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Research article

Numerical analysis on effect of furnace scale on heat transfer mechanism of coal particles in pulverized coal combustion field

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ABSTRACT

To investigate the effect of the furnace scale on the heat transfer mechanism of coal particles, numerical simulations of coal combustion fields in three different scale furnaces (915 MW_{th} actual large scale boiler, 2.4 MW_{th} and 0.76 MW_{th} test furnaces) were conducted. High accuracy of simulation methods was validated with the measured data. From the comparison of numerical simulations between three different scale furnaces, it was clarified that the particle residence time with high particle temperature for a small scale furnace is shorter than that for a large scale furnace even if the particle residence time passing the high temperature gas is the same. This is caused by the insufficient heat gain of particles for a small scale furnace due to the lower radiation heat transfer because of the thinner flame thickness in the small furnace. The sphericity of ash particles from small scale furnaces is lower than that for large scale furnaces due to the shorter particle residence time with high particle temperature. These findings should be considered when the usability of coal brands for actual large scale boilers is evaluated by the fly ash properties from a small scale experimental furnace.

1. Introduction

Pulverized coal combustion is introduced in a large part of coal-fired thermal power plants in the world. Even though the fundamental technology for pulverized coal combustion was established many decades ago, many types of problems, e.g., fouling, slagging, sulfidation corrosion, increase in particulate matter and NOx concentrations in exhaust gas and increase in unburned carbon in fly ash, occur in the operation of coal-fired furnaces. To solve the problems described above, understanding of the gas flow pattern, temperature distribution, gas species concentration distributions and coal particle behavior in the furnace is very important. However, the phenomena described above are largely affected by the design of furnaces. Numerical simulation is a powerful tool for understanding such phenomena in each furnace with a different design. Recently, numerical simulations of pulverized coal combustion field in large-scale furnaces have been conducted by various research groups [1–9]. For numerical simulations of pulverized coal combustion, simplified models are generally employed because of the limitation of computational resources. However, sometimes employing such simplified models causes relatively large errors in prediction of the phenomena in the furnaces. In Central Research Institute of Electric Power Industry (CRIEPI), new models such as the TDP model for detailed devolatilization modeling [10,11] and the RD model for detailed char combustion modeling [12] have been developed to improve the accuracy of the simulation of coal combustion. Since the development of new models requires various experimental data to validate the simulation results, various studies have been conducted using test facilities in CRIEPI such as the studies for the combustion characteristics of subbituminous coal [13,14], the combustion characteristics of high ash coal [15,16], the hydrogen sulfide formation in coal combustion field [17], the soot formation characteristics in coal combustion field [18], the influence of combustion condition and coal properties on physical properties of flay ash [19] and the detailed flow field in the coal combustion test furnace [20]. Experimental data from the facilities are also beneficial for the understanding of the coal combustion phenomena and the evaluation of coal brands for using in actual scale boiler. However, the thermal histories of coal particles in the experimental facilities can be different from that in the actual large scale boilers because the scale of flame can affect the heat transfer mechanism of the coal particles. Experimental apparatus with various sizes, e.g., the drop tube furnace (8–60 g-coal/h) [21,22], the small coal jet burner (0.5 kg-coal/h) [11, 23], the triple stream burner (0.36–2.16 kg-coal/h) [24,25], the RWTH furnace (6–7 kg-coal/h) [26,27], the RWEn Combustion Test Facility (70 kg-coal/h) [28], the BEACH furnace (100 kg-coal/h) [13,29,30,31], the IFRF furnace No. 1 (260 kg-coal/h) [32] and the MARINE furnace (300 kg-coal/h) [19,33], have been used to investigate the coal combustion phenomena or to evaluate the combustion characteristics of

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Nomenclature

$D_{s\text{-}ash}$: surface mean diameter, μm
h: time-averaged convection heat transfer coefficient, kW/(m^2 K)
HG_{rad}: integrated heat gain of particles by radiation heat transfer normalized by initial particle mass, MJ/kg
$HL_{dev,1750\ \mathrm{K}}$: integrated heat loss of particles by devolatilization while the particles are passing gas with temperature above 1750 K normalized by initial particle mass, MJ/kg
$Q_{net,1750\ \mathrm{K}}$: net heat gain of particles while the particles are passing gas with temperature above 1750 K normalized by initial particle mass, MJ/kg
S_{Ab}/S_{Ad}: reciprocal Carman's shape factor
$t_{p,1750\ \mathrm{K}}$: particle residence time with particle temperature above 1750 K, s
$t_{g,1750\ \mathrm{K}}$: particle residence time passing gas with temperature above 1750 K, s

various coal brands by some researchers. The difference in the thermal histories of coal particles should be considered to evaluate the usability of coal brands for actual large scale boilers by using the experimental data from small scale experimental apparatus. However, the effect of the furnace scale on the thermal histories of coal particles has not been clarified yet.

In this study, numerical simulations of coal combustion fields in three different scale furnaces (915 MW$_{\mathrm{th}}$ actual large scale boiler, 2.4 MW$_{\mathrm{th}}$ test furnace and 0.76 MW$_{\mathrm{th}}$ test furnace) were conducted to investigate the effect of the furnace scale on the heat transfer mechanism of coal particles. The accuracy of the simulation result for the large scale boiler was validated by comparing with the measured data from the large scale boiler. After that, the calculated particle data from the simulation results of three furnaces were examined statistically in detail to investigate the effect of the furnace scale on the heat transfer mechanism.

2. Numerical simulation

2.1. Mathematical models and numerical method

The models for numerical simulations of pulverized coal combustion field employed in this study are the same as those of Hashimoto et al. [14]. The models for main phenomena are summarized in Table 1.

The gas-phase time-averaged continuity equation and conservation equations of the momentum, turbulent kinetic energy, dissipation, enthalpy and species are

$$\frac{\partial}{\partial x_i}\left(\rho_g u_i\right) = 0 \tag{2.1}$$

$$\frac{\partial}{\partial x_i}\left(\rho_g u_i \phi\right) = \frac{\partial}{\partial x_i}\left(\Gamma_\phi \frac{\partial \phi}{\partial x_i}\right) + S_\phi + S_{p\phi}, \tag{2.2}$$

where ϕ denotes the generalized variables expressing fluid velocity components u_i, the turbulent kinetic energy k, the rate of eddy dissipation ε, the fluid enthalpy h and the mass fractions of chemical species Y_i. Γ_ϕ denotes the turbulent exchange coefficient, and S_f and $S_{p\phi}$ represent the gas-phase source terms that are in addition to the convection and diffusion terms and the particle-phase source terms, respectively. The continuity and momentum equations were solved using the PISO algorithm [40].

Table 1
Summary of mathematical models used in simulation.

Phenomena	Mathematical model
Turbulence	RNG k-ε [34]
Thermal radiation	Discrete ordinate [35]
Devolatilization	Modified TDP model [14]
Gas phase combustion	Combined model of kinetics and eddy dissipation [36]
Char combustion	Field et al. [37]
Char combustion zone transition	Essenhigh et al. [38]
Particle's tracking	Lagrangian
Turbulence effect on particle motion	Stochastic [39]

The equation of motion for the representative coal particles is given by

$$m_p \frac{du_{pi}}{dt} = \frac{1}{2} C_d \rho_p A_p \left|u_{fi} - u_{pi}\right| \left(u_{fi} - u_{pi}\right) \tag{2.3}$$

$$C_d = 24\left(1 + 0.15 \mathrm{Re}_p^{0.687}\right) \Big/ \mathrm{Re}_p \tag{2.4}$$

$$\mathrm{Re}_p = D_p \left|u_{fi} - u_{pi}\right| / \nu, \tag{2.5}$$

where, m_p, u_{pi}, ρ_p, A_p, u_{fi} and ν are the particle mass (kg), the particle velocity component for direction i (m/s), the density of particle (kg/m^3), the projected area of particle (m^2), the fluid velocity component for direction i (m/s) and the kinematic viscosity of gas (m^2/s). The equation for the drag coefficient of solid particles (Eq. (2.4)) was taken from Schiller and Naumann [41].

The particle temperature T_p (K) was calculated by considering the heat transfer due to convection, radiation, heat loss due to the evaporation of moisture and the devolatilization reaction in coal particle, and heat gain due to char combustion, using the following equation:

$$\begin{aligned} m_p c_{p,p} \frac{dT_p}{dt} = {} & -A_s h\left(T_p - T_g\right) + A_s \varepsilon_p \sigma\left(\Theta_R^4 - T_p^4\right) + \Delta h_{lat} \frac{dm_{p,w}}{dt} \\ & + \Delta h_{dev} \frac{dm_{p,v}}{dt} + \dot{q}_{char} \end{aligned} \tag{2.6}$$

$$h = k_g Z\left(2 + 0.6 \mathrm{Re}_p^{1/2} \mathrm{Pr}^{1/3}\right) / \left(e^z - 1\right) D_p \tag{2.7}$$

$$Z = -c_{p,g}\left(dm_p/dt\right) / \pi D_p k_g \left(2 + 0.6 \mathrm{Re}_p^{1/2} \mathrm{Pr}^{1/3}\right) \tag{2.8}$$

$$\Theta_R = (I/4\sigma)^{1/4}. \tag{2.9}$$

Here, $c_{p,p}$, A_s, ε_p and $\dot{q}_{char}$ are the specific heat of particle (J/(kg K)), the surface area of particle (m^2), the absorptivity of particle, and the heat gain due to char combustion (J/s). In this study, the particle temperature was assumed to be uniform and the temperature distribution inside the particle was not considered because of the computational cost limitation. The equation for the heat transfer coefficient (Eq. (2.7)) was taken from El Wakil et al. [42]. The absorptivities of the coal particles and wall are assumed to be 0.85 and 0.4, respectively. Also, the absorption coefficient of the gas was set at 0.075 [29]. The interaction of the conserved properties between the gas phase and the coal particles was calculated by the particle-source-in cell (PSI-Cell) technique [43].

In this study, the modified TDP model [14] was employed for devolatilization of coal particle. The FLASHCHAIN model [44,45] was used to produce the devolatilization database for the TDP model.

Gaseous combustion between the volatile matter and air was calculated using a combined model of the kinetics and eddy dissipation models [36]. The chemical mechanism consists of the following two global reactions.

$$\mathrm{VM} + \alpha \mathrm{O_2} \rightarrow \beta \mathrm{CO} + \gamma \mathrm{H_2O} \tag{2.10}$$

$$\mathrm{CO} + \mathrm{O_2} \rightarrow \mathrm{CO_2} \tag{2.11}$$