1 INTRODUCTION

The energy problems triggered by the shortage of oil resources and global warming caused by the greenhouse effect are two major intertwined issues in the modern era.1 But in the coming decades, fossil fuels will continue to provide more than 85% of global energy consumption. Compared with oil and natural gas, the attraction of coal lies in its abundant reserves and stable prices.2,3 Therefore, the efficient use of coal is increasingly paramount to the sustainable development of the world economy and society. The production efficiency and thermal efficiency of the blast furnace (BF) have distinct advantages compared with other iron making processes.4-7 However, since the coke and coke expensive
pollution, researchers inject a slice of cheaper auxiliary fuels into the blast furnace from the tuyere as a substitute for some metallurgical coke. The implementation of pulverized coal injection (PCI) technology has become one of the effective ways to counter the problems related to all coke operations and to reduce the energy cost in recent years.8-10 Especially in China, the total amount of coal injected into the blast furnace in 2018 was 1.033 billion tons.

The harsh working conditions in BF lead to the combustion process of the pulverized coal (PC) to be an individual and complicated physical and chemical process. There is a sea of factors affecting the combustion of pulverized coal in BF. One of the main factors that is easily overlooked is the high-temperature ash melting characteristics of the PC, and the BF is a gasification shaft furnace equipment for liquid slagging. The blast temperature of the BF is up to 1250°C, and the temperature of the tuyere region is 1600-1700°C, which has wide adaptability to the melting temperature of coal ash.11,12 However, when the ST of coal ash is lower than 1250°C, the PC is easily wrapped by molten ash during the combustion process, affecting the combustion efficiency of the PC, and even leading to slagging before the tuyere or injector. The slagging in front of the injector is shown in Figure 1, which will affect the stable production of the BF.

Coal ash is mainly composed of a complex mixture of SiO2, Al2O3, and CaO with alkali metals, alkaline earth metals, and transition metal oxides and their compounds.13-16 Generally, slagging situation can be predicted according to the ST of coal ash,17 then suitable combustion equipment is selected, and the apparatus further determines the coal species having a suitable ST. A host of scholars have done a lot of research on the ash melting characteristics of PC. Li et al18 studied the change of ash fusion behavior and its regulation mechanism of high ST coal. Coal blending is a promising method for adjusting the melting characteristics of coal ash to meet gasification requirements. A laboratory-scale drop tube furnace had been set up to examine the ash deposit properties between blended and single coals in air environment.19 Wei et al20 studied the effects of silica-alumina additives (SiO2, kaolin and fly ash) on ash melting characteristics. Results are indicative of that the AFT manifests a tendency to decrease in the first place and then increases as the proportion of silica-alumina additives increases. To obtain the coal ash with higher AFT, it is recommended that the mixing ratio of the silicon-aluminum additive is 9%. Lime and kaolin additives can effectively improve AFT, but Na2CO3 and SiO2 additives demonstrate a "V" shape on AFT. These general results can be used for the pretreatment of Zhundong coal in the combustion process, to reduce the slagging of the solution.21 Xiao et al22 studied the effects of two red mud (RM) samples (ZZ and ZM) on the ash fusion behavior of three high ash melting point coals (FZ, JC, and JZ). The results imply that the content of CaO, Fe2O3, and Na2O in RMs is higher than that of coal ash. They lead to the lower AFTs of RMs than the three high AFTs coals, and the formation of high-melting mullite may be the main factor of higher AFT of coal ash.

The above researches on the ash fusibility of single coal or coal blending ash mainly focused on the power generation industry and the coal chemical industry. And the results may not apply to blast furnace production. As mentioned above, the atmosphere in the blast furnace has its particularity (high temperature, high pressure 0.3-0.4 Mpa, gas turbulence). Usually, the BF site requires that the ST of the coal ash is higher than 1250°C. So some low ash melting bituminous with high caloric value are not fully utilized. In this paper, we mixed low ash melting bituminous with medium-high ash melting anthracite which selected from the BF production site and focused on the effect of blended coals on improving the fusibility of low AFT bituminous. The purpose of this work is to provide some evidence that bituminous with high CaO and low AFT (ST below 1250°C) can be applied to BF injection.

2 | EXPERIMENTAL

2.1 | Bituminous, anthracite selection, and preparation

In this work, two kinds of bituminous and one anthracite were used to test the AFT of coal blending ash. All three
types of coal produced in China. Anthracite comes from Anhui Province, marked B, and its ash melting temperature is high. Two kinds of bituminous come from Shanxi Province, marked as D and S. It is worth noting that coal B and coal D have been applied to BF injection. Coal S has a relatively high CaO content in its ash and low ash melting temperature (ST is 1149°C). To avoid slagging before the tuyere or injector, it cannot be directly used for BF injection. At present, coal S is only used as thermal coal for thermal power generation. Table 1 lists the proximate, ultimate analysis of three single coals.

### 2.2 Determination of ash composition

According to the Chinese standard GB/T1574-2011 (similar to ISO 1171:2010 and ASTM D3174-12), the coal samples were burned to ash in a muffle furnace at 815°C. The chemical composition of coal ash was determined by an X-ray fluorescence spectrometer (XRF-1800, Shimadzu) from the test center of the school of metallurgical and ecological engineering, University of Science and Technology Beijing. In this paper, coal D/S and coal B were mixed at a mass ratio of 1.0:1.0 and 1.0:1.5, respectively. These blended coals are labeled D1B1, S1B1, and D1B1.5, S1B1.5. Table 2 lists the ash composition analysis of single and blended coals.

### 2.3 Ash fusion measurements

The atmosphere has a considerable influence on the AFT. This can be attributed to the fact that ferrous iron, present in reducing conditions, has more affinity to clay minerals than ferric iron present in oxidizing conditions. There is an oxidizing environment (due to CO₂ and O₂) in the flame zone of the lower part in the blast furnace, and it is indispensable to determine the change in the ash melting behavior under such conditions since virtually all oxidation stages (i.e., iron) occur in the slag. According to the Chinese standard GB/T219-2008, the AFT was measured by the YX-HRD3000 ash melting characteristic analyzer (see Figure 2) under an air atmosphere.

The coal ash was mixed by the dextrin solution and then formed into a triangular gray cone. Regarding 2g of ashes were employed to make the ash cone for every ash fusion test. The ash cone was placed in the analyzer, heated to 900°C at a rate of 10°C min⁻¹, and then heated to 1500°C at a rate of 5°C min⁻¹ for measurement. During the test, the initial deformation temperature (T_{IDT}, also called IDT/DT in the paper), the softening (T_{ST}), and fluid temperature (T_{FT}) were identified from the ash cylinder (see Figure 3). The measurement deviation of the ash fusion test was ±10°C. Each sample was measured twice to obtain an average value to ensure the accuracy of the experimental results.

### 2.4 Mineral analysis

A RIGAKU Ultima IV X-ray powder diffractometer (XRD) with Cu-K (a) radiation (40 kV, 40 mA, Ka1 = 0.15408 nm) was used to determine the raw coal mineral composition and the ash mineral composition. The scanning speed was 4°, 20 min⁻¹ with a step size of 0.02° from 15° to 60°. The experimental sample size was <0.074 mm. Peak identification was performed through comparison with reference standards from JADE 6.0 software package.

### 2.5 Thermodynamic calculations

The thermodynamic calculation software (FactSage) can provide information on the type and content of minerals that are relatively accurate and reliable at high temperatures in the study of coal ash slag melt characteristics. In this work, we used the Equilib module of the FactSage 6.4 and the Phase Diagram module to simulate the mineral transformation and liquid phase formation behavior of the three single coals and blended coals in ash melting processes under air atmosphere. The first and foremost, each group of coal ash system simplified into different oxides (SiO₂, Al₂O₃, CaO, Fe₂O₃) according to the coal ash composition. The FToxid database is selected, and the equilibrium state corresponding to the system of 700-1600°C is calculated according to the principle of Gibbs minimum energy, and the interval is 100°C. The relative amounts and phase states of the respective products or intermediates were analyzed. Combined with the equilibrium phase diagram of SiO₂-CaO-Al₂O₃ ternary system, the effect of coal blending to change the coal ash composition on

| Samples | Proximate analysis (ad) | Ultimate analysis (ad) |
|---------|------------------------|-----------------------|
|         | M         | Ash   | VM     | FC   | C   | H   | O<sup>a</sup> | N   | S   |
| B       | 1.76      | 10.06 | 9.04   | 79.14| 80.78| 3.25| 3.84 | 1.04 | 0.49|
| D       | 7.71      | 9.04  | 28.78  | 54.47| 71.35| 4.27| 14.19| 0.79 | 0.36|
| S       | 5.26      | 5.44  | 32.07  | 57.23| 73.79| 4.44| 15.18| 0.84 | 0.29|

Note: Abbreviation: ad, air dry basis.

<sup>a</sup>Calculate by difference.
the fusibility of coal ash was analyzed. In the ternary phase diagram, an isotherm was marked in each phase region, which represents the reaction temperature at which the coal ash composition melted completely to the liquid phase at a specific temperature.

3 | RESULTS AND DISCUSSIONS

3.1 | Fusion characteristics of single coals and coal blending scheme

The fusibility test allows evaluation of both softening and fusion behavior of the coal ashes, which are also related to fluidity characteristics of the samples. Table 3 and Figure 4 show results from the fusibility test for samples.

As shown in Table 3 and Figure 4, the results demonstrate that the AFTs of the blended coals change nonlinearly with the change of the mixing ratio. It can be seen from Table 3 that the ST of coal B, coal D, and coal S are 1316, 1242, and 1149°C, respectively. The ST of coal D is 8°C lower than the hot air temperature and mixed properly with coal B (anthracite). It has been applied to BF injection. However, the ST of coal S is 101°C lower than the hot air temperature (1250°C), which limits the application of coal S in PCI. Coal B belongs to anthracite with high degree of metamorphism, and the Al₂O₃ content in ash plays a "skeleton" role in the melting process is the highest (25.7 wt%); these two points may be the main factors of its AFT higher than coal D and coal S.

Figure 5 is a graph showing the relationship between the ST and the main oxide SiO₂, Al₂O₃, and CaO. Combined with Table 2 and Figure 5, the content of CaO in the coal ash of coal B and coal S is relatively high, 15.14 wt% and 26.21 wt%, respectively, which belong to high calcium coal. The S/A of coal D is 2.33, which belongs to high silicon aluminum ratio coal. Besides, after blending coal, the content CaO in all coal blending schemes has been reduced, the range of CaO is 6.78 wt%‐14.74 wt%, and the content of SiO₂ and Al₂O₃ is higher than the content of corresponding single coals. Similar phenomena occur in other compounds such as F₂O₃, SO₃, and MnO. It may be due to the fact that the minerals in ash of the blended coals in the ashing stage undergo a chemical reaction or the mineral composition in the blended coal ashes has been renewed and recombined during the combustion process. Since the composition of coal B is relatively complicated, when coal B reacts with coal D and coal S at high temperature, the difference in the amount of coal B added gives rise to a significant change in the phase of the reaction product. Macroscopically, the high-temperature melting characteristics of blend coal ashes may be significantly different from single coals. Therefore, the coal blending process is equivalent to adding a plurality of components to coal at the same time, which can be regarded as a process of recombining minerals in coal ash.

Also, the high-temperature melting characteristics of coal ash are affected by the combination of acidic oxides and basic oxides. In general, the more the acidic oxide content, the higher the FT of the coal ash, and the higher the basic oxide content, the lower the FT of the coal ash. For reflecting the change in AFT, the base-to-acid (B/A) X ratio is often used:

\[
(B/A)_X = \frac{\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{TiO}_2}{\text{CaO} + \text{Fe}_2\text{O}_3 + \text{MgO} + \text{Na}_2\text{O} + \text{K}_2\text{O}}
\]
Quite a few works have shown that when the $X$ is $<1$ or $>3$, the melting temperature of coal ash is relatively high. This is because the content of CaO in coal ash is dominant when the $X$ is less than one. The SiO$_2$ content is dominant when the $X$ is greater than three, while the melting point of CaO and SiO$_2$ is extremely high, resulting in the higher melting temperature of coal ash. When the $X$ is between 1-3, the AFT of coal ash is relatively low, which is because the content of CaO and SiO$_2$ is not obvious; CaO, FeO, SiO$_2$, Al$_2$O$_3$ and other acidic oxides can occur low-temperature co-melting phenomenon. Accordingly, the AFT of coal ash is relatively low. From the calculation of $X$ in Table 2, it can be seen that the $X$ of coal S is 1.40, ranging from 1-3. Consequently, its ash melting temperature is the lowest, and the softening temperature is only 1149°C, which is far lower than the requirement of blast furnace injection. To avoid slagging at blast furnace tuyere and coal injector, anthracite with high AFT should be added to coal S to improve the AFT.

### 3.2 Mineral transformation of ashes

In order to further investigate the improvement mechanism of coal blending on ash melting, combined with the initial mineral compositions of raw coals, the main mineral transitions in ash B/D/S and their blended ashes D/B, S/B under oxidant atmosphere (air) are discussed based on the 2D graphical visualization of XRD results, which are

![Changes of cone shape during ash flow transformation](image)

**FIGURE 3** Changes of cone shape during ash flow transformation

**TABLE 3** AFTs of single coals and blended coals (°C)

| Samples | DT   | ST   | HT   | FT   |
|---------|------|------|------|------|
| B       | 1254 | 1316 | 1364 | 1385 |
| D       | 1230 | 1242 | 1249 | 1316 |
| S       | 1124 | 1149 | 1170 | 1202 |
| D1B1    | 1314 | 1353 | 1374 | 1390 |
| S1B1    | 1262 | 1324 | 1346 | 1368 |
| D1B1.5  | 1326 | 1363 | 1379 | 1404 |
| S1B1.5  | 1290 | 1350 | 1358 | 1387 |
given in Figures 6 and 7A,B. For the same mineral, the variation in XRD pattern-diffraction intensity reflects the approximate change in mineral content. It can be seen from Figure 6 that the main mineral compositions of the three raw coals are similar. They mainly include quartz (SiO$_2$), calcite (CaCO$_3$), kaolinite (Al$_2$(SiO$_2$)(OH)$_4$), dickite (Al$_2$SiO$_2$O$_2$(OH)$_4$), and pyrite (FeS$_2$). It is worth noting that while the coal D and coal S selected for this study are somewhat similar, the coal B differ significantly from the two bituminous coals, as evidenced by the analyses presented in Table 1 and Table 2. The diffraction intensity of kaolinite in coal B is significantly higher than that of coal D and coal S. The decomposition of kaolinite starts at around 300°C due to release of water leading to the formation of...
metakaolinite (MK). With the temperature rises, MK converts to mullite \((2\text{SiO}_2\cdot3\text{Al}_2\text{O}_3)\), as presented in Figure 7. Calcite decomposes into lime and carbon dioxide at about 700°C. The combustion reaction of pyrite begins at about 300°C, and the resulting iron oxidation continues to react with other minerals to form andradite.\(^{28,29}\) Consequently, during the combustion of pulverized coal in the combustion chambers of muffle furnace, the fine inherent minerals transform within the char particles and gradually are released during the char fragmentation. Decomposition of minerals and conversion in solid phase leads to the formation of gases which undergo homogeneous chemical reactions with subsequent heterogeneous or homogeneous condensation.\(^{30-32}\) And different minerals fuse and coalesce with one another to form ash particles.

On the other hand, as can be seen from Figure 7, ash D and ash S are mainly composed of high melting point (MP) quartz, low MP anhydrite, and lime. In addition, the diffraction intensity of quartz in ash D is significantly higher than that of ash S, and the diffraction intensity of calcium oxide in ash S is strongest. There are also some high MP minerals such as corundum \((\text{Al}_2\text{O}_3)\) and muscovite \([\text{KAl}_2\text{Si}_3\text{O}_{10}(\text{OH})_2]\), which are identified in ash D and ash S, but the diffraction intensity of these two minerals are relatively low. In contrast, the main mineral in ash B is high MP quartz, and the diffraction intensity of other low MP minerals such as anhydrite and lime is significantly lower than that of ash D and ash S. CaO plays a role in the melting of coal ash, which has not only been confirmed in many studies,\(^{33,34}\) but also verified in industrial production. From the perspective of the internal structure...

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**FIGURE 6** XRD patterns of main minerals of raw coals. 1-Quartz(SiO\(_2\)); 2-Calcite(CaCO\(_3\)); 3-Kaolinite(Al\(_2\)(SiO\(_2\))(OH)\(_4\)); 4-Dickite(Al\(_2\)SiO\(_2\)O\(_5\)(OH)\(_4\)); 5-Pyrite(FeS\(_2\))

**FIGURE 7** XRD patterns of main minerals of ashes B, D, S and their blended ashes D/B, S/B. 1-Quartz(SiO\(_2\)); 2-Anhydrite(CaSO\(_4\)); 3-Anorthite(CaAl\(_2\)Si\(_2\)O\(_8\)); 4-Lime(CaO); 5-Corundum(Al\(_2\)O\(_3\)); 6-Muscovite[KAl\(_2\)Si\(_3\)O\(_{10}\)(OH)\(_2\)]; 7-Andradite(Ca\(_3\)Fe\(_2\)Si\(_3\)O\(_{12}\)); 8-Mullite(3Al\(_2\)O\(_3\)-2SiO\(_2\)); 9-Wollastonite(CaSiO\(_3\)); 10-Grossularite(Ca\(_3\)Al\(_2\)Si\(_3\)O\(_{12}\))
of slag, a large amount of free Ca\(^{2+}\) in ash D and ash S can destroy the original Si-O covalent bond. Then, Ca\(^{2+}\) with two nonbridged trophic ions (0−) forms an ionic bond (O\(^{-}\)-Ca\(^{2+}\)-O\(^{-}\)), and causing the two broken SiO\(_2\) chains joined together. As the content of calcium oxide in ash increases, the original SiO\(_2\) split into SiO\(_2\) chains combined by (O\(^{-}\)-Ca\(^{2+}\)-O\(^{-}\)) ionic bonds, and the number of [AlO\(_4\)]\(^{−}\) tetrahedrons decreases. The correlation between [SiO\(_4\)]\(^{4−}\) and [AlO\(_4\)]\(^{−}\) in the structure is reduced, and then, the structural stability is destroyed. Macroscopically, the overall mechanical strength (low ash melting point) of the gray cone is diminished.

In the composition of coal ash, the content of Al\(_2\)O\(_3\) has a significant influence on the melting temperature of coal ash.\(^{35}\) It can be seen from Figure 7 that as the mass fraction of ash B in blended ashes (D/B and S/B) increases, the content of aluminized minerals increase and react with some refractory minerals such as quartz in ash D and ash S to form high MP aluminosilicate mineral (mullite, MP is about 1850°C). During the process of coal ash melting, mullite plays a role in supporting the structure of coal ash, and the melting point of coal ash increases with the increase of Al\(_2\)O\(_3\) content. Dyk\(^{36}\) studied the effect of acidic oxides on the melting point of ash and also pointed out that the content of Al\(_2\)O\(_3\) in coal ash is closely related to the fusibility of coal ash. Figure 7A,B shows that when the mass fraction of ash B was 50 wt%, mullite appeared in D1/B1, and a small amount of low MP andradite still existed in S1/B1. The most important reason may be a large amount of calcium oxide with SiO\(_2\) and Al\(_2\)O\(_3\) in ash S formed too much low-temperature eutectic. As the mass fraction of ash B further increases, low MP andradite in blended ash S1/B1.5 decreases with the decrease of CaO, and the content of mullite increases. The main mineral reactions that may occur during the muffle furnace ashing process shown as follows\(^{30}\):

\[
dolomite (\text{CaCO}_3 \cdot \text{MgCO}_3) \rightarrow \text{MgO} + \text{CaO} + 2\text{CO}_2 \uparrow \quad (1)
\]
\[
calcite (\text{CaCO}_3) \rightarrow \text{CaO} + 2\text{CO}_2 \uparrow \quad (500 - 900°C) \quad (2)
\]
\[
kaolinite (\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}) \rightarrow \text{Al}_2\text{O}_3 + 2\text{SiO}_2 + 2\text{H}_2\text{O} \quad (3)
\]

### 3.3 Computational analysis

Figure 8 manifests the thermodynamic software (FactSage 6.4) simulation results of the mineral composition and liquid phase formation of single coals and blended coals (1:1, 1:1.5) ash during heating. It can be seen from Figure 8A that the mineral components in coal D ash at 700°C mainly include anorthite, quartz, corundum, and a small amount of andradite. Another point, before 1200°C, with the increase of temperature, the content of anorthite in coal D ash showed a slowly decreasing trend. The content of quartz and corundum showed a slowly rise and gradually reduce. The content of andradite showed a gradually rise trend.\(^{35}\) the content of mineral components did not change much. With the further increase in temperature, when the temperature is between 1200 and 1300°C, the content of most mineral components decreased gradually first and then decreased rapidly. The content of liquid phase began to produce small quantities at 1200°C and increased significantly with the rapid decrease of mineral content at 1300°C. With the increase of temperature, the anorthite continues to melt and the amount of liquid phase increases to 100 wt%. Compared with coal D, coal B has a higher content of anorthite, while other minerals are much lower than coal D. When the temperature is 1100°C, coal B ash begins to appear liquid phase. As the increase of temperature, the amount of liquid phase increases, but the formation rate of liquid phase is much lower than coal D ash. It is worth noting that the content of SiO\(_2\) in the original coal B ash is 49.42 wt%, which is much higher than that of coal D ash and coal S ash. When the temperature is 800°C, the quartz of coal B ash completely disappears, and the new mineral tridymite appears. The MP of tridymite is higher than that of quartz. This may be due to the fact that other small amounts of alkaline substances in coal ash act as mineralizers to promote the conversion of quartz to tridymite.

\[
\beta - \text{quartz} \rightarrow \text{Tridymite} (800°C - 870°C) \quad (4)
\]

It can be seen from Figure 8B,C that when the D1B1 and D1B1.5 are between 800°C and 900°C, the quartz of blended coals rapidly reduced, and tridymite appears at the same time. In addition, D1B1 and D1B1.5 exhibit mullite at 700°C, while the mullite has a relatively high MP (about 1910°C), which may be due to the high content of Al\(_2\)O\(_3\) in coal B ash (25.7 wt%). After blending, the two kinds of coals caused the content of Al\(_2\)O\(_3\) in the ash of D1B1 and D1B1.5 to remain at a high level (24.86 wt% - 28.83 wt%) and form the new phase mullite (the reaction equation is as follows). Thus, the AFT of the blended coals is improved.

\[
\text{SiO}_2 + \text{Al}_2\text{O}_3 \rightarrow (3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2) \cdot \text{Mullite} \quad (5)
\]

Although coal D and coal S are both Shaanxi bituminous, the difference between the mineral composition of coal D ash and coal S ash is noticeable (Figure 8D). It is mainly because there is a significant difference in the content of the main components of the two coal ashes. The content of CaO in the coal D ash is 11.74 wt%, in the coal S ash is 26.21 wt%, and the difference is 14.47 wt%. Excessive CaO in coal S ash results in the occurrence of low MP minerals such as wollastonite, andradite, and grossularite. In the process of temperature rise, these minerals with lower melting points cause the liquid phase to occur prematurely, and the liquid
FIGURE 8  Amount of phases as a function of temperature, for single coals and blended coals. (A)-D; (B)-D1B1; (C)-D1B1.5; (D)-S;(e)-S1B1; (F)-S1B1.5; (G)-B
When the temperature is between 1200 and 1300°C, coal D ash begins to appear a small amount of liquid phase, and the amount of liquid phase of coal D ash is only 2 wt% at 1300°C. Coal S ash also begins to produce liquid phase at 1200°C. The amount of liquid phase of coal S ash is as high as 82.76 wt% at 1300°C, which is much higher than that of coal D ash. At 1400°C, the liquid phase of coal D ash is 89.54 wt%; however, the coal S ash is all converted into liquid phase, which corresponds to the previous AFT results of single coals.

The content of CaO in coal S ash is much higher than that of coal D ash. Coal B is a typical high silica aluminum coal with a
relatively high CaO content (15.14 wt%). After mixing, the content of Al₂O₃ is significantly higher than that of raw coals. At the same time, in the process of ash melting, the skeleton function of Al₂O₃ plays a leading role. The CaO of blending schemes chemically reacts with other minerals in the process of ash melting to form a large amount of low MP anorthite. With the increase of the addition ratio of coal B, a part of mullite (about 7 wt%) with high MP appears in the coal ash, which improves the AFT of the coal blending scheme S1B1. As can be seen from Figure 8E,F, the complete liquid phase temperature of S1B1 and S1B1.5 is 1500°C, which is 100°C higher than that of coal S ash and is 100°C lower than that of D1B1 and D1B1.5. However, the formation rate of the liquid phase in the range of 1200-1400°C is slightly smaller than the D1B1 and D1B1.5 (Figure 8B,C). Therefore, the high-temperature melting characteristics of S1B1, S1B1.5, and D1B1, D1B1.5 are relatively close. Thus S1B1 and S1B1.5 meet the requirements of the BF injection. By blending with anthracite B, coal S can be applied to BF injection. The ratio of coal S can reach about 50 wt%. From the trend of liquidus change, the liquid phase of single coals is formed between 1200-1300°C. As the ratio of coal B increases, the formation temperature of liquid phase delayed, and the slope of the liquidus change, the trend of total liquid phase temperature melting characteristics of coal D and coal S. From the trend of liquidus change, the trend of total liquid phase temperature of blended coal ash is consistent with the AFT test results, which further proves that coal B can significantly improve the high-temperature ash melting characteristics of coal S.

4 | CONCLUSIONS

In this paper, low MP bituminous mixed with medium-high MP anthracite which from the blast furnace production site in different proportions. By measuring the AFTs of single coals and blended coals, combined with the X-ray powder diffraction and the thermodynamic software FactSage, the influence of mixing ratio on the ash fusion behavior of coal ash and the effect of mineral transformation in coal ash fusion process was investigated. The main results of this work are summarized as follows:

1. Coal B and coal D are all come from the BF production site. And the ST of coal D is 8°C lower than that of the hot blast temperature. By adequately mixing coal B and coal D, it is easy to meet the requirements of pulverized coal injection. However, the high content of CaO in the coal S ash makes the AFT much lower than the hot blast temperature, which leads to the reluctance of the steel industry to inject coal S.

2. With the increase of coal B mass ratio, the content of high-melting eutectic matters (3Al₂O₃·2SiO₂ and tridymite) increases at high temperature, which leads to the increase of AFTs. And by blending with coal B (medium-high MP), the ST of blended coals S/B is higher than the hot blast temperature (1250°C) of the blast furnace; thus, coal S can be applied to blast furnace injection. And the injection ratio of coal S in blended coals can reach about 50%.

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CONFLICT OF INTEREST

The authors declare no competing financial interest.
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