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Heat transfer in a 4–MW_{th} circulating fluidized bed furnace operated under oxy-fired and air-fired conditions: Modeling and measurements

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ABSTRACT

Heat transfer to wall panels in the furnace of a circulating fluidized bed (CFB) was investigated by means of a mathematical model in combination with measurements obtained from a 4–MW_{th} CFB unit operated under air and oxy-fuel firing conditions. The conditions at the wall panels corresponded to a concentration of solids in the range of 0.35–18 kg/m^3 and temperatures of 1054–1168 K. The coefficient of heat transfer to the wall panels was similar for the oxy-fuel-fired and air-fired systems, since the solids flow, which plays a major role in heat transfer in CFB furnaces, was maintained at similar levels in the air- and oxy-fuel-fired cases. The modeled heat extraction of the furnace and the in-furnace vertical profiles of temperature and solids concentrations were found to be in good agreement with the corresponding experimentally measured values. The modeling results show that: (1) for all the cases studied, the share of radiation in the total heat extraction of the furnace exceeds 70% and increases with increases in furnace temperature; and (2) that gas radiation has little influence on furnace heat extraction.

1. Introduction

Oxy-fuel combustion is a major component of CO_2 capture systems for carbon capture and storage (CCS). Oxy-fuel combustion can be applied to circulating fluidized bed (CFB) boilers, which are commonly used for heat and electricity generation. Given the high thermal inertia of the solids in CFB units, oxy-fuel-fired CFB boilers may offer the possibility to operate at high inlet concentrations of O_2, thereby yielding compact furnace designs, which could lower the investment cost (Seddighi et al., 2010). Flue gas recirculation (FGR) is used in oxy-fuel CFB to control the furnace temperature while maintaining a certain gas velocity in the furnace.

Previous studies (Baskakov et al., 1973; Chen et al., 2005; Eriksson and Golriz, 2005; Huilin et al., 2000; Luan et al., 2000; Parmar and Hayhurst, 2002; Seddighi, 2013; Seddighi et al., 2010; Von Zedtwitz et al., 2007) have identified heat transfer in CFB furnaces as consisting of convection and radiation, whereby radiation predominates at low concentrations of solids (Basu and Konuche, 1988; Basu and Nag, 1996; Divilio and Boyd, 1993; Huilin et al., 2000; Seddighi, 2013; Wu et al., 1989). The importance of radiative heat transfer to the overall heat transfer in fluidized beds has been emphasized by (Saario et al., 2006) and (Chen, 1999) for air-fired combustion and by (Seddighi, 2013) for oxy-fuel combustion. According to (Basu and Nag, 1996) convective heat transfer dominates over radiative heat transfer only at solids concentrations >70 kg/m^3 for temperature levels that are typical for CFB combustion (i.e., 1123 K). Although there are reports in the literature on initial work on furnace heat transfer and heat balance in oxy-fuel-fired CFB (Seddighi, 2013; Seddighi et al., 2010), there has been no study to date that validates heat transfer modeling work with measurements carried out in a large-scale CFB oxy-fuel unit.

The in-furnace temperature distribution is of importance for the formation and reduction of harmful species within the furnace (Anthony, 2012; Basu, 1999; Cao et al., 2008; Gavin and Dorrington, 1993; Leckner, 1998; Liu et al., 2000). Air-fired CFB boilers are characterized by a relatively uniform temperature along the furnace height, (Brereton and Grace, 1993; Koornneef et al., 2007) which is due to the thermal inertia of solid particles. Thus, it is important to determine whether a relatively uniform temperature can also be maintained during oxy-fuel combustion.

The aims of the present work were to: (1) investigate experimentally the temperature and heat transfer profiles in a 4–MW_{th}

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oxy-fuel-fired CFB furnace under air-fired and oxy-fuel-fired conditions; and (2) present and validate a mathematical model of in-furnace heat transfer that accounts separately for convective and radiative heat transfer under air-fired and oxy-fuel-fired conditions. The experimental air-fired case is used to fit a convective heat transfer correlation, which is thereafter applied to validate the model against the experimental runs carried out under oxy-fuel conditions. In summary, this work addresses an existing gap in the literature regarding the modeling of and experimentation on in-furnace heat transfer in air and oxy-fuel-fired CFB beyond the laboratory scale, by providing modeling and experimental data on a unit that is relevant for industrial-scale operation.

2. Modeling

The semi-empirical heat transfer modeling presented in this work is part of a comprehensive process modeling framework (Seddighi et al., 2013a; Seddighi, 2013; Seddighi et al., 2010) that has been implemented in MATLAB. The modeling framework includes a combustion model developed by (Seddighi et al., 2013b) for both air-fired and oxy-fuel-fired conditions and a fluid dynamics model for the in-furnace solids flow developed (Johnsson and Leckner, 1995; Pallarès, 2008; Pallarès and Johnsson, 2008). The model applies a core wall-layer structure of the in-furnace flow (illustrated in Fig. 1) to reflect the flow features of large-scale CFB furnaces (Senior and Brereton, 1991). The modeling includes a global heat and mass balance with respect to gases [including Flue Gas Recirculation (FGR) and O_2 or air] that are introduced into the unit through primary or secondary gas injection points.

The model calculates the temperature in a calculation cell by performing a corresponding conservation of mass and energy calculation, which accounts for heat transfer through enthalpy flows of convection and radiation, q_{conv} and q_{rad}, which in turn are related to the streams of gas and solids entering and leaving the cell, q_g, and q_s (cf. Fig. 1) and the heat produced by homogeneous and heterogeneous combustion reactions within the cell, q_{comb}. The model is developed to account for radiative exchanges between the core, the wall layer, and the furnace wall in the nine possible combinations. Thus, the wall-layer to "opposite wall-layer" radiation (as well as the furnace wall to opposite furnace wall radiation) is represented by "self-absorption" of a fraction of the emitted radiation. Thus, the heat balance in these three types of calculation cells can be described as: For the core region,

$$q_{comb,\,core} + q_{g,\,core\,i-1} - q_{g,\,core\,i+1} + q_{s,\,core\,i-1} - q_{s,\,core\,i+1} - q_{s,\,lat} + q_{rad,\,core} = 0 \quad (1)$$

where the subscript core in Eq. (1) refers to the relevant value in the core, subscript lat refers to the solids leaving the core-region cell to the wall-layer cell, and subscripts i, i + 1, and i − 1 refer to the calculation cells, as shown in Fig. 1. For the wall-layer region,

$$q_{comb,\,wall\,layer} + q_{g,\,wall\,layer\,i-1} - q_{g,\,wall\,layer\,i+1} + q_{s,\,wall\,layer\,i+1} - q_{s,\,wall\,layer\,i-1} - q_{s,\,lat} + q_{rad,\,wall\,layer} - q_{conv} = 0 \quad (2)$$

where the subscript wall layer in Eq. (2) refers to the relevant values in the wall layer. For the walls,

$$q_{rad,\,well} + q_{conv} = q_{condtube} \quad (3)$$

where subscript wall refers to the walls, and $q_{condtube}$ is the heat conducted to the water-side through the heat extraction tubes.

In the following section, convective and radiative heat transfers, which comprise the semi-empirical parts of this heat transfer modeling, are described.

2.1. Convection

Convective heat transfer flux is generally calculated as:

$$q_{conv} = h_{conv}\Delta T \quad (4)$$

where h_{conv} is the convective heat transfer coefficient, and ΔT is the temperature difference between the two elements that are exchanging heat.

Gas convection and solids convection can be combined into a lumped gas–solids convective heat transfer coefficient, which can be correlated to the concentration of solids. (Breitholtz et al., 2001; Divilio and Boyd, 1993; Seddighi, 2013; Seddighi et al., 2010)

$$h_{conv} = \varphi C_s^{\beta} \quad (5)$$

where h_{conv} is the convective heat transfer coefficient, and C_s is the concentration of solids. The values of φ and β have been determined experimentally by (Breitholtz et al., 2001) as 25 and 0.58, respectively, and by (Divilio and Boyd, 1993) as 23.2 and 0.55, respectively. Both (Breitholtz et al., 2001) and (Divilio and Boyd, 1993) used cross-sectional average concentrations of solids to calculate the values for φ and β in Eq. (5), with the assumption that the local solids density in the wall layers was proportional to that in the core region, in line with experimental findings (Zhang et al., 1995; Zhang et al., 1997). However, for a more physically stringent description, expressions of the coefficient for convective heat transfer from the wall layer to the furnace walls should instead use the local wall-layer solids concentration in Eq. (5). Thus, since the present heat transfer model accounts for local (axial) variations in the wall-layer flow structure (e.g., exit effects on wall-layer flow), the wall-layer solids concentration is used for convective heat transfer modeling. In the present work, the pre-exponential factor φ in Eq. (5) is derived from a fit to a reference experimental case (under air-fired conditions). Regarding the value of β in Eq. (5), it is assumed to be the same as that (0.58) reported by (Breitholtz et al., 2001), given the experimentally-proven proportionality between the concentrations of solids in the core region and in the wall layers.

2.2. Radiation

The present work assumes gray radiation, as radiative heat transfer in a CFB riser is assumed to be dominated by the radiation from the hot solids. At a given height, the modeling accounts for the transfer of radiative heat between the two cells and the furnace walls, i.e., the core cell and the wall cell, and the furnace wall. Radiative heat transfer can be modeled using either the Monte Carlo method or the net radiation method (Dupert et al., 1990). The Monte Carlo method is based on statistics and is well-adapted to complex systems although it is computationally expensive for heat transfer modeling, (Dupert et al., 1990) and thus, the net radiation method was chosen for the present work, i.e., the net radiative heat transfer refers to the net rate of loss or gain of energy and is calculated as:

$$q_{rad} = q_{absorption} - q_{emission} \quad (6)$$

The value of the emitted radiative heat at each cell can be written as:

$$q_{emission} = \epsilon\sigma T^4 \quad (7)$$

where ϵ is emissivity, σ is the Stefan–Boltzmann constant, and T is the patch temperature, with "patches" herein referring to the surfaces of each calculation cell, which are assumed to be isothermal.

The emissivity of the heat extraction surfaces is assumed to be 0.8, which is the value for emissivity of oxidized surfaces used by (Yoshida et al., 1974) and (Breitholtz et al., 2001).