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Investigation into gas dynamics in an oxyfuel coal fired boiler during master fuel trip and blackout

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ABSTRACT

In an oxygen fired power plant, a large amount of flue gas is recirculated, leading to an unavoidable interaction between the involved fans. The presented paper investigates the dynamics of the gas side at different safety related scenarios. A dynamic simulation model is therefore developed to study the flue gas behaviour in an oxyfuel pulverized coal fired boiler during a master fuel trip and a blackout of the plant. The generated numerical model contains the water/steam side of the boiler, starting from economiser inlet and ending at the hot reheat outlet, and the gas side, including all relevant fans, convective heat exchangers, gas–gas heat exchangers and flue gas cleaning devices. Furthermore, a set of additional models for coast down behaviour of axial fans has been implemented. For the master fuel trip case, different relevant parameters of process control measures regarding the gas dynamics have been analyzed and an optimized master fuel trip scenario is proposed. The blackout of an oxyfuel coal fired boiler at nominal load is detailed demonstrated. The numerical results show that the blackout scenario will not have any negative impact on investigated gas part of the boiler system since the observed lowest negative furnace pressure of −36 mbar can be handled with current state of the art technology.

1. Introduction

In the last decade the carbon capture and storage (CCS) technology, which has a significant CO_2 reduction potential moved into the focus of scientist and industry [1,2]. One of the CCS technologies is the combustion of a fuel with a nitrogen-free oxidant. Air is therefore separated into nitrogen and 95% pure oxygen, employing an air separation unit (ASU), which can be designed as a cryogenic or a membrane based unit [3]. The obtained oxygen enriched air is burned with coal in a pulverized coal furnace or a circulated fluidized bed together with recirculated flue gas in order to keep the flame temperature below a reasonable limit. The exhaust flue gas is then cleaned and its water content is condensed. Finally, the CO_2 stream is fed into a gas processing unit (GPU) and prepared for storage or further utilization. The principle of the oxyfuel combustion was introduced in 1982 by Horn and Steinberg [4], however it had taken nearly three decades to construct the first pilot plant. Several pilot plants with various nominal thermal capacities ranged between 1 and 30 MW_{th} are now under investigation. An overview of the these test rigs in operation and planning was prepared by Wall [5].

One challenge for the design and operation of an oxyfuel fired power plant is the gas side with its complex recirculation path, the air separation and the gas processing unit. Knowledge of the transient behaviour of the gas dynamics during malfunctions or trips of different components are a key interest in order to prevent severe boiler damage or implosions [6]. These implosions in the past were often induced by the change from a forced draft system to a balanced draft system or by a larger retrofitted induced draft fans.

Unfortunately, the interaction between the involved fans is amplified in an oxyfuel plant by the recirculation path. The design and operation experiences of large conventional thermal power plants can only be used partly since whole structure of the gas side is quite different. Furthermore, the experiences of oxyfuel pilot facilities can only be partly adopted for large scale power plants due to test plants character and inadequate knowledge of the real process.

Transient one-dimensional simulation models offer an effective tool to evaluate the behaviour of thermal power plants and can contribute to a better understanding of the process, its capabilities and limitations. These models are applied to study the flue gas dynamics in conventional air fired pulverized coal power plants since many

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Nomenclature

c_p	heat capacity in kJ/kg K
F	force per volume in N/m^3
G	constant for coast down
h_0	stagnation enthalpy in kJ/kg
$\dot{m}$	mass flow in kg/s
M	torque in Nm
n	speed in rpm
p	pressure in MPa
P	power in W
$\dot{Q}$	heat flow in W
t	time in s
T	temperature in K
TF	transfer function
u	velocity in m/s
$\dot{V}$	volumetric flow in m^3/s
z	longitudinal distance in m
η	fan efficiency
Θ	inertia in kg m^2
κ	heat capacity ratio
ρ	density in kg/s
ω	angular velocity in rad/s

Subscripts

0	start of trip
air	air
f	fan
fal	false air
fur	furnace
grav	gravitation
in	inlet
m	motor
out	outlet
oxi	oxidant
rec	recirculation
rf	rotary feeder
sc	screw conveyor
w	wall

Abbreviations

AF	auxiliary fan
APROS	advanced process simulation software
ASU	air separation unit
BMCR	boiler maximum continuous rating
BUS	burn out supply
CCS	carbon capture and storage
CPH	condensate preheater
ESP	electro static precipitator
EVAP	evaporator
FECO	final economizer
FGC	flue gas condenser
FRH	final reheater
FSH	final superheater
GGH	gas–gas heat exchanger
GPU	gas processing unit
HP	high pressure
IDF	induced draft fan
IP	intermediate pressure
ISH	intermediate superheater
MFT	master fuel trip
PECO	primary economizer
PRH	primary reheater
REF	recirculation fan
RF	rotary feeder
RH	reheater
SC	screw conveyor
SCR	selective catalytic reduction
SCW	steam cooled wall
SH	superheater
SHA	superheater attemperator
TGF	transport gas fan
WFGD	wet flue gas desulphurization

decades. The numerical results obtained are of high relevance for prediction of the plant behaviour during the failure malfunctions. The first simulation studies on the gas side of conventional boiler have been conducted by Clelland in 1973 which included the gas dynamics during load changes [7]. In a further study, the developed model was modified in order to simulate a master fuel trip [8]. Similar investigation were also carried out by Smoak and Lansing [9], Kirchmeier et al. [10], Robinson and Holmes [11], Wu et al. [12] and Franke [13]. Compared to fuel trip scenarios, a thermal power plant blackout is far less presented. One was published by Franke [13] in which a 900 MW$_{th}$ coal fired power plant blackout scenario was simulated. According to best knowledge of the authors, there has been no work published for the international community, which investigates the gas dynamics in a large scale oxyfuel pulverized coal fired boiler during a master fuel trip or a blackout. The interaction between the induced fan and the recirculation fan during oxyfuel operation and possible malfunctions is an important issue for large oxyfuel fired power plants. Nevertheless several dynamic simulation models of oxyfuel fired power plants have been developed in the last years. Yamada et al. presented model of an oxyfuel fired power plant with supercritical steam parameters, a power output of 1000 MWe and a positive pressure operation mode for furnace control [14]. The model of Yamanda et al. was used for load change and start-up calculations and showed a good control of the positive furnace pressure during oxyfuel operation by the GPU. Seltzer et al. modelled a supercritical oxyfuel power plant with a power output 790 MWe and a balance draft system [15]. Here, the focus was on the oxidant switch over at 100% BMCR and showed the interaction between the fans since the furnace pressure degreased down to −7 mbar (g) during the switch. The dynamic model presented by Kuczynski et al. includes the ASU and GPU and discusses some problems of oxyfuel operation, unfortunately the only simulation result shown is the thermal input during a load change during air operation [16]. A very detailed investigation of the air to oxygen switch in an oxyfuel fired circulating fluidized bed boiler was carried out by Hunltgren et al. [17] and Lappalainen et al. [18] where different control strategies are discussed. Recently, Jin et al. developed a detailed dynamic model of a conceptual 600 MWe oxyfuel power plant and investigated the change of the air to oxygen and oxygen to air at constant load [19,20]. The implemented staged control strategy was capable to change the oxidant within 17 min while keeping oxygen concentration at 2–7 mol.-%. In this work, a dynamic simulation model of a 250 MWe oxyfuel coal fired boiler is built, employing the advanced process simulation software APROS. The scope of this article is to investigate the gas dynamics of the oxyfuel pulverized coal fired boiler during the master fuel trip and the blackout. For the specific investigation of the gas dynamics after fan trip the simulation platform has been enhanced by a model for the fan coast down behaviour. An optimized and reliable master fuel is proposed through the investigation into different influences of the process control measures. Additionally, the blackout of the plant, i.e. the complete loss of electrical power, is presented.