SLAGGING PREDICTION AND STRATEGY STUDY ON CIRCULATING FLUIDIZED BED GASIFICATION OF HIGH SODIUM COAL

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Abstract –Zhundong coalfield in Xinjiang is the largest integrated coal basin newly found in China. The predicted coal reserve of Zhundong is about 164 Gt, and the reasonable utilization of these huge coal resource is very important for China. Circulating fluidized bed gasification is a promising technology for high efficient and clean utilization of coal. However, the sodium content in Zhundong coal is very high, which may induce severe problems such as fouling and slagging, influencing the long-term stable operation. In this study, phase diagram analysis was used to predict the slagging tendency of two Zhundong coals and an Indonesia coal. The normalized ash compositions of Indonesia coal and Mulei coal are located near the liquidus projection zone of ternary phase diagram Na_2O-SiO_2-Al_2O_3, indicating great slagging tendency. Whereas WCW coal ash shows less slagging tendency, which is coherent with our previous experimental results. The results indicate that if coal ash is located within or near the liquidus projection zones, anti-slagging strategy would be considered for CFB gasification. In addition, the phase diagram could also provide some useful information on how to optimize utilization of easily slagging coals, such as selection of bed material or blending coal.

INTRODUCTION

Coal will continue to be the main energy resources in many countries worldwide, especially in China. Zhundong coalfield is a newly found coal basin, which is located in Xinjiang of China. The predicted coal reserve of Zhundong is about 164 Gt[1]. Due to the huge reserve, high reactivity and low environment load, the utilization of Zhundong coal has widely investigated. However, slagging, corrosion and contamination problems occur during the combustion of Zhundong coal in traditional power plant, which is mainly attributed to the high sodium content in Zhundong coal ash. Therefore, it is urgent to develop new technology to meet the environmental requirements and satisfy the steadily increasing demand in clean energy.

Circulating fluidized bed (CFB) gasification is a well-established coal conversion technology. Due to the moderate operating temperature (850-1000 ^{o}C), high efficient mass and heat transfer, and satisfied liquid-like gas-solid mixture, the research on CFB gasification has attracted widely interest. However, there are also some problems in industrial practice. One of the primary problems is slagging induced by bed material, operation conditions, and fuel characteristics, and so on. According to literature, many research work has been published on line to understand the slagging mechanisms and provide solving strategies. Even so, great challenges are also associated with CFB gasification of high sodium coal, especially in industrial practice.

Institute of Engineering Thermophysics (IET) has developed CFB gasification technology and realized industrial application [2]. Till now, 28 sets industrial CFB gasifiers (with fuel gas production capacity of 15000-60000 Nm^3/h) have been completed. In order study the fuel flexibility and expand the scope of industrial application coals, some research work has been done on utilization of high sodium Zhundong coal [2-4]. Significant experimental and thermodynamic calculation systems were established to evaluate the operational safety of high sodium Zhundong coal and provide strategies to improve the utilization of this huge coal resources via CFB gasification [4].

Phase diagram is a type of figure used to show status (pressure, temperature, composition, etc.) at which thermodynamically stable phases exist or coexist at equilibrium, which is widely used in physical chemistry, engineering, mineralogy, materials science and so on. In these years, phase diagram calculation is gradually used to predict the coal ash properties during thermal conversion process of special coal types.

This paper presents an overview of our recent research on high sodium coal gasification as well as its anti-slagging mechanisms and meaningful strategies. The research focus lies on the utilization of high sodium Zhundong coals. Ternary phase diagram of Na_2O-SiO_2-Al_2O_3 was calculated and used to predict the slagging tendency of high sodium coals, and anti-slagging strategies were proposed combined with the industrial CFB blended coal gasification.

FUEL CHARACTERISTICS

In this study, two high sodium Zhundong coals were studied comprehensively, and a high sodium Indonesia coal was selected as a comparative sample. Table 1 shows the fuel characteristics. The proximate and ultimate analysis results were obtained according to Chinese standards of GB/T212-2008, GB/T 214-2007, GB/T 476-2008 and GB/T 19227-2008. The net calorific value was obtained according to Chinese standards of GB/T 213-2008. The ash composition analysis results were obtained according to ASTM standard E1755-01 and the sodium content is obtained by sequential chemical extraction. Mulei (ML) coal and Wucaiwan (WCW) coal were obtained from Zhundong of Xinjiang. Indonesia coal (ID) was obtained from Indonesia. These coals are typical high sodium coals. The Na_2O content in coal ash of ML, WCW and ID is 7.86%, 8.53% and 8.10%, respectively. The ash fusion properties show that the deformation temperature, softening temperature, hemispherical temperature and flowing temperature of each studied coal are very close. The deformation temperature of WCW is 1320 °C, whereas the deformation temperatures of ML and ID are quite low.

Table 2 Properties of the used coals

Coal	ML	WCW	ID
Proximate analysis (wt.%, d)			
A_d	9.55	5.96	5.29
V_d	30.08	40.37	44.61
FC_d	60.38	53.66	50.1
V_{daf}	33.25	42.93	47.1
Ultimate analysis (wt.%, d)			
C	71.73	64.5	70.6
H	3.54	2.02	4.68
N	0.72	0.82	1.28
O	13.29	26.23	17.82
S_t	1.17	0.47	0.33
Cl	0.704	0.123	0.028
$Q_{net,ar}$ (MJ/kg)	21.99	16.69	20.30
Ash fusion temperatures (°C)			
DT	1030	1320	1080
ST	1060	1320	1100
HT	1080	1330	1100
FT	1100	1340	1120
Ash compositions (wt.%)			
SiO_2	23.28	17.24	40.92
Al_2O_3	9.26	11.90	16.23
Fe_2O_3	18.26	5.76	4.93
CaO	10.95	28.74	9.68
MgO	2.72	5.34	4.02
TiO_2	0.54	0.60	0.98
SO_3	18.58	19.58	9.46
P_2O_5	0.54	0.05	0.28
K_2O	0.86	0.38	1.16
Na_2O	7.86	8.53	8.10

d, dry basis. FC_d and O_d are obtained by difference. DT, deformation temperature; ST, softening temperature; HT, Hemispherical temperature; FT, flowing temperature.

PHASE DIAGRAM CALCULATION

The thermodynamic software FactSage is used to calculate the phase diagram of ternary phase diagram Na_2O-SiO_2-Al_2O_3. The calculation method is based on the principle of Gibbs free energy minimization, which is widely used in fields of ceramics technology and metallurgical technology. In recently years, phase diagram calculation is used to predict the coal ash properties during thermal conversion process.

In this study, Na_2O-SiO_2-Al_2O_3 ternary phase diagram was used to predict the slagging tendency of high sodium coals according to its ash compositions. The oxides used in the calculation are selected from FToxide database. The absolute pressure used for calculation is kept at 1 atm. The calculation temperature is 900 °C.

RESULTS AND DISCUSSION

Fig.1 shows the 900 °C calculation result of ternary phase diagram Na_2O-SiO_2-Al_2O_3. The normalized ternary ash compositions of Na_2O, SiO_2 and Al_2O_3 for the studied coals were marked on the appropriate position of the phase diagram. As shown in Fig.1, ML coal ash is located in the zone of nepheline and WCW coal ash is located in the zone of carnegieite. Carnegietite and nepheline are sodium-containing polymorphs with the chemical formula of $NaAlSiO_4$ and with melting point of about 1550 °C. The formation reaction of $NaAlSiO_4$ is given in Eq.(1).

$$Na_2O+Al_2O_3\cdot 2SiO_2\cdot 2H_2O \rightarrow 2NaAlSiO_4+2H_2O \quad (1)$$

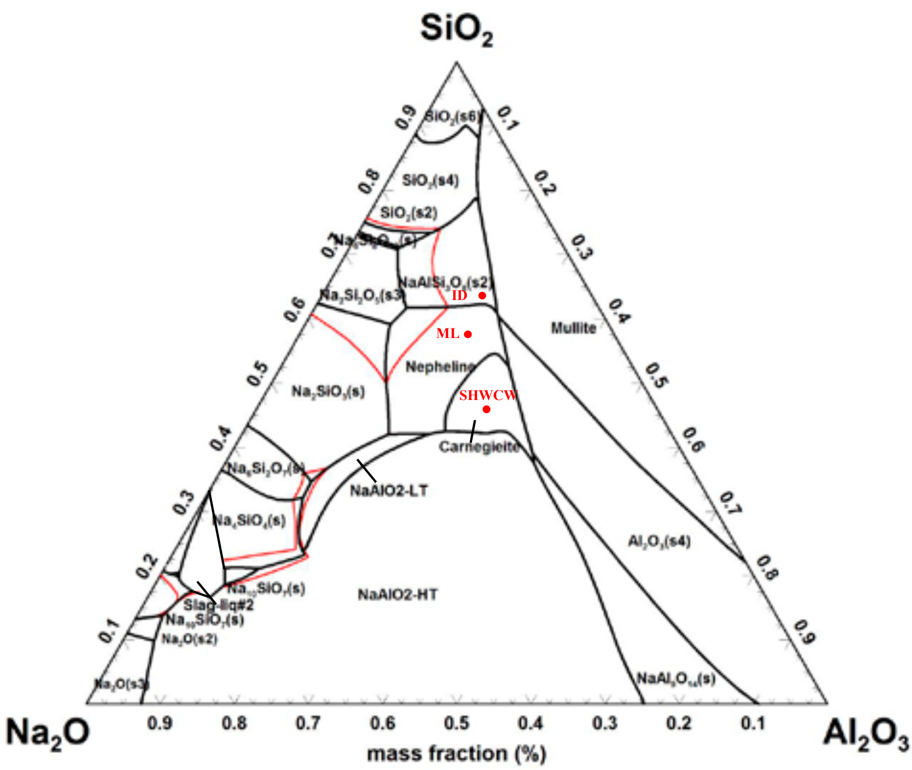

Fig.1 Ternary phase diagram of Na_2O-SiO_2-Al_2O_3

Fig.1 also shows the liquidus projection of ternary phase diagram Na_2O-SiO_2-Al_2O_3 at 900 °C, and the results are plotted with red lines. Although nepheline is a high melting point sodium-containing compound, some part of nepheline zone is included in the low temperature eutectic zones. That means slagging and defluidization may occur during CFB utilization process. Zhang et al. [3] investigated the transformation properties of sodium during ashing of high sodium ML coal using muffle furnace. The results show that $NaAlSi_3O_8$ (albite) shows up when the ashing temperature is set at 700 °C, and $NaAlSiO_4$ shows up when the ashing temperature increases to 800 °C. Slagging is observed for residual at ashing temperature of 800 °C, and the phenomenon is more obvious at higher temperatures. Combined with the analysis of ternary phase diagram Na_2O-SiO_2-Al_2O_3, the possible explanation of the slagging for ML coal may be the formation of low temperature eutectic. The ash composition of ML coal is located in the zone of nepheline and that is near the liquidus projection zone, indicating great slagging tendency. The analysis result of ternary phase diagram Na_2O-SiO_2-Al_2O_3 is agree with the experimental results as reported by literature [3]. Therefore, it is expected that ML coal may occur slagging during CFB gasification.

Although WCW coal is also a high sodium coal, the ash composition of WCW is located in the zone of carnegieite and keeps far away from the liquidus projection zone as shown in Fig.1. These results indicate little slagging possibility of WCW coal during gasification process. The thermodynamic prediction of ternary phase diagram Na_2O-SiO_2-Al_2O_3 is verified by Zhang et al. [4] using a novel design of fluidized bed gasifier. WCW coal is used as feedstock to study the influence of gasification temperature on sodium behavior, and the results show that no slagging phenomena occur when gasification temperature increases from 850 °C to 1050 °C. The primary reason of no slagging is due to the formation of high melting point sodium containing compound of $NaAlSiO_4$. The experimental results are in accordance with the ternary phase diagram prediction. The experimental method and analysis method of ternary phase diagram are essential to predict the slagging tendency of high sodium coal and helpful to select reasonable coal for industrial application.

Bartels et al. [5] reviewed the research status of slagging mechanisms, monitoring method and counteraction strategies. The proposed methods to alleviate slagging problem include: changing bed materials, adding additive, promoting process measurements and improving reactor design. These strategies could be divided as internal factor controlled method and external controlled method. The internal factor controlled method is to alleviate or inhibit slagging via chemical reaction, which is the essence to solve the slagging problem of CFB during high sodium coal gasification. The chemical reaction controlled strategy is to change the ash behavior and this could be achieved by alternative bed material, adding additive or blending coal.

Based on our recent experimental research results and industrial application of CFB gasification, some useful strategies could be obtained in this study. The strategies include slagging tendency prediction via measurements and calculation, select suitable bed material, and adding additive or blending other coal. These strategies could be improved or optimized via phase diagram analysis, which we want to highlight in this study with the aim to illustrate the practical application of phase diagram in fields of high sodium coal utilization.

IET has established cooperative relationship with Jiannan Huangtai Gas Furnace Co., Ltd. 5 sets of 40000 Nm^3/h CFB coal gasification systems for production of clean fuel gas were built in Guangxi, in May 2015. The produced fuel gas was used to provide heat for alumina calcination. Zhang et al. [2] studied the blended coal gasification of ID high sodium coal and a Chinese coal. As shown in Fig.1, the ash composition of ID coal is located in the zone of $NaAlSiO_8$, which is a low melting point sodium-containing compound. Moreover, the position of ID coal ash is near the liquidus projection zone, indicating great slagging tendency. The ash fusion properties of ID coal show that the deformation temperature is quite low, about 1080 °C. In addition, the difference of the four ash fusion temperatures is very close. If ID coal is solely used as feedstock during industrial CFB gasification, slagging may occur. In order to achieve long-term stable operation, a high ash content Chinese coal with normalized ash composition far away from the liquidus projection zone was selected as the blending coal. The used Chinese coal is located in mullite zone of ternary phase diagram Na_2O-SiO_2-Al_2O_3, and the blended coal is also located in mullite zone. Mullite is a high melting point substance. The ternary phase diagram analysis indicates that slagging could be greatly alleviated by blending coal. The industrial experiment of CFB blended coal gasification was conducted in the 40000 Nm^3/h CFB gasification system. By adding another coal to the high sodium coal gasification system greatly changed the sodium transformation behavior, and long-term stable operation was achieved in the industrial CFB gasifier. The industrial experimental result is agree with the ternary phase diagram prediction, indicating the practical application of phase diagram analysis.

The above results indicate that phase diagram is a useful investigation method to predict the slagging tendency of high sodium coal, which also can provide some useful information on how to optimize utilization of easily slagging coal. In practice, local availabilities and economic factors are important to select gasification coal. For easily slagging coals, phase diagram could be used firstly to predict the slagging tendency and identification the possible phase state of the specific coal ash. Subsequently, phase diagram could also be used to select strategy, and this method is helpful to select bed material, additive or blending coal.

CONCLUSION

CFB gasification is a useful coal conversion technology. However, slagging phenomena may occur, especially when high sodium coal is used as feedstock. In this study, ternary phase diagram of Na_2O-SiO_2-Al_2O_3 was used to predict the slagging tendency of two high sodium Zhundong coals and a high sodium Indonesia coal. The normalized ash composition of Mulei coal is located in the zone of nepheline and shows great slagging tendency. The normalized ash composition of Wucaiwan is located in the zone of carnegieite and keeps far away from the liquidus projection zone, with rarely little slagging tendency. The phase diagram prediction is agree with the experimental results of our previous experimental investigations. The results indicate that if coal ash is located within or near the liquidus projection zones, anti-slagging strategy would be considered for CFB gasification.

Ternary phase diagram analysis of Na_2O-SiO_2-Al_2O_3 is concluded to be effective in terms of slagging prediction in case of high sodium coal gasification. In addition, the phase diagram could provide some useful information on how to optimize utilization of easily slagging coals.

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