Mineral Distribution in Pulverized Blended Zhundong Coal and Its Influence on Ash Deposition Propensity in a Real Modern Boiler Situation

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**ABSTRACT:** This study aims to explore the mechanism under which ash deposition propensity is improved by coal blending in a real modern boiler situation. In this paper, Zhundong coal (ZD), from northwestern China, known to have a heavy ash deposition problem in boilers, was blended with Jincheng anthracite (JC), which has a high ash fusion temperature (AFT). The density composition of the coal blend, which reflects the mineral distribution in pulverized coals, was found to change during the intergrinding process. The higher rank coal JC was found to be more concentrated in its lower and highest density fractions. The variances in the chemical composition among density fractions in the pulverized coal blend were found greatly narrowed as compared with the parent coals. AFT results indicate that the ash melting behavior in the coal blend (ZD/JC = 50:50) varies with density, which is confirmed by corresponding slag contents calculated with FactSage 7.1. Particle size distributions of the density fractions in ZD, JC, and the coal blend were determined with a laser particle analyzer. The size distribution of ash particles in each density fraction was estimated according to the char morphology, which is deduced from the ash content and coal particle size distribution. Minerals in the lowest density fractions will form ash with a particle size of around 2 μm. Included minerals in the medium density fractions will form ash particles with size related to its ash content, and excluded minerals will undergo slight fragmentation and have a ash particle size similar to the corresponding coal particles. A comprehensive comparison between ash volume, ash particle size, and softening temperature indicates that ash deposition propensity of the coal blend is improved not only because of an apparent increase in AFT but also because of an apparent decrease in the total volume of ash particles possibly arriving on the deposition surface.

1. **INTRODUCTION**

Although new energy sources (e.g., solar energy, wind energy, biomass energy etc.) are developing rapidly in China, coal is still and will continue to be its main energy source. With persistent high speed economic development, the coal reserves near heavily populated areas are nearly depleted. Zhundong coalfield with a reserve of 39 Gt was explored in the Xinjiang province in northwestern China in 2005. It is expected to be its major energy source in the future. As the Xinjiang province is more than 3000 Km away from the relatively developed areas of southeast China, the coal is preferably converted to electricity or gas, which can be transported more economically. The low rank Zhundong coal (ZD) is regarded as a high quality coal for power generation, as it is characterized by its high volatile matter (in general higher than 30 wt %) and low contents of ash (typically at 3–6 wt %) and sulfur (less than 0.5 wt %). However, its severe ash slagging problem in the radiant heat transfer section and fouling problem in the convective heat transfer section observed in power plants, limit its utilization. To mitigate its ash deposition problem, many methods (e.g., leaching, preheating, admixtures etc.) were proposed, in which coal blending is the most economical and thus currently practiced.

Although there are many methods (e.g., thermo-mechanical analysis, pressure-drop technique, deposition probe, etc.) to predict ash deposition propensity in utility boilers burning solid fuels, such as coal, biomass, or coal blends, ash fusion temperature (AFT) is most widely employed in labs and power plants. It is determined by preparing a pyramid with 1 g of ash, which is then heated and observed in a tube furnace under a weakly reducing atmosphere. Four characteristic temperatures, that is, deformation temperature (DT), softening temperature (ST), hemisphere temperature (HT), and flow temperature (FT), can be determined and used to reflect a
basic ash melting characteristics. However, many authors noticed that AFT may not accurately predict coal performance in a real modern boiler situation.\textsuperscript{10,11} The problem with AFT mainly results from the fact that it is related to the bulk chemistry and the bulk AFTs. It fails to address the heterogeneous nature of ash properties from particle to particle in pulverized coal combustion in a real modern boiler.\textsuperscript{12}

A computer-controlled scanning electron microscope (CCSEM) analysis can provide very useful details and insight in the heterogeneity of solid fuels.\textsuperscript{12,13} Three types of particles, that is, pure organic particles, organic particles with included minerals, and excluded minerals are characterized in pulverized coals. CCSEM provides information on the form (included or excluded), chemical composition, and size distribution of minerals. However, there are some limitations and disadvantages when using CCSEM techniques.\textsuperscript{12,13} In order to obtain statistically meaningful and quantitative results, a sufficiently high number of particles have to be analyzed. In addition, particles in the sub-micrometer range (<2 μm) cannot be detected. Furthermore, the mineral information determined with CCSEM on the two-dimensional surface is not the three-dimensional reality. The float-sink method is a simple tool to separate fine coal samples (<0.5 mm) into different density fractions, which is widely used in coal preparation labs. It was also found to be an effective tool to quantitatively characterize the proportions of included and excluded minerals.\textsuperscript{14,15} Zhang et al. used this method to determine an accurate distribution of mineral matter in pulverized coals\textsuperscript{16} and to study the influence of included minerals on the structure and intrinsic reactivity of pulverized coal chars.\textsuperscript{17}

Ash deposition in a real modern boiler situation is complicated. With the application of computational fluid dynamics (CFD) in solid fuel combustion simulations, a panoramic view of ash deposition process has been unfolded.\textsuperscript{15,18,19} When ash particles impact the heat transfer surfaces, only a few particles will deposit on these surfaces. Several transport and deposition mechanisms are responsible for the buildup of the ash deposit on heat transfer surfaces. These mechanisms include thermophoresis, condensation, inertial impaction, and chemical reactions. Inertial impaction is considered as the most important mechanism that contributes significantly to the ash deposition build-up process.\textsuperscript{15,18} The amount of ash particles that may hit a depositing surface can be estimated by particle impaction efficiency. For a certain boiler, factors, such as particle velocity, gas temperature, the diameter of the deposition pipe, and so forth, are set. The particle impaction efficiency mainly depends on the size, density, and the proportion of the liquid phase present in the ash particles. This method was used to study the ash deposition mechanism during the combustion of pulverized ZD.\textsuperscript{20}

Therefore, although AFT is widely used in labs and power plants in predicting ash deposition propensity, its accuracy between prediction and reality needs to improve as it fails to address the heterogeneous nature of minerals from particle to particle. CFD studies indicate that inertial impaction is the most important mechanism that contributes significantly to the ash deposition build-up process, which mainly depends on the size, density, and the proportion of the liquid phase of the ash particles. The present work studies the volume, composition, and size distribution of minerals as well as AFT in ZD and its coal blend, so as to predict ash deposition propensity more accurately than the traditional AFT in a real modern boiler. This mechanism can also be applied to develop a new criterion to predict ash deposition propensity in pulverized coal boilers for all coals.

2. RESULTS AND DISCUSSION

2.1. Effect of Coal Blending on Their Density and Chemical Composition. For pulverized coals, coal particles can be divided into three categories, that is, pure organic particles, organic particles with included minerals, and excluded minerals, which can be reflected by density.\textsuperscript{16} The two parent coals and the coal blend (ZD/JC = 50:50) were separated into density fractions from 1.3 to 2.0 g/cm\textsuperscript{3} with the traditional float-sink method. Their density composition and ash content of the two parent coals are shown in Figure 1.

![Figure 1](https://dx.doi.org/10.1021/acsomega.9b02928)

**Figure 1.** Density composition and ash content of pulverized ZD and JC coal samples.

From Figure 1, the density fractions in pulverized ZD sample can be divided into three types according to their ash content. The three fractions with densities <1.6 g/cm\textsuperscript{3} have ash contents less than 6.15%. They are predominantly organic particles. As their minerals cannot be observed under a microscope or SEM as they are finely distributed in the organic matrix,\textsuperscript{21} they are called organic particles. The two heaviest fractions have ash contents higher than 90.14%, which can be taken as excluded minerals. The 1.6–1.7 g/cm\textsuperscript{3} fraction
represents organic particles with included minerals. According to their type and yield, pulverized ZD coal sample was separated into three density fractions, that is, <1.6, 1.6−1.7, and >1.7 g/cm³ for further study. They are abbreviated as ZD16, ZD1617, and ZD17, respectively.

For the pulverized JC sample, the two fractions with densities <1.6 g/cm³ have ash contents less than 7.86%, representing organic particles. The fraction with a density >2.0 g/cm³ has an ash content of 68.98%, representing the excluded minerals. The three fractions between 1.6 and 2.0 g/cm³ have ash contents between 12.69 and 33.23%, indicating that they are organic particles with included minerals. For further study, the pulverized JC coal sample was separated into four density fractions, that is, <1.6, 1.6−1.7, 1.7−2.0, and >2.0 g/cm³. They are abbreviated as IC16, JC1617, JC1720, and JC20, respectively.

The drastic difference in the density composition between pulverized ZD and JC samples can be attributed to their rank difference. Zhang et al.21 found that with the decrease of rank, the organic part and the mineral matter in a coal tend to be loosely intertwined, resulting in higher separation of the organic part and the inorganic part during the grinding process.

The density composition and corresponding ash contents for the coal blend (ZD/JC = 50:50) are shown in Figure 2.

![Figure 2](https://example.com/figure2.png)

Figure 2. Density composition and their ash contents of the coal blend (ZD/JC = 50:50).

For Figure 2, it can be found that for the coal blend, its density distribution looks more like ZD sample, but the corresponding ash content distribution more like JC sample. For further study, it was separated into four density fractions, that is, <1.6, 1.6−1.7, 1.7−1.8, and >1.8 g/cm³ with ash contents <9.79, 26.76, 67.99, and 82.72%, respectively. They are abbreviated as B16, B1617, B1718, and B18, respectively.

Interesting phenomenon was found when the change of volatile contents with density was compared with their calculated weight-averaged results in the coal blend.21 It may look strange that CaO is concentrated in the organic part, representing organic particles with included minerals. According to their type and yield, pulverized ZD coal sample was separated into three density fractions, that is, <1.6, 1.6−1.7, and >1.7 g/cm³ for further study. They are abbreviated as ZD16, ZD1617, and ZD17, respectively.

For Figure 2, it can be found that for the coal blend, its density distribution looks more like ZD sample, but the corresponding ash content distribution more like JC sample. For further study, it was separated into four density fractions, that is, <1.6, 1.6−1.7, 1.7−1.8, and >1.8 g/cm³ with ash contents <9.79, 26.76, 67.99, and 82.72%, respectively. They are abbreviated as B16, B1617, B1718, and B18, respectively.

The weight-averaged results were calculated by multiplying the volatile content of each density fraction with corresponding density content in the parent coals from Figure 1, and with their blending ratio 50:50 in the coal blend, assuming no change in the density composition during the intergrinding process. From Figure 3, it can be found that the practical volatile contents in the two <1.5 g/cm³ fractions are both much lower than the calculated weight-averaged results. As the parent coal ZD has a much higher content of volatile matter than the parent coal JC, it can be deduced that JC is more concentrated in <1.5 g/cm³ fractions in the coal blend. In contrast, the two density fractions between 1.5 and 1.7 g/cm³, their volatile contents are higher than the calculated results, which imply that ZD is more concentrated in these medium density fractions in the coal blend. This phenomenon implies that the density composition or mineral matter distribution was changed during the intergrinding process of coal blends as compared with single coals. As compared with JC, ZD has a much lower Hardgrove grindability index (HGI) value. When they are ground together, ZD acts as a grinding aid to accelerate the separation of the mineral matter from organic-minerals intertwined particles in JC. Thus, the mineral matter in JC will be more thoroughly separated from the organic matter, which explains the change of density composition of the coal blend.21

The chemical compositions of the density fractions of ZD, JC, and the coal blend (ZD/JC = 50:50) were analyzed with X-ray fluorescence (XRF). The basic to acid (B/A) ratios were also calculated as they can reflect ash fusion tendency. The results are shown in Table 1.

From Table 1, it can be found that the chemical compositions are highly different among their density fractions in all the pulverized coals. For the pulverized ZD sample, CaO, MgO, and SO₃ are highly concentrated in <1.6 g/cm³, the lowest density fraction. CaO attains to surprisingly 28.03%, in contrast to only 4% in the other two density fractions. It may look strange that CaO is concentrated in the organic fraction. X-ray diffraction (XRD) results indicated that there are high contents of calcite and anhydrate in its ash prepared under 450 °C.22 The maceral composition of coal can be divided into vitrinite, inertrinite, exinite, and mineral. Mineral matter tends to be concentrated in inertrinite, as inertrinite is highly porous as compared with other organic maceral constituents. Usually, coal in China contains the highest amount of vitrinite and then inertrinite and exinite.23 In contrast, ZD consists of 80% inertrinite.24 Pores in the inertrinite of ZD provide the best place for the precipitation of CaCO₃.

For the other pulverized parent coal JC, a similar chemical composition can be found in the three density fractions other
than >2.0 g/cm³, the highest density fraction. The content of Fe₂O₃ in the highest density fraction attains 17.28%, in contrast to around 5% in the other three density fractions. Petrographic observation indicates that pyrite is concentrated in the highest density fraction.

As compared with parent coal ZD and JC, the variations in the ash chemical compositions among the density fractions of the coal blend are greatly decreased. For sample ZD, the variances of SiO₂ and CaO among the density fractions are 34 and 24%, respectively. For sample JC, the variances of Al₂O₃ and Fe₂O₃ are both close to 12%. For the coal blend, the variances of SiO₂, CaO, Al₂O₃, and Fe₂O₃ are narrowed to 10, 6.5, 7.5, and 2.6%, respectively. Apparently, this phenomena result from the change of density composition of the coal blend.

2.2. Ash Melting Behaviors of Blended Coals and the Density Fractions of the Coal Blend. 2.2.1. Influence of Blending Ratio on the AFTs of Coal Blends. The influence of the blending ratio of ZD to JC on the AFTs of blended coals is shown in Figure 4.

From Figure 4, it can be found that with the increase of JC proportion, the coal blend has higher AFT, which implies that ash deposition performance of blend coals will be improved as compared with the parent coal ZD. ZD has an ST only 1180 °C. According to empirical knowledge, it will have a serious ash deposition problem. When blended with JC, ST of the coal blend (ZD/JC = 50:50) is increased to 1280 °C. Thus, an apparent improvement in deposition can be expected. It should be noted that the increase in AFT is not in a linear relationship with a blending ratio, which was also observed by many other authors. AFT’s are nonadditive for coal blends, as AFT is determined by the chemical composition of the ash in coal blends, rather than by the blending ratio.

2.2.2. Ash Melting Behavior of the Density Fractions of the Coal Blend. In this part, the ash melting behaviors of the density fractions in the coal blend (ZD/JC = 50:50) were studied with AFT and FactSage. The AFTs of the density fractions of the coal blend are shown in Figure 5.

![Figure 5. AFTs of the density fractions in the coal blend (ZD/JC = 50:50).](https://dx.doi.org/10.1021/acsomega.9b02928)

In Figure 5, it is shown that the AFTs of the coal blend were differentiated according to their density. ST, the softening temperature, is also used here as an index to explain the changes. The <1.6 g/cm³ fraction, representing organic particles with little mineral matter, has the highest ST, 1300 °C. With the increase of density, its ST is decreasing. A sharp decrease of 40 °C can be found from <1.6 g/cm³ fraction to 1.6–1.7 g/cm³. The >1.8 g/cm³ fraction, representing the excluded minerals, has an ST of 1250 °C. The range of ST among the different density fractions in the coal blend is 50 °C.

The slag contents, or liquid contents, in the melt of the four density fractions of the coal blend between 900 and 1500 °C at equilibrium were calculated with FactSage 7.1. The chemical

| sample | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO | SO₂ | TiO₂ | K₂O | Na₂O | B/A |
|--------|------|-------|-------|-----|-----|-----|------|-----|------|-----|
| ZD16   | 30.40| 12.54 | 6.77  | 28.03| 8.51| 8.32| 0.69 | 0.35| 1.14 | 1.02|
| ZD1617 | 63.15| 13.28 | 6.82  | 4.93 | 1.85| 2.91| 0.66 | 1.91| 3.07 | 0.24|
| ZD17   | 64.79| 12.93 | 7.36  | 3.54 | 1.60| 2.82| 0.67 | 1.94| 3.55 | 0.23|
| JC16   | 48.94| 37.53 | 4.58  | 3.29 | 0.65| 0.64| 1.34 | 0.96| 0.43 | 0.11|
| JC1617 | 49.76| 36.86 | 5.41  | 2.71 | 0.50| 0.50| 1.22 | 1.03| 0.61 | 0.12|
| JC1720 | 50.68| 34.99 | 5.41  | 2.96 | 0.53| 0.65| 1.16 | 1.12| 0.50 | 0.12|
| JC20   | 45.81| 25.78 | 17.28 | 4.25 | 0.42| 3.51| 1.03 | 0.82| 0.44 | 0.32|
| B16    | 42.98| 27.50 | 5.61  | 10.66| 3.10| 3.19| 1.02 | 1.01| 2.94 | 0.33|
| B1617  | 55.38| 24.12 | 7.77  | 4.46 | 1.19| 2.19| 0.92 | 1.37| 1.72 | 0.21|
| B1718  | 57.81| 20.84 | 7.41  | 4.08 | 1.08| 2.72| 0.84 | 1.48| 1.79 | 0.20|
| B18    | 58.37| 20.06 | 8.21  | 3.57 | 0.99| 3.19| 0.83 | 1.53| 1.88 | 0.20|

![Figure 4. Influence of blending ratio on AFTs of the coal blends.](https://dx.doi.org/10.1021/acsomega.9b02928)
composition in Table 4 was input into the model for multiphase equilibrium prediction. The results are shown in Figure 6.

![Figure 6. Liquid contents in the melt of the four density fractions of the coal blend between 900 and 1500 °C.](image)

From Figure 6, it can be found that the ash melting behavior, reflected by liquid content, of each density fraction in the coal blend was differentiated too. The <1.6 g/cm³ fraction has a much lower liquid content under equal temperature or a much higher temperature at equal liquid content. The other three density fractions have similar liquid contents with a 1.6–1.7 g/cm³ fraction a little bit more difficult to melt. These results coincide well with the AFT results shown in Figure 5, which imply that the difference in ash melting behavior of the density fractions of the coal blend results from their change in the chemical composition.

It should be noted that there is a slight difference between the liquid content calculated with FactSage and the AFT determined. In the calculation, all major components determined with XRF, that is, SiO₂, Al₂O₃, Fe₂O₃, CaO, MgO, SO₃, TiO₂, Na₂O, and K₂O, have been involved. Minor constituents, such as Cl, P₂O₅, BaO, MnO, and so forth, were neglected, so as not to be involved in a complicated situation.

2.3. Size Distributions of Coal Particles in Different Density Fractions of the Parent Coals and the Coal Blend. In a real modern boiler situation, deposition is influenced by the ash particle size besides other factors, which will be discussed in the next part. In this part, the size distributions of coal particles in the density fractions of ZD, JC, and their coal blend (ZD/JC = 50:50) were analyzed with a laser particle analyzer. The results are shown in Figure 7.

From Figure 6, it can be found that the ash melting behavior, reflected by liquid content, of each density fraction in the coal blend was differentiated too. The <1.6 g/cm³ fraction has a much lower liquid content under equal temperature or a much higher temperature at equal liquid content. The other three density fractions have similar liquid contents with a 1.6–1.7 g/cm³ fraction a little bit more difficult to melt. These results coincide well with the AFT results shown in Figure 5, which imply that the difference in ash melting behavior of the density fractions of the coal blend results from their change in the chemical composition.

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For the pulverized coal blend samples shown in Figure 7, the coal particle size distribution for each density fraction is greatly changed as compared with the parent ZD samples. Coal particles in the <1.6 g/cm³ (organic particles) and >1.8 g/cm³ (excluded minerals) fractions are much coarser than the other two medium density fractions (with included minerals). Just as-discussed above, very fine ash particles will be formed from a >1.6 g/cm³ fraction. The ash formed from a >1.8 g/cm³ fraction will have a similar particle size as its coal fraction, assuming a full coalescence. As to the 1.6–1.7 g/cm³ fractions, each coal particle will shrink into smaller ash particles during burnout, as they have ash content only 26.76 and 67.99%, respectively, even assuming a full coalescence.

2.4. Comprehensive Discussion on the Influence of the Mineral Distribution in Coal Blend on Ash Deposition Propensity in Boilers. Ash deposition in a real boiler situation is complicated. Numerous ash deposition models were proposed. It is now widely agreed that the ash deposition rate is determined by the sum of four independent rates, inertial impaction, thermophoresis, condensation, and chemical reaction. Inertial impaction is the dominant deposition mechanism in most cases. Because of the influence of the gas flow, not all the particles carried by the gas stream...
will impact on the depositing surface. The impaction efficiency is dependent on the particle size, density, sticking ability, and the aerodynamics of the gas. Given a certain boiler, gas aerodynamics is fixed. Large particles with high density show much higher values of arrival velocity than small particles with low density. Furthermore, not all the arriving particles that reach a deposition surface will stick to the surface. The stickiness of the ash particles plays a critical role in the formation of ash deposit. ST in the four characteristic AFT temperatures of an ash is recognized as the temperature at which the ash particle has a high tendency to stick to the deposition surface.\textsuperscript{11} Therefore, ash deposition is the result of the combined effect of the volume, particle size, and ST of the incoming ash.

In this study, the ash volume, estimated average particle diameter, and ST of parent coal ZD and the coal blend are summarized in Table 2.

| Sample       | Density Fraction (kg/cm\(^3\)) | Ash Content in Density Fraction (wt %) | Ash Volume in Coal (wt %) | Estimated Average Ash Particle Diameter (\(\mu\)m) | ST (°C) |
|--------------|---------------------------------|----------------------------------------|---------------------------|-----------------------------------------------|--------|
| ZD           | <1.6                            | 3.86                                   | 3.40                      | 2                                             | 1240   |
|              | 1.6−1.7                         | 72.07                                  | 2.85                      | 15                                            | 1190   |
|              | >1.7                            | 91.65                                  | 7.49                      | 20                                            | 1180   |
| Coal Blend   | <1.6                            | 7.18                                   | 5.91                      | 2                                             | 1300   |
|              | 1.6−1.7                         | 26.76                                  | 1.58                      | 6                                             | 1260   |
|              | 1.7−1.8                         | 67.99                                  | 3.87                      | 10                                            | 1250   |
|              | >1.8                            | 82.72                                  | 4.95                      | 46                                            | 1250   |

From Table 2, it can be found that when ZD is blended with JC, AFTs of all the density fractions in the coal blend are increased 60−70 °C, which will greatly decrease the sticking ability of ash particles on the whole. It is the main effect of coal blending of ZD with JC.

Besides AFT, distributions of the ash and ash particle size in density fractions are also changed, which determines the arriving volume of ash particles on the deposition surface. The volume of the finest ash particles around 2 \(\mu\)m from the organic coal particles is increased from 3.40% in ZD to 5.91% in the coal blend. Coal particles with included minerals in the coal blend are estimated to form ash particles with an average size less than 10 \(\mu\)m, in contrast to 15 \(\mu\)m in ZD. Particles with a diameter less than 10 \(\mu\)m will flow with the gas stream and has little contribution to ash deposition.\textsuperscript{18} Although the size of excluded mineral particles in the coal blend will form larger ash particles than ZD, its volume is decreased from 7.49 to 4.95%. On the whole, the total possible arriving volume of ash particles on the deposition surface will be decreased from 10.14% in ZD to 4.95% in the coal blend.

Thus, when low-rank ZD coal with a heavy ash deposition problem is blended with anthracite JC with high AFT, ash deposition propensity of the blended coal is improved not only because of an apparent increase in AFT but also because of an apparent decrease in the total volume of possible arriving ash particles on the deposition surface.

3. CONCLUSIONS

The present work systematically studied the influence of coal blending of low rank ZD with a heavy ash deposition problem with anthracite Jincheng coal with high AFT on the state, chemical composition, ash melting behavior, and particle size distribution of minerals in the coal blend. Mineral distribution reflected with the density composition was found changed in the coal blend during the intergrinding process. JC is more concentrated in the lowest and highest density fractions, which is attributed to its higher rank as compared with ZD. The variances in the chemical composition among density fractions in the coal blend were found highly narrowed as compared...
with its two parent coals. AFT was found differentiated with density, which is well related to its chemical composition calculated with FactSage.

Particle size distribution of the density fractions in ZD, JC, and coal blend (ZD/JC = 50:50) was determined with a laser particle analyzer. The size distribution of ash particles was estimated according to the char morphology, which is deduced from the state of minerals in pulverized coals. Minerals in the lowest density fractions will form ash with an average particle size of around 2 μm. Included minerals in the medium density fractions will form ash particles with size related to its ash content. Excluded minerals will undergo slight fragmentation and have a ash particle size similar to corresponding coal particles.

A comprehensive comparison indicates that when parent coal ZD is blended with JC, ash deposition propensity of the coal blend is improved not only because of an apparent increase in AFT but also because of an apparent decrease in the total volume of possibly arriving ash particles on the deposition surface.

This work provided a deep understanding of ash deposition propensity of pulverized blended coal as well as the pulverized single coal in real modern boilers.

4. EXPERIMENTAL SECTION

4.1. Parent Coals. ZD was sampled in the ZD field in the Xingjiang province in northwestern China. Jincheng anthracite (JC) from the Shanxi province in China was chosen for the preparation of coal blends for its high AFTs. Proximate and ultimate analyses of the two parent coals are shown in Table 3. Their AFTs and chemical composition are shown in Tables 4 and 5, respectively.

Table 3. Proximate Analysis and Ultimate Analysis of Zhundong and Jincheng Coals

| sample | M_d (wt %) | A_d (wt %) | V_d (wt %) | FC_d (wt %) | C_d (wt %) | H_d (wt %) | N_d (wt %) | O_d (wt %) | S_d (wt %) |
|--------|------------|------------|------------|-------------|------------|------------|------------|------------|------------|
| ZD     | 9.05       | 14.15      | 25.54      | 51.26       | 80.15      | 3.38       | 0.73       | 14.95      | 0.73       |
| JC     | 3.66       | 16.91      | 6.31       | 73.12       | 88.60      | 3.24       | 1.11       | 3.94       | 3.11       |

“By difference.

4.2. Preparation of Coal Blends and Their Density-Separated Fractions. The two parent coals were crushed into lumps of less than 3 mm and dried, respectively. They were then mixed in proportions with weight ratios of ZD/JC at 100:0, 70:30, 50:50, 30:70, and 0:100, respectively.

There may be two blending strategies for coal blending, blending before or after coal grinding. Most authors chose to grind parent coals separately and blend them after grinding, as it is easy to operate in labs. However, such technology is scarcely used in power plants, as it would be far more complicated and expensive. In this study, to simulate a practical coal preparation process in power plants, blend-before-grinding technology was chosen.

The parent coals were weighed according to the experimental design. They were then mixed and ground. The grounding time was regulated according to specific samples so as to give similar fineness to an industrial fineness control strategy, which is to pass a 125 μm mes sieve with a residue around 10%. It should be noted that no part of the samples was discarded.

All the pulverized coal samples were separated into density fractions from 1.3 to 2.0 g/cm³ with the traditional float-sink test method as follows. Each sample (60 g) was placed in four 250 mL plastic centrifuge tubes and 100 mL of the heavy liquid was added to each tube. The tubes were shaken by hand to ensure thorough dispersion of the sample particles in the heavy liquid. Each sample was then centrifuged at 3000 rpm for 10 min to reach complete float-sink separation. The solids in the upper section of the tubes were transferred to be filtered and then dried at 105 °C so as to get the light density fraction of the sample. The heavy part in the bottom was added with heavier liquids to repeat the former procedure to separate the next density fraction. Mixtures of benzene/carbon tetra chloride and carbon tetrachloride/bromoform provided densities in the range from 1.3 to 2.0 g/cm³.

4.3. Ash Fusion Behavior Study. Ash fusion behavior was studied with AFT and FactSage calculation. AFTs were measured using an AFT analyzer under a weakly reducing atmosphere according to Chinese standard GB/T 219-2008. The weakly reducing atmosphere was produced by placing some powered anthracite around ash pyramids in the furnace. The four characteristic temperatures, namely, DT, ST, HT, and FT, respectively, were determined by the change of ash cones during heating from ambient temperature to 900 °C at a rate of 15 °C/min and then to 1600 °C at a rate of 5 °C/min.

FactSage 7.1 was used to calculate the slag content of coal ash at different temperatures under a reducing atmosphere. The reducing atmosphere of 60% CO₂ and 40% CO was employed in the FactSage calculation. The temperatures were set from 900 to 1500 °C at intervals of 50 °C. The FactOxide and solid solution databases in the FactSage database were selected for calculation.

Table 4. AFTs of Parent Coal Zhundong and Jincheng

| sample | DT (°C) | ST (°C) | HT (°C) | FT (°C) |
|--------|---------|---------|---------|---------|
| ZD     | 1140    | 1160    | 1170    | 1180    |
| JC     | 1530    | 1550    | 1560    | 1580    |

4.2. Preparation of Coal Blends and Their Density-Separated Fractions. The two parent coals were crushed into lumps of less than 3 mm and dried, respectively. They were then mixed in proportions with weight ratios of ZD/JC at 100:0, 70:30, 50:50, 30:70, and 0:100, respectively.

There may be two blending strategies for coal blending, blending before or after coal grinding. Most authors chose to grind parent coals separately and blend them after grinding, as...
4.4. Analysis Methods. XRF spectrometry and laser particle size analyzer were employed to obtain further information about the pulverized coal samples.

To analyze the ash chemical composition, the coal samples were heated in a muffle furnace at 815 °C for 1 h under air atmosphere according to Chinese standard GB/T1574-2011. The ash samples were analyzed with an X-ray fluorescence spectrometry (S8 Tiger, Bruker, Germany).

The particle size distribution of the pulverized coal samples were analyzed with a laser particle analyzer (Beckman Coulter LS100Q, USA), which is based on the principle of laser ensemble light scattering. Each sample (0.5 g) was mixed with distilled water with a few drops of alcohol to prevent agglomeration. It was then placed in an ultrasonic bath for 3 min to destroy agglomeration before the particle size analysis was completed.

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Notes
The authors declare no competing financial interest.

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