, and CaCO₃. The SiO₂ polymorph maintains spectroscopic predominance in all cases, and its diagnostic reflections demonstrate a marked predominance compared to other phases.

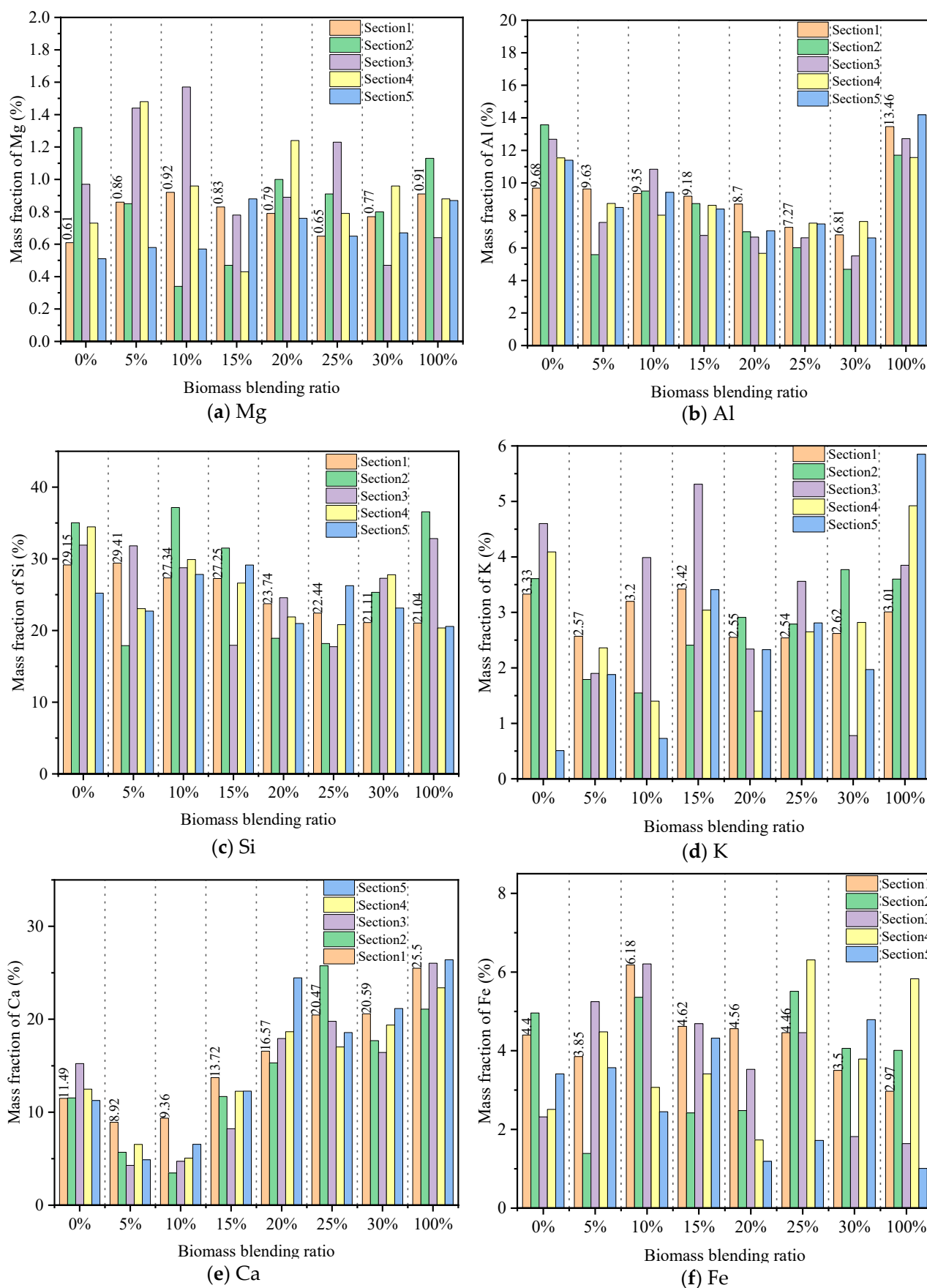


Figure 3. Effect of different biomass blending ratios on element composition of ash samples.

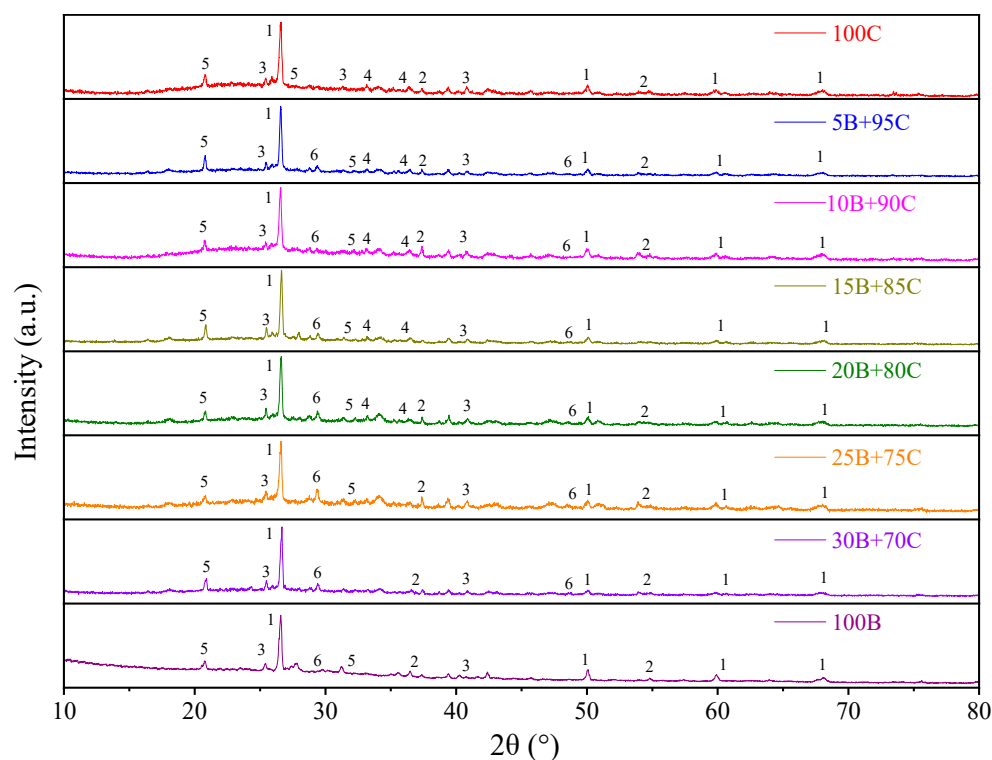


Figure 4. XRD analysis results of ash samples at different biomass blending ratios (1—SiO₂; 2—CaO; 3—CaSO₄; 4—Fe₂O₃; 5—KAl(SO₄)₂; 6—CaCO₃).

Diffractometric data reveal CaCO₃ phase emergence correlating with incremental biomass additions, progressing from undetectable levels to quantifiable crystallization. Thermal decomposition of CaCO₃ generates CaO and CO₂, inducing ash fusion point depression while enhancing structural density and interparticle cohesion. Similar conclusions are reached in the study by Tomasz Kupka [20]. Therefore, when biomass is combusted with coal, the proportion of biomass should be selected according to the fuel characteristics. The concentration of other components exhibits no appreciable variation, thus exerting minimal impact on the overall performance of the ash sample.

3.2. Effect of Flue Gas Temperature on Ash Deposition Characteristics

3.2.1. SEM-EDS Analysis

Figure 5 shows the micro-morphologies of ash samples under two magnifications at different flue gas temperatures. The red boxes in the scanning electron microscopy (SEM) images demarcate regions subjected to energy-dispersive spectroscopy (EDS) analysis: Section 1 encompasses the entire field of view, providing a comprehensive elemental profile of the sample, while Sections 2–5 in figures target localized zones of interest (e.g., molten particles and porous structures) to probe spatial heterogeneity in composition. The figures indicate that the post-combustion particulates are predominantly constituted by fine particulates, interspersed with a minor proportion of larger particles. The impact of flue gas temperature on the micro-morphology of the ash samples is relatively limited. At 800 °C, the ash sample displays a fluffy texture, an increased number of interstitial spaces, and the presence of numerous spherical substances. Ash agglomeration occurs at 900 °C. Under progressive heating conditions, a significant number of granular substances in the ash form strong bonds with one another, resulting in a more compact texture, a reduction in void space, and an increase in particle adhesion. At 1200 °C, at high magnification, the ash samples mainly consist of large, massive particles and small spherical particles, which

are alternately dispersed. Some of the particles adhered to each other due to melting, and agglomeration occurred.

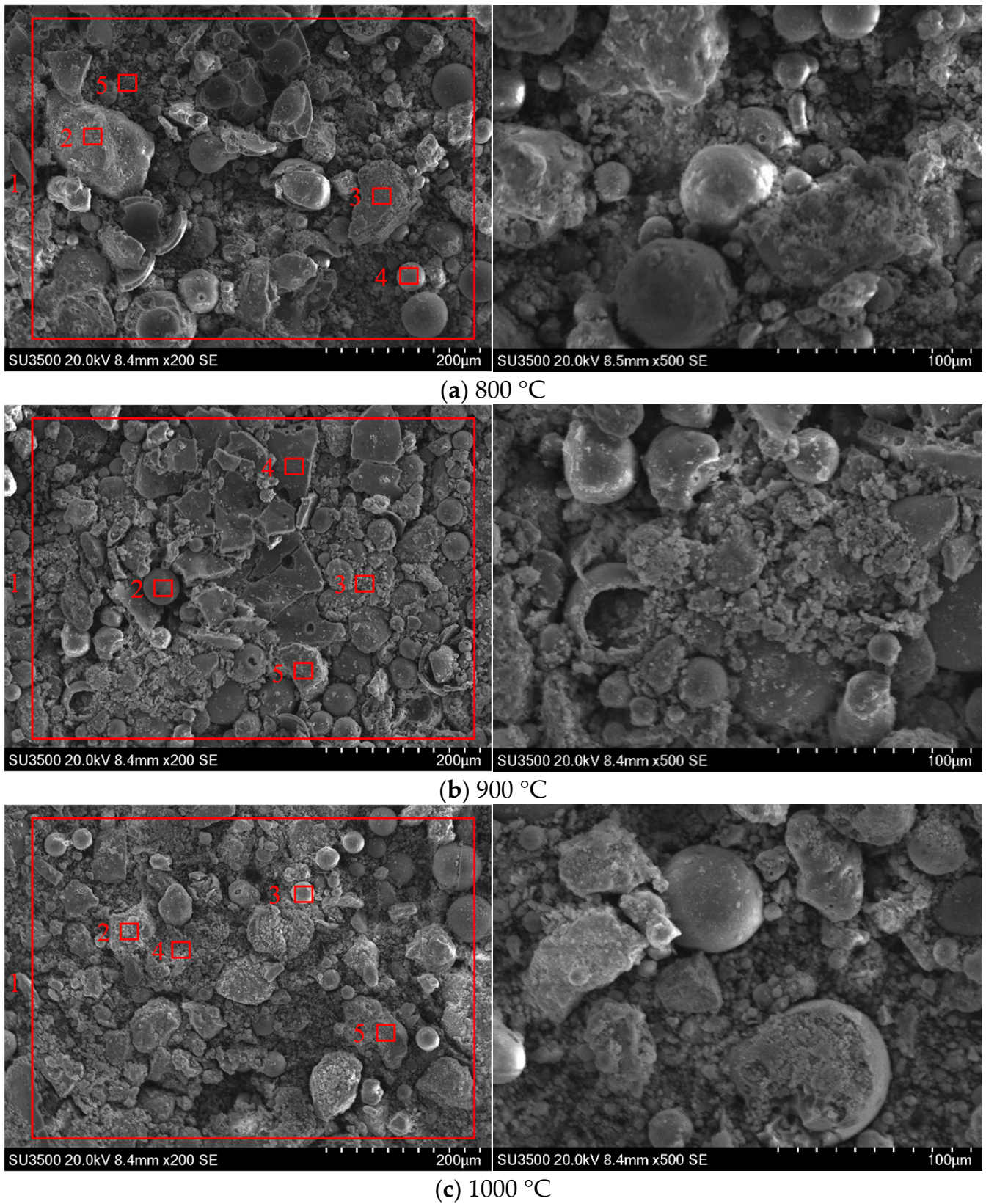


Figure 5. Cont.

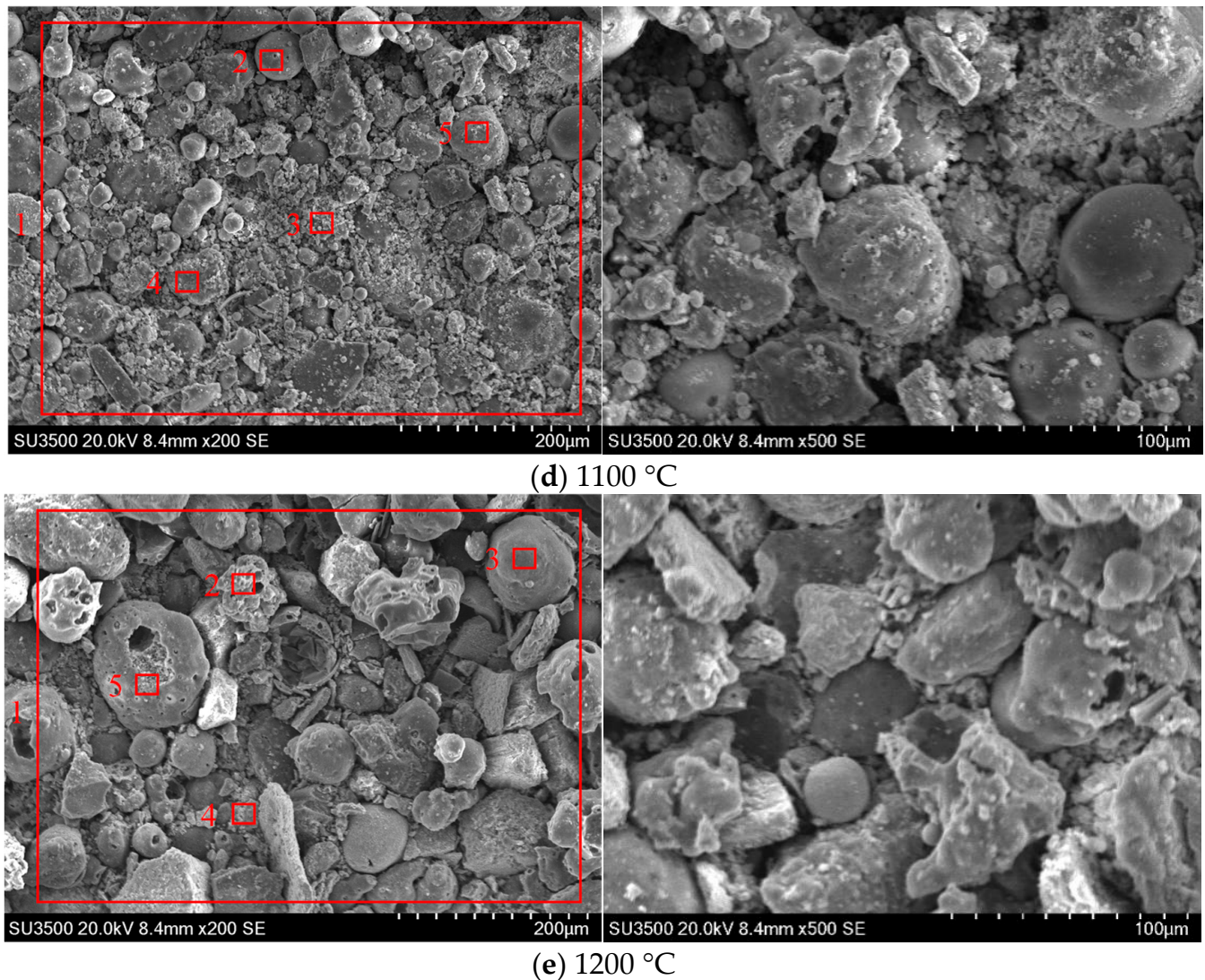


Figure 5. Micrograph of ash samples at different flue gas temperatures under 200 and 500 times.

Figure 6 shows the EDS diagram of the element composition of the ash at different flue gas temperatures. There is a slight enrichment of the K element in the ash samples at different temperatures, which just shows that alkali metals have an important effect on the formation of ash. Guo et al. [58] found that the heterogeneous condensation of alkali metals on the convection heating surface is a necessary condition for the formation of ash. The proportion of alkali metal mass decreased with the decrease in flue gas temperature. Under the condition of low flue gas temperature, alkali metals do not easily adhere to other ash particles. When the alkali metal comes into contact with the cold probe surface, it forms the initial deposition ash alone. With the decrease in flue gas temperature, alkali metals adhere to other ash particles, agglomerate to form large particles, and jointly participate in the formation of sedimentary ash.

At 800 °C, the overall structure of the ash sample is relatively loose. Beyond 900 °C, the phenomenon of ash and slag accumulation is more obvious, and the Ca element in this section is always higher. At 1000 °C and 1100 °C, the content of Ca elements decreases, and the entire section tends to be dense and compact. At 1200 °C, the ash sample becomes smooth as a whole, which is because the high temperature promotes more precipitation of low-melting-point compounds, so that the ash particles have an obvious melting and agglomeration phenomenon.

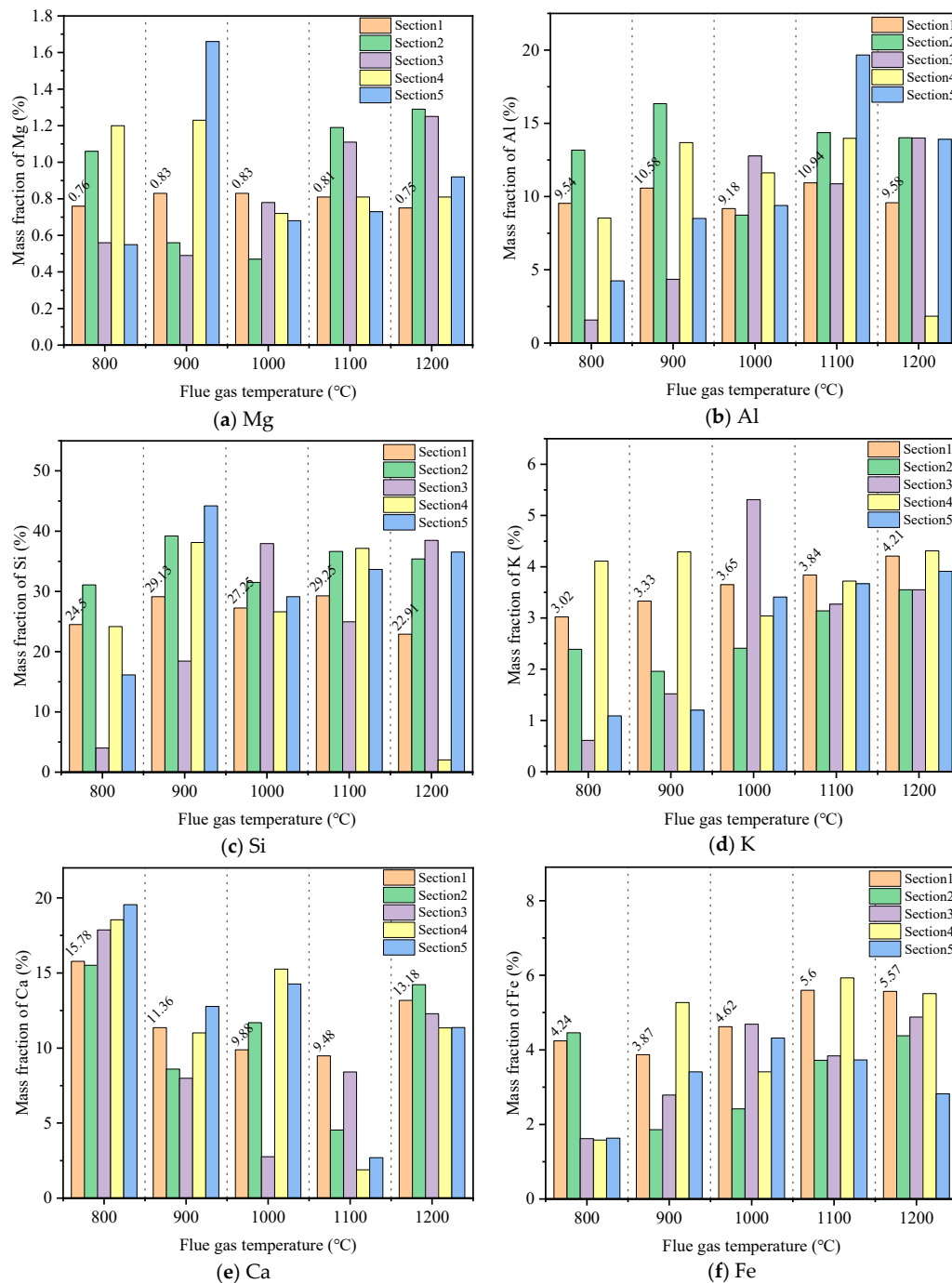


Figure 6. Effect of flue gas temperature on element composition of ash samples.

3.2.2. XRD Analysis

Figure 7 shows the XRD results of ash at different flue gas temperatures. $KAl(SO_4)_2$ diffraction peaks of high intensity can be observed in ash samples exposed to varying temperatures, suggesting that the predominant release of K and Al occurs as $KAl(SO_4)_2$. At low temperature (800 °C), SiO_2 dominates the ash layer. The CaO content is relatively low, which is indicative of a deficiency in both the adhesion and compactness of the ash layer. When reaching 900 °C, $KAl(SO_4)_2$ still shows high concentrations. The ash that forms tends to be dry and powdery rather than clumping together. At 1000 °C, ash buildup patterns alter dramatically. At this stage, ash deposits become notably stickier and denser. XRD results show that although SiO_2 is the main component, the way it combines with other components has changed, resulting in a denser structure and stronger adhesion of

the sediment. At higher temperatures (1100–1200 °C), the content of $\text{KAl}(\text{SO}_4)_2$ decreases, while CaCO_3 almost completely disappears. This indicates that under high-temperature conditions, some minerals in the sedimentary ash (such as CaCO_3 and $\text{KAl}(\text{SO}_4)_2$) undergo significant chemical changes or decomposition to form alkaline compounds, resulting in a tighter structure and stronger adhesion of the sediment.

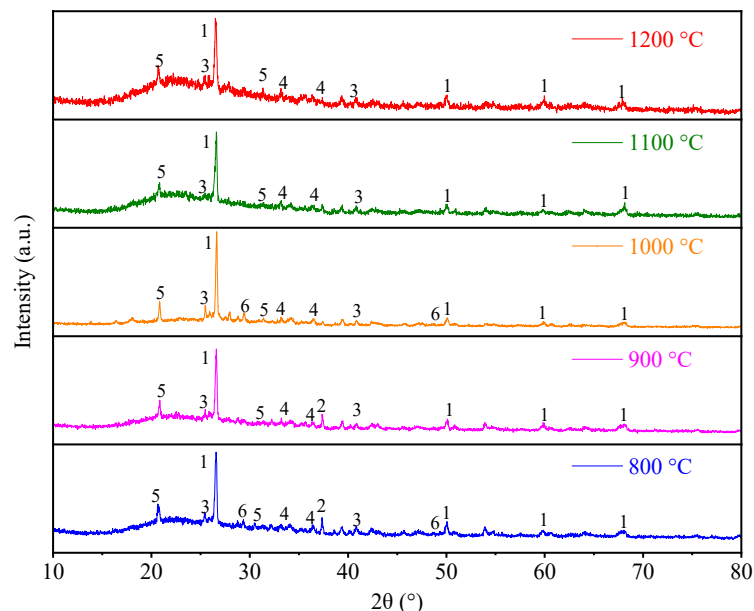


Figure 7. XRD analysis results of ash samples at different flue gas temperatures (1— SiO_2 ; 2— CaO ; 3— CaSO_4 ; 4— Fe_2O_3 ; 5— $\text{KAl}(\text{SO}_4)_2$; 6— CaCO_3).

The analysis reveals that elevated flue gas temperature causes the chemical decomposition of many compounds, which leads to a tighter structure and stronger adhesion of the sediment. When the temperature is 1200 °C, more serious adhesion and melting agglomeration of ash particles appear, and the adhesive ash accumulation formed is difficult to remove. Therefore, it is recommended that the temperature of the flue gas entering the convective heating surfaces be controlled below 1200 °C to avoid sticky ash buildup in these areas.

3.3. Effect of Wall Temperature on Ash Deposition Characteristics

3.3.1. SEM-EDS Analysis

Figure 8 shows the scanning electron microscope (SEM) images of 200 and 500 times at different wall temperatures. With the increase in the wall temperature of the ash probe, the proportion of ash spherical particles gradually decreased, and the bulk particles gradually increased. This is mainly because when the wall temperature rises, the melting degree of some substances with low melting temperature deposited on the wall is intensified, the viscosity of the wall is enhanced, and the trapping and adhesion of large particles is strengthened, increasing the proportion of large massive particles in the ash sample. When the wall temperature varies between 500 and 650 °C, the adhesion and morphology of ash particles do not show a very significant difference, but more changes are reflected in the surface structure of particles, the degree of looseness, and the slight connection trend between particles.

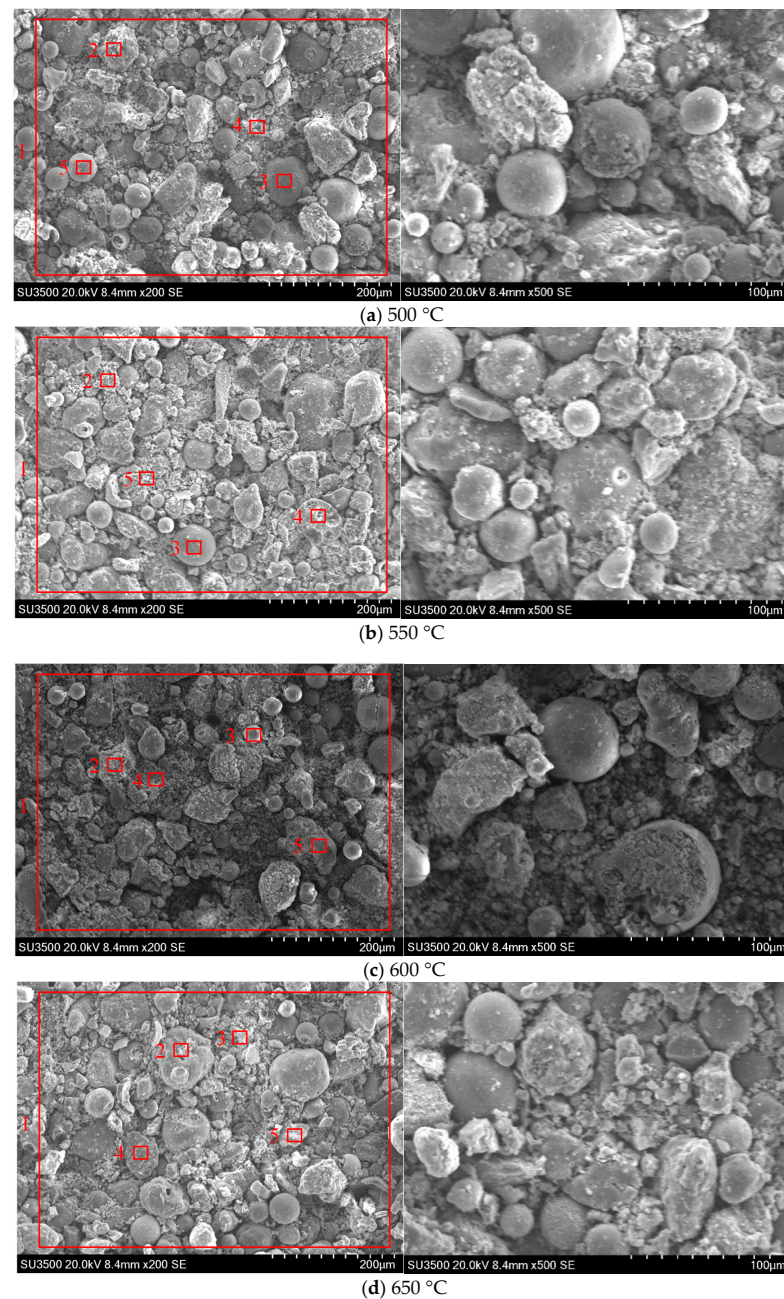


Figure 8. Micrograph of ash samples at different wall temperatures under 200 and 500 times.

At 500 °C, the particles are mainly spherical or irregular blocky, the surface is relatively smooth, and a large gap is maintained between the particles. The boundary of the particles is clear, the independence from each other is strong, and no obvious traces of melting appear. When the temperature rises to 550 °C, the space between particles decreases, and local particle agglomeration occurs. At 600 °C, the surface of the particles become no longer completely smooth, and there are slight signs of fusion between some particles. At 650 °C, the particle boundaries are more blurred, and the space between particles is further reduced.

Figure 9 shows the changes in gray element composition under different wall temperatures. At 500 °C, the ash particles maintain greater independence, which is related to the low content of alkali metals and alkaline earth metals and the high content of Si. Because Si exists in the form of SiO_2 at this time, the chemical properties are stable, helping to maintain the shape and independence of the particles. Once the temperature is 550 °C,

the differences between the different sections begin to show. For example, the Ca content in Section 3 is significantly increased, which leads to enhanced intergranular adhesion in this section, and the ash accumulation structure becomes denser. In contrast, Section 2 has less metal content, and the ash accumulation remains relatively loose. At 600 °C, the differences between the different sections become more pronounced. The content of alkali metals and alkaline earth metals in Section 3 increased significantly; in particular, the content of K and Ca reached a high level in this section. These increases lead to a significant intensification of slag formation. At 650 °C, the content of Al and Si is still high, and silicate may be formed at this high temperature, which increases the adhesion between particles. In addition, the metal content tends to be average. For example, Ca and K contents are higher in different sections, and slagging in each section becomes more common.

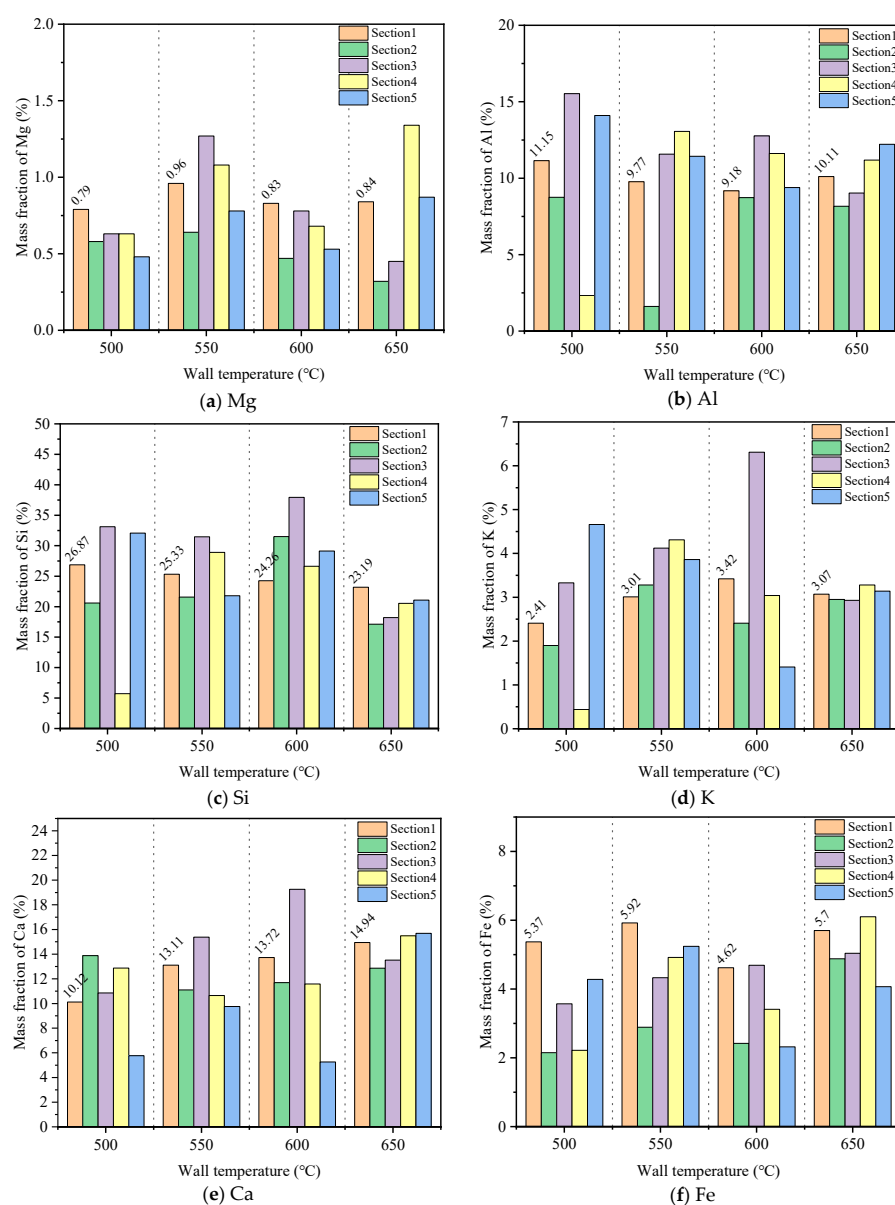


Figure 9. Effect of different wall temperatures on the element composition of ash samples.

3.3.2. XRD Analysis

Figure 10 shows the XRD analysis results of ash samples at different wall temperatures. The XRD analysis results show that CaCO_3 and CaSO_4 show an upward trend with the increase in temperature. CaCO_3 decomposes into CaO and CO_2 gases at high temperature,

but the increase in the content within this temperature range indicates its deposition at the low temperature stage. The rise of CaSO_4 indicates its gradual accumulation in ash samples. The accumulation of CaCO_3 and CaSO_4 promoted the formation of hard blocks in the ash samples, making the structure of the sediments denser and adherent. The interaction between CaO and CaSO_4 generated by the decomposition of CaCO_3 strengthens the viscosity of the ash layer, makes the binding between sediments closer, and reduces the fluffiness, thus leading to a more obvious deposition phenomenon.

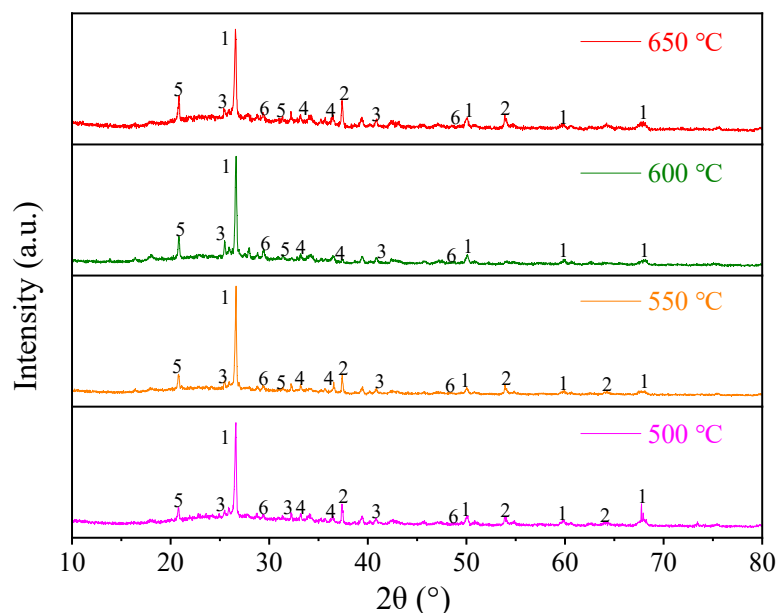


Figure 10. XRD analysis results of ash samples at different wall temperatures (1— SiO_2 ; 2— CaO ; 3— CaSO_4 ; 4— Fe_2O_3 ; 5— $\text{KAl}(\text{SO}_4)_2$; 6— CaCO_3).

4. Conclusions

- (1) Salix, a key afforestation species in China's arid regions, has fostered a significant planting industry in Inner Mongolia. The abundance of pruned salix branches exceeds the fuel demands of local power plants, suggesting a wide variety of potential applications. Salix biomass exhibits significant industrial value as a renewable resource. Its high calorific value (comparable to coal) makes it a key feedstock for bioenergy production, including power generation and biofuel synthesis. The high CaO content in salix ash (31.94%) and its inherently low sulfur composition synergistically contribute to the reduction in sulfur oxide emissions during combustion.
- (2) The addition of biomass will exacerbate the fuel ash deposition, which is related to the high alkali metal content of biomass fuel. As the biomass blending ratio increases from 5% to 30%, the content of Ca in ash increases from 8.92% to 20.59%, forming a lower melting point, which results in an obvious melt flow. The surface viscosity of the ash deposition probe increases, enhancing the ability to capture large particle sizes. In particular, when the biomass blending ratio exceeds 20%, serious adhesive ash accumulation will be caused. Therefore, it is recommended to control the biomass blending ratio to not exceed 20%.
- (3) As flue gas temperature increases, a distinct melting and flow phenomenon becomes apparent between ash particles. The shape of ash particles gradually becomes irregular and they lose their individual integrity under high-temperature thermal treatment. Ash particles begin to adhere to each other, during which a pronounced molten flow phenomenon becomes observable. When the flue gas temperature reaches 1200 °C, there is a serious ash particle melting flow under different biomass combustion ratio

conditions, and the low-melting-point material containing calcium covers the surface of the ash particles, making the ash particles adhere to each other. Practical boiler systems must integrate real-time temperature monitoring and adaptive combustion controls. Therefore, it is recommended that the flue gas temperature entering the convective heating surface be controlled below 1200 °C to avoid the growth of cohesive ash deposition on the convective heating surface.

- (4) As the wall temperature increases, the adhesion between the ash particles increases significantly, resulting in a denser ash deposit structure. The experimental results show that this is related to the increase in alkali metals and the decrease in Si content. When the wall temperature is increased from 500 °C to 600 °C, the Ca and K contents increase by 35.6% and 41.9%, respectively, while the Si content decreases by 9.7%. The increase in K and Ca content leads to the thickening of the initial layer of the ash deposit, which facilitates the formation of the sintered layer of the deposited ash. The reduction in Si content is not conducive to maintaining the shape and independence of the particles, which makes the particles fuse and adhere, resulting in difficulty in removing the ash accumulation. When the wall temperature reaches 600 °C, the degree of ash slagging increases markedly, especially in the section of high alkali metal content, and the bonding strength between particles increases, forming ash that is more difficult to remove. Therefore, it is recommended that the wall temperature should not exceed 600 °C.

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