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Numerical simulation of radiation intensity of oxy-coal combustion with flue gas recirculation

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ABSTRACT

Oxy-fuel combustion is one of potential technologies for carbon dioxide (CO_2) capture in fossil fuel fired power plants. Characterization of flue gas composition in the oxy-fuel combustion differs from that of conventional air-coal combustion, which results in the change of radiative heat transfer in combustion processes. This paper presents a numerical study of radiation intensity on lateral walls based on the experimental results of a 0.5 MW combustion test facility (CTF). Differences in the oxy-coal combustion are analyzed, such as flue gas recycle, absorption coefficient and radiation intensity. The simulation results show that an effective O_2 concentration ($[O_2]_{effective}$) between 29 and 33 vol% (equivalent to the flue gas recycle ratio of 72–69%) constitutes a reasonable range, within this range the behavior of oxy-coal combustion is similar to air-coal combustion. Compared with the air-coal combustion, the lower limit (29 vol%) of this range results in a similar radiative heat flux at the region closed to the burner, but a lower radiative heat flux in the downstream region of the CTF; the upper limit (33 vol%) of this range results in a higher radiative heat flux at the region closed to the burner, while a similar radiative heat flux in the downstream region of the CTF.

1. Introduction

Oxy-fuel combustion is considered as one of the most promising carbon dioxide (CO_2) capture technologies since it has potential to be applied in conventional steam power plants (Faber et al., 2011; Wall et al., 2011). In the oxy-fuel combustion, a mixture of oxygen (O_2) and recycled flue gas is used for fuel combustion to make the flame characteristics similar to air-fuel combustion conditions. Due to the differences in gas properties of nitrogen (N_2) and CO_2, oxy-fuel combustion differs from air-fuel combustion in several aspects, such as heat transfer, char burnout (Gharebaghi et al., 2011), nitrogen oxides formation (Normann et al., 2009). Especially for radiative heat transfer, the N_2 free combustion environment in the oxy-fuel (O_2/CO_2 recycle) combustion results in substantially higher concentrations (vol%) of CO_2 and water (H_2O), which are considered as the major radiating gases (Hu et al., 2012b). The heat transfer by radiation, in excess of 95% of the total heat transfer in the boiler furnace (Neal et al., 1980), is quite different from that in air-fuel combustion. Fig. 1 shows the comparison of spectral radiation properties of the two combustion environments (calculated using RADCAL FORTRAN code (Grosshandler, 1993)). The spectral transmittance (equals to (1-assorptivity)) in the air-combustion is considerable higher than that in the oxy-coal combustion at several bands (2–11 μm). As the change of the spectral radiation properties, flame radiation and its radiation intensity (or radiative heat flux) on lateral walls of furnaces will change correspondingly.

To identify the effects of the oxy-fuel combustion environment on radiative heat transfer, many efforts have been carried out through numerical and experimental studies (Álvarez et al., 2013; Wang et al., 2012; Al-Abbas et al., 2011; Andersson and Johnsson, 2008). Currently, modeling of combustion processes by computational fluid dynamics (CFD) has become state-of-the-art for conventional air combustion (Scheffknecht et al., 2011). Due to a much lower H_2O/CO_2 ratio and longer pressure path-lengths in oxy-fuel combustion, the parameters of approximate radiation models developed for the air-fuel combustion are no longer applicable to the computational fluid dynamics (CFD) modeling of the oxy-fuel combustion (Becher et al., 2011a,b, 2012), such as the coefficients for weighted sum of gray gases (WSGG) model evaluated by Smith et al. (1982). To cover the conditions of high radiating gas concentration ($H_2O + CO_2$) in oxy-fuel combustion, Johansson et al. (2010) and Yin et al. (2010) derived new coefficients for the WSGG model respectively. On the other hand, Andersson et al.

Abbreviations: CFD, computational fluid dynamics; CTF, combustion test facility; DO, discrete ordinates model; EDM, eddy dissipation model; FGR, flue gas recycle; FRC, finte rate chemistry; IFRF, international fluame research foundation; RANS, Reynolds-averaged Navier–Stokes equations; RTE, radiative transfer equation; UDFs, user-defined-functions; WSGG, weighted sum of gray gases.

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Nomenclature

Symbols

α_i	weighting factor
$A_{r,i}$	pre-exponential factor, s^{-1} or kg/(m^2 s Pa)
A_p	particle surface, m^2
c_f	local time mean fuel concentration, kg/m^3
c_{O_2}	local time mean O_2 concentration, kg/m^3
C_i	mass diffusion-limited constant, s/$K^{0.75}$
C_p	heat capacity at constant pressure
d	diameter, μm
D	thermal diffusivity, m^2/s
$E_{r,i}$	activation energy, J/kmol
L	mean beam length, m
k_a	absorption coefficient, 1/m
k_r	kinetic rate, kg/(m^2 s Pa)
m_p	mass of coal particle, kg
$m_v(t)$	Volatile yield up to time, kg
M	molecular weight, kg/kmol
p	partial pressure, Pa
r_f	stoichiometric coefficients of O_2
r	rate constants, kmol/(m^3 s)
R	idea gas constant, 8.314, J/(mol K)
S_0	swirl number
t	time, s
T_g	gas temperature, K
T_p	particle temperature, K
α	stoichiometric coefficients of volatile
β	stoichiometric coefficients of char; temperature exponent
η_r	effectiveness factor
λ	thermal conductivity, kW/m K; stoichiometric ratio
μ	viscosity, Pa s
ε/k	large-eddy mixing time scale

(2011), Andersson and Johnsson (2008) carried out experimental study on coal- and gas-fired oxy-fuel combustion. They found that the significant increase in the CO_2 content of the oxy-fuel flame resulted in the increase of gas radiation, but did not contribute much to its radiation compared to air-fuel combustion since the particle radiation dominates the high-temperature zones in both two combustion environments. Smart et al. (2010) made experimental studies on radiative heat transfer in the oxy-coal combustion, and reported that peak radiative heat flux is inversely proportional to the flue gas recycle ratio (FGR ratio). From the systematic perspective, further studies would be carried out to quantitatively descript the amount of flue gas recycle and its effect on radiative heat transfer in the oxy-coal combustion with flue gas recirculation.

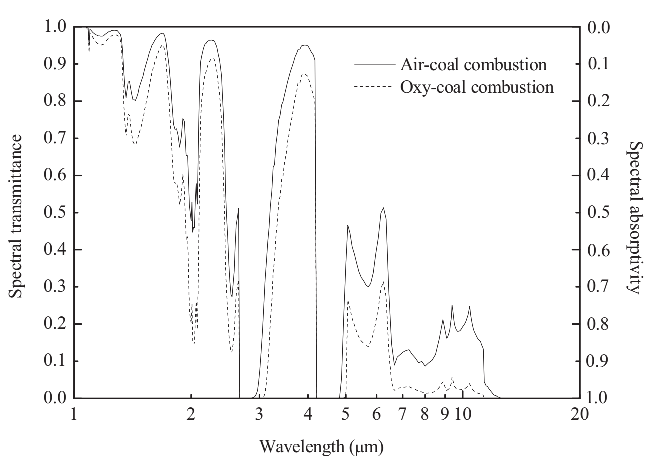

Fig. 1. Comparison of spectral radiation properties of air- and oxy-coal combustions.

Our previous study (Hu et al., 2012b) found that the oxy-coal combustion results in a higher emissivity of flue gas and enhance the radiative heat transfer compared with the air-coal combustion due to the higher radiating gas contents ($H_2O + CO_2$). On the other hand, due to the flue gas recirculation, the recycled flue gas will absorb an amount of heat and weaken the radiative heat transfer. Although combustion takes place with same load (heating value input), it has a great impact on the radiative heat transfer section of boilers due to the change of combustion environment. From engineering point of view in particular for the retrofit applications, oxy-coal combustion technology would be easily implemented if it can operate under the conditions that are similar to air-coal combustion. Therefore, the adequate prediction of the radiation intensity on lateral walls of furnaces is crucial for the retrofitting and design of industrial boilers.

The objectives of this paper was to quantitatively descript the flue gas recycle with combustion parameters and numerically study oxy-coal combustion based on a real oxy-coal combustion test (Smart et al., 2010). Specifically, to identify the relationship between FGR ratio and effective O_2 concentration in oxy-coal combustion through the results calculated from CFD simulations; to evaluate the effect of absorption coefficient models on radiative heat transfer, and analyze the characteristics of incident radiation distribution and intensity under various operating conditions.

2. Description of combustion test facility (CTF) (Smart et al., 2010)

Numerical simulations of pulverized coal combustion were performed based on a test on the RWEn CTF with a 0.5 MW international flame research foundation (IFRF) aerodynamically air staged burner. The available experimental results from the test were selected for the validation of these simulations. The CTF has a refractory lined combustion chamber with an inner cross-section of 0.8 m × 0.8 m and approximately 4 m long (Fig. 2), and the detail dimensions of the burner are shown in Fig. 3. For all cases, the primary air transporting pulverized coal enters from the internal annulus with an axial velocity of 15 m/s and secondary swirled air enters from the external annulus with a swirl number (S_0) of 0.6; the temperatures of the primary and secondary streams were maintained at 343 K and 543 K, respectively; the O_2 concentration of primary stream ($[O_2]_{primary}$) was maintained at 21 vol% and the O_2 concentration of secondary stream ($[O_2]_{secondary}$) was tuned to drive the exit O_2 concentration ($[O_2]_{exit}$) to an expected value. The effective O_2 concentration ($[O_2]_{effective}$) was defined as the average of the $[O_2]_{primary}$ and the $[O_2]_{secondary}$.

3. Mathematical models for pulverized coal combustion

The commercial software, ANSYS FLUENT 13.0 (2011), was used to simulate combustion, fluid and particle flow, as well as heat and mass transfer inside the CTF. The mesh system of fluid domain consisted of 28,000 cells as shown in Fig. 4. The cell size is about 1.2 cm, which is equivalent to the cell size in the reference (Al-Abbas et al., 2011) and is of acceptable accuracy. The mesh was refined at the location of the burner, where the ignition and most of the combustion reactions occurred. When the coal particles travel through the CTF, drying, devolatilization, volatile combustion, and char burnout occur in series. The discrete phase (coal particles) was modeled using the Eulerian–Lagrangian approach with pressure-based solver to this two-dimensional axisymmetric swirl problem.