



Reduction of air pollutants emissions from industrial furnaces and boilers

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Abstract

The comprehensive methodology of industrial complete systems redesigning towards reduction of combustion pollutants emission has been developed and used at Division of Heat and Furnace Technology since eighties. This methodology used to reduce emissions of CO, NO_x, SO_x and particulates in complex industrial combustion systems is based on complementary use of physical and numerical modelling.

Physical modelling is always used to select the most efficient design for clean and efficient combustion process. Three-dimensional physical models of the combustion chamber are manufactured to study the aerodynamics and effectiveness of mixing. Flow pattern visualisation and acid-alkali neutralisation method are used. Mathematical modelling is used to reproduce the results from the physical modelling.

Complementary results of both modelling attempt results in a new design of the combustion process and often in a new design of the plant. The redesigning of the power plants or district heating plants based on pulverised coal-peat fired boilers, oil fired boilers, and fluidised bed MSW incinerator is presented in this work. The plants were rebuilt accordingly and tested. The work shows great potential for correctly used modelling techniques when, designing new advanced and environmentally friendly combustion processes.



1 Introduction

There is a need for a retrofit control technology, which can achieve significant reductions in SO_x and NO_x emissions at low total cost. Firing low sulphur coals instead of conventional, medium and high sulphur coals as well as conventional flue gas scrubbing could be used to effect such reductions. This would however, cause severe economic hardship for coal-mines producing these coals. This may be very important, especially in case when locally used coals contain too much sulphur and/or nitrogen. Also, scrubbers are costly to install and operate, and all this increases the cost of electric power, even awhile the permissible levels of emission of sulphur oxides remain high.

An efficient and less costly way to reduce both SO_x and NO_x is a combination of sorbent injection for sulphur, and staged air and fuel injection for nitrogen oxides, directly in the combustion chamber or application of the SNCR technology. The air and fuel staging and sorbent injection is a retrofit technology with applicability to all types of boilers. Together they offer possibilities to reduce the emissions of nitrogen and sulphur oxides up to 80 and 60 % respectively. Retrofitting of industrial boilers and furnaces is based on comprehensive application of mathematical and physical modelling techniques.

2 Physical modelling and mathematical modelling as a base for redesign

Numerous studies in the field of heat and combustion technology have shown that physical modelling is a valuable technique for the study of aerodynamics in combustion chambers. The importance of physical modelling techniques in two- and three-dimensional are even more evident when combined with mathematical modelling to study industrial boilers, furnaces or burners. Both techniques can be used to verify and complement each other and give greater confidence in the accuracy of the obtained results, [1].

The physical modelling technique uses small scale isothermal, Plexiglas models. Water is used to represent the combustion gases or products and their mixing. Two- or three-dimensional models are used primarily to provide qualitative information. The technique visualises the flow patterns of the gas phase and simulates and visualises non-isothermal combustion processes despite isothermal conditions in the physical model. The so-called acid/alkali technique is used to simulate and visualise combustion in a water model. The main principle of this technique is that the combustion process is controlled by turbulent mixing between fuel and air. The neutralisation process is visualised by pH value colour indicators and recorded by a computer controlled video system and then analysed. Based on this analysis the efficiency of mixing in the different designs of combustion systems can be evaluated. The performance of the studied systems can then be compared and the best one selected.



To physically simulate flow and mixing behaviour in two- and three-dimensions the isothermal water or air model must meet a number of similarity criteria. These are necessary for qualitative and quantitative measurements in the model. To properly model the interaction between the hot furnace gases and cooler air jets in a cold isothermal model. The thermal expansion of the air jets is taken into account using so called equivalent dimensions for the OFA ports and burners. To model mixing between fuel and combustion air in a burner and the mixing and penetration of the OFA jets, it is necessary to create the same momentum ratios between each flow in the model as in the real combustion chamber.

Numerical modelling is used to reproduce the results from physical modelling, using a general purpose (Computational Fluid Dynamics) CFD code. This code uses a finite volume technique to solve the basic equations of fluid dynamics in 3-D. Detailed information on heat and mass transfer in the combustion chamber is in this way obtained. The calculation method is based on a finite difference solution of the basic equations of fluid dynamics together with mathematical sub-models. Sub-models of turbulence, combustion, soot, radiation, wall-effects and formation of NO pollutants are applied to predict properly combustion phenomena, [2].

3 Air pollutants

Atmospheric emissions from combustion systems are mainly in the gaseous phase, with some quantities of liquid and solid matter held in suspension. Some of the combustion products (e.g. CO₂ and water vapour) create not health hazard, although their effect on the local climate (the "greenhouse effect") may be noticeable. However the majority (including CO, NO_x, SO_x and oxygenated hydrocarbons) are toxic and may cause contamination of water and soil through rainfall and produce corrosion of metals and buildings.

Carbon monoxide is the product of incomplete combustion. It has been reported that the time required for the oxidation of CO is about 10 times that the time needed for oxidation of hydrocarbons. Experience shows that temperatures in excess of 750°C and 0.5 second residence time are required. In the absence of water CO is extremely difficult to burn. Incinerator experience shows that temperatures of 750 - 800°C are required with an actual residence time at this temperature of 0.2 - 0.4 seconds and 4 - 5 % O₂ as a minimum to achieve nearly complete oxidation of CO to CO₂. At these conditions less than 200 ppm CO in the flue gas can be expected. Units with poor mixing patterns exhibit outlet CO concentrations higher than 1000 ppm though temperatures are at 750 - 800°C level, [3].

The formation of NO_x during combustion involves three routes. The first is the well established **thermal route** which is often termed the **Zeldovich mechanism**. The second involves the reaction of fuel hydrocarbon fragments with molecular nitrogen and is termed the **prompt-NO route**, and the third is the reaction of organic-nitrogen compounds present in the fuel and its contribution is



dependent upon the origin of the fuel. This is so called **fuel-NO route**. In practical situations the nitric oxide formed is most radically influenced by **operating temperature, the level of excess air and the residence times**. In boilers, the NO_x produced is approximately proportional to the fuel firing rate and so in practice the NO_x in combustion gases ranges from 100 ppm for small installations to 1000 ppm for larger units, [4].

4 Primary modifications of the combustion process

Primary, in-furnace measures to reduce NO_x reduction as air staging, fuel staging and flue gas recirculation are applied usually taking into account the combustion chamber geometry and operating conditions. Control of temperature levels, residence time distribution and flow pattern are used to determine optimal conditions for CO, SOx and particulates reduction.

4.1 Air and fuel staging

The principle of the "over fired air" (air staging) method is that part of the combustion air is introduced after the main combustion zone in order to reduce the level of available oxygen in zones where it is critical for NO_x formation. Additional ports above the upper burner level can introduce air. The possible NO_x reduction by means of this method is about 20 - 50 %.

It is known that if the first stage of the combustion takes place in a fuel rich zone, the formation of NO_x is greatly reduced. The aim of the fuel staging technology is to reduce the, already formed NO_x , back to nitrogen during combustion. Three distinct zones in the boiler: a fuel - lean primary zone, a fuel - rich reducing zone, and a fuel- lean burnout zone can be separated.

The fuel, for instance coal, is supplied in two stages. Combustion of pulverised coal is mainly achieved in the first zone, while the second stage maintains a reducing atmosphere, in which the NO_x , which is formed in the first stage, is reduced. The temperature and stoichiometry of fuel and air in the reduction zone are to be so adjusted that NO_x reduction is maximised. The combustion process is completed in a fuel-lean burnout zone.

The following parameters have to be taken into consideration in order to determine the optimum process design: fuel type, stoichiometry, residence time, and temperature, air and fuel mixing. In addition, the following fuel properties are important: fuel nitrogen content and distribution, volatile matter content and release rate and char reactivity.

To succeed with the air-fuel staging, it is important that the operational conditions are optimised. The fuel staging technology can, in principle, be used on all type of fossil fuel fired boilers. The possible NO_x reduction by means of this method is 50 - 60%.



4.2 Sorbent injection

Since application of the air-fuel staging technology demands an accurate evaluation of the temperature and flow field inside the boiler, air-fuel staging may be easily combined with one of the injection of calcium-based sorbents methods.

Two major parameters control the utilisation of the calcium in the sorbent and thus the cost effectiveness of the process. These are: reactivity of the calcium oxide formed by calcination, residence time of the calcine under conditions conducive to sulfation. Due to rate and equilibrium limitations, significant sulfation cannot occur above approximately 1230°C. The rate of sulfation becomes negligible below approximately 870°C. Thus, residence time of the active particles within this temperature window is critical in the sulphur capture process. To make best use of available upper boiler residence time, sorbent must be injected at the point where the flue gases have cooled to about 1230°C; the ideal injection temperature. The low-cost calcium based sorbents can be injected at one or more locations further downstream in the boiler, and/or into the flue gas duct between the air and the precipitator. Calcium based sorbents react with SO_x to form CaSO_4 (gypsum) solids. These solids are then removed by normal ash handling equipment. The possible SO_x reduction by means of this method is about 60%.

4.3 Selective Non Catalytic Reduction (SNCR)

NO_x can be also reduced by injection of urea or ammonia (with additives) into flue gases. Technology has been widely applied in many countries to reduce nitrogen oxides in different types of boilers. The results in NO_x reductions vary between the installations depending on the boiler, fuel and operation. The NO_x reduction rates are between 30 % and 70 %. Urea is used, with or without additive in many installations as well as ammonia based solutions. The SNCR installations seems in general to be of simple design. In some cases the injection nozzels are located in existing holes in boiler walls.

Like in case of the sorbent injection an accurate evaluation of the temperature and flow field inside the boiler (residence time) is essential to successful performance of the SNCR (Selective Non Catalytic Reduction) system. The system wrongly installed can cause severe corrosion problems and tube leakage. The fuel in some cases can also cause operational problems with the SNCR system due to variations in moisture content causing temperature variations. Thus, the SNCR needs to be very carefully designed and well fitted to the boiler in the whole range of the load.



5 Design of a new combustion process

To succeed with NO_x/SO_x reduction it is also important to achieve the most efficient mixing of fuel, sorbent and ammonia with air and flue gas respectively. The objective is to mix the flue gas and the sorbent as quickly and effectively as possible. The same holds true for mixing between fuel and flue gas in the fuel rich zone. This can be achieved only by proper designing of the locations, size and shape of the air, fuel, sorbent or ammonia inlets, as well as by proper selecting of the injection velocities and flow rates for all of the mediums inside the boiler.

In order to get optimum conditions for combustion and reduction processes, all the process variables have to be optimised. This can be done by physical modelling of the flow field combined with very advanced mathematical modelling of each retrofitted boiler. It has to be stressed that each retrofit application should be carefully evaluated, since various physical constraints and other site specific factors may limit all nozzles design or location. With this technique, all the combustion zones can be operated under known and controlled conditions with no concern of corrosion.

As it was stated earlier, the possible maximum NO_x and SO_x reduction by means of the fuel staging, sorbent injection and the SNCR technology in both cases is about 60%. The application of the overfire air technique and modification of the existing burners each may give 20 - 30% additionally in reduction of nitrogen oxides. Taken all together then the total reduction of SO_x and NO_x emissions is up to 60% and 80% respectively.

6 Reduction of NO_x emissions from an industrial oil fired boiler

The complete combustion system of a 267 MW_{el} oil-fired boiler has been redesigned based on results from mathematical and physical modelling, [5]. The aim of the boiler modification was to reduce NO_x emissions by 75 percent.

Primary in-furnace measures to reduce NO_x reduction as air staging, fuel staging and flue gas recirculation were studied taking into account the boiler furnace geometry and operating conditions. The design of a new, low NO_x combustion process was based on experimental (physical modelling) and theoretical (mathematical modelling) studies of the boiler furnace aerodynamics, effectiveness of mixing and combustion processes.

Complete combustion during under-stoichiometric conditions at the burner level was obtained when 25 - 30 percent of the combustion air and 20 percent of recirculated flue gases was supplied via the OFA nozzles. Six of the OFA nozzles were placed at the boiler's "bullnose" and five (two with a turbulator) on the opposite wall. Finally, the distribution of fuel between the different burner levels was found to create even deeper under-stoichiometric conditions in

the combustion chamber, which is positive from a NO_x reduction point of view. During these conditions, the combustion can be completed at 5 % air excess. One of the best designs for the combustion system is shown in Figure 1. Transparent zone at the “bullnose” level means completed combustion. Plant tests showed that after installation of the system, a very low emission of NO_x (below 50 µg/MJ) was achieved without increased emissions of other pollutants.

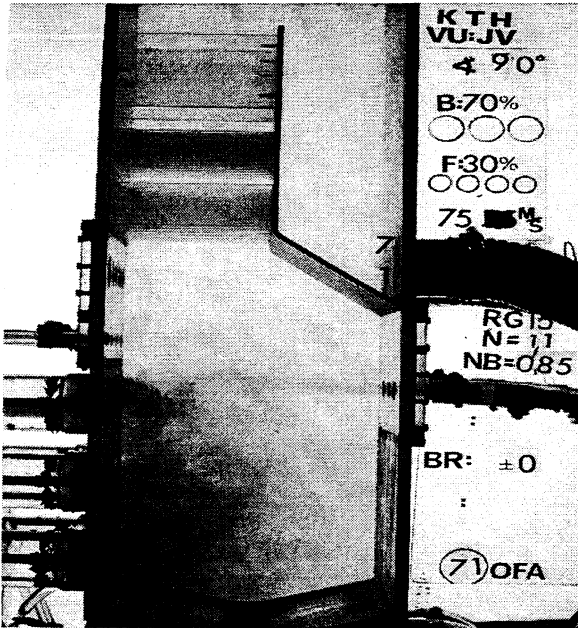


Figure 1: The best configuration of the oil fired boiler supply system found by physical modelling.

7 Reduction of NO_x emissions from a pulverised fuel boiler

The combustion system of a 400 MW_{el} pulverised fuel boiler has been design for two types of fuels, caol and peat, on the results of physical and the numerical modelling, [6]. The main task of the boiler redesign was reduction of NO_x emissions.

Primary in-furnace measures to reduce NO_x emission as air and fuel staging and flue gas recirculation were studied for two types of fuels taking into account the boiler furnace geometry and operating conditions (400 MW, 280 MW and 450 MW). The design of a new, low NO_x combustion proces for two different types of fuels was based on experimental, physical modelling, and theoretical, numerical modelling, studies of the boiler furnace aerodynamics, effectiveness of mixing and combustion processes.

Complete combustion during under-stoichiometric conditions at the burner level was obtained when 20 - 30 percent of the combustion air and 20 percent of recirculated flue gases was supplied via the OFA nozzels. Finally, the distribution of fuel between burner levels was found to create even deeper under-stoichiometric conditions in the combustion chamber to reduce NO_x . The combustion can be completed at 5 % air excess. One of the best configuration of air and fuel supply system for pulverised fuel (PF) fired boiler is shown in Figure 2. Completed combustion zone (transparent) above the burners level is followed by darkly marked OFA air jets. Plant tests showed that after redesign of the system for different type of fuels, a very low emission of NO_x (below 20 - 30 $\mu\text{g}/\text{MJ}$) was achieved without increased emissions of other pollutants.

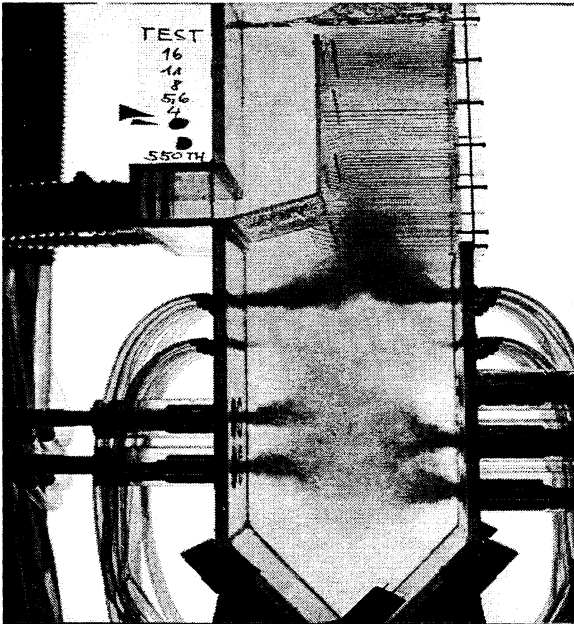


Figure 2: Optimised configuration of air and fuel supply system for pulverised fuel (PF) fired boiler.

8 Reduction of CO and optimisation of combustion in a fluidised bed MSW incinerator

The whole combustion system of a 100 MW_e fluidised bed boiler has been design on the results of physical and the numerical modelling, [7]. The main aim of the boiler redesign was reduction of CO emission. This modernization has caused for decreasing of NO_x emissions as well.

Primary in-furnace measures to reduce CO emission as air and fuel staging and flue gas recirculation were studied taking into account the boiler furnace

geometry and operating conditions (95 MW, 92.9 MW). The design of a new, low CO combustion process was based on experimental - physical modelling, studies of the boiler furnace aerodynamics, effectiveness of mixing and combustion processes.

Complete combustion during under-stoichiometric conditions at the burner level was obtained when 50 percent of the combustion air and 30 percent of recirculated flue gases was supplied via the OFA nozzels. Nine OFA nozzels were placed at the boiler's "bullnose" (four with a turbulator). Finally, the distribution of fuel between burner levels was found to create even deeper under-stoichiometric conditions in the combustion chamber, which is positive from a NO_x reduction point of view. The combustion, during these conditions, can be completed at 10 % air excess. One of the best configurations of air and fuel supply system for fluidised bed boiler is shown in Figure 3. Transparent zone at the "bullnose" level means completed combustion. Plant tests showed that after redesign of the system a very low emission of CO (below $50 \mu\text{g}/\text{MJ}$) was achieved. After boiler retrofitting the emission of NO_x was decreased too.

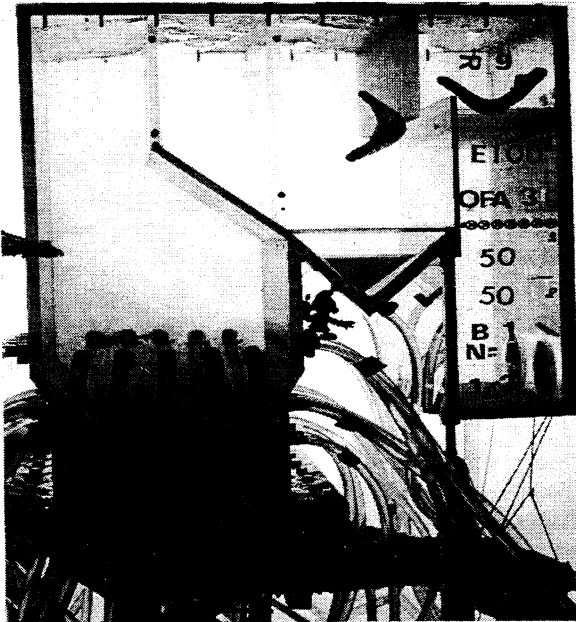


Figure 3: The best configuration of the fluidised bed boiler supply system found by physical modelling.



Summary

Complementary results of both modelling techniques result in a new design of the combustion processes. The plants were rebuilt accordingly and tested. The practical results confirmed the results of the modelling, with a very high reduction of combustion pollutants emissions well below Swedish national limits. The work shows great potential for correctly used modelling techniques when, designing new advanced and environmentally friendly combustion processes.

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