EMISSION IMPROVEMENTS IN CFB BOILERS – MODEL PREDICTIONS AND FIELD VALIDATION

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Abstract – This paper gives a general overview of the utilization of Amec Foster Wheeler's comprehensive three-dimensional steady-state in-house model for optimization of NOx emission control in a circulating fluidized bed boiler. NOx reactions used in the model are presented along with main methods to affect NOx emission in CFB boilers. The object of the study is a 270 MW coal firing reference unit. Over 35% lower NOx emission was achieved with the new modified design compared to the original design.

INTRODUCTION

Emission permit limits for power plants are tightening all the time, forcing to find new ways to lower emissions. Fig.1 presents the basic methods of decreasing NOx and SO_2 emission of CFB boilers. NOx emission can be affected with primary methods, for example by the lowering of CFB furnace design temperature and excess air amount, and increasing air staging. As long as NOx can be lowered with these design and operational changes, there are less need for secondary means that increase the operating cost in terms of additive consumption and also investment cost in case of selective catalytic reduction (SCR) or slip catalyst. SO_2 reduction in the furnace requires limestone injection and proper temperature and oxygen levels to be captured efficiently. CaO in the bed as well as high temperature and oxygen levels on the other hand have negative effect on NOx emission. SO_2 capture can also be divided between furnace and cold-end device, like CFB scrubber (CFBS), spray dryer absorber (SDA) or dry sorbent injection (DSI).

This paper is focused on optimal NOx reduction by primary means. Typically, SO_2 emission cannot be minimized at the same time as the reactions have conflicting needs, meaning some deterioration in the SO_2 retention is inevitable and this aspect is taken into account in this study. If SO_2 emission permit limit is very strict, cold-end device might be viable and furnace can be designed more in the NOx point of view. If SO_2 capture in furnace is preferred, then it might be necessary to include selective non-catalytic reduction (SNCR) or even SRC for NOx reduction. Execution of emission optimization is always case specific.

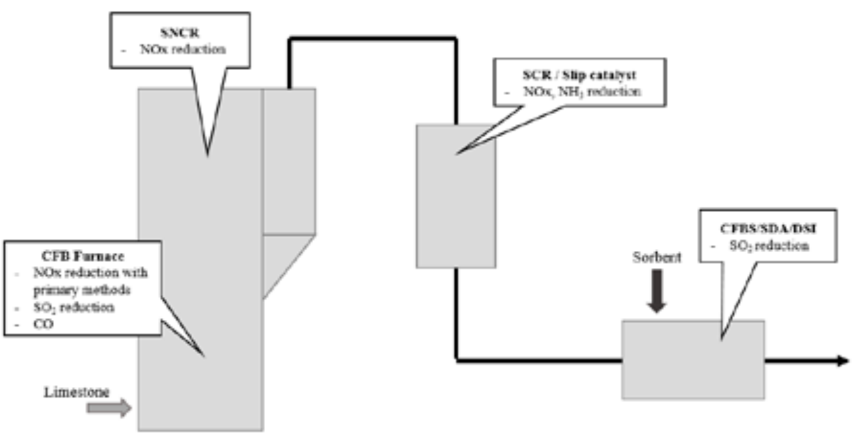

Fig.1. Flow diagram of total optimation of emissions in CFB boiler.

In this paper, the reduction possibilities of NOx emissions of coal firing CFB unit are examined with specific in-house emission tools and comprehensive three-dimensional steady state model called CFB3D (Lyytikainen et al., 2014; Myöhänen & Hyppänen, 2011; Myöhänen et al., 2005). NOx reactions in CFB3D model are presented. NOx and SO_2 formation are studied with CFB3D model in a realized 270 MW coal firing reference unit with original and new modified design. Also one of the latest Amec Foster Wheeler reference boilers with excellent emission performance is presented in the end of this paper.

MODEL DESCRIPTION AND VALIDATION

The applied model is a semi-empirical engineering model for simulating circulating fluidized bed furnaces (Fig. 2). The model theory has been presented earlier (Myöhänen & Hyppänen, 2011). This document gives only a brief description of the model. The NOx reaction modelling is described in more details in the next chapter.

The furnace is modeled by a Cartesian structural mesh, in which the different field variables are solved by a control volume method. In a usual calculation, the number of solved 3D field variables can be about 100, which include pressure, gas velocities, solid velocities and concentrations for inert bed, fuel phase, and sorbent species, concentrations of 16 gas species, and temperature. All solid phases are divided to six particle size classes to enable simulation of attrition. The model can handle unlimited number of fuels (multifuel combustion). Because of large number of solved variables, defining a similar process system for a commercial CFD software would be challenging and would result to very long calculation times. In the CFB3D-model, a fast calculation time is achieved by using fairly coarse mesh resolutions (typical mesh dimensions 0.2...0.5 m) and by using empirical correlations for defining the solid concentration profiles inside the furnace. In addition to three-dimensional simulation of the furnace, the model includes separate submodels, which describe the hot loop systems (separators, external heat exchangers, and return legs) and their interaction with the furnace.

The validation of the model is based on field studies ranging from pilot-scale to commercial-scale CFB boilers (Lyytikäinen et al., 2014). The characterization of fuels and sorbents is carried out by bench-scale studies. The model has been originally created for air-fired CFB combustion, but over the years it has been developed and applied to oxygen-fired combustion, calcium looping, gasification, and bubbling fluidized bed combustion (Koski et al., 2012; Myöhänen et al., 2009, Myöhänen et al., 2014, Parkkinen et al., 2017).

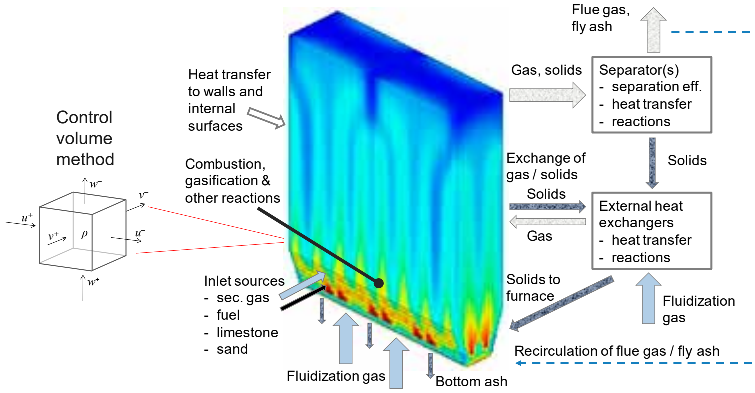

Fig.2. CFB3D model.

NOX REACTIONS IN CFB3D MODEL

In general, the following factors are identified to have the most significant effect on NOx emissions:

- Fuel properties such as fuel nitrogen and volatile content have direct effect on NOx reactions.
- Combustion temperature affects reaction kinetics.
- Amount of free lime (CaO) in the bed ash has direct effect on NOx reactions.
- Excess air level, O_2 concentration has direct effect on NOx reactions.
- Air arrangement and lower furnace design have indirect effect as they affect the residence time in certain oxygen conditions.

Fig. 3 presents the reactions that affect the calculation of NOx emission in CFB3D model (Vepsäläinen et al., 2009) and in-house emission model. NOx is formed from char nitrogen by reaction 2 or indirectly from volatile nitrogen through NH_3 by reactions 7, 8 and 9 (grey/black dash line). All NOx forming reactions require oxygen, thus, they are suppressed in furnace zones with reducing conditions. CaO and char catalyze reactions 8 and 9. NOx is reduced by volatile reactions 5, 10, 11, 12 (black/white dash line). Reactions are expressed according to the fundamentals of chemical kinetics, i.e., according to the Arrhenius formulation. However, the kinetic rate attributed to each reaction is derived empirically from boiler measurements. CFB3D model allows the investigation of reaction rate profiles of NOx reactions, and to study their dependence on process parameters like local oxygen concentration.

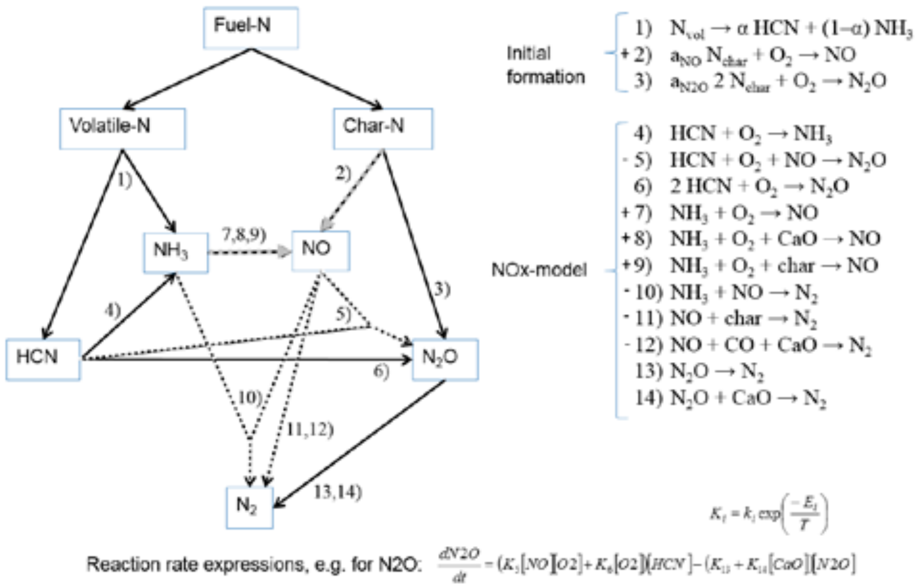

Fig.3. NOx model reactions in CFB3D model.

NOX REDUCTION WITH DESIGN MODIFICATION

The usual means of lowering NOx emission are lowering the design temperature and excess air amount, and increasing the air staging. The key thing is to create under-stoichiometry in the lower part of the furnace and provide sufficient residence time for gas in these conditions. This can be realized for example by keeping the grid air moderate and increasing the elevation of the secondary air level. With proper air arrangement, there is an area created where both the O_2 concentration and gas velocity decrease. This gives more time for the reductive NOx reactions to take place.

Reduction of NOx emissions in CFB boiler must always be done as overall optimization, as all the primary methods applied in order to reduce the NOx emission, also affect SO_2 and CO emissions. Lower design temperature and O_2 reduce NOx but they hinder the effect of limestone in capturing SO_2 and increase the amount of unburned components like CO. Very low air stoichiometry in the lower part of the furnace might lead to significantly higher limestone consumption and in excessive occurrence of gasification reactions. Also, too low design temperature of high load makes it difficult to meet minimum load targets.

Model based analyses were done to study the effect of changes in the process parameters and furnace geometry to NOx emission. Amec Foster Wheeler's 270 MW coal firing CFB unit was used as a reference. One boundary condition was to keep the furnace temperature at original level as temperature's effect to NOx emission is already well known. It was also important to make sure there are no reducing conditions created on the bare tube walls that could cause erosion/corrosion.

Clear emission reductions compared to reference were achieved with concepts that create areas with low oxygen content and low gas velocities to the lower part of the furnace. Fig. 4 presents relative NOx emissions of some of the calculation cases, along with the decrease in SO_2 reduction. In design 1, only the air distribution was changed, other designs include geometry modifications in the lower part of the furnace. According to CFB3D, over 30% NOx reduction is achievable by applying selected design modifications. Limestone flow was kept constant in the calculations. Depending on the design, SO_2 reduction degraded 0.2-4.7% compared to the reference calculation. Highest SO_2 and lowest NOx were achieved in the same case. In worst case, this would mean approximately 13% increase in the limestone flow to reach the original SO_2 emission. In many cases, the SO_2 emission limit is so low that it is no more viable to use only furnace capture, but optimize reduction between furnace and cold-end. For example, limestone utilization can be maximized by applying Amec Foster Wheeler's CFB scrubber, which utilizes still unreacted lime in fly ash for SO_2 capture. Lower limestone feed rate and higher SO_2 after furnace allow to design the boiler more in the NOx point of view. For some situations, design 2 or design 3 could be the most applicable if cold-end SO_2 capture is not an option. Over 20% reduction in NOx would still be achieved with only very low or moderate increase in limestone consumption.

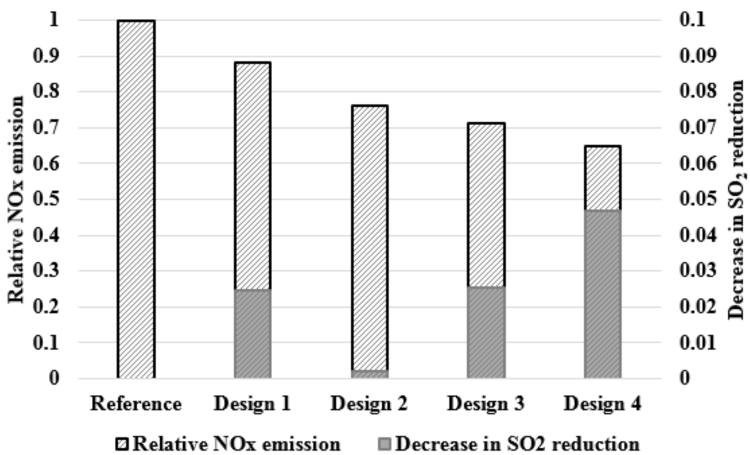

Fig.4. NOx reductions on a coal fired CFB unit with different design changes.

Following results are all from reference versus design 4, where NOx emission reduced by 35%. Residence time in under-air stoichiometry (λ<1) more than tripled from reference to design 4 and oxygen concentration below secondary air feeding was significantly lowered.

CFB3D model calculates reaction rates for each calculation cell as [mol_{NO}/m^3s]. Reactions can be observed in 3D or in 1D as a function of furnace height. In case of 1D observation, reaction rate is in this study presented as [mol/s]. Fig. 5 presents the reaction rates of individual NOx reactions summed for the entire furnace for reference case and modified design case. Reductive reactions are presented as negative. NOx generation from char nitrogen (R2) is greater in case of modified design but generation through NH_3 (R7) is diminished. Overall formation rate is equal to reference calculation. Reduction of NOx with NH_3 (R10) and CO (R12) are clearly greater in modified design bringing the overall reduction rate greater and therefore the total generation of NOx is lower than in reference. Lower oxygen concentration in the lower part of the furnace ensures that NH_3 is more likely to react with NOx than to combust with O_2 and create more NOx. Also, more CO is always present when oxygen is low. Secondary air feed before the end of bottom refractory ensures the combustion of CO.

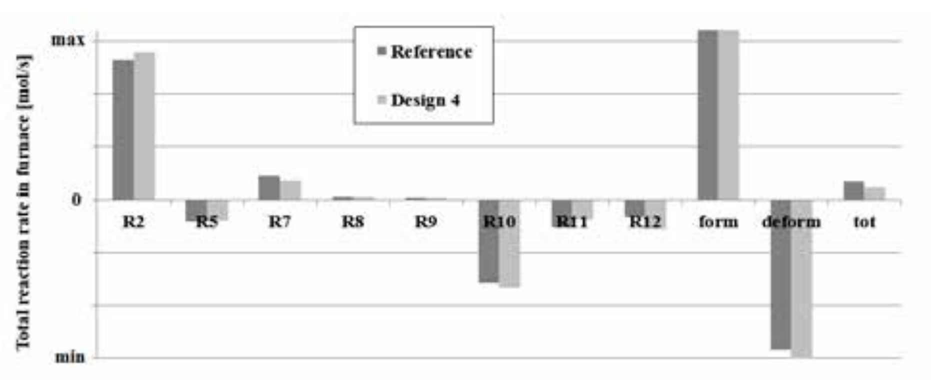

Fig.5. Total reaction rates [mol/s] in furnace of individual NOx reactions.

Then sum of NOx reactions is calculated by decreasing the reduction reactions from the formation reactions:

$$NO\ tot = R2+R7+R8+R9-(R5+R10+R11+R12)\ [mol/m^3s] / [mol/s] \quad (1)$$

Fig. 6 presents the total NOx reaction rate as function of furnace height and Fig. 7 presents the same in 3D plot from the middle slice of the furnace. Formation on the bottom is more minor in the modified design and total rate starts to be reductive earlier. Fig. 6 shows that reduction of NOx is much greater in modified design. After the secondary air is introduced, some NOx is inevitably formed as there is combustion of unburned components occurring. This generation has still very little meaning compared to the reactions before that. Fig. 5 includes only part of the furnace height. NOx reactions occur mostly in the lower part of the furnace and reaction rates in the upper part are very low.

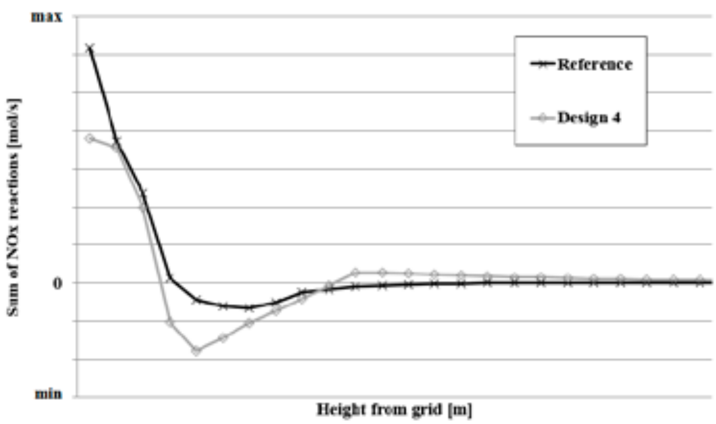

Fig.6. Total NOx reaction rates [mol/s] as function of furnace height (only part of the furnace).

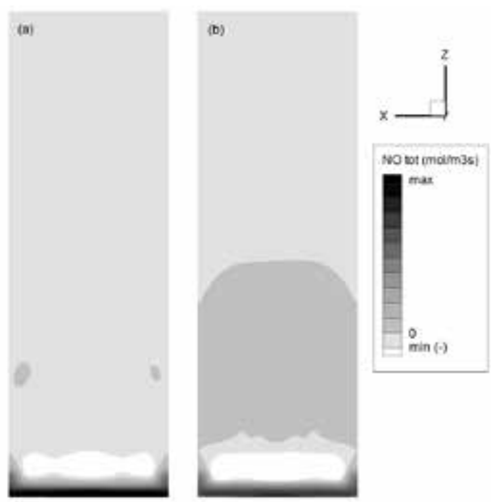

Fig.7. Modeled total NOx reaction rate for (a) Reference (b) Design 4.

Fig. 8 presents the modeled NOx concentration profile from the middle slice of the furnace. NOx is expressed in dry flue gas and in 6% O_2. Same conclusions can be made from this figure than earlier. In reference case NOx is high in the lower part of the furnace and keeps reducing along the furnace height. In the modified design there is an area below secondary air feeding where NOx is little bit lower than in the furnace exit. Fig.9 presents the SO_2 concentration profile from the middle slice of the furnace. It can be seen that SO_2 is not captured as efficiently in the lower part of the furnace in design 4 as in the reference calculation. Emission in the end of the furnace remains higher. Some compensation would be able to be achieved with further optimization of air and limestone feeds but this high reduction on NOx inevitably leads to higher SO_2 or higher limestone feed need.

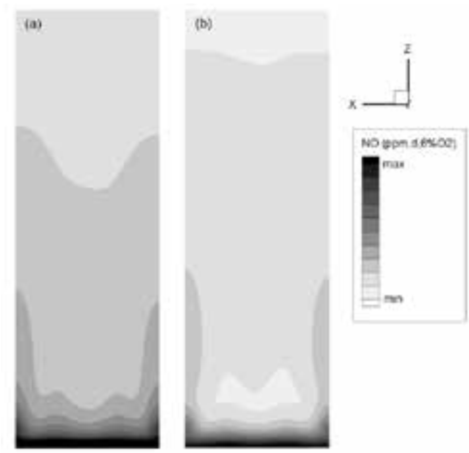

Fig.8. Modeled NOx concentration [ppm,d,6%O_2] for (a) Reference (b) Design 4.

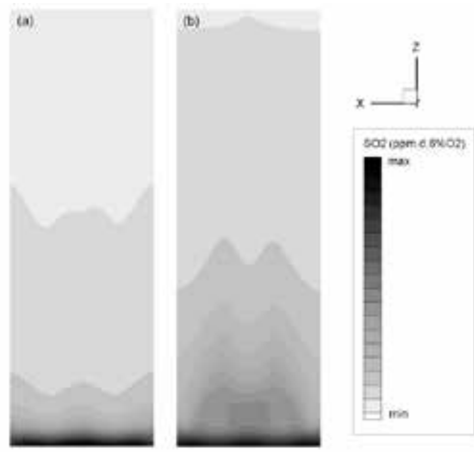

Fig.9. Modeled SO_2 concentration [ppm,d,6%O_2] for (a) Reference (b) Design 4.

FIELD VALIDATION

One of Amec Foster Wheeler's latest CFB references fires bituminous coal and includes design features to achieve the most stringent NOx and SO_2 emissions in European new builds. Boiler has natural circulation steam-cycle and is equipped with two separators and two INTREX™ superheating heat exchangers. The unit is in the scale class of 150 MW_{th} and is designed for ~545 °C and 120 bar steam. Coal contains nearly 2 % sulfur and 1.2 % nitrogen in dry basis.

Figures 10 and 11 present the relative NOx and SO_2 emissions of the reference boiler on full load and minimum load compared to emission limits. The NOx limit is met easily without SNCR. The SO_2 limit is also achieved with Ca/S ratios (i.e. limestone consumptions) considerably lower than the original design value. Utilization of the limestone is very high.

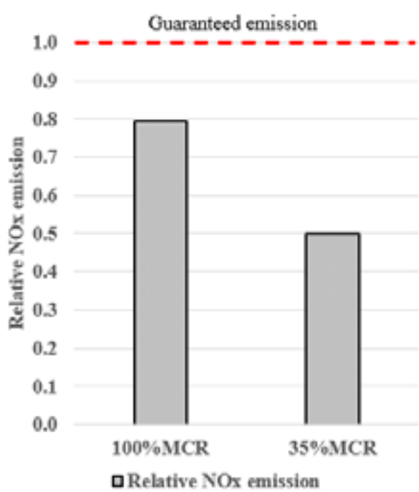

Fig.10. Realized NOx emission compared to the guarantee.

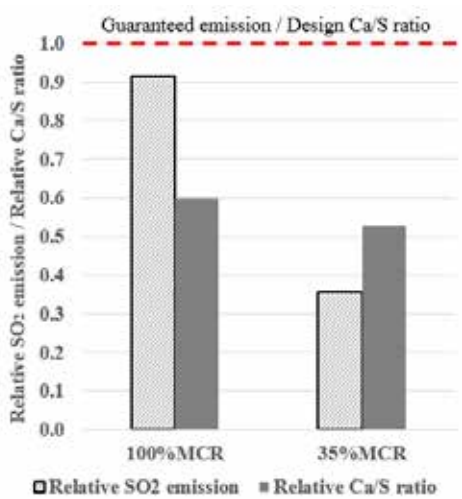

Fig.11. Realized SO_2 emission and Ca/S ratio compared to guarantee / design value.

CONCLUSIONS

Reduction of emissions in CFB boiler must be done as overall optimization, as all the primary means applied to lower NOx affect the SO_2 and CO emissions as well. Lower furnace gas temperature and O_2 reduce NOx but they hinder the effect of limestone in capturing SO_2 efficiently and increase the amount of unburned components like CO. Very low air stoichiometry in the lower part of the furnace might lead to significantly higher limestone consumption. SO_2 capture can be divided between furnace and cold-end device, like CFB scrubber, enabling to design the furnace more for NOx reduction and meet the NOx emission limit without additives or catalyst. In this study, as much as 35% NOx reduction was achieved in a 270 MW coal firing reference unit with novel design modifications, as compared to standard design, with a certain SO_2 penalty. A reduction of over 20% NOx was achieved with nearly no SO_2 penalty. The modifications in questions created a zone with low oxygen concentration and gas velocity in the lower part of the furnace, increasing the residence time in under-stoichiometric conditions by a factor of three without adding risk for erosion/corrosion in the furnace, while boosting the reactions that reduced NOx. Based on the study, the new design of the CFB furnace lower part combined with proper fuel and air feeding arrangements provide excellent NOx performance and gives broader capability for overall emission performance optimization and hence for reduction of operational costs.

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