Modeling Study of the Slag Behaviors Based on Temperature–Time–Viscosity of Crystalline Slag in an Entrained-Flow Gasifier

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ABSTRACT: The crystal growth process has an important influence on the viscosity of the slag, which affects the characteristics of the slag layer on the wall of the gasifier. The slag flow and heat transfer model based on temperature–time–viscosity of crystalline slag were established, to predict the slag behaviors and protect gasifier. The results showed the overall viscosity of the slag after considering the residence time effect was higher than that when using the measured viscosity–temperature curve value. The liquid slag thickness, solid slag thickness, and residence time increased after the slag viscosity amendment, while the slag flow velocity and heat flux density decreased. Moreover, several types of crystallized slag were constructed to study the effects of crystal morphology and degree of crystallization difficulty on slag behaviors. The result indicated that the difficulty and crystal morphology of the slag crystallization cannot be ignored when using crystallized slag in gasification.

1. INTRODUCTION

Coal gasification is a key supporting technology in the field of coal chemical industry, and entrained-flow gasification is one of the most widely used technologies because of the high efficiency and extensive of coal species.1–3 In a membrane wall entrained-flow gasification, the ash particles and unreacted residual carbon particles from the gasification chamber deposit on the wall and form a slag layer. One part of the slag layer is composed of the solid slag adhered to the wall, and the other part is composed of the flowing liquid slag. The slag layer with high thermal resistance prolongs the life of refractory materials, and the stable flow slag ensures the high efficiency of slag discharge.3 Therefore, understanding the slag layer behaviors are critical for the safety and stability of gasifier operation.

There were many researches about the slag behaviors inside the gasifier,4–11 but the in situ experiment study for slag behaviors in the gasifier was limited due to the high-temperature and high-pressure environment. Wang et al.12 conducted a cold model experiment which used the syrup to simulate the liquid slag at the slag tapping hole. The results showed that the slag would be broken up into slender liquid filaments and partly deposited on the screen wall by the high-speed swirling gas flow. Liang et al.13 studied the slag deposition and heat flux based on the operation experiences data in the opposed multiburner (OMB) refractory brick-lined gasifier. The results showed that the average flux heat of slag was about 80–200 kW/m² and increased with the operating temperature. Hosseini and Gupta14 used a special collector probe to collect ash deposition and analyze slag formation and blockage probability with the effect of operating conditions and particle trajectory.

Numerical simulation and model calculation are the main methods to study the slag behaviors under high temperature in a gasifier. Several models have been proposed to research the slag flow and heat transfer properties based on some assumptions. Segginai15 proposed a classical and widely used model to study the time varying slag accumulation and flow on the wall in a Prenflo gasifier. The author simplified the physical model of the slag layer on the basis of some assumptions: The slag on the wall was divided into liquid layer and solid layer, and the interface temperature was defined as the temperature of critical viscosity (Tcv); the liquid slag was considered as Newtonian fluid, and the slag was regarded as solid when the temperature was higher than Tcv. Subsequently, several modified models about slag behaviors were built and used in different processes.16–21 Yong et al.22,23 considered that the temperature profile inside slag was controlled by boundary conditions instead of linear variation. The shear stress from the
gasifier chamber gas flow was not negligible, which had different influence on the slag layer thickness and refractory brick corrosion rate while concurrent or countercurrent flowed with the slag.\textsuperscript{24,25} There were different opinions on the definition of liquid—solid interface: some authors considering the slag still regarded it as flowing when the temperature was between $T_{cv}$ and the flow temperature;\textsuperscript{36} other authors considered that the interface viscosity of the solid slag and liquid slag layer should be absolutely viscosity (about 100 Ps s$^{-1}$) when the slag types were not crystal slag.\textsuperscript{27} In addition, the slag viscosity—temperature characteristics were considered to have an important influence on the slag discharge behaviors both in steady state and unsteady state.\textsuperscript{28,29} The slag was regarded as bubble-containing heterogeneous matter, which would affect the thermal conductivity and slag behaviors.\textsuperscript{30} Above all, most of the literature established the slag flow and heat transfer model with simplified slag physical properties, especially considering that the slag viscosity was only related to temperature.

However, the factors that affect the viscosity of the coal slag are not only temperature but also the chemical composition, atmosphere, and others. Researchers found that slag viscosity was mainly influenced by the chemical composition (Si/Al, CaO, Al$_2$O$_3$, MgO, and MnO) and its content.\textsuperscript{31–33} For instance, as the Al$_2$O$_3$ content increased, slag viscosity increased initially and decreased afterward in CaO–SiO$_2$–MgO–Al$_2$O$_3$ molten slag. The effect of decreasing temperature on the viscosity was more significant than increasing Al$_2$O$_3$ content. The MnO was a viscosity reducing component, and the author proposed the viscosities estimation model to estimate and predict the viscosities of the aluminoisilicate melts containing MnO. Moreover, the mass ratio of CaO/SiO$_2$ and MgO/Al$_2$O$_3$ also could be used to judge the slag viscosity.\textsuperscript{34,35} Besides, Zhou et al.\textsuperscript{36,37} used the malt syrup and the particles with different sizes and morphologies as the simulation medium to study the slag viscosity with the influence of solid phase. The author established the viscosity prediction formula of slag with the liquid phase viscosity and correction factor; the correction factor was affected by the solid particle morphology and content. The solid phase, that is, the crystal content, could be predicted by the FactSage software on the basis of the slag composition, but a better method was to observe in situ through experiments. Shen et al.\textsuperscript{38,39} studied the generation and growth of crystals in coal slag under cooling process. The results showed that low cooling rate and long residence time promoted the growth of crystals. Xuan et al.\textsuperscript{40,41} studied the influence of isothermal temperature and cooling rates on crystallization characteristics. The author established the relationship between the crystallization ratio, temperature, and incubation time fitted the Avrami equation and found that crystals were precipitated when the temperature was higher than. Therefore, in the cooling process from the beginning of crystal precipitation to the period before it became solid, the investigation of slag viscosity, especially the relationship between viscosity and temperature and residence time, were particularly important.

In summary, the generation and growth of crystals in slag were affected by the temperature and incubation time (equal to the residence time), and the viscosity of a specific component of the slag was related to the crystal content and temperature. Therefore, the viscosity distribution of slag on the wall in a gasifier depended on the temperature distribution and the residence time distribution. After the relationship between viscosity and temperature and residence time was figured out, the slag flow and heat transfer model prediction results were more accurate and could better reflect the real situation in the gasifier.

The slag flow and heat transfer model were built on the basis of the temperature–time–viscosity of crystalline slag in an entrained-flow gasifier. The slag behaviors were predicted in a commercial gasifier with some given conditions, which included the distribution of slag layer thickness, temperature, velocity, residence time, and heat flux density. Moreover, several types of slag were used to investigate the effects of the slag crystallization difficulty on the characteristics of slag layer.

\section{MODEL DESCRIPTION}

\subsection{Slag Flow and Heat Transfer Model}

The main structure of the gasifier is a cylinder; the wall structure and slag distribution are relatively uniform. Thus, the slag flow and heat transfer on the wall can be studied on a two-dimensional plane in the vertical direction, as shown in Figure 1. The control volume related to the flow and heat transfer process can be divided into liquid slag, solid slag, SiC refractory wall, and metal wall. The slag flow and heat transfer model were established according to the Seggegni\textsuperscript{15} method and our previous study,\textsuperscript{35} which mainly includes momentum con-
servation equation, mass conservation equation, energy conservation equation, and some other related equations.

2.1.1. Momentum Conservation. The whole slag on the wall was divided into \( j \) layers along the slag flow direction. The momentum conservation equation in each layer was given as follows:

\[
\frac{d}{dx} \left( \mu(x_j) \frac{du_j}{dx_j} \right) = -\rho g, \quad \mu(x_j) \frac{du_j}{dx_j} = 0
\]

where the slag viscosity, \( \mu \), could be obtained from the viscosity–temperature curve (Figure 3), which could be expressed as a numerical relationship related to temperature. The temperature distribution of the \( j \) slag layer, \( T_{sl} \), obtained from the viscosity and real time. Therefore, in order to explore the relationship between the slag temperature, residence time, and viscosity, the value of these parameters at each position in the slag layer should be known. The schematic diagram cross-section along the slag flow direction and perpendicular to the wall of liquid slag was shown in Figure 2. The liquid slag in this cross-section was divided into 400 layers along the slag flow direction (\( y \)) and 400 layers perpendicular to the wall (\( x \)).

\[
\frac{T_{0,i} - T_{1,i}}{\delta_{i,j}/\lambda_{0-i}} = \frac{T_{0,i} - T_{1,i}}{x_j/\lambda_{0-i}}
\]

where the liquid–solid slag layer interface temperature, \( T_{sl} \), was obtained from the viscosity–temperature curve, while the liquid–solid slag layer interface viscosity was defined as 100 Pa·s. The slag thermal conductivity, \( \lambda \), was influenced by temperature and could be calculated by the empirical formula

\[
\lambda = k_x e^{k_y T}
\]

where the \( k_x \) and \( k_y \) were model constants and provided by previous research.

2.1.2. Mass Conservation. For the \( j \) slag layer, the increased mass included the particle deposition from the gasifier chamber and inflow from the upper slag layer, and the reduced mass was the slag flowing to the lower layer. Then the mass conservation equation for the \( j \) slag layer was given as follows:

\[
m_{in,j} + m_{ex,j-1} - m_{ex,j} = 0
\]

where the mass flow rate, \( m_{ex} \), was calculated as follows:

\[
m_{ex,j} = \rho D \int_0^{\delta_{i,j}} u(x_j) \, dx_j
\]

2.1.3. Energy Conservation. In the steady state, the heat flux density in the direction perpendicular to the wall was unchanged. Then the heat flux density for the \( j \) slag layer, \( q_0 \), could be expressed as follows:

\[
q_{ij} = \frac{T_{0,j} - T_d}{\delta_{i,j}/\lambda_{0-i}} = \frac{T_{sl} - T_{1,j}}{\delta_{i,j}/\lambda_{3-i}} = \frac{T_{ex,j} - T_{m,j}}{\delta_{i,j}/\lambda_{t}} = \frac{T_{m,j} - T_{w,j}}{\delta_{i,j}/\lambda_{m}}
\]

where the metal wall and SiC refractory wall thickness and thermal conductivity were known and constant, the cooling water temperature could also be regarded as a constant value.

2.2. Computational Meshing and Viscosity Amendment. The liquid slag flow characteristics were critical for the slagging and safety of gasifier, which were influenced by the slag deposition rate, operating temperature, slag viscosity, and thermal conductivity. According to previous research, the slag thermal conductivity was mainly affected by the temperature and the gas volume fraction. The slag viscosity was influenced by the temperature and crystal content, and the crystal content depended on the temperature and residence time.

\[
x_{sl,j} = \sum_{i=0}^{j} \delta_{i,j}
\]

Combining eq 2 and eq 7, the temperature of the slag cell was obtained as follows:
The overall residence time when slag flow to the slag cell \( (x_o, y_j) \) was given as follows:

\[
t_{i,j} = \sum_{i=0}^{j} t_{cell}(i, j)
\]  

After the crystal content was considered, the amended viscosity could be calculated by the formula \(^{36,37}\)

\[
\mu_{i,j}' = \mu_{i,j}(1 - \beta X)^{2.5}
\]

where \( X \) was the crystal volume fraction, which was affected by the slag types, temperature, and crystal growth time. The value of \( X \) was 0–1, but whether the crystal volume fraction can reach 1 mainly depends on the slag types and set temperature. \( X \) could be calculated by the JMA (Johnson–Mehl–Avrami) equation: \(^{43}\)

\[
X(t) = A \exp(-K t^n)
\]

where \( k \) and \( n \) were the model parameters, \( n \) was the Avrami parameter representing mechanisms of crystal growth, and \( K \) was a coefficient corresponding to the nucleation and growth mechanism, which was related to the isothermal temperature. In addition, \( t \) was time and \( A \) referred to the upper limit of crystallinity that could be reached at this temperature; \( A < 1 \). Moreover, the correction factor \( \beta \) was influenced by the particle size \( (\beta_1) \), particle shape \( (\beta_2) \), and the aspect ratio \( (\beta_3) \), given as follows: \(^{38,37}\)

\[
\beta = \beta_1 \beta_2 \beta_3 = 0.9672 C e^{-0.0022d} e^{0.0126(\theta - 1)}
\]

where \( d \) was the particle size and \( \theta \) was the particle aspect ratio. \( C \) was constant, which was related to the particle shape: when the particles were spherical, \( C \) was 1; when the particles were nonspherical, \( C \) was 1.235.

After the slag viscosity was revised, the characteristic parameters of slag flow and heat transfer were changed. The amended parameters were brought into the equation for iterative calculation with the help of Matlab software; until the error was less than a certain value, the result was considered to converge. Then the amended slag behaviors were obtained with the correction of temperature–time–viscosity, the schematic diagram of the calculation method was shown in Figure 3. The main content of the calculation was to establish a 400 \( \times \) 400 two-dimensional calculation unit and to solve the boundary value problem of the second-order ordinary differential equation unit by unit. In addition, the convergence error was set to combine each slag unit for iterative solution.

### 2.3. Simulation Conditions and Methods

The prediction of slag behaviors with the slag flow and heat transfer model is tested on a 2000 t/day coal consumption Shell pulverized coal gasifier (under 50% load condition, operating temperature is 1432 \(^\circ\)C and ash content of coal is 23 wt %) with the boundary conditions from CFD simulation. The simulation method refers to our previous research, \(^{44}\)and the particle deposition rate distribution and the near-wall gas temperature distribution along the wall are shown in Figure 4.

The measured viscosity–temperature curve of slag is obtained from a high-temperature rotational viscometer (Theta Industries, RV DVIII type, America), as shown in Figure 5. The temperature of critical viscosity, \( T_{cr} \) is the temperature in the point of mutational viscosity, and \( \mu_{cr} \) is the corresponding critical viscosity value. According to our previous study, \(^{27}\)the liquid–solid slag layer interface viscosity, \( \mu_{is} \) is defined as 100 Pa·s; thus the corresponding liquid–solid slag layer interface temperature, \( T_{is} \) is 1608 K from the viscosity–temperature curve.

In addition, Table 1 shows the model parameters and boundary conditions. According to the previous study, \(^{30}\)the dimension of the gasifier and refractory wall parameter are given and the thermal conductivity of metal wall and refractory wall are considered as constant. The cooling water temperature is considered as constant and approximately equal to the metal wall–water interface temperature. In this study, the crystal in slag is assumed as spherical and the average size is 75 \( \mu \)m. The model parameters \( A \) and \( n \) are related to the slag types and temperature, based on refs \(^{38–41}\); the assumed relationship of \( A \) and \( n \) and temperature is shown in Figure 14 (slag B). Moreover, according to the ref \(^{43}\), the assumed model parameter \( k \) is equal to 0.12 and considered as constant.

### 3. RESULTS AND DISCUSSION

#### 3.1. Liquid Slag Characteristic Parameters Distribution in Longitudinal Section

3.1.1. Temperature Distribution of Molten Slag in Longitudinal Section

Figure 6 shows the temperature distribution of molten slag in longitudinal section after the temperature–time–viscosity
amendment. The liquid–solid slag interface temperature is constant (corresponding to the $\mu_{sl}$); thus the temperature gradually increases from the liquid–solid slag interface to the furnace. The temperature difference on both sides of the liquid slag is quite large; the biggest gap almost drops from 2000 to 1600 K, which indicates that the liquid slag layer blocks and takes away a lot of heat to protect the refractory lining. Especially, the temperature near the 1.5 m height of the gasifier is higher than that of the other position, the reason being that this location is close to the nozzle and the heat radiation of the high-temperature flame is larger.

3.1.2. Residence Time Distribution of Molten Slag in Longitudinal Section. Figure 7 shows the residence time distribution of molten slag in longitudinal section.

\begin{table}[h]
\centering
\caption{Model Parameters and Slag Component}
\begin{tabular}{|c|c|}
\hline
model parameter or condition & value \\
\hline
$T_{cv}$ (K) & 1618 \\
$\mu_{cv}$ (Pa s) & 6.79 \\
$T_{sl}$ (K) & 1608 \\
$\mu_{sl}$ (Pa s) & 100 \\
$\rho$ (kg/m$^3$) & 2830 \\
$T_w$ (K) & 523 \\
$\lambda_w$ (W/(m·K)) & 40 \\
$\lambda_r$ (W/(m·K)) & 8 \\
$\delta_m$ (m) & 0.008 \\
$\delta_r$ (m) & 0.015 \\
$H$ (m) & 5.7 \\
$D$ (m) & 2.9 \\
k & 0.12 \\
\hline
slag component & value (wt %) \\
\hline
SiO$_2$ & 40.07 \\
Al$_2$O$_3$ & 22.14 \\
CaO & 14.16 \\
Fe$_2$O$_3$ & 20.59 \\
Na$_2$O & 0.36 \\
MgO & 0.62 \\
TiO$_2$ & 1.43 \\
K$_2$O & 0.63 \\
\hline
\end{tabular}
\end{table}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Particle deposition rate (a) and near-wall gas temperature (b) distribution along the wall.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Viscosity–temperature characteristics of the coal slag.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{Temperature distribution of molten slag longitudinal section.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{Residence time distribution of molten slag in longitudinal section.}
\end{figure}
distribution of molten slag in longitudinal section after the temperature–time–viscosity amendment. The residence time of molten slag on the wall is calculated from the deposition of slag particle on the surface. When the slag flows from top to bottom, it will be covered by new deposited slag particles; thus the residence time of molten slag gradually increases from top to bottom and from outside to inside. Moreover, the mean residence time of molten slag on the wall is given as follows:

$$\tau = \frac{\sum (t_{4,000m_x,400})}{\sum m_{x,400}}$$

(16)

The value of $\tau$ is about 187 s in this study. The mean residence time of molten slag on the wall is a significant characteristic and can be used to measure the total length of slag flowing on the wall.

3.1.3. Viscosity Distribution of Molten Slag in Longitudinal Section. Figure 8 shows the viscosity distribution of liquid slag in longitudinal section after the temperature–time–viscosity amendment. Contrary to the trend of temperature distribution, the viscosity gradually increases from the slag layer surface to the solid slag layer, where the viscosity of liquid–solid slag interface is defined as 100 Pa·s in this study. Similarly, the viscosity of molten slag near the nozzle flame position is relatively small due to the high temperature.

3.2. Slag Layer Characteristics Distribution.

3.2.1. Thickness Distribution of Slag Layer. Figure 9 shows the original and viscosity-amended thickness distribution of liquid slag layer along the gasifier. The liquid slag thickness gradually increases along the slag flow direction because of the continuous deposition of slag particle from the furnace to the wall. Especially, the trend of liquid slag thickening is slowed near the nozzle position, the reason being that the deposition rate of the slag particle significantly reduced near the nozzle (as shown in Figure 4). After amendment with temperature–time–viscosity, the thickness of liquid slag increases, especially in the lower part of the gasifier. According to Figure 7, the residence time of molten slag increases along the slag flow direction; thus, the crystals content also increases with this trend from eq 14, and then the amended viscosity increases with the same trend from eq 13. At last, the amendment of liquid slag increasing thickness is getting larger along the slag flow direction.

Figure 10 shows the original and viscosity-amended thickness distribution of solid slag layer along the gasifier.

The thickness distribution of solid slag layer depends on the furnace temperature distribution, deposition rate distribution, and the position of the nozzle from eq 6. The overall trend is that the thickness of solid slag near the nozzle is higher than that of the other position. The reason is that the high-temperature flame will melt the solid slag in this part, and the deposition rate of particle is little in this position. After amendment with temperature–time–viscosity, the thickness of solid slag increases significantly. On the one hand, the thickened liquid slag increases the heat flux of the slag. One the other hand, the thickened liquid slag increases the heat resistance of the slag; thus, the interface temperature of solid slag and refractory lining decreases as follows. Therefore, according to Fourier’s law, the thickness of solid slag will increase significantly.

3.2.2. Liquid Slag Average Velocity Distribution. Figure 11 shows the original and viscosity-amended average velocity distribution of liquid slag along the wall. The velocity of liquid slag increases along the slag flow direction due to gravity. Similarly, the trend of liquid slag being faster is slowed near the nozzle position due to the decrease in particle deposition rate at this location. Moreover, the average velocity of liquid slag

![Viscosity distribution of molten slag in longitudinal section.](image)

![Liquid slag thickness distribution along the gasifier.](image)

![Solid slag thickness distribution along the gasifier.](image)
residence time distribution (RTD) density function of molten slag is calculated as follows:

\[ E(t) = \frac{m_{e,i,400}}{(t_{i,400} - t_{i-1,400}) \sum m_{e,i,400}} \]  \hspace{1cm} (17)

The RTD curve is shown in Figure 12, which relates to the residence time distribution of molten slag and the mass flow rate distribution. From the RTD curve, most of the molten slag stays on the wall for a short time, about tens of seconds. Especially, there is less molten slag in the 30–50 s residence time period. The reason is that this residence time period corresponds to the slag particle deposited near the nozzle height position. Moreover, the RTD curve moves to the right after the amendment with temperature—time—viscosity, resulting in the mean residence time of molten slag increasing. From eq 17, the mean residence time of molten slag ranges from 187 to 199 s after the amendment with temperature—time—viscosity.

3.2.4. Heat Flux Density Distribution of Slag Layer. Figure 13 shows the original and viscosity-amended heat flux density distribution of the slag layer along the wall. The heat flux distribution of slag depends on the furnace temperature distribution, deposition rate distribution, and the position of the nozzle from eq 6. The heat flux density of slag near the nozzle height position is much higher than that of the other position due to the high temperature and less particle deposition rate. Moreover, the heat flux density of slag increases after the amendment with temperature—time—viscosity, especially near the nozzle height position. The reason is that the temperature difference on both sides of the liquid slag is constant and the slag layer is thinner; thus, the heat flux density of the slag increases.

3.3. Effects of Crystal Morphology and Degree of Crystallization Difficulty on the Slag Behaviors. The crystallization ratio and crystal morphology are of great importance to the fluidity of the slag. In order to study the effects of crystal morphology on the slag behaviors, the spherical and acicular crystals with different size and aspect ratio are selected. According to the results of Shen et al.45,46 and Shen et al.38,39, the sizes of crystals range from 0 to 140 μm by the high-temperature-stage microscope; thus, sizes are assumed as 25, 50, 75, 100, and 150 μm in spherical crystals in this study, respectively. Moreover, the aspect ratios are assumed as 5, 10, 15, 20, and 25 in acicular crystals, respectively, as shown in Table 2. In addition, in order to study the effects of degree of crystallization difficulty on the slag behaviors, three slag types with different model parameters are constructed (Figure 14). According to the results of Xuan et al.40,41 and Shen et al.38,39, the value of A ranges from 0 to 1 and the value of n ranges from 1 to 4. The larger the A and the smaller the n, the easier it is for the slag to crystallize. Thus, the degree of crystallization difficulty follows slag A > slag B > slag C.

3.3.1. Effects of Crystal Morphology on the Slag Behaviors. In order to study effects of crystal morphology on the slag behaviors, the model parameters relationship of slag A, B, and C is used to ensure the degree of crystallization difficulty is unchanged. Figure 15 shows the average thickness and heat flux density of slag with different crystal sizes. The average thickness of a slag layer decreases with the increasing crystal size, and the decrease rate is about 42% when the crystal size changes from 25 to 150 μm. While the average heat flux density of slag increases with increasing crystal size, and the increase rate is about 40% when the crystal size changes from 25 to 150 μm.

Table 2. Crystals Morphology in This Study

| shape     | size (μm) | aspect ratio |
|-----------|-----------|--------------|
| spherical | 25, 50, 75, 100, 150 | 1           |
| acicular  | 50        | 5, 10, 15, 20, 25 |

Figure 11. Liquid slag average velocity distribution along the gasifier.

Figure 12. RTD curve of molten slag.

Figure 13. Heat flux density distribution of slag along the gasifier.
25 to 150 μm. The results indicate that the smaller the crystal size, the larger the slag amended viscosity, and the thicker the slag layer thickness, the more difficult it is to discharge slag.

3.3.2. Effects of Degree of Crystallization Difficulty on the Slag Behaviors. In order to study effects of degree of crystallization difficulty on the slag behaviors, the spherical crystal with 75 μm size is used to ensure the degree of crystallization is unchanged. Figure 17 shows the average thickness and heat flux density of slag with different slag types.

The average thickness of a slag layer becomes thicker as the difficulty of slag crystallization decreases, and the increase rate is about 66% when the slag type changes from A to C, while the average heat flux density of slag decreases as the difficulty of slag crystallization decreases and the decrease rate is about 9% when the slag type changes from A to C.

Therefore, the degree of slag crystallization difficulty has significant influence on slag behaviors. The easier the slag to crystallize, the higher the slag viscosity after amendment, and the thicker the slag layer thickness, the more difficult it is to discharge slag. In summary, when selecting crystallized slag coal type for the gasifier, it is necessary to comprehensively consider the difficulty and crystal morphology of the slag crystallization.

4. CONCLUSIONS

The slag flow and heat transfer model were built with the amendment of temperature−time−viscosity, and amended slag behaviors were obtained. The results show that from the furnace to the direction of solid slag, the temperature of molten slag gradually decreases, the residence time of slag gradually increases, and the molten slag viscosity gradually increases. After the temperature−time−viscosity amendment, the thickness of liquid slag and mean residence time of molten slag increase, the velocity of liquid slag and heat flux density of slag decrease, and especially, the thickness of solid slag has a significant increase.

Moreover, several slags with different crystals morphology are constructed to study the influence of crystal morphology on the slag behaviors. The results show the average thickness of a slag layer decreases, while the average heat flux density of slag increases with the increasing crystal size and increasing crystal aspect ratio. Three slag types with different model parameters are constructed to study the effects of the degree of
crystallization difficulty on the slag behaviors. The results show the average thickness of a slag layer becomes thicker, while the average heat flux density of slag decreases as the difficulty of slag crystallization decreases. Therefore, the difficulty and crystal morphology of the slag crystallization should be considered while selecting crystallized slag coal type for a gasifier.

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### NOMENCLATURE

- $A$: model parameter
- $C$: model parameter
- $d$: particle size (m)
- $D$: gasifier diameter (m)
- $E$: residence time distribution density (s$^{-1}$)
- $g$: gravitational constant (m/s$^2$)
- $h$: height of slag cell (m)
- $H$: gasifier height (m)
- $k_0$: model parameter
- $K$: model parameter
- $k_0$: pre-exponential factor (mg/(cm$^2$·s))
- $m_{ls}$: mass flow rate of deposited slag (kg/s)
- $n$: model parameter
- $q$: heat flux density (W/m$^2$)
- $t$: residence time of molten slag (s)
- $T$: temperature (K)
- $T_0$: temperature of slag surface (K)
- $T_c$: temperature of critical viscosity (K)
- $T_m$: temperature of metal wall surface (K)
- $T_w$: temperature of SiC refractory wall surface (K)
- $u$: slag flow velocity (m/s)
- $X$: crystal volume fraction
- $x$: vertical distance from the solid–liquid slag interface (m)
- $\beta$: correction factor
- $\lambda$: thermal conductivity of slag (W/(m·K))
- $\lambda_m$: thermal conductivity of metal wall (W/(m·K))
- $\lambda_r$: thermal conductivity of SiC refractory wall (W/(m·K))
- $\mu$: liquid slag viscosity (Pa·s)
- $\mu_c$: critical viscosity (Pa·s)
- $\rho$: slag density (kg/m$^3$)
- $\tau$: mean residence time of molten slag (s)

### Greek Letters

- $\alpha$: particle aspect ratio
- $\delta$: thickness of slag layer (m)
- $\delta_m$: thickness of metal wall (m)
- $\delta_r$: thickness of SiC refractory wall (m)
- $\delta_s$: thickness of solid slag layer (m)
- $\theta$: model parameter
- $\lambda$: thermal conductivity of slag (W/(m·K))
- $\lambda_m$: thermal conductivity of metal wall (W/(m·K))
- $\lambda_r$: thermal conductivity of SiC refractory wall (W/(m·K))
- $\mu$: liquid slag viscosity (Pa·s)
- $\mu_c$: critical viscosity (Pa·s)
- $\rho$: slag density (kg/m$^3$)
- $\tau$: mean residence time of molten slag (s)

### Subscripts

- $0$: slag surface
- $c$: small slag cell
- $cv$: critical viscosity
- $e$: out of the slag unit
- $f$: slag flow in slag deposition from reaction area
- $l$: liquid slag
- $m$: metal wall
- $r$: SiC refractory wall
- $s$: solid slag

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