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Numerical simulation of sub-bituminous coal and bituminous coal mixed combustion employing tabulated-devolatilization-process model

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ABSTRACT

To investigate the cause of the increase in the unburned fraction when sub-bituminous coal is mixed with bituminous coal observed in previous experimental research using a 100 kg-coal/h-class coal combustion test furnace, numerical simulations of the mixed combustion of sub-bituminous coal and bituminous coal are performed. To take into account the effect of the particle heating rate on the devolatilization parameters, the tabulated-devolatilization-process model (TDP model) is employed. The results show that the simulation could qualitatively reproduce the experimental results, which are an increase in flame lift-off with increasing sub-bituminous coal mixing ratio and a maximum value of the unburned fraction at a sub-bituminous coal mixing ratio of 25%. Furthermore, it is clarified from the simulation results that the nonlinear increase in the overall unburned fraction in the case of sub-bituminous coal mixing with bituminous coal is caused by the steep increase in the unburned fraction of bituminous coal particles with increasing sub-bituminous coal mixing ratio.

1. Introduction

Pulverized coal combustion is utilized in the majority of coal-fired thermal power plants. Even though the basic pulverized coal combustion technology was established many decades ago, there are still various ongoing researches on the coal combustion, because the combustion characteristics are largely affected by the coal properties that vary widely depending on the coal grade. For instance, Dios et al. [1] recently conducted the study on new emission factors for burning a mixture of lignite and sub-bituminous coal. Wang et al. [2] conducted the study on the effect of the air staging and blending ratio of bituminous coal on the combustion characteristics of dried lignite. Due to the upward trends of the consumption and price of coal [3], the usage of low-grade coal such as sub-bituminous coal or lignite is becoming increasingly important to hold down the fuel cost and to ensure energy security. However, using low-grade coal in coal-fired thermal power plants that are designed to use bituminous coal sometimes causes problems such as a decrease in combustion efficiency, an increase in NO_x emission, slagging or fouling. The combustion characteristics of sub-bituminous coal mixed with bituminous coal have been experimentally investigated in Central Research Institute of Electric Power Industry (CRIEPI) [4–6] and a decrease in combustion efficiency caused by mixing sub-bituminous coal with bituminous coal was reported by Ikeda et al. [6]. A decrease in combustion efficiency is a significant problem in thermal power plants because of their high consumption of fuel. Although the general influence of sub-bituminous coal mixing has been clarified in the previous research [6], the actual influence of sub-bituminous coal mixing in actual large-scale boilers cannot be predicted solely by the experimental investigation because the designs of furnaces and burners employed in actual boilers are generally different from that employed in the experimental facility. Therefore, numerical simulation techniques for coal combustion fields have been developed at CRIEPI [7–11]. Kurose et al. investigated the combustion characteristics of high ash coal [7], effects of moisture in coal on combustion characteristics [8] and the combustion characteristics of the low-NO_x burner [9] by the numerical simulation. Hashimoto et al. [10] investigated the multiburner effect on the pulverized coal combustion by the numerical simulation, and Watanabe et al. [11] investigated the detailed swirling flow characteristics of a complex burner.

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Nomenclature

$A_{c,I}$	pre-exponential factor for Eq. (2.48), 1/s
A_g	pre-exponential factor for Eq. (2.44), 1/s
A_p	projected area of particle, m^2
A_s	surface area of particle, m^2
A_v	pre-exponential factor for the volatile matter evolution rate equation, Eq. (2.2), 1/s
C	char mass, kg
C_{ash}	mass fraction of ash in coal obtained by proximate analysis (dry basis), kg/kg-coal
$C_{p,p}$	specific heat of particle, J/(kg K)
$C_{p,g}$	specific heat of gas, J/(kg K)
D_p	particle diameter, m
$D_{p,i}$	initial particle diameter, m
D_{H_2O}	mass diffusivity of gaseous water, m^2/s
$E_{c,I}$	activation energy for Eq. (2.48), J/kmol
E_g	activation energy for Eq. (2.44), J/kmol
E_v	activation energy for the volatile matter evolution rate equation, Eq. (2.2), J/kmol
GCV	calorific value of coal obtained by proximate analysis, J/kg-coal
h_x	enthalpy of chemical species X, J/kg
k_g	thermal conductivity of gas, W/(m K)
K_v	devolatilization rate coefficient, 1/s
MF_p	mass fraction for representative particles
m_p	particle mass, kg
m_{moist}	moisture mass in particle, kg
m_{vola}	mass fraction of volatile matter in particle, kg/kg-coal
m_x	mass fraction of chemical species X or chemical element X in a coal particle, kg/kg-coal
M_x	molecular weight, kg/kmol
N_p	the number of representative particles
P_{g,O_2}	partial pressure of oxygen, Pa
P_x	mass fraction of substance X obtained by proximate analysis (as-received basis), kg/kg-coal
Pr	Prandtl number
$\dot{q}_{char}$	heat gain due to char combustion, J/s
R	gas constant, J/(mol K)
R_g	gaseous reaction rate, mol/(s m^3)
$R_{g,ed}$	gaseous reaction rate regarding the eddy dissipation model, mol/(s m^3)
$R_{g,ki}$	gaseous reaction rate regarding the kinetics, mol/(s m^3)
Re_p	particle Reynolds number
T_{boil}	boiling temperature of water, K
T_g	gas temperature, K
T_p	particle temperature, K
T_t	transition temperature defined by Eq. (2.47), K
u_{fi}	fluid velocity component for direction i, m/s
u_{pi}	particle velocity component for direction i, m/s
Ul_x	mass fraction of chemical element X obtained by ultimate analysis (dry basis), kg/kg-coal
U_C	unburned carbon concentration in fly ash, kg/kg
U_C^*	unburned fraction, %
V	mass of volatile matter that has been evolved from a coal particle, kg
V^*	initial mass of volatile matter in particle, kg
Y_i	mass fraction of chemical species i, kg/kg
$Y_{H_2O,s}$	mass fraction of water at particle surface, kg/kg
$Y_{H_2O,\infty}$	mass fraction of water of surrounding gas, kg/kg
[X]	molar concentration of chemical species X, mol/m^3

Greek symbols

ε_p	absorptivity of coal particles
κ	mass fraction of nitrogen remaining in char particle after devolatilization
η	combustion efficiency, %
ν	kinematic viscosity of gas, m^2/s
ρ_g	density of gas, kg/m^3
ρ_p	density of particle, kg/m^3
σ	Stefan–Boltzmann constant
Δh_{char}	calorific value of char, J/kg
Δh_{dev}	required heat for devolatilization, 6.279×10^5 J/kg [41]
Δh_{lat}	latent heat of water, 2.254×10^6 J/kg
Δh_{vola}	calorific value of volatile matter, J/kg
Δh_{CH_4low}	calorific value of CH_4low, J/kg
Δh_{CH_4high}	calorific value of CH_4high, J/kg
$\Delta h_{C_2H_2low}$	calorific value of C_2H_2low, J/kg
$\Delta h_{C_2H_2high}$	calorific value of C_2H_2high, J/kg
Δh_{C_n}	calorific value of C_n, J/kg
Δh_{H_2}	calorific value of H_2, J/kg

Recently, numerical simulations of combustion fields in large-scale pulverized-coal-fired furnaces have been performed by many researchers [12–23] for various purposes. Constenla et al. [12] conducted a numerical simulation of a 350 MWe furnace to validate their numerical methods. Al-Abbas et al. [13] conducted numerical simulations of brown coal combustion in a 550 MWe furnace with various operating condition to find the optimum condition. Hwang et al. [14] conducted a numerical simulation of a 500 MWe boiler to optimize the ash supplying position to reduce the carbon content in ash with reburning. Belosevic et al. [15] conducted a numerical simulation of a 350 MWe furnace to predict the NO_x emission at the furnace exit. Fang et al. [16] conducted a numerical simulation in a 200 MWe boiler to optimize the supply rates of blast furnace gas and coke over gas for reducing NO_x emission at the furnace exit. Vuthaluru et al. [17] conducted a numerical simulation of a 330 MWe boiler to predict the slagging characteristics on the water wall. Agraniotis et al. [18] conducted a numerical simulation of a 600 MWe boiler to predict the combustion characteristics of the co-combustion of solid recovered fuels with brown coal for optimization of co-firing concepts. Modlinski [19] conducted numerical simulations of a 300 MWe boiler and a 315 MWe boiler to evaluate the effect of introducing new type swirl burners to the boilers. Tian et al. [20] conducted a numerical simulation of a 375 MWe furnace to find the optimum operating condition. Pallarés et al. [21] conducted a numerical simulation of a 350 MWe boiler to examine the effect of the co-firing some biomass fuel with coal and found the limit in the maximum mixing ratio of the biomass fuel to keep reasonable boiler efficiency. The numerical simulations have also employed for the development of the oxy-fuel combustion from the viewpoint of the demands for CO_2 emission reduction. Granados et al. [22] conducted a numerical analysis of the oxy-fuel combustion in a rotary cement kiln to examine the flue gas recirculation on the clinkering characteristics. Álvarez et al. [23] conducted a numerical simulation of oxy-fuel combustion in an entrained flow reactor to validate the applicability of the sub-models to the oxy-fuel combustion field.

In most of the researches cited above, comparatively simplified models for the devolatilization and combustion of coal particles