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Modelling and dynamic simulation of a supercritical, oxy combustion circulating fluidized bed power plant concept—Firing mode switching case

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ABSTRACT

Dynamic process simulation provides a tool to evaluate operational issues of a new process concept before the plant construction. This paper studies a carbon capture and storage (CCS) capable power plant concept with a model including a supercritical once-through CFB boiler with gas and water steam sides, a turbine island, an interface from the air separation unit (ASU) and the control system to manage typical operational transients. Switching between the air and oxy firing modes is one of the key operations in oxy combustion processes. The selected mode switching strategy uses simultaneous linear ramps for the mass flows of the primary and secondary air, oxygen, and recirculated flue gas. The results show that the firing mode can be successfully switched within 25–37 min. The flue gas path difference between the air-firing and oxy-firing modes due to the flue gas recirculation causes significant differences in dynamic behaviour. The simulations emphasize importance of good control and coordination of the gas flows. Feedback control of the flue gas and/or oxidants O_2 content during the mode switching is suggested to improve robustness against disturbances, for example, in oxygen delivery, flow measurements, fuel feeding and combustion.

1. Introduction

Finding effective ways to slow climate change and reduce greenhouse gas emissions is one of the greatest environmental challenges today. Carbon capture and storage (CCS) may be the most promising of the available technologies to significantly reduce carbon dioxide (CO_2) emissions. The three major technologies for carbon capture and storage in the power industry are pre-combustion, post-combustion and oxy (oxyfuel) combustion (Kunze and Spliethoff, 2012). This paper investigates oxy combustion, which refers to a method in which oxygen (O_2) is used in combustion, and flue gases are recirculated as such, or after cleaning stages, to dilute the O_2 content in the oxidants to a feasible range. As the oxidants are close to nitrogen – (N_2) free, a high CO_2 content in the flue gas can be reached, which facilitates its capture in the CO_2 purification unit (CPU). Some N_2 and argon remain in the flue gas due to air inleakage and impurities in the O_2 produced. The oxy combustion process differs from the conventional plants, but retrofitting to oxy combustion is possible.

The oxy combustion power plant, including the supplementing process units needed for continuous O_2 production and CO_2 capture, is a challenging topic from the operability point of view. Synchronization of process units and flexibility in operation is required especially in the oxy firing mode. The plant start-up and shut-down are conducted in the air firing mode, which makes the switch between the modes a rather frequent task. Fast mode switching from oxy to air is also needed in case of operational issues

Abbreviations: AIR, air stream into primary/secondary oxidant; ASU, air separation unit; CPU, CO_2 purification unit; CFB, circulating fluidized bed; FG, flue gas side; GOX, gaseous oxygen stream into primary/secondary oxidant; HP, high pressure; IP, intermediate pressure; LP, low pressure; LOX, liquid oxygen; PC, pulverized coal; RFG, recirculated flue gas stream into primary/secondary oxidant; WS, water steam side.

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in flue gas recycling or O_2 supply. The mode switching comprehensively affects the compositions, density and heat capacity of the flue gases, inducing changes into heat transfer, operational aspects, as well as safety requirements. The gas side process experiences a structural change due to the flue gas recycling, which is used only in the oxy mode. Moreover, the switching includes/excludes the ASU and CPU units, which emphasizes the system design in the interfaces with the boiler island. These are examples of issues, which dynamic process simulation can address thus justifying the development efforts for models with adequate scope and rigour. Dynamic simulation is the proven tool to evaluate the process design and control design together.

The literature on dynamic simulation of the oxy combustion processes is very limited. Moreover, the majority of the studies belong to the domain of computational fluid dynamics (CFD) (see, e.g., Scheffknecht et al., 2011). Because the CFD methodology is not generally suited for control and operability analysis of large systems, only the dynamic process simulation studies were reviewed, see Table 1.

Most of the papers investigate PC plants and show only few simulation results. This paper presents a modelling and dynamic simulation of the oxy combustion supercritical once-through CFB boiler, including the flue gas and water steam sides, the turbine island, and the interface between the ASU and boiler. The modelling and simulation were conducted with the commercial simulation platform Apros. The plant dynamics is demonstrated with a wide set of process variables in firing mode switches. A simple switching strategy with ramp-wisely controlled mass flows was selected. The mass flows (instead of volume flows) are used to give insights on the mass balances and dynamics. Furthermore, no O_2 content controls of the gas streams were used during the switching to highlight the system behaviour with the strategy selected.

The structure of this paper is as follows. Section 2 describes the power plant concept, the modelling platform and the scope of the modelling. More details on the simulation methodology and description of the new CFB model component are given in supplementary material. Section 3 first presents a base case simulation of firing mode switches from air to oxy and back to air. Sensitivity aspects are then discussed and illustrated by additional simulations. Finally, the methods used and the results are discussed in Section 4, and Section 5 sums up the main conclusions of the study.

2. Methods

2.1. Power plant concept

The work here presented has been part of the FLEXI BURN CFB project (VTT, 2013) under the EU Seventh Framework Programme (FP7), which developed and demonstrated an oxy combustion concept based on CFB combustion and a supercritical once-through water steam cycle. The project included experimental work within oxy combustion and CFB technology in the laboratory, pilot, and industrial demonstration scale. It also included the development of an OXY-CFB-300 power plant concept, which has been the basis for this modelling and simulation study. The concept was designed for high flexibility in respect of fuels and oxidants; continuous operation both in the air and oxy modes is possible.

The CFB technology has been intensively developed in the last two decades for use in utility boilers. Thus far the largest power-generating unit (460 MW_e) with supercritical CFB (traditional air firing) started operation in 2009 in Łagisza, Poland. The advantages of circulating fluidized bed combustion include high efficiency, fuel flexibility, the option to use a large proportion of biomass in the fuel, and emission control without any use of secondary systems (Ostrowski and Goral, 2010). The fuel flexibility helps to compensate for the additional costs of CCS by allowing the use of lower quality fuels. The functionality of the oxy combustion CFB technology has recently been proven in the CIUDEN demonstration power plant in Spain, which is the largest (30 MW_{th}) operational oxy combustion CFB plant.

Fig. 1 presents schematic flow diagrams of this 300 MW_e CCS-capable power plant. The system is comprised of the ASU, the boiler island, the turbine island and the CPU. The ASU performs cryogenic air separation to produce O_2 (96.6 mol% purity) for the oxy firing operation, and the CPU purifies and compresses the CO_2 for transportation or storage. Estimates for the energy penalty of the CCS with the oxy combustion approach are generally 7–12% (Zapp et al., 2012).

The boiler island design is based on Foster Wheeler's Flexi-Burn[TM] technology. The boiler island includes feed systems for fuel, sand and limestone; primary and secondary oxidant streams; furnace; cyclone; return leg; baghouse; heat recovery system to preheat the gaseous oxygen (GOX) streams; flue gas recirculating (RFG) system; and different types of heat exchangers to transfer heat from flue gas and fluidized solids into water and, on the other hand, from water steam cycles to gas streams. The term oxidant stream (or simply oxidant) is used here to describe the gas stream, which carries O_2 to the furnace. The primary and secondary oxidant streams begin in the point where GOX and RFG streams are mixed. In the air mode the gas stream to the same point is obtained from outside air, hereafter simply called as AIR. The flue gas circulation is only used in the oxy firing mode. The circulated CO_2-rich flue gas is divided into primary and secondary streams, which are mixed with the corresponding GOX streams, thus diluting the formed synthetic oxidants into a reasonable range of O_2 content to control the combustion temperature and guarantee safe and economic operation of the boiler. After the mixing point, there are steam preheaters to heat up the oxidants before injection to the furnace. The flue gas is recirculated as wet gas; the flue gas water is removed in the CPU process area before the gas compression.

Fuel, limestone and sand are fed into the bottom of the CFB furnace. The limestone is fed to capture sulphur in the bed, thus minimizing the SO_X emissions. The sand feed is needed at start-up and, occasionally, during the operation to maintain the bed material balance. The oxidant streams fluidize the solid material, which is partly carried to the upmost parts of the furnace. The primary oxidant is used to control fluidizing, whereas the secondary oxidant is used to control the flue gas O_2 content. As the smaller particles of the fluidized bed in the furnace rise up, some of the solids are withdrawn in the outlet flow. The solids are separated and returned (circulated) back to the furnace. Special fluidized bed heat exchangers (INTREX[TM]) are used to extract heat from the circulated, hot material into the water cycles.

The water steam side consists of cycles that serve the high pressure (HP), intermediate pressure (IP) and low pressure (LP) turbine stages, and the preheating of the oxidant and GOX streams. The supercritical HP cycle includes an economizer, hanger tubes, INTREX[TM] chamber, evaporator, furnace roof heat exchangers and superheaters I–IV. More details on a similar type of supercritical CFB design, yet limited to air firing, can be found, for example, in Ostrowski and Goral (2010).

2.2. Modelling platform

The modelling and simulation tool used in this study is the commercial simulation software Apros (Apros Combustion 5.13). The Apros platform (Apros, 2014) provides an environment for configuring and running simulation models of industrial processes, such as combustion and nuclear power plants (Silvennoinen et al., 1989). Besides the process systems, the controls and binary automation, as well as the electrical systems, can be modelled. The simulation