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In situ experimental study on the combustion characteristics of captured chars on the molten slag surface

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ABSTRACT

Captured char particles on the molten slag continue to burn or transform into residual carbon in a slagging combustor or furnace, which affect the complete carbon conversion. This study applied a high temperature stage microscope to investigate the combustion behavior of captured chars on the molten slag surface. The combustion process of captured chars with air on the slag surface was observed and recorded, compared to the original char combustion. Particle size evolution calculated from the measured cross section area versus time indicated that the burnout time of chars was prolonged on the molten slag surface. Besides the heat transfer analysis also showed that the temperatures of char particles on the molten slag were decreased due to the thermal conduction between char and slag. Molten slag layer reduced the char reactivity from the analysis of combustibility index, indicating the captured char combustion on the molten slag surface was hindered. Coupled with heat transfer analysis, shrinking particle model (SPM) was applied and modified to predict the combustion time at carbon conversion of 0.9, and results showed an agreement with the experimental data.

1. Introduction

Coal combustion technology is widely applied in the world for power generation, and has been improved for pollutant control and CO_2 capture [1]. Pulverized coal (PC) fired power plants account for about 90% of the electricity generated from coal [2]. The energy conversion efficiencies of traditional PC power plants still need improvement while a high carbon conversion of combustor or furnace ensures an effective utilization of coal.

Coal combustion is a multi-phase, multi-scale and multi-components process which contains different reactions and transport processes [3]. The aims of a high carbon conversion or combustion efficiency lead experimental and numerical studies to focus on the models and kinetics of coal combustion in varied environments of gaseous reactants. Oxygen-enriched environment benefits a sufficient combustion of coal, increases the char combustion temperature and reduces the char burnout time [4]. Coal particle combustions in the O_2/N_2 and O_2/CO_2 environments have also been studied for varied coal species and reactivity [3,5–7]. Higuera [8] simulated the combustion of a single char particle and found that burning rate increased with the velocity of particle in O_2 and CO_2 heterogeneous reactions. Smart et al. [9] applied a digital imaging technique to detect the combustion flames of a high-volatile coal and a low-volatile coal in the air and O_2/CO_2 mixtures. For the modeling and simulation of coal/char combustion, an intrinsic reaction model was proposed to study the effect of internal reaction with an effectiveness factor [10]. Hurt [11] considered the effects of mineral matters and annealing process on coal combustion, and proposed a char burnout kinetic model. Simulation and modeling for the burning characteristics and conversion of porous chars have been also researched in Refs. [12–14].

In the coal combustion furnace or boiler, an increase in the wall temperature would increase the slagging tendency and the deposition of ash and char particles [15–17]. The captured particles on the molten slag surface continued to react with the gas and performed as different reaction characteristics, which was has been studied in the gasification condition by Shen et al. [18]. Similarly in a slagging combustor or furnace, high combustion temperature made the molten slag layer cover the wall and capture the particles [19]. Char particles did not penetrate the molten slag surface due to the large surface tension in the pulverized coal

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Nomenclature

A	pre-exponential factor (kg m^{-2} s^{-1})
$A_{c,t}$	surface area above slag level at time t (m^2)
$A_{cs,t}$	surface area immersed in liquid slag at time t (m^2)
$A_{p,t}$	surface area of char particle at time t (m^2)
D_{O2}	oxygen diffusivity in the bulk phase (m s^{-1})
D	particle diameter (m)
d_0	initial particle size (m)
d_t	particle size at time t (m)
$d_{t\text{-}0.2}$	particle size at time $t-0.2$ (m)
E	activation energy (kJ mol^{-1})
f	stoichiometric mass ratio of char and oxygen
g	gravitational acceleration (m s^{-2})
h_g	convection coefficient (W m^{-2} K^{-1})
h_t	depth of char immersed in the molten slag at time t (m)
k_{O2}	mass transfer coefficient of oxygen (m s^{-1})
k_{rea}	reaction rate coefficient (kg m^{-2} s^{-1})
l	shell thickness consumed per unit time (m)
m_p	mass of char particle (kg)
m_t	mass of char particle at time t (kg)
$m_{t\text{-}0.2}$	mass of char particle at time $t-0.2$ (kg)
m_0	mass of char at initial time (kg)
m_{O2}	mass of oxygen consumed (kg)
M_c	molar mass of carbon (g mol^{-1})
Nu	Nusselt number
P_r	Prandtl number
Q	heat transfer rate of endothermic reaction (J/s)
Q_c	heat transfer rate of thermal conduction (J/s)
Q_h	heat transfer rate of convection (J/s)
Q_r	heat transfer rate of radiation (J/s)
Q_{cp}	heat transfer rate of thermal conduction for char particle (J/s)
Q_{cs}	heat transfer rate of thermal conduction on char-slag interface (J/s)
r_c	Carbon reaction rate (kg s^{-1})
$r_{p,t}$	radius of char particle at time t (m)
r_0	radius of char particle at initial time (m)
R	gas constant (J mol^{-1} K^{-1})
Re	Reynolds number
S	combustibility index (m^2 kg^{-1})
Sc	Schmidt number
t	time (s)
$t_{0.9}$	time at carbon conversion of 0.9
T_i	reaction temperature (K)
T_b	burnout temperature (K)
T_g	gas temperature (K)
$T_{p,t}$	temperature of char particle at time t (K)
$T_{p,t\text{-}0.2}$	temperature of char particle at time $t-0.2$ (K)
T_s	temperature of molten slag (K)
T_w	temperature of wall (K)
u	particle velocity (m s^{-1})
v	kinematic viscosity (m^2 s^{-1})
v_{O2}	oxygen mass diffusion rate (kg s^{-1})
v_C	carbon mass consumption rate (kg s^{-1})
V_p	volume of char particle (m^3)
V_{cs}	volume of char particle immersed in molten slag (m^3)
w	mass of char consumed (kg)
x	carbon conversion
$Y_{O2,b}$	mass fraction of oxygen in the bulk phase
$Y_{O2,s}$	mass fraction of oxygen on the particle surface

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
α_g	gas absorptivity
ε_p	particle surface emissivity
η	area correction factor defined in the text
λ	thermal conductivity of char (W m^{-1} K^{-1})
λ_g	thermal conductivity of gas (W m^{-1} K^{-1})
ρ_c	density of char (kg m^{-3})
ρ_s	density of slag(kg m^{-3})
ρ_g	density of gas (kg m^{-3})
σ	Stefan–Boltzmann constant (W m^{-2} K^{-4})
φ	ash content defined in the text
$\Delta\mathrm{H}$	heat of reaction (kJ mol^{-1})
Δm	mass of char consumed per unit time (kg s^{-1})

Subscripts

0	at initial time $t=0$ or conversion $x=0$
0.9	at carbon conversion of 0.9
b	bulk phase
c	thermal conduction or char
cp	thermal conduction for particle
cs	portion of char particle immersed in molten slag
g	gas
$\mathrm{O_2}$	oxygen
p	char particle
r	radiation
rea	reaction
s	molten slag or particle surface
t	at time t
$t-0.2$	time $t-0.2$
w	wall

combustion [20,21]. Shimizu and Tominaga [22] have proposed the char capture model for predicting the probability of char capture. Researches focused on the probability of char capture were also concerned with viscosities of molten slag or char and slag [23,24]. The gas flow types, wall effect and the characterization of dispersed phase/wall interactive patterns for the simulation of char capture were referred in the references of Troiano et al. [25,26].

Char particles on the molten slag surface continued to burn with the near-wall gas for the complex environment in a furnace or chamber. A wall burning model coupled with a slag flow model was developed to simulate the interaction of char and slag in a coal-fired slagging combustor [19]. Chen et al. [27] also developed a slag model to simulate the slag behavior in a vertically-oriented oxy-coal combustor coupled with the char wall burning model. For the oxidation of coal char, char-slag transition occurred above the ash flow temperature while no transition occurred below the ash flow temperature [28]. Shoatokha and Sokolovskaya [29] studied the effect of coal treatment with blast furnace slag on char reactivity, and found slag reduced activation energy of the combustion of chars. However, seldom literature has focused on the in situ experimental study of char combustion behaviors on the molten slag surface.

The purpose of this study was to investigate the combustion characteristics of chars on the molten slag surface. In situ experiment with a high temperature stage microscope (HTSM) observed and recorded the combustion process of char particles on the molten slag for different particle sizes. Evolution of particle diameter versus time was measured and analyzed by ImageJ software. Carbon conversions of char particles were given with the comparison results of original chars. The energy balance equation was built to analyze the heat transfer rates between char, gas and molten slag during combustion. The combustibility indexes were calculated and compared to present the combustion characteristics