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Numerical investigation of influence of homogeneous/heterogeneous ignition/combustion mechanisms on ignition point position during pulverized coal combustion in oxygen enriched and recycled flue gases atmosphere

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ABSTRACT

It is expected that pulverized coal combustion will continue to play a major role in electricity generation for the foreseeable future. Oxy-fuel coal combustion is actively being investigated, as alternative to conventional pulverized-coal combustion, due to its potential to easier carbon dioxide sequestration. This paper presents experimental and numerical analysis of ignition phenomena in oxy-fuel conditions. A modification of standard sequential coal combustion model is proposed. The new model is developed following the criteria for the particle ignition mechanism as the function of surrounding conditions. The implemented model was validated based on ignition point position obtained from the drop tube facility experiments in various O_2–N_2 and O_2–CO_2 conditions. The obtained numerical results showed a much better agreement with the experimental results when compared with the simulations performed with the default FLUENT sub-models for coal particle ignition/combustion, thus enabling a quantitative determination of pulverized coal flame ignition point position using numerical analysis.

1. Introduction

It is expected that, for the foreseeable future, pulverized coal combustion will keep its leading position in electricity generation sector. Alternatives to conventional pulverized-coal (pc) furnaces are being investigated to enhance energy efficiency, reduce greenhouse-gas and pollutant emissions, and minimize the size and capital costs of future coal-based power plants. Among several possible alternatives to conventional pc combustion are oxygen-enhanced combustion and pc combustion in oxygen mixed with recycled flue gases [1]. However, switching from conventional to oxy-fuel pulverized coal combustion brings a number of technical and technological challenges. Different heat capacity and densities of the main gases, i.e., N_2 and CO_2, will change the mass flows and velocities of the primary and secondary oxidants (to attain a similar adiabatic flame temperature to the conventional pulverized coal combustion mode) thus affecting burner aerodynamics. This will result in different fuel ignition properties, flame propagation, flame shape, and residence time [2]. As an important preliminary stage in the pulverized coal combustion process ignition has influence on main flame characteristics: flame stability, pollutants formation and emission and flame extinction. Thus ignition has important role in boiler and furnace design as well as in combustion process itself. Number of studies of pulverized coal flame properties, in particular ignition position, ignition temperature, flame shape and stability, during oxy-fuel combustion have been undertaken [3–6].

In the last several years commercial computational fluid dynamics (CFD) codes such as FLUENT have been more extensively used to predict the behavior of pulverized coal in utility boilers and experimental combustion chambers of different sizes [7]. Despite their extensive use in this area, there are still limitations concerning the accuracy of these predictions.

Coal combustion models represent an ensemble of sub-models that describe processes that particles undergo during their combustion history. Generally, these models are split in four steps: particle heating, devolatilisation, volatile combustion, and combustion of char. In addition, other sub-models, like those for pollutant formation or slagging and fouling, can be included in the case of more complex ones. Among the most important sub-models constituting the coal combustion model are devolatilisation and char combustion. There are several ways to describe these phenomena, ranging from basic sub-models up to complex formulations aiming to describe morphological and intrinsic phenomena occurring in combusting coal particles. Devolatilisation sub-models can be expressed as simple reaction rate formulations, or formulations based upon structural networks of the coal. Char combustion sub-models are considered to be either global or of intrinsic type. Commonly two models based upon the work of Baum and Street

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Nomenclature

A	surface area (m^2)
C	molar concentration of gaseous species ($kmol/m^3$)
C_1	diffusion rate constant ($s/K^{0.75}$)
D	diffusion reaction rate coefficient (s/m)
E	activation energy (J/kmol)
F	force per unit particle mass (m/s^2)
f	mass fraction
g	gravity acceleration (m/s^2)
i	direction vector
j	direction vector
K_0	pre-exponential factor (m/s)
M	molar mass (kg/kmol)
m	mass (kg)
p	static pressure (Pa)
R	kinetic rate coefficient (s/m)
r	reaction rate (kg/s)
R_{gas}	gas constant (J/(kmol K))
Sh	Sheerwod number
T	temperature (K)
t	time (s)
u	velocity component in x-axis direction (m/s)
V	volume (m^3)

Greek symbols

α, β, γ	stoichiometric coefficients
ρ	density (kg/m^3)

Subscripts

cell	computational cell
char	char species
coal	coal particle
D	drag
devol	devolatilisation reaction
het	heterogeneous combustion reaction
hom	homogeneous combustion reaction
ox	oxidant species
P	computational particle
vol	volatile species

[8] and Smith [9] are used in CFD commercial codes. The former is based on apparent activation energy, having the reaction rate controlled by either chemistry or by oxygen diffusivity towards the particle surface. In the case of the intrinsic model, chemical reaction rate is explicitly expressed in terms of intrinsic chemical and pore diffusion rates, depending on the effectiveness factor (ratio of the actual combustion rate to the rate if no particle pore diffusion resistance existed) [10].

Although commercial CFD codes can predict fluid dynamics and transport phenomena fairly well, and thus volatile combustion as well to some extent, the main limitation of CFD modelling of coal combustion comes from sub-models for devolatilisation and char combustion [7].

Commonly, the standard combustion sub-models implemented in commercial CFD codes assume sequential combustion of coal particles, which means that the first step is devolatilisation, and when a coal particle is totally devolatilised, char combustion takes place [10]. However, experiments with single coal particle combustion showed that this assumption is only partially true. Types of coal particle ignition, depending on the coal type, particle size and volatile matter content, can change from homogeneous to heterogeneous [11]. It was experimentally shown that the type of pulverized coal ignition/combustion strongly influences the increase of coal particle temperature and thus the position of ignition point and char burnout [12,13].

Ignition of pulverized coal in an oxidizer flow represented by a mixture of O_2–N_2 or O_2–CO_2 has been studied both experimentally and numerically. Experimental study was conducted using the visualization techniques. First, primary oxidant was added to the pulverized coal at a room temperature and then heated secondary oxidant was added. Numerical investigation was conducted by means of the FLUENT 6.3.26 package. The assumption of sequential combustion, available by default, in FLUENT 6.3.26, was used in all numerical cases at the first stage of the simulations. The obtained numerical results showed a considerable difference in ignition point position compared with the experimentally obtained data. The difference between the experimental and numerical results was significant at high temperature and oxygen concentration, which agrees with the transition from homogeneous to heterogeneous ignition.

The aim of this paper is to describe an improved sub-model for pulverized coal particles ignition/devolatilisation. This sub-model was developed following the criteria for the particle ignition mechanism as the function of surrounding conditions. Details are described in the following paragraphs. Each numerical simulation was repeated with the use of the proposed sub-model which is built in FLUENT 6.3.26 code using user-defined functions. The obtained numerical results showed a much better agreement with the experimental results when compared with the simulations performed with the default FLUENT criteria for coal particle ignition/combustion, thus enabling a quantitative determination of pulverized coal flame ignition point position using numerical analysis.

2. Experiment apparatus

All experiments were carried out in the ignition test facility built at the Institute of Power Engineering, Warsaw, Poland. The main elements of this facility are shown in Fig. 1.

The ignition test facility consists of a vertical reactor (1) which has an ellipsoidal cross-section with inner dimensions 150 × 100 mm and height of 1.5 m. The reactor is made of six identical half-cylindrical ceramic modules. Three modules are positioned one on top of the other thus forming two sides of a cylinder. At the front, between the two half-cylinders, a quartz glass tube is positioned, allowing optical observation of flame characteristics.

The reactor is closed at the rear with a brick wall which has the same width as the quartz glass tube. The temperature of oxidant inside the reactor is controlled by six thermocouples (7) which can be shifted along the radial axis of the reactor. Fine pulverized coal particles are introduced from the oscillating feeder (2) and mixed with the cold primary oxidant inside the duct (3). Air-coal mixture is introduced into the reactor through the single circular inlet with the inner diameter of 10 mm (5). The secondary preheated oxidant is carried through the duct (4) and supplied into the reactor through 200 concentric circular inlets with the inner diameter of 5 mm (5). Flow rates of primary and secondary oxidants are controlled using valves (v2). The desired composition of the primary and secondary oxidants is obtained using control valves (v1) positioned on the top of the tanks with CO_2, O_2 and N_2 gases (8) and (9). The combustor and the secondary oxidant duct are insulated in order to prevent heat loss and to maintain a constant temperature inside the combustion chamber. Gas samples are collected using an exhaust pipe (10).