2nd Oxyfuel Combustion Conference

Assessment of Oxyfuel Circulating Fluidized Bed Boilers – Modeling and Experiments in a 5 MW Pilot Plant

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Keywords: oxyfuel combustion, fluidized bed, CO_2 capture, modeling, experiments

Introduction

As in air-firing, oxy-fired combustion using the Circulating Fluidized Bed (CFB) technology may offer advantages in that the CFB technology provides high fuel flexibility, in-furnace reduction of SO_x emissions and a relatively smooth distribution of the extracted heat flux. Furthermore, the thermal flywheel induced by the solids flow and the possibility of heat extraction in the solids recirculation system (*i.e.* outside the furnace) represent a potential to achieve high oxygen concentrations while limiting the temperature level. Allowing such higher oxygen concentrations would imply significantly more compact (and thus less costly) furnaces than those used in air combustion.

The present work summarizes the current status of an ongoing project which has the aim to assess the oxyfuel CFB technology by means of pilot testing and modeling. The pilot testing is carried out in a 5 MW oxyfuel CFB pilot plant (representing the largest oxy-fired CFB unit running at present date). The model is an extended version of a model for air-fired CFB combustion developed over the last six years by the authors and validated for utility-scale units.

Considering that the model has previously undergone an extensive validation against data from air-fired large-scale boilers, the model is expected to represent a useful tool for the assessment, design and scale-up of oxyfuel boilers once validated with measurements from the 5 MW oxyfuel unit,. An obvious application of the model is in the dimensioning and designing heat extraction surfaces. High oxygen concentrations require more heat extraction in the solids recirculation system, which is allowed by means of increased external circulation of solids. Such increased solids circulation can be established with modifications to the furnace design and a change in operating conditions and/or solids properties. A first estimate of the operational conditions and limits for oxy-fired CFB is given in [1].

Modeling procedure

The model is comprehensive in that it is able to provide 1.5 and 3-dimensional descriptions of the fluid dynamics, chemistry and heat transfer in the furnace of large-scale CFB units and is described in detail in [2]. The present work

provides results from the 1.5-dimensional version, in which the furnace is resolved in the vertical direction with a horizontal separation between core region and wall layer (yielding a "1.5-dimensional" model). The model includes transient characterization of the total solids inventory accounting for the dynamics of solids attrition (characterized by feedstock tests) [3] and different possibilities in the configuration of the flue gas recirculation (FGR) system. The model solves the transient behavior of the solids inventory in direct coupling with the fluid dynamics (due to the strong coupling between these).

The solids flow in the furnace is described accounting for one dense solid phase in the bottom of the furnace and two solid phases in the freeboard: a cluster phase dominating the splash zone in the lower freeboard and a dispersed phase establishing a core-annulus flow structure in the upper freeboard (with upflow in the core and downflow in the region near the furnace walls), according to [4]. Mixing of the fuel particles accounts for the varying fluid dynamical behavior of fuel particles as they undergo conversion (and thus change size and density), as described in [5]. The fluid-dynamics modeling is linked to a submodel describing the kinetics of fuel conversion and as a result, the release rate fields for moisture, volatiles and char conversion products are obtained. Such conversion kinetics is modeled by a pseudo-steady state solving of the heat diffusion into the fuel particle, with the expressions proposed in [6]. The model includes fuel fragmentation, based on experimental data from digital image analysis as input. Gas mixing in the furnace is described using potential flow theory at a macroscopic scale and accounts for the fluctuating nature of the gas flow in fluidized beds, as described in [7]. These gas fluctuations originate from the dense bed dynamics and influence the local mixing, since dynamics of the gas play an important role (controlling for example volatile combustion) and reducing and oxidizing conditions can alternate at a given location in the furnace. This latter feature is of great importance and unique for this model.

The dominant heat transfer mechanism in heat extraction from CFB boilers is convection (*i.e.* direct contact of fluidized solids with the heat extraction surface), although radiation may dominate role in the upper and more dilute part of the furnace. An important feature of the model is the separate modeling of convective and radiative heat transfer, often lumped together in CFB modeling. Radiative and convective heat transfer coefficients used in the model (including optical factors and average emissivity of gas-solid suspensions of different concentration and with different solids sizes) have been taken from large-scale CFB data [8]. With solids radiation expected to dominate under CFB conditions, gas radiation is neglected.

Experimental setup:

Figure 1 illustrates the 5 MW oxyfuel CFB boiler. In addition to providing experimental results for comparison with the modelling, the boiler experiments are used to evaluate safety and technical feasibility of oxyfuel combustion. The experimental project has been carried out by Metso Power Oy and Fortum with partial funding by Tekes (the Finnish Funding Agency for Technology and Innovation). Experiments included both air-fired and oxy-fired cases.

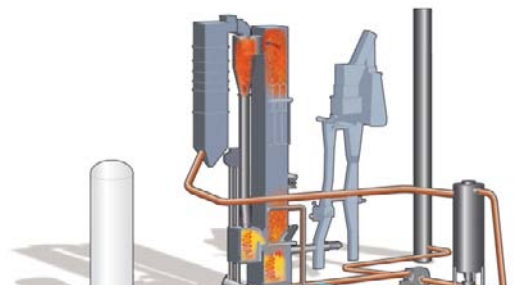

Figure 1: View of the 5MW oxyfuel CFB pilot plant used for the experimental runs.

The furnace has a height of 13 m with a cross section of 1x1 m^2 at the furnace top. The unit is equipped with a single cyclone while Oxygen is provided from a 50 m^3 liquid oxygen tank to the system. Another feature of this unit is a great flexibility in heat extraction capabilities by means of movable heat extraction panels attached to the furnace walls resembling waterwalls. Also, flexible heat extraction from the solids recirculation system is available through a tube heat exchanger placed in the particle seal. Makeup material was used in order to control the solids bed inventory during the runs. Two different coal types have been used as fuel during the tests. Different parameters have been varied during the runs in order to study their influence on the combustion process: feed oxygen concentration (ranging from 16 to 36$\%_{vol,\ wet}$), Ca/S ratio, bottom bed temperature (between 800 and 900 Celsius), humidity of RFG used in seal fluidization, fluidization velocity,
primary-to-secondary gas and oxygen ratios. The heat extraction duty and the loop seal heat extraction has been used in a way to achieve the predefined dense bed temperatures. Also, fuel batch experiments to study dynamical response of the unit and kinetics of char combustion were performed. The experimental data collected for analysis comprises heat extraction rates of the different panels, temperature, pressure, gas composition profiles and solids samples.

Results:

Figure 2 exemplifies modeling results with vertical gas concentration profiles corresponding to an oxy-fired (36% O_2) case and an air case, both with thermal fuel inputs of 4.7 MW (corresponding to the pilot plant test conditions). Secondary gas injections at two levels above the gas distributor can be seen from the sharp jumps in the curves. These model results show that a major part of the combustion in the oxyfuel case can be expected to take place in the bottom regionof the furnace, i.e. the oxyfuel case gives a much steeper gradient in oxygen concentration than in the air case. This is due to an inctreased rate of char combustion with char being mostly present in the lower part of the furnace.

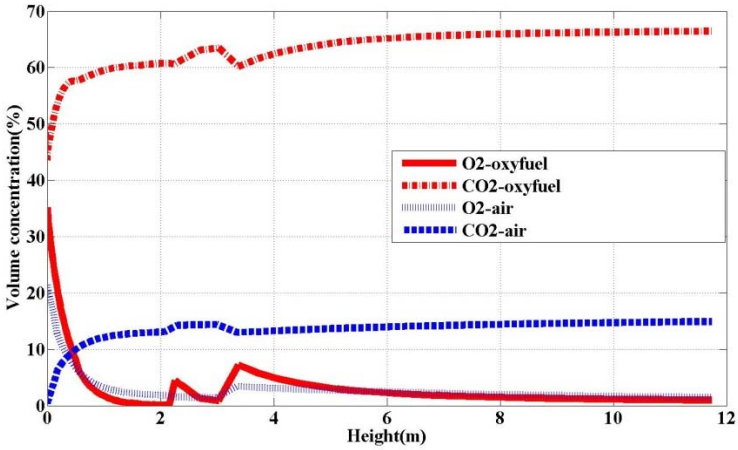

Figure 2: Modelled vertical concentrations of O_2 and CO_2 for the 5 MW pilot plant. In addition to O2 and CO2, the flue gases contain moisture (in significant amounts, since flue gas is recirculated on a wet basis).

The conference presentation will provide results from the ongoing evaluation of experimental runs, including a comparison with modelling.

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