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Experimental and numerical study of MILD combustion in a lab-scale furnace

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Abstract

Moderate or Intense Low-oxygen Dilution (MILD) combustion has been proven to be a clean and efficient combustion technology in industrial process furnaces due to its capability of combining low NOx emission and air preheating. Jet in hot coflow burners[1,2] were used to mimic the dilution of air by recirculation of combustion products in furnaces. Semi-industrial furnace[3] work in similar way as industrial furnaces, and represent almost all their features, but it is very difficult to make detailed measurements in it. Lab-scale furnaces[4–6] offer the best opportunities for studying, experimentally and numerically, MILD combustion processes in the presence of significant recirculation and heat transfer.

The inner dimensions of the furnace are $320mm \times 320mm$ with a height of $630mm$, operating with a recuperative Flame-FLOX burner. To heat up the furnace the burner first works in flame mode, with premixed flames stabilised on the nozzles that subsequently when the burner operates in MILD mode are used as air nozzles. The switch to MILD mode is made when the furnace temperature reaches $850°\mathrm{C}$. Then natural gas and air are injected through the central fuel nozzle ($\phi 4.5mm$) and four air nozzles ($4 \times \phi 8.6mm$), respectively. Flue gas is introduced into the recuperator to preheat the combustion air. The top wall of the combustion chamber is air cooled and can act as a heat sink. Quartz windows provide full optical access to the interior of the furnace to enable laser diagnostics.

The furnace was fired with Dutch natural gas (DNG) at $10kW$, equivalence ratio 0.8 with one vertical window ($105mm \times 600mm$) and without top plate cooling. The OH* chemiluminescence originates only from the reaction zone so that it yields information about the position and size of the reaction zone[7]. To find out the location of reaction zone, the OH* chemiluminescence images were collected at different heights with an intensified high-speed camera, equipped with a UV lens and a bandpass UV filter centred at 308 nm with a bandwidth of 20 nm. In chemiluminescence measurements, 4000 single instantaneous images were recorded and averaged, and then reconstructed. The reconstructed OH* chemiluminescence image as shown in figure 1 covers the region from $165mm$ to $525mm$ above the nozzle and shows reactions start from $300mm$ above the nozzle and intensity is relatively uniformly distributed around the fuel jet axis.

Although Eddy Dissipation Concept (EDC) model shows its power in MILD combustion modeling in furnace, it is too computational expensive when incorporating with detailed chemistry mechanism. Flamelet Generated Manifold (FGM) approach is more attractive in this sense. The challenge of modelling combustion in furnace with FGM approach is the dilution effect of internal recirculated flue gas. FGM approach has been extended to consider the flue gas as a dilution stream[8–10]. In the extended approach, an additional independent variable, in addition to mixture fraction, progress variable and enthalpy is introduced, namely a dilution variable Y_d. It describes the dilution by recirculation and entrainment of flue gas. Local gas mixture is consider as a mixture of fuel, air and diluent, and local mixture fraction Z is written as: $Z = (1-\alpha)Z_0 + \alpha Z_d$, where Z_0, Z_d and α denote the mixture fraction of fresh fuel and air, mixture fraction of flue gas and flue gas mass fraction, respectively. α is calculated as the ratio between local dilution variable (Y_d) and dilution variable in flue gas (Y_d^{dil}).

However, using flue gas as dilution is not appropriate when furnaces are working at lean condition. On the one hand, the excess air left in the flue gas also takes part in reactions, especially it reacts with fuel immediately when entrained by fuel jet. On the other hand, the local dilution variable is larger than that in flue gas when local mixture fraction Z_0 of fuel and air is at stoichiometric mixture fraction $Z_0 = Z_{st}$,

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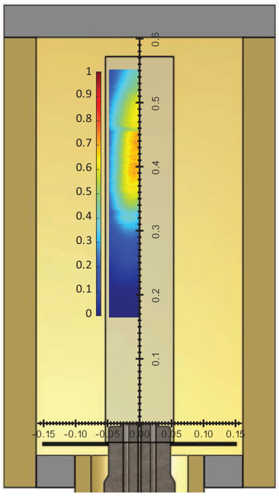

Figure 1: OH* chemiluminescence

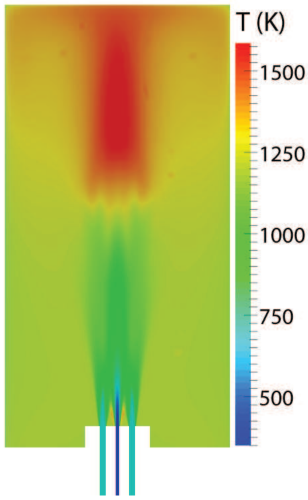

Figure 2: Predicted temperature on the mid-plane

resulting in mass fraction $\alpha > 1$ which is not physical. How to define the dilution stream determines the model is physical or not. To use combustion products at stoichiometric condition as the diluent is proposed. Flue gas is treated as a mixture of excess air and diluent. The local mixture fraction Z is then expressed as: $Z = (1-\alpha)Z_0 + \alpha Z_{st}$. Now, Z_0, Z_{st} and α denote the mixture fraction of fuel and air (excess air is included), mixture fraction of diluent and diluent mass fraction. The newly introduced dilution variable is solved by its transport equation with a source term $\dot{\omega}_{Y_d}$ which transfer the products to diluent at local condition when reaction is complete, that is progress variable equals to 1.

Numerical simulations are made based on the extended FGM approach including also the effects of radiation. Influence of turbulence on local flame structure is taken into account by presuming β-shape PDF for mixture fraction and progress variable. Control parameters in this approach are mixture fraction, mixture fraction variance, progress variable, progress variable variance, enthalpy loss parameter and dilution variable. The 6 dimensional tables are pre-calculated. Modeling results show the high temperature zone (figure 2) is consistent with the reaction zone indicated by OH* chemiluminescence measurements. The reactions between fresh fuel and air left in flue gas are predicted when fuel enters the furnace. Radiation significantly influences the heat transfer inside the furnace.

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