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Prediction of ignition behavior in a tangentially fired pulverized coal boiler using CFD

T. Asotani [a,c,*], T. Yamashita [b], H. Tominaga [b], Y. Uesugi [c], Y. Itaya [c], S. Mori [d,1]

[a] Technical Department, Idemitsu Engineering Co., Ltd., 3-1 Nakase, Mihama-ku, Chiba City, Chiba 261-8501, Japan
[b] Coal and Environment Research Laboratory, Idemitsu Kosan Co., Ltd., 3-1 Nakasode, Sodegaura, Chiba 299-0267, Japan
[c] Department of Chemical Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8603, Japan
[d] Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8603, Japan

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Abstract

Prediction of pulverized coal ignition behavior in a 40 MW tangentially fired commercial boiler is studied. Pulverized coal combustion simulation is performed considering radiation properties of particles. Coal devolatilization and char combustion are modeled and the first order spherical harmonic approximation is used to model the radiative transfer equation. To confirm the accuracy of the simulation method, the results are confirmed by available operating data, design data, and the ignition image in the boiler whose inside is observed by the developed high temperature resistant CCD video camera system. The work indicates that the simulation method can be applied to commercial boilers and predict the ignition behavior with considering not only coal properties but also boiler operating conditions.

Keywords: Ignition; Pulverized coal; Tangentially fired boiler; Combustion simulation

1. Introduction

Pulverized coal combustion phenomenon can be divided into two steps; devolatilization and char combustion. Ignition, which is a crucial factor for flame stability, the emission of pollutants, boiler design and operating conditions, is a subsequent step of the devolatilization. As the ignition characteristic depends on the type of coal, it should be reflected in boiler design and the operating conditions should also be determined by preliminarily consideration of the compatibility with the design coal. However it is difficult to predict the ignition character of coal only from the proximate and ultimate analysis data. So several experimental methods have been investigated to provide a better evaluation. Although captive particle experiment in TG [1], particle suspension experiment in drop tube furnace [2] and other experiments in a particle suspending apparatus [3] are general experiment methods, these gas flow patterns are not turbulent but laminar and the combustion air temperatures are higher than commercial boiler operating conditions. These differences in combustion conditions between experiments and commercial boilers make it difficult to directly apply the experimental results to commercial boilers, in addition the experimental cost is high.

On the other hand, over 20 years CFD (computational fluid dynamics) has been applied to pulverized coal combustion in bench-, pilot-, and commercial-scale furnaces to predict the combustion phenomena in furnaces and substituted for experiment [4–8]. However, the number of applications of CFD to ignition phenomena of pulverized coal combustion is very few. In our previous investigation, an evaluation method of ignition properties by CFD was given and applied to an experimental coal fired furnace (coal feed: 6 kg/h). The results showed the importance of

* Corresponding author. Address: Idemitsu Engineering Co., Ltd., 3-1 Nakase, Mihama-ku, Chiba City, Chiba 261-8501, Japan. Tel.: +81 43 296 6951; fax: +81 43 296 6949.
E-mail address: toshimitsu.asotani@si.idemitsu.co.jp (T. Asotani).
[1] Emeritus Professor.

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Nomenclature

a	surface area of particle (m^2/kg)
A_c	frequency factor of char combustion (kg/(m^2 s Pa))
A_p	particle projected area (m^2)
A_v	frequency factor of devolatilization (1/s)
C	weight of char (kg)
E_c	apparent activation energy of char combustion (kJ/mol)
E_v	apparent activation energy of devolatilization (kJ/mol)
f	asymmetric factor of particle scattering (–)
h	heat transfer coefficient (W m^{-2})
H_{reac}	heat generated by char combustion (W)
I	radiation intensity (W m^{-2} sr^{-1})
I_b	radiation intensity from black body (W m^{-2} sr^{-1})
k_v	reaction rate of devolatilization (1/s)
m_p	weight (kg)
n	order of reaction (–)
P_O^2	partial pressure of oxygen (Pa)
P_0	total pressure (Pa)
r_p	particle reflectivity ($=1-\varepsilon_p$) (–)
R	universal gas constant (kJ mol^{-1} K^{-1})
s	distance along the direction of radiation propagation (m)
t	time (s)
T_i	temperature (K)
U_c	ratio of unburned carbon (–)
V	weight of volatile matter (kg)
V^*	ultimate weight of volatile matter (kg)
ε_p	particle emissivity (–)
θ	scattering angle (rad)
θ_R	radiation temperature ($=I/4\sigma$) (K)
κ	absorption coefficient (m^{-1})
σ_s	scattering coefficient (m^{-1})
σ	Stefan–Boltzman constant (W m^{-2} K^{-4})
ϕ	circumferential angle (rad)

Subscripts

c	char
d	diffusion
g	gas
n	number of particle trajectory
p	particle
w	wall

the radiation model and the radiation property of coal because the pulverized coal particle temperature is rapidly preheated prior to ignition, mainly by radiation dominating the heat transfer from flames [9].

In this study, to predict the ignition condition in commercial pulverized coal boiler directly, the CFD evaluation method was performed for the commercial 40 MW tangentially fired pulverized coal boiler. The validity of the simulation result was confirmed by available operating data and design data as well as by the observed ignition images in the boiler.

2. Simulation models

2.1. Overview of simulation models

The simulations in the present work were done using the commercial CFD software "FLUENT". The standard k–ε model and Lagrangian particle tracking method with the random walk model were used for a gas-particle turbulence flow simulation. Although volatile matter contains many kinds of gas, the released volatile matter was represented by a single virtual material. Because the reaction rate of the volatile matter was limited by the turbulent mixing rate of the evolved gas and oxidizer at the near-burner condition, the eddy break-up model was employed for the volatile matter reaction with the following reaction paths.

$$\text{Volatile matter} + \alpha_1 O_2 \rightarrow \alpha_2 CO + \alpha_3 H_2O \quad (1)$$

$$CO + 0.5O_2 \rightarrow CO_2 \quad (2)$$

The pulverized coal combustion model in this CFD software has been modified as described below. The suitability of the modification was proven by experimental furnace data [10].

2.2. Coal combustion model

The pulverized coal combustion phenomenon should be divided into two processes, namely, devolatilization and char combustion. In FLUENT, coal combustion model consists of the two competing rates devolatilization model [11] and kinetics/diffusion char combustion model [12,13]. The devolatilization model was developed from experiments in an inert atmosphere; on the other hand, the char combustion model was investigated under combustion conditions. Each process was modeled without consideration of the interaction with each other, so the combination requires sequential execution. It should be pointed out, however, that volatile matter evolution and char combustion occurred simultaneously in the initial stage of coal particle combustion [14], and the particle temperature of combusting coal particles is more than 500–600 K higher than the surrounding gas temperature [15], which brings increasing volatile matter evolution. Consequently the sequential execution causes ignition delay in the initial stage of coal particle combustion simulation [10].

In this study, the weight loss of coal particle by devolatilization and char combustion was estimated by global weight loss model proposed by Saito et al. [16] given by